



IAHS 2025

October 05 - 10, 2025

Indian Institute of Technology Roorkee, India

ABSTRACT BOOK

**XIIth Scientific Assembly of
International Association of
Hydrological Sciences
(IAHS 2025)**

October 05-10, 2025

Organized by





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Indian Institute of Technology Roorkee, India

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IAHS 2025 Scientific Assembly

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Preface

The XIIth International Association of Hydrological Sciences (IAHS) Scientific Assembly is set to make a grand return to India after a remarkable gap of 16 years. Scheduled to take place from October 5 to 10, 2025, the Assembly will be hosted in the historic city of Roorkee.

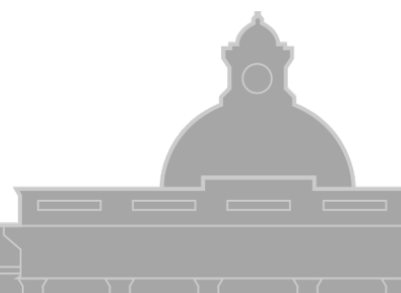
The XIIth International Association of Hydrological Sciences (IAHS) Scientific Assembly is set to make a grand return to India after a remarkable gap of 16 years. Scheduled to take place from October 5 to 10, 2025, the Assembly will be hosted in the historic city of Roorkee, which is renowned for its pioneering contributions to hydrological research, cutting-edge water resource management education, and its proximity to critical Himalayan watersheds. Roorkee's legacy as the site of India's oldest engineering institution, now IIT Roorkee, further underscores its status as a global leader in hydrological studies. This is an exciting milestone for India's hydrological community, as the last IAHS Assembly held in the country was in 2008, in Hyderabad.

The IAHS Scientific Assembly, established in 1922, has served as a pivotal platform for advancing the science of hydrology globally. With a mission to promote the study of water resources and their sustainable management, the Assembly facilitates collaboration among hydrologists, geoscientists, and policymakers. Over the decades, it has become a hub for presenting groundbreaking research, exchanging ideas, and shaping the future of water science. Its periodic gatherings have consistently addressed pressing water-related challenges, making significant contributions to global hydrological knowledge and practices.

The 2008 IAHS Scientific Assembly in Hyderabad was organized by the National Geophysical Research Institute (NGRI) in collaboration with the Indian Association of Hydrologists (IAH). Their efforts brought together experts from across the globe, fostering important discussions on water resource challenges and hydrological advancements. Proper acknowledgment of these contributions highlights the significant role of Indian institutions in advancing hydrological sciences.

The 2008 Assembly in Hyderabad was a landmark event that brought together researchers, scientists, and policymakers to address pressing challenges in water resources and hydrology. It provided a platform to discuss innovative solutions and collaborative opportunities, leaving a lasting impact on global hydrological studies. Sixteen years later, the XIIth IAHS Scientific Assembly in Roorkee promises to build on that legacy, addressing contemporary challenges such as increasing water scarcity, the impact of hydro-climatic extremes, innovative approaches to water resource management, and the integration of hydrological sciences with climate adaptation strategies.

Roorkee, home to the prestigious Indian Institute of Technology (IIT) Roorkee, NIH Roorkee, IRI Roorkee, and CBRI Roorkee, is renowned for its contributions to hydrological research and education. With its strategic location near the Himalayan watersheds and a vibrant community of researchers, Roorkee is an ideal venue for such a global event. The Assembly will be jointly organized by IIT Roorkee, NIH Roorkee, IRI Roorkee, and CBRI Roorkee, showcasing the region's collective expertise in hydrology and related fields.



About IAHS



The International Association of Hydrological Sciences (IAHS) is a non-profit, non-governmental scientific association that promotes hydrology and related sciences worldwide. With over 12,000 members in more than 150 countries, IAHS represents the largest international community of hydrologists. Legally registered in the United Kingdom as a charity (IAHS Ltd), the Association operates under the umbrella of the International Union of Geodesy and Geophysics (IUGG) and the International Science Council (ISC).

Founded in 1922 in Rome during the General Assembly of IUGG, IAHS was established to recognize hydrology as a scientific discipline and to promote its advancement at the international level. Since then, it has grown into the oldest global community of hydrological scientists, dedicated to fostering scientific collaboration, knowledge exchange, and interdisciplinary approaches to understanding water. Over the past century, IAHS has been instrumental in organizing conferences and workshops, producing influential scientific publications, and launching initiatives that have shaped the field of hydrology.

IAHS's **vision** is to enable inclusive scientific knowledge exchange in hydrology for sustainable development in a changing world. Its **mission** is to collectively advance and promote hydrological sciences worldwide, contributing to the interdisciplinary understanding of water-cycle processes, the sustainable use of water resources, and the mitigation of water-related risks. Central to this mission is a long-standing commitment to equality, diversity, and inclusion—regardless of geographic origin, ethnicity, language, culture, career stage, gender identity, or ability.

The Association has also been proactive in establishing task forces and committees that address emerging challenges and strengthen community engagement. For example, the Early Career Committee, founded in 2017, ensures that the next generation of hydrologists is fully integrated into IAHS activities. The Committee for Africa, launched in 2018, works to enhance the participation of African scientists, foster mentorship, and promote connections between the African hydrological community and the global stage.

Aligned with the principles of the ISC, IAHS supports the right of all people to engage in scientific enquiry, benefit from advances in science and technology, and freely exchange knowledge. This philosophy is reflected in its contributions to international frameworks such as the UNESCO Recommendation on Open Science, which emphasizes the importance of openness and cooperation in addressing global scientific challenges.

Today, IAHS continues to embody more than a century of international scientific collaboration. Through its assemblies, scientific commissions, publications, and initiatives, it serves as a vital platform for advancing hydrology, strengthening international networks, and ensuring that scientific knowledge contributes to sustainable solutions for water-related challenges worldwide.

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About IAHS Scientific Assembly



The IAHS Scientific Assembly is a premier international conference in the Hydrology domain held every four years around the globe and attracts many participants worldwide. The **XIIth Scientific Assembly of the International Association of Hydrological Sciences (IAHS 2025)** is jointly organized by the Indian Institute of Technology Roorkee, in coordination with the National Institute of Hydrology Roorkee, Irrigation Research Institute Roorkee and CBRI–Central Building Research Institute (CBRI) Roorkee, four leading institutions in the field of water resources in India, from 05 - 10 October, 2025.

The objective of the XIIth IAHS Scientific Assembly is to provide an opportunity to communicate, exchange and project on all major topics in the hydrological sciences within the framework of sessions organized by all IAHS Commissions and Working Groups. In the context of the multiple instabilities that prevail today, the task is immense and yet scientists have a duty to provide elements of answers and solutions to the challenges facing us in the coming years. In this respect, the diversity and quality of the expected participants is the guarantee of a productive and high-level Assembly.

The conference brings together researchers, practitioners, policy-makers, and students worldwide to discuss and exchange ideas on the latest developments, best practices, and innovative water resource management approaches. The conference covers a wide range of topics related to water resources, including water conservation, water quality, water governance, water-related disasters, climate change impacts on water resources, and emerging technologies for water management. The conference provides a unique platform for interdisciplinary knowledge sharing, collaboration, and networking opportunities. In addition to keynote speeches, technical presentations, and panel discussions, the conference includes field visits, workshops, and training programs. The conference provides an excellent opportunity for participants to engage with experts, interact with fellow professionals, and learn about the latest water resource management tools and techniques. Overall, the XIIth IAHS Scientific Assembly envisages playing an essential role in advancing the knowledge and practice of Hydrology.

This year IAHS experimented with a new program form, to encourage scientific outlook and interactions between participants. Everyone will get an opportunity to speak in a Forum for the plenum. In addition, there will be less but more engaging presentations for the broad community of hydrological sciences, without any parallel sessions.

Scientific Program

IAHS Commissions and Topics

IAHS Commissions and Topics:

1. Continental Erosion (ICCE)
2. Coupled Land-Atmosphere Systems (ICCLAS)
3. Groundwater (ICGW)
4. Human-Water Feedbacks (ICHWF)
5. Remote Sensing (ICRS)
6. Statistical Hydrology (ICSH)
7. Snow and Ice Hydrology (ICSIH)
8. Surface Water (ICSW)
9. Tracers (ICT)
10. Water Quality (ICWQ)
11. Water Resource Systems (ICWRS)
12. The 23 Unsolved Problems in Hydrology
13. Measurements and Observations in the XXI Century (MOXXI)
14. Citizens and Hydrology (CANDHY)
15. History of Hydrology
16. Global and Local Interactions (HELPING theme 1)
17. Holistic Solutions for Water Security (HELPING theme 2)
18. Cross-Cutting Goals (HELPING theme 3)

Contribution Types

Participants at the XIIth IAHS Scientific Assembly 2025 can present their research through the following contribution types, designed to maximize engagement and knowledge sharing:

1. **Plenary Oral**
Share key findings and scientific perspectives in a 15-minute oral presentation with a 10-minute dedicated discussion.
2. **Forum Oral**
In the forum oral, the author shall introduce research through a brief 1-minute flash presentation in the plenary room.
3. **Forum Oral with Poster**
Forum oral with poster allows you to present your research through a brief 1-minute flash presentation in the plenary room and a traditional poster presentation.
4. **Forum Oral with Poster and Video-Interview**
Forum oral with poster and video interview combine a brief 1-minute flash presentation in the plenary room, traditional poster, and 3-minute video interview. The video will be posted on the IAHS YouTube channel.
5. **Poster with Video-Interview**
Poster and 3-minute video interview enable the author to present research by traditional poster and supplement it with a video interview shared online.
6. **Poster**
Display your work through a traditional poster in designated poster spaces.

Program at a Glance

SCIENTIFIC PROGRAM						
Timing	Sunday, October 5	Monday, October 6	Tuesday, October 7	Wednesday, October 8	Thursday, October 9	Friday, October 10
09.00 – 10.30		1.1 Opening Ceremony (from 08.30)	2.1 Oral+ForumOral	3.1 Oral+ForumOral	4.1 Stockholm Water Prize Laureates Session (from 08.45)	5.1 Oral+ForumOral
10.30 – 11.00		Chai break				
11.00 – 12.30		1.2 Oral+ForumOral	2.2 Oral+ForumOral	3.2 Oral+ForumOral	4.2 Oral+ForumOral	5.2 Poster
12.30 – 13.30		Lunch break				
13.30 – 15.00		1.3 Oral+ForumOral	2.3 Oral+ForumOral	3.3 Oral+ForumOral	4.3 Oral+ForumOral	5.3 Oral
15.00 – 15.30	Registration	Chai break				
15.30 – 16.30		1.4 Oral+ForumOral	2.4 Oral+ForumOral	3.4 Poster	4.4 Oral+ForumOral	5.4 Closing Ceremony
16.30 – 18.00		1.5 Poster	2.5 Poster	3.5 IAHS AWARDS (from 16.00)	4.5 Poster	
SOCIAL EVENTS						
18.00 – 19.00	Ice Breaking Food & Drinks	*Sports Events	Science for Solution PANEL SESSION (from 17.00)		Cultural Event	Visit to Haridwar (from 17.30)
			IAHS Agora (from 18.00)	Gala Dinner (from 18.30)		
19.00 – 22.00			Buffet Dinner			

Abstracts

Continental Erosion (ICCE)

Geostatistical modeling of the spatial sediment distribution in the largest Arctic drainage basin, Lena, Russia

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ID: IAHS25_ABS_T7024

Sediment load runoff in the largest cryolithozone basin (the Lena River) has long been studied, but the data are irregularly distributed and last estimates were done for the end of XXI century. Therefore, the task of predicting sediment load remains relevant.

This study is based on stationary observations at hydrological gauges. Runoff data databank were updated on the basis of observation series twice as long as the previous ones, using new data on the surface with a significant improvement in spatial resolution. Correlation sediment concentration with factors of its formation were constructed for two periods. The following aspects were considered: morphometric characteristics of the topography, soil erosion factors, distribution of permafrost, climatic and hydrological drivers, as well as the influence of anthropogenic deformation of channels during open-cast placer mining.

Geostatistical modelling makes it possible to assess the contribution of factors to the spatial patterns of sediment distribution in a large catchment. We identified areas where the influence of several factors was predominant. Regression relationships between turbidity and the relevant factors were constructed for these areas. Dividing the basin into small and medium-sized catchments, the obtained relationships allowed to prepare a spatial map of water sediment concentration distribution. Additionally, contribution of basin and channel sources to the sediment load was assessed.

Keywords: sediment load, catchment, morphometry, erosion, climate, Lena River

Gully erosion in India: Land degradation impact, geomorphic attributes and evolutionary dynamics

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Gully erosion is the rapid incision of soils by concentrated overland and/or subsurface runoff. Despite gully erosion landforms being omnipresent across India, little was known about the spatial

extents of their land degradation impact, morphological attributes and erosion rates. Therefore, through exhaustive mapping, possibly the most extensive fieldwork ever undertaken in the domain of gully erosion research and multitemporal remote sensing, this work highlights the spatial distribution and areal extents of gully erosion, the spatial variability in gully morphological attributes and the dynamics of gully erosion and reclamation in India. Overall, the findings indicate that India not only has some of the largest gullies worldwide (up to 412 m wide and 78 m deep) but select locales of the country also experience some of the worst gully erosion rates (up to 800 t/ha/year) on our planet. Although the badlands of Central and Western India account for a large 70% of the total gully-affected land area, we have found that gully erosion in Eastern India is currently a particular cause of concern not only due to the widespread occurrence, but also because of high activity rates that seldom remain within the local permissible soil loss rates. On the contrary, the badlands are stabilised, and the gullies therein exhibit limited activity, if at all, which has prompted large-scale land reclamation activities in said regions. Gully morphological attributes such as width-depth ratio and cross-sectional area differ considerably, with statistically significant differences observed across climates, geomorphological settings, soil types and land cover/use classes. By providing critical insights into the scale, nature, and severity of gully erosion in India, this project's findings support practical strategies for sustainable land management by aiding in the identification of particularly erosion-prone regions where management efforts should be prioritised, which has relevance for the ongoing national land degradation neutrality drive.

Keywords: India, Gully erosion, Gully systems, Badlands, Gully morphology, Gully dynamics, Gully rehabilitation, Gully reclamation

Using Cs-137 measurements to detect changes in sedimentation rates in a floodplain area of northern Norway. Preliminary results of a field sampling campaign.

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Introduction

Floodplain sediment records may provide important information on soil erosion and deposition rates over large catchments and for different time windows. In this context, the use of anthropogenic and geogenic radiotracers has recently attracted increasing attention for their ability to act as sediment markers and to reflect the environmental impacts due to variation in land use and recent climate changes. ¹³⁷Cs is one of the most employed radiotracers for sediment chronology due to its easy detectability in the environment and to its strong ability to be retained by sediments in depositional areas. ¹³⁷Cs activity in sediments reflects the temporal fallout occurred in the area and, as such, it proves to be a very effective indicator to reconstruct the trend of soil erosion and sedimentation rates during the last 6-7 decades.

Aims and objectives

In this contribution, a floodplain area in northern Norway was identified as a 'pilot site' to explore possible anthropogenic impacts and climate change effects on deposition rates from uncultivated sites.

Methods

A sampling campaign aimed at collecting different sediment cores was undertaken. The cores were sectioned in the lab and analysed for ^{137}Cs activity and particle size distribution. Contextually, information on precipitation and temperature dataset was obtained from meteo stations available in the study area.

Results

The radiometric analyses provided evidence of bomb test and Chernobyl fallout in the area. These results made it possible to obtain information on sedimentation rates for different time windows (i.e. 1963-1986 and 1986-2024).

Conclusions

The overall results suggested an increase of sedimentation rates during the last 4 decades that is consistent with the increasing trend of mean annual temperature and total rainfall. The study provided evidence of climate change in the area and confirms the effectiveness of the use of radiotracers to detect similar problems in different geographic contexts.

Keywords: Cs-137, Soil erosion, Sedimentation rates, Radiotracers, Sediment chronology, Norway

Sediment Dynamics across the estuarine reach of the monsoon-dominated Subarnarekha Basin

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The sediment dynamics of the Subarnarekha Basin, an east-flowing tropical river system in India (West Bengal), are significantly influenced by the monsoonal seasonality, especially in its estuarine reach. This study aims to establish seasonal and spatial patterns of the suspended sediment concentration (SSC), the nature of particle size, determine the organic to mineral ratio of Non-Volatile Suspended Solids (NVSS) to Volatile Suspended Solids (VSS), the settling velocities (SV), and potential sediment mass retention-resuspension. The research results summarize the first year of monitoring, which consisted of water sampling at the key locations along the 50 km estuarine section. The samples were subjected to laboratory analyses, including the gravimetric method of suspended particles falling in the water column developed in Owen Tube. Preliminary findings indicated seasonal variability in SSC, SV, median diameter of particles, and NVSS/VSS, with peak sediment loads occurring in conjunction with monsoon-induced flows. Additionally, local land-use practices were found to exacerbate sediment delivery and variabilities of spatial patterns of concentrations during specific periods, particularly during high-flow events.

The study emphasizes the implications of sediment dynamics and seasonal hydrological changes regarding appropriate watershed management in the Subarnarekha Basin. It contributes to a broader understanding of the sediment processes in non-perennial, monsoon-driven river basins. It provides key insights for developing water and soil management strategies in estuarine and coastal areas.

Keywords: Monsoon-induced flows, Sediment dynamics, Suspended Sediment Concentration (SSC), Settling velocity (SV), Non-Volatile Suspended Solids (NVSS), Volatile Suspended Solids (VSS),

The volume of water stored in Mackenzie Delta lakes during freshet flows and their impact on sediment dynamics. Case study of Big Lake in Inuvik, Canada.

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River deltas are a crucial link in the transport of sediments and nutrients between the basin and the sea. Climate change is accelerating the melting of the permafrost occurs under the bottom of the Mackenzie River Delta, which is driving hydrological and morphological changes in the river system. In this contribution, lake morphological parameters were identified as a 'pilot site' to develop an indicator of lakes' ability to retain sediments.

The study area is the Mackenzie River delta in the Inuvik region, approx. 130 km from the Arctic Ocean, and a lake called Big Lake located on it. It is one of 2,000 lakes that have a year-round connection with one of the main water distribution channels in the delta.

We used satellite images taken during the open water season to capture shoreline ranges and relate them to water table heights from the East Channel gauging station in Inuvik, located several hundred metres from the study site.

As a result, we have established that the water storage capacity in individual years differs both in terms of the maximum water volume and its retention time. For example, in 2024, the lake stored 8.2 million m³ of water for 49 days.

The future acquisition of additional in-situ data on sediments (including grain size and its concentration) will allow us to precisely answer the total volume of sediments retained by the lakes connected to the river.

The research is carried out as part of the project funding from the Polish Ministry of Education and Science - National Research Agency, title: Evaluation of the settling velocity and trapping capacity of sediments in lakes in the Great Arctic River deltas, grant no. 2023/50/O/ST10/00597.

Keywords: river delta, Arctic, hydrological modelling, sediment retention, floodplain lakes

Integrated catchment-scale sediment transport model

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Soil erosion models are often limited to parameterization on field and slope scales. However, sediment flux assessment is required at larger scales in many studies, such as sediment-related pollution transport. We investigated a combination of semi-distributed hydrological model ECOMAG with catchment erosion and channel transport models of several designs to assess the amount of sediment load from different hydrological response units to stream network. The downhill erosion is parametrized on an elementary watershed scale as a weighted average from multiple hydrological response units within it and is contributed to the channel network. Subsequently, the channel transport is calculated as the balance between the neighboring cells and with the contribution from the adjacent elementary watersheds. We test the approach on several case studies in Russia, where the monitoring data was available, such as the Primorskaya water balance station in the Far east of Russia, and several others.

Keywords: erosion model, catchment hydrology, hydrological modelling

Simplified approaches to estimate rainfall erosivity from coarse temporal resolution precipitation data in the Mediterranean Belt

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Rainfall erosivity represents a pivotal element of the Revised Universal Soil Loss Equation (RUSLE) and its precursor, i.e. the Universal Soil Loss Equation (USLE). The determination of erosivity is dependent upon the use of fine-resolution (at most 30 minutes) rainfall data. Datasets of this temporal resolution are usually accessible from low-density tipping bucket rain-gauge networks and for relatively short periods of time in the majority of Mediterranean countries. Therefore, it is often necessary to resort to simplified empirical equations to estimate rainfall erosivity based on coarse resolution (e.g., daily) rainfall time series, usually available from higher-density rain-gauge networks for multi-decadal time periods. In the present study, two new empirical relationships were developed and compared with eight existing empirical equations. The analysis was carried out using 10-minute rainfall data from 2004 to 2023, available at 335 automatic rain gauge stations across three pilot regions in southern Italy (Campania, Sardinia, and Sicily), which allowed the calculation of 132,609 benchmark values of mean annual rainfall erosivity. The first proposed model is parsimonious and exploits two compound meteorological predictors, namely the rainfall episodicity index and the rainfall concentration ratio, obtained from daily aggregated rainfall data (i.e., mean annual rainfall, Gini's coefficient of daily rainfall distribution, mean annual number of rainy days). The

second model is multi-parametric and includes geographic and topographic covariates (latitude, elevation, and minimum distance to the coastline). The two proposed models outperformed the eight existing equations based on statistical performance metrics, including the root mean square error, the mean error, the adjusted coefficient of determination, the Kling-Gupta efficiency, and the Akaike information criterion. Results provided valuable insights for testing model transferability in other regions of the Mediterranean Belt in future studies.

Keywords: Soil erosion, RUSLE, R factor, Daily rainfall erosivity models, Gini's coefficient

Hydrological Analysis and Prioritisation of Best Management Practices in the Hirakud Catchment using SWAT and ACPF

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Comprehensive management planning of the Hirakud Catchment was undertaken using hydrologic modelling and evaluation of the Best Management Practices (BMP). Trend analysis of climate and discharge data was undertaken, and the Soil and Water Assessment Tool (SWAT) hydrological model was calibrated and validated using a multi-site approach to identify areas prone to soil erosion for implementing and assessing BMPs. Key findings from the trend analysis indicate stable trends in rainfall, maximum temperature, and minimum temperature over time. Streamflow dynamics were analysed for five stations within the catchment, showing different patterns, with some locations experiencing statistically significant decreases in both annual and monsoonal streamflow. Calibration and validation of the SWAT model using SUFI2 improved prediction accuracy, yielding NSE values of 0.66, 0.68, and 0.66 for Ghatora, Kurubhata, and Basantpur stations during calibration, and 0.54, 0.58, and 0.55 during validation, respectively. Soil erosion at the basin and sub-basin levels was estimated, identifying varying severity across different sub-basins, with erosion rates ranging from 3.44 t/ha/yr to 63 t/ha/yr. The implementation of BMPs significantly reduced soil loss under various conditions, with filter strips and contour bunding achieving reductions of approximately 85% to 98%. To further enhance conservation planning, this study proposes the integration of the Agricultural Conservation Planning Framework (ACPF) with SWAT to prioritize conservation practice locations more effectively. ACPF, which identifies suitable conservation practice locations based on landscape characteristics, will be utilized alongside SWAT simulations of erosion-prone areas. A multicriteria ranking approach will be explored to prioritize conservation practices based on sediment loss hotspots, cost efficiency, and pollutant reduction potential. This planned integration aims to facilitate more targeted and effective interventions, ensuring optimal placement of BMPs for soil erosion mitigation and improving watershed management strategies.

Keywords: SWAT, BMPs, ACPF, Trends, Soil erosion, Hirakud

Multi-tool data set on Northern Eurasian Riverbank Erosion: methodology, spatial variations

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Measuring and predicting of riverbank erosion has a long history in Earth system science. The existing literature mostly relies on basin-wide and reach-scale observations, whereas the existing global data of riverbank erosion is related to classifications of Landsat imagery, which does not provide sufficient spatial and temporal resolution. Here we aim at constructing representative dataset of riverbank migration observations based on diverse measurement methods: image processing tools, including the application of high-resolution mapping of global surface water, and repeated field surveys. The dataset presents the data from nine large river basins around Northern Eurasia, which includes rivers of the Baltic Sea, The Arctic and Pacific Oceans and the Caspian Sea, namely the Vistula, Volga, Ural, Ob, Nadym, Yenisey, Lena, Indigirka, Kolyma and Kamchatka catchments. The rivers included in the dataset comprise different environmental conditions and rivers with year-round average discharges ranging from 0.3 to 19,700 cms. In total, 23,000 km of small, medium and large rivers of Northern Eurasia using up to 70 years of data on water classifications from satellite images (LandSat and Keyhole) over 150,000 river channel reaches were analyzed in this study. The dataset captured information of channel erosion rates (average bank retreat rates [m/year]; maximum bank retreat value in meters per year [m/year]; average area of bank retreat [m²/year]; volumes of channel erosion [t/year]) and possible drivers (both hydrological and catchment parameters such as permafrost, natural zones and geology). We demonstrate that river discharge and permafrost distribution are the best first-order predictors of riverbank erosion in Northern Eurasia. These data will help improve understanding of bank erosion mechanisms and drivers and will support improved predictive models of river channels.

Keywords: bank erosion, large rivers,

Assessing the impact of uncertainty in global soil property datasets on soil erosion predictions.

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ID: IAHS25_ABS_A1559

Soil maps are essential for understanding and managing Earth's resources, with applications in hydrology, agriculture, climate modeling, and disaster response. Conventional soil maps group soils based on their similar cartographic properties, as on the legendary soil surveys, while digital soil mapping predicts the values of various soil properties through available soil point datasets and geostatistics or other modeling techniques. It is expected that both types of soil mapping contain some degree of uncertainty. Traditional soil maps, based on field surveys, can be subjective, while digital soil maps, derived from geostatistical and pedometrical techniques, may suffer from limited data and modeling errors. This study evaluates the representativeness of global and pan-European

digital soil maps by comparing them to detailed national soil data from Greece. Specifically, we compare gridded datasets from the European Soil Data Centre (ESDAC) and ISRIC World Soil Information (SoilGrids) with point data from the soil map of Greece repository and field surveys, focusing on soil properties relevant to erosion prediction (e.g., soil texture, depth, infiltration capacity, organic matter). Initial results show significant spatial variability in the agreement between datasets, with larger discrepancies in areas with distinct soil characteristics (e.g., fine soil types). These differences can significantly impact soil erosion predictions. This research highlights the importance of multi-source data integration for developing more robust and reliable global soil datasets and provides recommendations for future mapping initiatives.

Keywords: SoilGrids, Global Soil Datasets, RUSLE, soil erosion modeling

Evaluating the temporal dynamics of potential soil losses: Idice River Basin (Emilia Romagna Region, Northern Italy) case study

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The potential estimation of precipitation-induced soil loss, based on approaches such as the USLE and its modifications, is usually derived from multi-year averaged values. While this facilitates data processing and information sharing to non-experts, it also overlooks crucial aspects (and the concomitant occurrence) such as the pronounced seasonality of rainfall patterns, variations in anthropo-induced land cover as those due to agricultural cycles or unintentional as the occurrence of hydrological disturbances (e.g., wildfires).

Under such premises, this study presents a framework for the temporally dynamic estimation of triggering and predisposing conditions inducing precipitation-induced soil erosion. The proposed approach is applied to the Idice River basin, which has been affected by multiple extreme precipitation events from May 2023 to October 2024. While the impacts of these events in terms of landslides and floods have been extensively investigated, the assessment of soil loss impacts at the event scale remains a recognized knowledge gap.

The evaluation of the factor related to the land cover/use exploits the interpretation of high-resolution spatial and temporal remote sensing data while, for rainfall erosivity, multi-year continuous rainfall observations at a resolution of 15 minutes are adopted.

This research enables a comparison between conventional soil loss estimates and those derived from a temporally dynamic evaluation of contributing factors. Furthermore, what-if scenarios provide insights into the significance of accounting for transient patterns in rainfall erosivity and land use conditions. The findings are expected to support the identification of climate-proofing adaptation measures, acting locally on land use and land cover and ensuring a proper protection of the soil surface during the periods where the most impactful triggering conditions (extreme rainfalls) are expected to occur in the investigated test cases. Finally, it permits a clearer understanding about how the most common hydrological disturbances can exacerbate soil loss in the affected areas.

Keywords: soil loss, rainfall erosivity, seasonality, remote sensing, land cover, adaptation measures

Enabling large-scale soil erosion assessments: exploring the potential of Earth Observation and Artificial Intelligence

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Rainfall-induced soil erosion has significant ecological and socio-economic consequences, pushing the development of soil erosion indicators to monitor policy implementation and effectiveness. In the European Union, soil erosion is also used as a proxy for the UN SDG 15.3.1 indicator “Proportion of land that is degraded over total land area”. While essential for land management and planning, large-scale soil erosion assessments remain challenging due to data limitations, methodological transparency, and infrequent updates. This work presents recent efforts to develop open-access, scalable tools for assessing soil erosion dynamics over space and time. These tools implement the empirical Revised Universal Soil Loss Equation (RUSLE) model by integrating diverse data sources, including Earth Observation products. Additionally, they combine data-driven artificial intelligence techniques to improve the estimation of some RUSLE components. These tools were developed through a co-design approach, ensuring their usability across different contexts, and active stakeholder engagement. After presenting the tool design, the potential for replicability and scalability will be discussed, in addition to the remaining challenges in enhancing accessibility, validation, and operational uptake. Finally, practical examples from selected use case studies across Europe will be shown by referring to the Horizon Innovation Action (IA) project “AI-augmented ecosystem for Earth Observation data accessibility with Extended reality User Interfaces for Service and data exploitation” (EO4EU) and some synergies from the Horizon Research Innovation Action (RIA) “SDGs-EYES”, the Italian “IRIDE” initiative in collaboration with ESA, and the “SEEDS” project funded by IFAB.

Keywords: soil erosion, land management, tools, earth observation, artificial intelligence, co-design

Sediment Budget Formation in Permafrost-Affected Siberian Rivers: Ob, Yenisey, Lena, and Kolyma

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The formation of sediment transport and channel processes in Arctic river basins is heavily influenced by physiogeographic and climatic conditions, with permafrost playing a critical role. Permafrost regulates climate, hydrology, and geomorphology, altering sediment transport patterns and promoting unique fluvial and denudation processes in cryolithozone regions. However, assessing

these processes remains challenging due to limited observational data and a lack of reliable re-search methods.

This study focuses on the sediment origin and transport processes in the watersheds of major Siberian rivers—the Ob, Yenisey, Lena, and Kolyma based on remote sensing, field data and modelling. A classification system for processes involved in sediment budget in cryolithozone rivers was developed, alongside numerical methods to evaluate sediment budget components. These methods include watershed component assessment using the WATEM-SEDEM and Larionov-Krasnov (Erosion) models, as well as remote sensing-based quantification of bank erosion and retrogressive thaw slumps (RTS).

The results provide a numerical assessment of sediment transport processes and reveal the relationship between basin-derived and channel-derived sediment components. The findings contribute to a better understanding of sediment budgets in large Siberian watersheds, which is essential for predicting the impacts of climate change on Arctic hydrology and geomorphology.

Keywords: Erosion, fluvial processes, permafrost, sediment runoff,

A Quantitative Assessment of Riverine Erosional Hazard and Vulnerability in Upper Tapi River, India

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This comprehensive study examines riverine erosion vulnerability in the Upper Tapi River region across two periods: 1978-2000 and 2020. The research integrates satellite imagery analysis, geospatial techniques, and socio-economic indicators through three main indices: exposure, susceptibility, and resilience. The erosion hazard assessment revealed significant hazard levels in central areas, particularly around Chira and Kasaikheda, while northeastern and southwestern sections showed moderate to low hazard levels. The exposure index, which considers factors like geology, relief, geomorphology, and soil conditions, remained relatively stable, with 62% of the area maintaining very high exposure values, especially in forested regions. A notable trend emerged in the susceptibility index, where high-susceptibility areas increased substantially from 3% in 2000 to 16% in 2020. This increase was primarily driven by population growth, higher settlement density, and agricultural land conversion. However, the study also found improving resilience factors, with high-resilience areas growing from 3% to 27%, attributed to better socioeconomic conditions, greater forest cover, and improved medical facilities. The vulnerability patterns showed significant spatial shifts between 2000 and 2020. Initially, high vulnerability was concentrated in downstream villages like Dodhe, Hamidpura, and Ner, characterized by low resilience combined with high exposure and susceptibility. By 2020, the high vulnerability zone had expanded to include middle and downstream regions, affecting villages such as Rangubeli, Gogaipur, Ahukhana, Hatnur, and Birpura. These findings emphasize the need for targeted erosion management strategies and sustainable practices, particularly in newly identified high-vulnerability areas. The study demonstrates that despite improvements in resilience factors, the combined effects of exposure and susceptibility continue to create significant erosion vulnerability challenges in the region.

Keywords: Upper Tapi River, Erosion hazard, Exposure, Susceptibility, Resilience, Vulnerability

Comparative Analysis of Machine Learning Algorithms for Predicting Local Scour Depth Around Bridge Piers

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Scour is a significant concern that affects the integrity of a hydraulic structure. Bridge collapses due to scour can cause significant property damage and loss of life, hence its prediction is of utmost importance for the safety of the bridge. The prediction of scour depth around bridge foundations is a difficult task due to the complex processes and the involvement of a variety of uncertain factors, making it very difficult to obtain precise results using conventional models. Computer science breakthroughs have led to a paradigm shift toward Artificial Intelligence (AI). They have many advantages over traditional methods reducing time and cost in scour depth prediction. The current study estimates scour depth around piers utilizing three distinct machine learning (ML) models: Random Forest (RF), Support Vector Regression (SVR), and Artificial Neural Network (ANN). The main objective of this research is to examine the precision of artificial intelligence techniques in predicting maximum scour depth around piers. The results of the ML models were also compared with empirical equations for enhanced insights. USGS Pier-Scour Database (PSDb) reported by Benedict and Caldwell (2014) was employed in the research. Total number of datasets used was 522. Out of 522 datasets, 47 were used as the unseen set for checking the generalization performance, while the remaining 475 were divided into 70% (332 row-data) for model training and 30% (143 row-data) for testing. Two empirical equations developed by Yanmaz (2001) and Arneson et al. (2012) were used for comparing the ML models. Out of the three ML models the RF model performed the best ($R^2 = 0.9346$) followed by ANN ($R^2 = 0.9323$) and SVR ($R^2 = 0.8813$). All the ML models outperformed empirical equations. AI techniques can enhance scour prediction near bridge piers, by employing data-driven solutions that align with advancement in smart water management systems.

Keywords: scour, piers, machine learning, random forest, data driven

Multi-Decadal Shoreline Dynamics in Chilika Lagoon: Progradation, Retreat, and Their Drivers

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Coastal wetlands are dynamic systems controlled by the balance between hydrodynamic forces and sediment supply. Chilika Lagoon, Asia's largest brackish water wetland, shows significant accretion along its northern lagoon borders due to sediment flux from Mahanadi distributaries, and erosion along its open coastline from tide and wave action. This study uses a hotspot analysis to identify and quantify zones of extreme shoreline change and link them to dominant drivers. Using multispectral images from GEE (1972–2025), we applied Otsu thresholding and AWEI to define shoreline positions. The boundary of Chilika was divided into seven sections, with transects at 40m intervals analysed via DSAS. "Hotspots" are defined as the transects in the upper 10 percentile of accretion or erosion rates.

Based on the results, we identified four distinct morphodynamic zones across the lagoon and its

adjacent coastline, driven by varied terrestrial and coastal processes. The northern sector, with progradation rates up to 150 m/yr, is attributed to intense fluvial sedimentation and expansion of aquaculture and agriculture. The northeastern sections exhibit mixed patterns—accretion from sediment inflow alongside erosion driven by human activities, particularly aquaculture. The southeastern lagoon margin endures significant erosion (up to 25 m/yr), likely due to storm activity and proximity to the open coast. The adjacent coastline shows localized accretion, while most other areas predominantly experience erosion driven by coastal processes and storm activity. Shoreline change measures and change detection maps aid understanding of these patterns. Factors such as lithology, slope, land-use changes, and extreme events influence regional variability, while upstream regulation and artificial channels are referenced in the literature but not specifically quantified. Overall, the results underscore the combined impact of natural processes and human activities on Chilika's shoreline dynamics. These findings offer insights into targeted measures for improving long-term resilience and stability of Chilika Lagoon's coastal and lagoon habitats.

Keywords: Chilika lagoon, Coastal Wetland Dynamics, DSAS, Erosion & Accretion, Hotspot Analysis, Remote Sensing, Sediment Flux

Coupled Land-Atmosphere Systems (ICCLAS)

Water Balance From Percolation Scaling and Ecological Optimality

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Introduction: The Water Balance, or partitioning of precipitation into evapotranspiration and run-off, defines the scope and the goal of hydrologic sciences. According to "Opportunities in the Hydrologic Sciences," otherwise known as the Eagleson Report, it is also the template for the carbon cycle and, moreover, "ecological optima are [likely] the preferred operating domain of the climate-soil-vegetation system." Additionally, "the abundance of species and their spatial distribution are related to [these] ecological optima." Finally, "scaling theories are not only of theoretical interest but also of immense practical importance."

Aim and Objectives: Solve the water balance based on scaling theories and ecological optimality (maximization of net primary productivity, NPP) and generate associated predictions for carbon cycle, species richness, and water resources.

Methods: Use scaling relationships for soil formation and vegetation growth from percolation theory, the most accurate treatment of scale-dependences on networks for flow and solute transport.

Results: Percolation optimal paths scaling relationship yields the time dependence of root growth from minutes to 100kyr and the climate dependence in terms of evapotranspiration rates ET and the fundamental network scale. The solute transport scaling relationship from percolation theory yields soil formation rates from years to 120Myr and across the world's climates from the Atacama Desert to the New Zealand Alps in terms of P-ET and the same spatial scale. Since plants require both soil and ET to grow, an optimal partitioning between ET and $P-ET=Q$ exists that maximizes NPP. The evapotranspiration rates relate to the horizontal dimensions of root mass and the soil depth is important for the vertical dimension, allowing a formulation for the root volume that can be maximized by setting its derivative with respect to ET = 0 and achieving an optimal partitioning of water P between soil formation (Q) and plant growth (ET). Validation of resulting predictions for NPP (WRR, 2024), streamflow elasticity (AGU Advances, 2023), the water balance itself (WRR 2021, STOTEN 2023), and species richness (Entropy, 2024) reveals not only the genius of the authors of the Eagleson Report, but thereby solves some (6,7) and makes contributions to others (1,19-22) of the 23 unsolved problems in hydrology. Note that it also generates the observed scale-dependence of ET (WRR, currently in review).

Summary: The unifying nature of a physically-based solution of the water balance is demonstrated across scales and continents, as well as disciplines. Although it is physically based, the solution integrates Newtonian and Darwinian concepts.

Conclusions: Addressing heterogeneity and its scale-dependent effects on solute transport using appropriate theoretical techniques as applied to a heterogeneous network model of the soil provides the soundest basis for attempting a Darwinian solution of the water balance, because such effects are most limiting to growth and productivity.

Keywords: Water Balance, Scaling, Percolation Theory, Prediction

Science-based information for adaptation to climate change in rainfed agriculture

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Globally about 60% of our food is produced under rainfed agriculture (RFA), i.e. without significant irrigation infrastructure. In some regions of the world, such as sub-Saharan Africa, Southeast Asia, etc., RFA can cover more than 90% of food production. At the same time, RFA is extremely vulnerable to climate variability and change, through changes in rainfall (timing and intensity) and air temperature (warming and higher evaporative demand). This significantly challenges the future of food security and the livelihoods of farmers in RFA regions, particularly in small-holder subsistence systems. It is therefore a high priority to be able to provide stakeholders in such RFA systems with state-of-the-art information about their vulnerabilities today and in the future, so they can prepare and adapt. Here we provide an example of such science-based information on the key aspects (climatic, hydrological, agroecological) of the functioning of RFA systems in Ethiopia, combining publicly available gridded climate, soil, land use, and crop data with hydrological models and data analytics. We present three main results of such analyses: (a) We show how the temporal characteristics of rainfall can be quantified, particularly the onset of the rainy season and the seasonal distribution of rainfall, which fundamentally determine the growing season water availability, and we show how delays in the rainy season led to measurable crop yield losses. (b) We show how water-limited crop yields (crop yield gaps) within the growing season can be estimated by combining hydrological modelling of soil water and evapotranspiration under present and future climates, and we illustrate where rainfall or temperature changes dominate the response. (c) We show how the potential changes in cropland suitability given by a combination of climatic and soil properties for staple crops can be quantified, allowing good spatial predictions of where/which crops can grow today and in the future. Ultimately, this work shows that climate change is likely to negatively affect future water availability and crop yields, especially in dry areas across the RFA region of Ethiopia. The anticipated impacts on cropland suitability are severe, leading to elevation-related shifts and an overall reduction in suitable cropland areas for major cereal crops such as maize, teff, sorghum, and wheat. Our methods can be replicated in other RFA regions globally and we argue that such analyses can be a critical source of science-based information needed for risk management and for developing long-term climate adaptation plans for climate resilient crop production.

Keywords: rainfed agriculture, hydrological modelling, climate change, cropland suitability, water limited crop yields

Mechanisms of onset, termination and propagation of pre-monsoon heatwaves in India

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In this study, we analyse the linkages between the onset, termination and propagation of pre-monsoon heatwaves in India. We first use complex network theory to identify the regions of origin and termination of heatwaves and their spatial synchronization. We find that heatwaves most frequently originate in northwest India and propagate either northeast or southeast. Heatwaves propagating northeast tend to have higher intensity but shorter duration and smaller areal coverage than those propagating southeast, which are more influenced by El Niño Southern Oscillation (ENSO). The analysis of surface energy budget during heatwave events shows that high net short-wave radiation due to low cloud cover is the dominant driver of onset of heatwaves. However, the mechanisms driving heatwave termination exhibit regional variability with heatwaves in eastern India terminating with rainfall and those in northwest India terminating with advection of heat to downwind regions.

Keywords: Heatwaves, Event synchronization, Radiative fluxes, Complex networks, Heatwave trajectories

Evaluation of Surface Flux Equilibrium model for evapotranspiration estimation

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Accurate estimation of evapotranspiration (ET) at the watershed scale is crucial for water budget analysis and management of water resources. Models based on the Penman-Monteith (PM) equation, which are most commonly used for ET estimation, require the estimation of surface resistance which depends on the land surface characteristics. Therefore, the estimation of "effective" parameter values of these models at large spatial scales becomes challenging under heterogeneous land surface characteristics such as vegetation type, soil moisture, topography, and land use. Recently, several equilibrium-based methods have been proposed which assume that land and atmospheric variables achieve a steady state due to exchange of mass and energy fluxes, and therefore the atmospheric state variables can be used for estimating ET fluxes at large scales. One such method - the surface flux equilibrium (SFE) method - uses relative humidity and air temperature to estimate ET rates. While the model has been shown to provide reasonable estimates of annual ET at watershed scales, it has not been evaluated at shorter timescales. In this study, we evaluate the ET estimation using SFE model at the 8-day scale using reanalysis datasets in India. We identify the regions with large differences in ET estimate from the two methods and investigate the physical factors responsible for these differences.

Keywords: Evapotranspiration, Evaporation, Evaporative fraction, Relative humidity, Equilibrium

An analytical approach for quantifying the role of vapor pressure deficit in flash drought evolution

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Several studies have attributed the rapid drying during flash droughts to vapor pressure deficit (VPD) by using VPD anomaly-based metrics. In this study, we use an analytical approach to investigate the role of VPD in flash drought evolution and evaluate if the anomalies actually reflect the role played by VPD in soil moisture depletion. We model the energy and water balance of the land and lower atmosphere using a simplified slab model and use the energy and water balance equations of the model to decompose the daily changes in soil moisture during flash droughts into those caused by external forcings such as precipitation, wind and radiation on a day and the system response driven by the initial conditions of ground temperature, air temperature, soil moisture and specific humidity on the day. We apply this approach to investigate the role of VPD in flash drought evolution in ten major watersheds of India. We find that VPD anomalies can correctly identify its role in soil moisture depletion only in semi-arid regions. In arid regions, even low anomalies of VPD can contribute significantly to soil moisture depletion due to the large magnitude of VPD, whereas in humid regions even large VPD anomalies do not lead to significant impact on soil moisture depletion. Our results show that the influence of VPD is underestimated in arid regions and overestimated in humid regions if metrics based on VPD anomalies are used for analysing its effect on flash droughts.

Keywords: Flash droughts, land-atmosphere interaction, physical mechanisms, vapor pressure deficit

Long Term Variability in Low Level Jet and its Relationship with the Indian Summer Monsoon Rainfall

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The Monsoon Low Level Jet (MLLJ) is considered as one of the pivotal component of monsoon. The LLJ is a manifestation of strong cross equatorial flow driven by the thermal gradient between landmass and surrounding ocean regions. Objectives of the present study are to investigate the intra-seasonal and interannual variability of Low Level Jet Stream over two decades 2000-2023 and its relation with Indian monsoon rainfall variability. Changes in horizontal and vertical extent of LLJ and its influence on the regional differences in rainfall are studied on intraseasonal and interannual timescales. The daily and monthly mean horizontal wind at different standard pressure levels obtained from the multi-model reanalysis during the monsoon period is utilised to investigate LLJ Characteristics like LLJ Peak Speed, Peak Height, Wind Reversal Height over Indian monsoon region. The GPCP and IMD gridded rainfall data is used to analyse rainfall and correlate with LLJ variability. Day composites of precipitation corresponding to strong LLJ days and weak LLJ days shows the regions receiving more and less precipitation respectively. Long-term variability of LLJ is found out and is correlated with Indian Summer Monsoon Rainfall. Some of major conclusions

arrived from the study include that the strength of LLJ influence the regional distribution of monsoon precipitation and its quantity.

Keywords: LLJ, Monsoon variability, Precipitation, Long-term Variability.

Atmospheric moisture linkages to flood inducing Multiday extreme precipitation in India

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Extreme precipitation events are becoming more frequent and intense worldwide, significantly elevating the risk of devastating floods. India, as a hydrologically vulnerable region, experienced recurrent floods that lead to substantial economic losses and fatalities. This study explores the atmospheric drivers and moisture linkages responsible for multi-day extreme precipitation events that resulted in meteorological floods across India. Severe meteorological flood events were identified across India using the Dartmouth Flood Observatory (DFO) database. The study examines the interplay between Integrated Vapor Transport (IVT) & Integrated Water Vapor (IWV) at different vertical layers of the atmosphere, and precipitation at hourly timescales. Results highlight the critical role of elevated moisture transport in the lower atmosphere, which intensifies prior to flood events. Spatial analysis reveals a strong correspondence between IWV and precipitation patterns, suggesting that IWV provides a more consistent spatial signal for extreme precipitation events than IVT. The findings indicate that sustained moisture influx alone is insufficient to trigger extreme precipitation. However, its interaction with local atmospheric instability and synoptic-scale disturbances creates a conducive environment for prolonged precipitation, culminating in floods. This study underscores the importance of atmospheric moisture dynamics in driving extreme precipitation events and calls for deeper investigation into regional moisture budgets to improve flood prediction and mitigation strategies.

Keywords: Meteorological floods, Atmospheric moisture transport, Multi-day extreme precipitation, Flood drivers

Understanding the Characteristics of Western Disturbances in Changing Climate

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Global climate change has been influencing the local and regional climate systems, including the Western Disturbances (WDs) over the Indian Region. The increasing variability in the snowfall over the Himalayas and the occurrence of WD events has been observed in recent decades. However,

research on WDs in the backdrop of climate change is still in its infancy stage. This study comprehensively analyzes the changing attributes of Western Disturbances from 1950 to 2022 during winter (DJF) and summer (MAM) over the WD impact zone (20- 40°N and 60-90°E) using track dataset provided by Hunt et al. (2018) and European Centre for Medium-Range Weather Forecasts Reanalysis v5(ERA5) dataset. Furthermore, the composite structure method has been incorporated to analyze the variations in the atmospheric patterns of all the WDs present during that period. The trends in the characteristics of these events, such as frequency and seasonality, have also been studied using the Mann-Kendall and Theil-Sen estimator test. The study unravels the increasing frequency of strong WD events in the summer, whereas there is no significant change in winter. The expansion in the travel paths of WDs in recent decades has also been observed. The findings can enhance conceptual understanding of these atmospheric phenomena, including addressing the variability in WD events and strengthening climate resilience efforts.

Keywords: Western Disturbances, India, Climate Change, Atmospheric Patterns

Understanding Hydrological Seasonality in a Himalayan River Basin under Changing Climate

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This study addresses potential in runoff seasonality as a consequence of climate change in an important region for water resources and electricity production of the Indian Himalayas. A sub-catchment, Balganga River, as part of the Bhilangana River basin in the Indian Central Himalayas, was analysed using observed and projected future climate data. Examining the maximum monthly rainfall data provided by the India Meteorological Department (IMD) for 1901 to 2020 reveals a noteworthy shift in the peak towards earlier months, particularly up to June. This observation suggests seasonal changes in flood peaks associated with a warming regional climate. Upon comparing different data sets, it was found that the IMD precipitation dataset best matches the observations. The projected climate ensemble of the dataset NEX-GDDP required significant bias correction before it could be used for any purpose. Hydrological modelling is conducted with the CemaNeige-GR4J model system to project changes in floods for historical and future conditions. The model was calibrated with observed discharge data for the Sarasgaon gauge station and showed good agreement with discharge observations. Scenario simulation was done for historical (1971-1999), RCP 4.5 (2071-2099), and RCP 8.5 (2071-2099) scenarios. The results indicated potentially vanishing snow-packs in the future. Due to higher temperatures and precipitation in the future, the simulated future discharge series is significantly higher, in particular for the RCP 8.5 scenario. Regarding the timing of annual maximum flood peaks, a possible early shift is indicated for future conditions if a combination of snowmelt and rainfall-induced floods occurs. This shows the possible occurrences of changing flood composition, though uncertainties of projected future precipitation, temperature, and the resulting streamflow, are significant. The study highlights the potential impact of climate change on hydrological seasonality in this Himalayas region, emphasizing different runoff-generating processes. One shows the need for measuring programs, modelling and data analysis.

Keywords: Flood Seasonality, Himalayas, Climate Change, Streamflow Simulation

Influence of Land Use/Land Cover and Climate Change on Hydrological Processes

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Impact of Land Use Land Cover (LULC) and Climate change (CC) on runoff and sediment yield (SY) is a critical global issue, significantly influencing agricultural productivity, water quality, and food security. Separating the contributions of these factors is vital for effective infrastructure planning, best management practices, water resource management, etc.? Hence, this study aims to study a small watershed in India, analyse LULC dynamics from 2000 - present year, project changes for 2030, and discuss the possible anthropogenic influences using Water Erosion Prediction Project (WEPP) model. Secondly, individual and combined effects of LULC and CC on runoff and SY have been quantified over the specified period.? To achieve the desired result, the research adopts a multi-site and multi-temporal calibration approach to improve the model efficacy for simulating the hydrological responses (Runoff and SY) at the watershed outlet, also to find the sensitive parameters for Indian hydro-climatological conditions. The simulation of runoff and SY values were in good agreement with the observed value, since we have used multi-site multi-temporal calibration approach the simulated results are very useful in data scarce region as this approach of calibration makes sure that the errors are not getting aggregated till the watershed outlet. The findings reveal that both LULC and CC significantly affect runoff and SY, but the influence of LULC changes is more pronounced, particularly in terms of sediment yield. Although climate variables have contributed to runoff and SY variations since 2000, the effects of CC are overshadowed by the dominant impact of LULC. Projections for 2030 indicate an increase in runoff to 100.13 m³/s and SY to 3.97 t/ha/yr. When we calculate the percentage of increase from 2000 to future, runoff increases by 14.69% and the SY has increased by 49.23%. Detailed discussion of the results will be made in the upcoming session.

Keywords: WEPP model, Climate and LULC change, Soil Erosion and Sediment Yield

A global intercomparison and evaluation of flash drought indicators

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Flash droughts are distinguished by a rapid development and intensification, which reduces the time for early warning and decision-making, increasing the potential agricultural, environmental and hydrological impacts. Although the scientific community's interest in flash droughts has grown considerably in recent times, the ambiguity surrounding the concept and the lack of broadly accepted

approaches and indicators for its identification make them difficult to analyse. Over the last few years, numerous studies have employed a wide variety of indicators for flash drought monitoring and assessment from regional to global scales. Such studies have demonstrated remarkable variations and discrepancies in the trends and spatio-temporal patterns of flash droughts.

Here, we provide a comprehensive comparison of flash drought characteristics at global scale based on different indicators that have been widely used for the identification and quantification of this type of event. For this purpose, we generate a new high spatial- (0.1 degree) and temporal- (weekly) resolution dataset for the period 1982-2020, which includes the following standardized indicators for monthly accumulated periods: (i) Standardized Precipitation Index (SPI), (ii) Evaporative Drought Demand Index (EDDI), (iii) Standardized Precipitation Evapotranspiration Index (SPEI), (iv) Standardized Evapotranspiration Deficit Index (SEDI) and (v) Standardized Soil Moisture Index (SSMI). Our findings highlight the ongoing challenge of adopting one flash drought metric over others even when the same approach for flash drought definition is used - unsurprisingly, there is no 'one size fits all' metric. Nonetheless, we recognise some key attributes of each approach that can provide useful information for future research and applications. Our consistent, global-scale analysis provides a benchmarking of different flash drought indicators, that could pave the way towards guidance for their use in diverse environments and settings. This establishes a foundation for greater consensus on the most appropriate approaches and indicators for flash drought assessment and monitoring.

Keywords: flash droughts, standardized drought indices, precipitation, evapotranspiration, potential evapotranspiration, soil moisture

Exploring Arctic Sea Ice and Indian Summer Monsoon teleconnections using a multiscale approach

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The unprecedented warming in the Arctic region is influencing global climate systems through complex atmospheric and oceanic processes interacting across varying spatial and temporal scales. Although the influence of the Arctic on midlatitude climates is well-documented, its connections to the tropics, particularly the Indian Summer Monsoon (ISM), remain largely unexplored. Therefore, the present study aims to unravel the multiscale association between Arctic Sea Ice Concentration (SIC) and ISM precipitation using the Maximum Overlapping Discrete Wavelet Transform (MODWT) and correlation analysis. The study also accounts for regional variability in Arctic Sea Ice by partitioning the Arctic into the Atlantic Arctic Sector (AAS) and Pacific Arctic Sector (PAS). The results reveal significant disparities between AAS and PAS in their influence on ISM across interannual to multidecadal scales. Further, the cross-correlation analysis was performed to explore the relationship between Arctic Sea Ice variability, large-scale oscillations like the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO), and ISM rainfall, followed by the composite analysis to explain the plausible mechanism behind Arctic-ISM teleconnections. These findings underscore the critical role of Arctic warming in shaping tropical climate and highlight the importance of incorporating regional heterogeneity and multiscale perspectives to improve our predictions of ISM.

Keywords: Indian summer monsoon, Arctic warming, seaice, teleconnection, wavelet

Expanding Woody Encroachment - Is it a Concern for Water Yield? Case studies from South Africa under Varying Climates

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Grasslands and savannas are undergoing significant transformation due to woody encroachment. Woody encroachment, a recognised form of degradation, is the gradual spread and thickening of indigenous trees and/or shrubs in a grassland or savanna, within or beyond their natural ranges. These species displace grasses and herbaceous vegetation eventually leading to a closed canopy resembling that of a dense shrub or forest. While the drivers of woody encroachment are well understood, its impact on hydrology remains uncertain and concerning.

To explore the effects of woody encroachment on hydrology, paired "plot" experiments were conducted in a semi-arid savanna and a mesic grassland. Evapotranspiration (ET) was monitored simultaneously over encroached and non-encroached areas at both sites. The mesic grassland site consisted of long-term paired catchments: one fire-adapted grassland that senesces in winter and another dominated by evergreen tree encroachment. The savanna site was part of a long-term woody plant clearing trial, comparing a dense stand of mopane trees with an annually cleared plot. Additional measurements of climate, soil moisture, and streamflow were also taken.

At the mesic grassland site, ET was significantly higher in the encroached catchment, particularly during the dry winter months, due to the evergreen trees maintaining transpiration while the grassland senesced. Tree canopies intercepted 29% of event rainfall, and over time, the runoff ratio of the encroached catchment declined compared to the grassland catchment. Similarly, in the savanna, ET was higher in the encroached mopane plot, with the most pronounced increases occurring during wet seasons and above-average rainfall years. As mopane encroachment expanded, its impact on ET became more evident.

Regardless of climate, encroachment consistently reduced water yields, underscoring the need for active management, particularly in the face of global change and increasing water scarcity.

Keywords: Evapotranspiration, interception, paired plots, global change, water security

Understanding the Spatiotemporal Variability of Precipitation Recycling in the Ganga River Basin

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The study of the precipitation recycling ratio (PRR) within the Ganga Basin reveals significant insights into the dynamics of the local water cycle. PRR, defined as the ratio of locally generated precipitation to that originating from external moisture sources, was meticulously analyzed using high-resolution ERA-5 reanalysis data and a bulk model method. The investigation encompassed spatial and temporal trends across four distinct Indian seasons-summer, winter, monsoon, and post-monsoon-spanning from 1990 to 2023. Findings indicate a predominance of external moisture flux contributing to precipitation in the Ganga Basin, with elevated PRR values observed during the summer and monsoon seasons, attributed to increased evapotranspiration and moisture transport. Conversely, winter seasons illustrated the lowest PRR. This research emphasizes the critical need for a comprehensive understanding of PRR in the context of water cycle mechanisms, which is vital for effective water resource management and the assessment of climate change impacts.

Keywords: Precipitation Recycling Ratio (PRR), Ganga Basin, ERA-5 reanalysis data

Critical Soil Moisture thresholds of plant water stress over India in response to Atmospheric Variability

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Understanding and quantifying the critical soil moisture threshold (θ_{crit})-the soil moisture (SM) level at which the soil-plant continuum shifts from energy-limited to water-limited regime during drying periods-is crucial for gaining insight into land-atmosphere-vegetation interactions. θ_{crit} plays pivotal role in determining transpiration limits and vegetation productivity under SM drying scenarios. In this study, we quantify θ_{crit} for Indian biomes using Soil Moisture Active Passive satellite data with two independent methods. The first method, grounded in the conceptual frameworks of the Budyko Curve and Soil Moisture-Evapotranspiration coupling, explores relationship between evaporative fraction (EF) and SM by characterizing three intervals of this piecewise linear function, which are separated by wilting point and θ_{crit} (SM-EF method). The second method relies on covariance between gross primary productivity (GPP) and vapor pressure deficit (VPD) under varying SM conditions (cov(GPP-VPD)-SM method). This approach captures subtle variations in θ_{crit} more effectively than the SM-EF method, particularly in assessing seasonal dynamics and impacts of different hydrological forcings. Using the cov(GPP-VPD)-SM method, we analyzed seasonal variations in θ_{crit} across India. Our results indicate that during the monsoon season, θ_{crit} is higher by $0.1036 \pm 0.0019 \text{ m}^3/\text{m}^3$ compared to the non-monsoon season. Additionally, we examined how θ_{crit} responds to drying pulses driven by rainfall versus irrigation, revealing that rainfed pulses exhibit a higher θ_{crit} (by $0.0376 \pm 0.0012 \text{ m}^3/\text{m}^3$) than irrigation-driven pulses. This suggests that variations in atmospheric

aridity-characterized by higher (lower) VPD in non-monsoon (monsoon) and irrigation-driven (rain-driven) scenarios-play a crucial role in shaping θ_{crit} . Our findings highlight the significant influence of VPD on seasonal and hydrological input forcings variations in θ_{crit} , underscoring the need to integrate VPD into methodologies for estimating θ_{crit} . Furthermore, the distinct responses between rainfed and irrigated conditions underscore the importance of adopting context-specific approaches for assessing these dynamics in diverse agricultural landscapes.

Keywords: Critical soil moisture threshold, Evaporative fraction, Vapor pressure deficit, soil-plant continuum.

A Novel Framework for Assessing Drought-Flood Abrupt Alternation: Insights from the Columbia River Basin , USA

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Floods and droughts, traditionally considered distinct natural disasters, are increasingly occurring in rapid succession, a phenomenon known as drought-flood abrupt alternation (DFAA). Understanding the probability and frequency of these events is crucial for enhancing community resilience in the face of climate change. However, existing methodologies and indices have limitations in reliably identifying and characterizing DFAA events. To address this gap, we introduce a novel methodology that provides a more realistic assessment of droughts and floods. We integrate meteorological, agricultural, and hydrological perspectives by utilizing precipitation, soil moisture, and streamflow conditions. We apply this methodology to the Columbia River Basin, a region of significant agricultural and hydropower importance in the United States. We utilize the PNWNAm database, sourced from the Pacific Climate Impacts Consortium (PCIC), which provides data for historical (1945-2012) and future (2013-2099) periods under medium and high representative concentration pathway (RCP4.5 and RCP8.5) radiative forcing scenarios. Our findings indicate that areas with lower event frequency experience more abrupt transitions between droughts and floods, whereas regions with higher event frequency exhibit smoother transitions and greater climatic stability. The timing of drought to flood transitions remains relatively stable but shows a slight shift toward later in the year, while flood to drought transitions display greater variability. A trend analysis based on data for 1945-2099 reveals an overall increase in the frequency, intensity, and duration of both transition types. However, these trends lack statistical significance across historical and future scenarios.

Keywords: Precipitation whiplash, Lagged compound extreme events, Dry and wet spells, Multi-variable standardized index, Hydroclimatic swings

Examining the interplay between Droughts and Floods in India amidst Climate Change

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Droughts and floods are two extreme hydrological events that pose significant challenges to water resource management, agriculture, and livelihoods in India. The interplay between these extremes is becoming increasingly complex under changing climatic conditions, leading to cascading socio-economic and environmental impacts. This study examines the dual phenomena of droughts and floods, focusing on their spatial and temporal patterns, underlying mechanisms, and socio-economic impacts. Furthermore, we also analyse the drivers influencing these shifts, including temperature anomalies, precipitation variability, and land use. Our findings reveal a growing frequency of compound extreme events. The study further explores the role of climate change in intensifying these interactions, emphasizing the need for adaptive water management strategies. By identifying hotspot regions and key influencing factors, this research aims to provide crucial insights into the interactions between flood-drought extremes.

Keywords: drought, flood, flood-drought extreme, climate change

Developing a multi-risk impact-based forecasting and warnings system for India

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Impact-based forecasts and warnings (IbFW) are used to convey the likelihood of impacts associated with different hazardous meteorological and hydrological conditions leading to cyclones, floods and droughts. The appraisal of impacts is generally made on a hazard-by-hazard basis and does not always consider the interplay between different hazards or the cascading risks that can occur. This has the potential to lead to inaccurate assessments of the risk associated with hazardous events. For example, the predicted impacts are often underestimated because the risks posed by multiple hazards occurring together or in quick succession (i.e., multi-hazards), as well as the indirect, cascading impacts and risks are not accounted for. This paper, supported by the UK Met Office's Weather and Climate Science for Service Partnership (WCSSP) programme in collaboration with multiple Indian partners including the India Meteorological Department, explores the latest 'multi-risk' methods and tools that describe the interactions between multiple hazards and the varying vulnerabilities and exposures in time and space, and discusses which approaches would be appropriate for implementing a multi-risk IbFW system in India. We focus on the Indian Himalayan region - a region that is prone to multiple hazards. In July 2023, intense rainfall in the state of Himachal Pradesh in India led to flash flooding and landslides, resulting in 330 fatalities, thousands of blocked

roads and damage to other critical infrastructure. We show the results of an international review of state-of-the-art of multi-hazard(risk) assessments and communication approaches, including quantitative semi-quantitative and qualitative approaches, which are applicable to developing a multi-risk IbFW system in India. We describe a case study where different approaches to multi-risk IbFWs will be piloted. We conclude by discussing the practical challenges of implementing IbFWs in the Indian context, including data availability, verification, the assessment of uncertainty and methods of communication.

Keywords: multi-risk, multi-hazard, flood forecasting, impact-based forecasting, warnings

A Novel Network-Based Methodology for Analysis of Atmospheric Rivers

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Atmospheric Rivers (ARs) are narrow corridors of concentrated moisture transport that play a crucial role in global precipitation and extreme weather. The present study employs complex networks-based concepts to explore the spatial structure and connectivity of ARs. The Integrated Vapor Transport (IVT) along the West Coast of North America over a 25-year period (1995-2019) are analysed and spatial linkages in moisture transport patterns are identified. Based on IVT magnitude, the ARs are classified into three categories-Type-1, Type-2, and Type-3. Each grid point is treated as a node, and network connections are established using a correlation-based threshold to assess the relationships in IVT variability. The average shortest path length is used as a measure to examine the structural characteristics of AR networks. This metric quantifies the efficiency of moisture transport by measuring how easily different regions within the network are connected. The results indicate strong spatial connectivity in AR networks. Regions with longer average shortest path lengths may act as key conduits for moisture distribution, potentially influencing extreme precipitation patterns. These findings highlight the usefulness of shortest path length and other complex networks concepts to understanding the AR dynamics and their role in extreme weather events.

Keywords: Atmospheric River, Integrated Water Vapor, Complex Networks, Average Shortest Path Length

Soil Moisture Dynamics under Elevated CO₂: Implications for Land-Atmosphere Feedbacks in India

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The interaction between rising atmospheric CO₂ and terrestrial ecosystems plays a crucial role in shaping hydroclimatic and ecological processes. A fundamental aspect of this interaction is the critical soil moisture threshold (θ_{crit}), which delineates the transition from energy-limited to water-limited conditions, governing plant water stress. In this study, we explore the response of θ_{crit} to increasing CO₂ over India, an ecologically diverse region with strong land-atmosphere feedback. Using the Weather Research and Forecasting (WRF) model coupled with the Noah-MP land surface scheme with dynamic vegetation, we conducted three simulations: (i) Varying CO₂, (ii) Fixed CO₂ in 2004, and (iii) Fixed CO₂ in 2022. Our findings reveal a decline in θ_{crit} under higher CO₂ concentrations, indicating reduced soil moisture constraints due to enhanced water-use efficiency. However, despite lower plant water stress, vegetation productivity decreased across all agroecological zones, driven by an increasing influence of warming and corresponding atmospheric aridity. Additionally, CO₂-induced warming led to a reduction in runoff by narrowing the gap between precipitation and evapotranspiration (P - ET), thereby intensifying pressure on water resources. These results highlight the intricate land-atmosphere interactions under rising atmospheric CO₂, where the benefits of improved plant water use efficiency are counteracted by atmospheric drying, ultimately suppressing carbon assimilation and altering hydrological cycles.

Keywords: Critical soil moisture threshold, Dry-downs, Water-use efficiency, Vegetation productivity, Atmospheric aridity

Diurnal Soil Temperature Range as a Proxy for Representing Hydrological Regimes and Land-Atmosphere Coupling Strength

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Hydrological regimes act as a fundamental driver and determinant of land-atmosphere (LA) interactions. Greater LA feedbacks are observed in water-limited regime (WLR) compared to the energy-limited regime (ELR), which are delineated by the critical soil moisture (CSM) threshold. Typically, estimation of CSM and delineation of associated regimes has been undertaken by regressing diurnal soil temperature range (dT), evaporative fraction (EF) and temporal rate of SM loss (dSM) with respect to SM in Broken Stick Regression. However, the robustness and mutual agreement of three CSM values and identified regime properties by them remain untested and are examined in this study. The three CSM values are strongly associated ($r=0.8$), particularly in semi-arid and sub-humid climatic regions characterised by herbaceous vegetation. Despite a strong correlation, biases are observed, wherein dT-based CSM is slightly higher compared to EF and dSM-based, which results in higher persistence of WLR and less frequent regime transition. However, dT-based CSM effectively identifies similar regimes concerned to EF and dSM-based CSM for more than 80% of the time in 84% of regions experiencing regime transitioning. Nonetheless, the agreement (tipping potential) of identified regimes by three CSMs is highest (lowest) during the dry seasons, which decreases during the summer. This comparative assessment of three CSM estimates and their influences on the spatiotemporal regime dynamics facilitates the understanding of the mutual consistency and applicability of the respective variables for inferring landscape responsiveness to climate, which has not previously been attempted. Furthermore, dT when coupled with SM, is found

to effectively represent the global hotspots of land feedback and coupling, primarily corresponding to transitional regions. Therefore, dT represents a viable proxy for coupled water-energy dynamics at the surface, and provides means for understanding local LA interactions, ecosystem responses, land surface modelling and the understanding of the evolution of dry extreme events.

Keywords: Evapotranspiration Regimes, Critical Soil Moisture Threshold, Land-Atmosphere Interactions, Diurnal soil temperature range, Evaporative Fraction, Persistence, SMAP, ERA5

Impact of Urbanization on Monsoon Rainfall Over Complex Terrain: A Case Study of Doon Valley

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Urbanization significantly alters microclimates by modifying land surface characteristics, energy balances, and atmospheric dynamics, yet its influence on monsoon precipitation over complex terrains remains poorly understood. This study aims to assess the influence of urbanization on monsoon rainfall patterns over the Doon Valley using numerical modelling approaches. The Weather Research and Forecasting (WRF) model, coupled with the multilayer Urban Canopy Model (UCM), will be employed to simulate monsoonal precipitation under urban and non-urban scenarios. Two model configurations, a Control simulation with existing urban land cover and a No-Urban scenario without urban surfaces were compared to assess the role of urbanization in modulating precipitation. Model outputs were validated against observational data from automatic weather stations, focusing on key climate variables such as 2m relative humidity, 2m temperature, 10m wind speed, and rainfall. By identifying key processes such as the urban heat island effect, moisture convergence, and orographic influences, this study aims to improve understanding of urban-induced precipitation changes in complex terrains. The findings of study will enhance understanding of the key processes influencing rainfall variability and support the development of adaptive strategies for sustainable urban planning in regions with similar geographical and climatic conditions.

Keywords: Urbanization, Rainfall, Microclimate, WRF, Urban Canopy Model

A Global Assessment of Vapor Pressure Deficit as the Primary Driver of Sap Flow Variability in Forests

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Sap flow is a fundamental process regulating plant water use, influencing ecosystem hydrology, and mediating land-atmosphere interactions. Identifying the key drivers of sap flow is crucial for understanding forest responses to climate variability and water stress. In this study, we analyze the global SAPFLUXNET dataset to assess the dominant controls on sap flow across three major forest biomes: evergreen broadleaf forests (EBF), evergreen needleleaf forests (ENF), and mixed forests (MF). Using an information theory-based process network, we identify the primary environmental variables influencing sap flow. Our results highlight vapor pressure deficit (VPD) as the dominant causal driver of sap flow variability across all forest types, highlighting its pivotal role in the soil-plant-atmosphere continuum. While soil water content (SWC) plays a secondary role, its influence is more pronounced during periods of prolonged dry conditions, suggesting an interactive effect with VPD. VPD exerts an immediate influence on sap flow, while SWC exhibits lagged responses, reflecting the time-lagged adaptations of trees to soil moisture availability. The strength of these interactions varies seasonally and across biomes, with stronger coupling observed in regions experiencing higher atmospheric aridity. Our findings highlight that VPD is the major driver of sap flow, providing new insights into plant-water relations and their sensitivity to climate extremes. This advances our understanding of forest hydrodynamics and has important implications for improving land surface models.

Keywords: Sap Flow, Soil-Plant-Atmosphere Continuum, Climate Extremes, Land-Atmosphere Feedback, Hydrometeorology

High-Resolution Climate Models Capture Monsoon Rainfall Changes More Accurately in the Ganga-Brahmaputra-Meghna Basin

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This study examines the influence of model resolution on the simulation of South Asian monsoon rainfall, with a focus on the Ganga-Brahmaputra-Meghna (GBM) basin. By comparing high- and low-resolution versions of four CMIP6 HighResMIP model families against observational datasets (MSWEP and ERA5), we highlight the benefits of high-resolution models in capturing key monsoon characteristics, including total rainfall, onset, intensity, and duration. Results show that high-resolution models better align with observed data, outperforming their low-resolution counterparts. Between 1979 and 2014, the high-resolution ensemble (HR-models) accurately captures monsoon timing shifts, such as delayed onset and withdrawal, leading to a modest increase in monsoon duration. In contrast, low-resolution models (LR-models) exhibit more pronounced delays in onset. Observational datasets indicate an earlier (7 ± 3 days) and later (3 ± 1.2 days) onset in MSWEP and ERA5, respectively, both suggesting an extended monsoon duration, which is more pronounced in MSWEP than in model simulations. HR-models also more accurately represent observed trends in total and extreme rainfall changes over 1979-2014. Future projections (2015-2050) suggest continued delays in monsoon onset, with HR-models predicting greater increases in total and extreme rainfall (up to 4.5% per decade for the 95th percentile) compared to LR-models, which exhibit smaller

increases and higher variability. These findings underscore the critical role of high-resolution models in improving monsoon rainfall simulations, offering more reliable historical representations and robust future projections essential for water resource management and agricultural planning in the GBM basin.

Keywords: monsoon, high resolution models, CMIP6, HighResMIP,

Root zone in the Earth system

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Introduction:

The root zone is a vital part of the Earth system and a key element in hydrology, ecology, agronomy, and land surface processes. However, its definition varies across disciplines, creating barriers to interdisciplinary understanding. Moreover, characterizing the root zone is challenging due to a lack of consensus on definition, estimation methods, and their merits and limitations.

Aim and objectives:

This study provides a holistic definition of the root zone from a hydrology perspective, including its moisture storage, deficit, and storage capacity.

Methods and results:

We demonstrate that the root zone plays a critical role in the biosphere, pedosphere, rhizosphere, lithosphere, atmosphere, and cryosphere of the Earth system. We underscore the limitations of the traditional reductionist approach in modeling this complex and dynamic zone and advocate for a shift towards a holistic, ecosystem-centered approach.

Summary and conclusion:

We argue that a holistic approach offers a more systematic, simple, dynamic, scalable, and observable way to describing and predicting the role of the root zone in Earth system science.

Keywords: Root zone, Earth system, Hydrological modelling, Land surface process

Disentangling the effects of aerosols on precipitation under varying meteorological conditions

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Precipitation plays a crucial role in the hydrologic cycle, influencing water availability, flood risk, and ecosystem sustainability. However, its interaction with atmospheric aerosols and meteorological variables - such as vertical velocity, wind speed, temperature, humidity, and atmospheric stability - remains complex, leading to inadequate representation in weather and climate models and, consequently, reduced forecasting accuracy. The present study aims to untangle these interactions by analyzing the influence of aerosol loading on precipitation under varying meteorological conditions. To achieve this, Principal Component Analysis (PCA) is utilized to manage the collective effects of meteorological variables. By systematically exempting one parameter at a time, its individual influence is isolated while the sensitivity of precipitation to changes in aerosol optical depth (AOD) is analyzed across various ranges of that parameter, with the remaining meteorological variability captured by the first principal component (PC1). The study employs the newly launched GSMaP ISRO Rain precipitation data (a collaboration between ISRO and JAXA), meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5, and aerosol data from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). This methodology contributes to a deeper understanding of aerosol-precipitation interactions, leading to improvements in hydrological models and weather forecasting, thereby supporting more effective strategies for water resource management and climate adaptation.

Keywords: Precipitation, Aerosols, Meteorology, PCA, AOD

Towards Identifying the Precursors of Heatwaves in the Indo-Gangetic Plains - Perspective of Land-Atmosphere Interaction

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Heatwaves are one of the worst phenomena that puts millions of people at risk. Over India, the dominant season for heatwaves is the pre-monsoon season. Anomalous blocking over the North Atlantic Ocean, where rising temperatures cause quasi-stationary Rossby waves throughout Eurasia, are linked with the pre-monsoon heatwaves. These heatwaves are caused by upper-level anticyclonic anomalies that arise over Northern India as a result of the waves stalling over Northern Africa. However, considering the tight coupling of land and atmosphere over India at multiple spatiotemporal scales, the local processes responsible for triggering these events should be scrutinized.

In the present work, the land and atmosphere conditions prior to the heatwave onset are investigated using ERA5 reanalysis data over Indo-Gangetic Plains over India. This region experiences both moist and dry heatwaves thus, understanding the local factors responsible for causation of the

onset of heatwave is important. The local processes for moist heatwave formation are pre-monsoon convective showers, increased nighttime cloud cover, and low longwave cooling. The dry heatwaves are associated with cloud-free conditions, low specific conditions, and high daytime temperatures. The coupling of land and atmospheric conditions exhibits distinct patterns in energy partitioning between near-surface and atmosphere and boundary layer. The shift in energy partitioning is towards latent heat flux prior to the onset of moist events due to the presence of elevated humidity, which results in high evapotranspiration. On the other hand, for the onset of dry heatwaves, the dry atmosphere heats the atmospheric column and is not utilized in evaporative processes thus, high sensible heat flux is observed. The findings conclude that local conditions are important, resulting in land-atmosphere interactions leading to heatwave onset over the Indo-Gangetic Plains of India for both moist and dry mechanisms.

Keywords: Heatwave, precursors, land-atmosphere interactions

Multi-Hazard Susceptibility Mapping over India through Deep Learning Technique

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Disaster Risk Reduction and Resilience in India require identifying potential hazard-prone zones with multiple hazard occurrence characteristics. The susceptibility of the areas to multi-hazard makes the risk reduction (or mitigation) policies designed to cater to one type of hazard inefficient for that region. This conundrum calls for an integrated assessment of the probability of occurrence of multiple hazards in different parts of the Indian subcontinent. This study focuses on hydrological and meteorological hazards, such as floods, drought, heat waves, cold waves, landslides, and cyclones. Important geomorphological and hydro-meteorological indicating factors were identified for each hazard and used to train a convolutional neural network to yield multi-hazard susceptibility maps. These show the probabilities of the occurrence of multiple hazards at the pixel level. A hazard inventory was prepared for training and testing using the observed hazard data gathered from various sources. The non-uniformity of data requires resampling it to a standard resolution. The pre-processed data was used after performing correlation analysis and standardisation. Evaluating the output performance from the deep learning-based model, susceptibility maps were generated for a single hazard. Overlaying them would reveal a multi-hazard susceptibility map with different combinations illustrated by a multi-variate representation. This study will benefit various aspects of disaster management, viz. comprehensive risk assessment, devising sustainable risk reduction and resilience measures, proper resource allocation and land use planning, community preparedness, decision-making, and formulation of adaptation strategies.

Keywords: Multi-Hazard, Hydrometeorological, Susceptibility, Convolutional Neural Network, India, Risk Assessment, Adaptation

Investigating Coupled Land-Atmosphere Moisture Dynamics Using Rainwater Isotopes across distinct Indian Climatic Zones

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Land-use change significantly impacts the water cycle by altering key hydrological processes, including evapotranspiration, infiltration, runoff, and groundwater recharge. Changes in land cover affect the atmospheric moisture budget by modifying surface temperature, humidity, and wind patterns. These alterations influence local and regional precipitation patterns, affecting moisture recycling in the atmosphere. The IPCC AR6 report highlights that land-use change contributes to shifts in regional and global hydroclimatic extremes (e.g., droughts and heavy rainfall). Rainwater stable isotopes (^{18}O and ^2H) serve as natural tracers to investigate moisture recycling by capturing the processes of evaporation, condensation, and moisture transport. The isotopic composition of precipitation reflects the history of air mass movement, helps identify moisture sources, and provides insights into the duration of moisture recycling. This study examines moisture recycling across distinct climatic zones in India using an isotope-based approach during the Indian Summer Monsoon (ISM; June- September) season from 2015 to 2018. Rainwater samples were routinely collected from multiple strategic locations, including tropical mountain, tropical wet evergreen forest, an island and littoral forest. Isotopic compositions of the samples were measured at the Indian Institute of Tropical Meteorology, Pune. The results indicate significant spatial and interannual variations in moisture recycling during the ISM season. Our study shows that duration of recycling varies from 1 day to 12 days in our study area, with a minimum over the tropical mountain and a maximum over the littoral forest. This study critically evaluates the efficacy of stable water isotopes as indicators of moisture recycling in ISM, providing new insights into land-atmosphere interactions across diverse hydroclimatic settings in India.

Keywords: Moisture recycling, stable isotope, precipitation, land-atmosphere interaction

Assessing future changes in hydrological and vegetation resources in the agro-pastoral Sahel

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The Sahel is considered a climate change hotspot where the majority of the population relies on subsistence agriculture. Future changes could have a major impact on agricultural sustainability

and food security. This highlights the need to anticipate the evolution of hydrological and vegetation resources. Currently, there is a lack of projection studies in this region, since global models do not always accurately represent monsoon characteristics and are available only at a daily timescale. Consequently, the available climate scenarios are not compatible with impact models for water and vegetation resources, which require high temporal resolution climate forcing. This study proposes an original approach to generate climate scenarios at a 30-minute time step, by combining an observational dataset with CMIP6 data. The scenarios are developed in a Sahelian context (southwest Niger) for five CMIP6 models, two CO₂ emission scenarios (SSP245 and SSP585), and two temporal horizons (2050 and 2100). All the generated climate scenarios are then used in a detailed land surface model, simulating water and energy cycles. Results show that scenarios including rainfall intensification lead to significant increases in runoff and groundwater drainage. Additionally, results particularly show that evaporation increases at the beginning of the rainy season, while transpiration slightly rises at the end of the season, indicating longer water availability for the crops, potentially allowing for a longer growing season. Moreover, these results suggest that the risk of flooding could become even greater and contribute to an intensification of the Sahelian paradox, leading to increased underground water storage. Future developments will focus both on assessing the sustainability of current agricultural practices and alternatives, and on the joint evolution of hydrological and vegetation resources. These steps are crucial for developing resilient adaptation strategies to manage water resources and maintain sufficient yields to feed the population.

Keywords: climate scenarios, land surface modelling, agro-pastoral Sahel, water resources, vegetal resources

High-Resolution Climate Projections for Hydrological Applications in the Himalaya Using WRF-Based Dynamical Downscaling

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The Himalayas, often referred to as the "Third Pole," are undergoing rapid climate changes, significantly impacting water resources, agriculture, and disaster management. Due to the region's complex topography, coarse-resolution global climate models (GCMs) struggle to capture fine-scale climate variations. High-resolution climate projections are essential for understanding climate variability and supporting hydrological decision-making.

This study aims to generate high-resolution climate projections for the Himalayan region using the Weather Research and Forecasting (WRF) model. The objectives are:

(1) To dynamically downscale climate simulations from MPI-ESM-HR CMIP6 GCM to higher spatial resolutions. (2) To assess temperature, precipitation, and extreme weather patterns over the Himalayas. (3) To analyze spatial and temporal climate variability and projected trends over the 21st century.

Dynamical downscaling is performed using WRF with bias-corrected MPI-ESM-HR boundary forcing. Two nested domains are configured: an outer domain (27 km) covering the Indian subcontinent and an inner domain (9 km) focused on the Himalayas to capture orographic influences.

The WRF model effectively captures seasonal temperature and precipitation patterns over the Indian Himalayan Region (IHR), showing strong agreement with IMDAA reanalysis (12 km). The high

resolution improves the representation of orographic effects, leading to more accurate climate simulations. Precipitation patterns align well with IMDAA, particularly during the monsoon (JJAS), though localized biases persist in high-altitude regions. Winter (DJF) precipitation is well represented, while moderate biases appear during pre-monsoon (MAM) and post-monsoon (ON) seasons. Temperature distributions are well simulated, with minor cold biases in winter. Simulations are conducted on the Param Porul supercomputer at NIT Trichy, with ongoing work assessing future climate extremes under warming scenarios.

This study provides high-resolution climate datasets crucial for hydrological modeling, disaster preparedness, and climate resilience planning. The results emphasize the importance of fine-scale regional modeling in understanding climate change impacts and improving adaptation strategies for this vulnerable region.

Keywords: WRF, dynamical downscaling, MPI-ESM-HR, climate projections, Himalayas, high-resolution modeling, regional climate change

Sub-seasonal to Seasonal Soil Moisture Drought Prediction Using Deep Learning

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Soil moisture drought (SMD), defined as a deficit in soil moisture, is a complex natural hazard phenomenon that causes extreme damage to water supply, food production, and socioeconomic loss at different time scales. India is a developing country that experiences repeated extreme drought conditions every three years. India's 60% population is dependent on agriculture. Thus, the accurate prediction of SMD at a sub-seasonal to seasonal (S2S) scale would help the farming community to demise the economic loss by cropping appropriate crops for the season and conserving water for irrigation. The regional variation in SMD is considerable in India, primarily due to the unpredictability of local climate conditions resulting from the substantial rise in global temperatures.

This study proposes a deep learning-based regression framework to forecast the SMD at various lead times, including 1-, 2-, and 3-months over India. Soil moisture percentile (SMP) below the 20th percentile is used to identify the drought phases. Precipitation, maximum-minimum air temperature, vapour pressure deficit, potential evapotranspiration, NDVI, soil moisture, and wind speed are considered as the local-scale input features. Large-scale features, including El Nino, NAO, IOD, PDO, and MJO, are also considered. The essential contextual information of the study area is included using static variables such as soil type, elevation, and land use as a predictor. The ConvLSTM and transformer model were selected in this study due to their ability to extract spatiotemporal information. The model training was performed from 1981 to 2015, and testing from 2015 to 2024. The evaluation matrices, such as the probability of detection, percentage correct, false alarm rate, and equitable threat score, are used to analyse the model performance. This research aims to contribute to developing functional drought early warning systems, which will eventually influence drought management techniques.

Keywords: SMD, SMP, ConvLSTM, Transformer, Deep Learning

Drivers of Rising Land Surface Temperature in a Lesser Himalayan Catchment

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Land Surface Temperature (LST) is crucial for understanding land-atmosphere energy and water fluxes, owing to its key role in weather, climate, and ecological models. In the anthropogenically influenced Lesser Himalayan Henva catchment, satellite-derived LST reached alarming levels ($>48^{\circ}\text{C}$) in May-2023 and -2024. Traditional topographic variables (DEM, slope, aspect, hillshade) alone cannot fully explain such anomalies. Therefore, this analysis incorporates atmospheric pollutants (NO_2 , SO_2), LULC, and evapotranspiration (ET). Increasing vehicular movement due to tourism, fossil fuel use and urbanization elevate pollutants, enhancing local greenhouse effects and driving up ET. NO_2 may not accumulate sufficiently to suppress ET due to rapid dispersion or chemical reactions. High LST and ET foster vertical mixing and contribute to increase in the atmospheric boundary layer height, promoting SO_2 oxidation into sulfate under warm and humid conditions. While sulfate aerosols can scatter solar radiation and serve as cloud condensation nuclei-potentially cooling the surface-these aerosols may also be removed via wet deposition. Unlike NO_2 , SO_2 concentrations are less sensitive to temperature or seasonal changes, possibly explaining their declining observed levels. Using geographically weighted regression, LST was modeled with environmental and anthropogenic drivers from 2019-2024. R^2 values ranged from 0.71 to 0.87 and geographically weighted correlation from 0.66 to 0.82, indicating strong spatially varying relationships. Results show that NO_2 , urbanization, aspect, and hillshade are contributing significantly in elevating LST over the years, while SO_2 's cooling role declines. In contrast, non-built-up areas, slope, and elevation continue to mitigate rising LST effectively. This study offers actionable insights for climate adaptation and sustainable environmental planning in the Lesser Himalayas.

Keywords: Land surface temperature, topographic variables, pollutants, LULC, evapotranspiration

Overestimation of evapotranspiration across India if not considering the impact of rising atmospheric CO_2

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The commonly used FAO Penman Monteith (FAO-PM) equation, which does not account for atmospheric CO_2 , is used extensively for calculating reference evapotranspiration (ET_0), leading to limitations in the accuracy of climate change impact studies because rising CO_2 is known to cause reduction in stomatal conductance.

We use a modified version of the FAO-PM equation that considers the impact of CO₂ concentration on stomatal behaviour and, consequently, on ETo. To evaluate this, a comprehensive methodological framework was followed. This involved validating the original and modified FAO-PM models, calculating daily ETo with and without CO₂ adjustment, and conducting spatio-temporal analyses using meteorological and CO₂ data from 5GCMs under SSP1-2.6 and SSP5-8.5 scenarios. Decadal and seasonal averages of ETo differences were computed to generate spatial maps, while national averages were derived using multimodal ensembles. Additionally, sensitivity analyses were carried out for distinct locations by varying CO₂ and temperature inputs.

The differences in ETo estimated using the original FAO-PM and modified equation for contiguous India for the near-term (2021-2030), mid-term (2051-2060), and the long-term (2091-2100) periods were calculated to be between 0.11-to-1.29 mm day⁻¹, 0.06-to-1.47 mm day⁻¹ and 0.17-to-3.14 mm day⁻¹, respectively, for the scenario SSP5-8.5, and 0.12-to-1.26 mm day⁻¹, 0.16-to-1.9 mm day⁻¹ and 0.11-to-1.37 mm day⁻¹, respectively, for SSP1-2.6. The impacts were larger during the pre-monsoon season, with seasonal variations ranging from 0.05-to-4.06 mm day⁻¹ for SSP5-8.5 and 0.05-to-2.38 mm day⁻¹ for SSP1-2.6.

Neglecting the impact of CO₂ would overestimate the evapotranspiration in the national water budget by ~28.4% and may lead to erroneous predictions about heat waves, droughts, water demand and supply, and flooding under projected climate in India.

Keywords: Evapotranspiration, FAO Penman-Monteith, stomatal conductance, regional climate in India, water resources, elevated CO₂

Spatio-temporal characteristics of flooding over India and their links to moisture sources

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Floods are catastrophic occurrences that consistently challenge regions across the globe. The increasing impact of climate change has led to a substantial rise in both the frequency and intensity of floods. In the past fifty years, India has witnessed a threefold rise in the occurrence of extreme events. We examined the evolving characteristics of flooding in India, concentrating on trends in magnitude, frequency, and seasonality across major basins to discern flood patterns and any potential alterations in recent decades. Findings reveal that prolonged rainfall spells are escalating the floods. Additionally, the study utilized the Lagrangian moisture diagnostic to examine the moisture sources associated with flood events, aiming to identify the underlying factors that may be influencing changes in flooding mechanisms and patterns. The findings are expected to improve our understanding of extreme events while also strengthening risk management strategies and water resource planning.

Keywords: Floods, Trend, Seasonality, Moisture Sources

Hydro-Climatic Impacts of Oak-to-Pine Transition in the West-Central Himalayas: A Multi-Scale Perspective

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The Himalayas, termed the Earth's third pole, are vital for global and regional climate regulation, supporting biodiversity and key ecosystem services like carbon storage and water availability. In the west-central Indian Himalayas, a shift from moist, broad-leaved oak (*Quercus leucotrichophora*) forests to dry, fire-adapted Chir Pine (*Pinus roxburghii*) forests presents ecological and hydrological challenges. This study examines hydro-climatic impacts through field observations in Uttarakhand's Pine and Oak forests (~1600m elevation, 23° slope). Measurements include evapotranspiration, sap flux-based transpiration, streamflow, and meteorological variables. Bowen ratio assemblies at 27m (Pine) and 18m (Oak) heights, equipped with temperature, humidity, radiometer, and soil heat flux sensors, reveal consistently higher evapotranspiration in Pine forests across seasons, with peak latent heat flux during the monsoon for Oak (~300 W/m²) and monsoon-post-monsoon for Pine (~350-400 W/m²). Pine-dominated catchments show lower rainfall-to-runoff ratios (Oak: 40.13%, Pine: 20.19%) and baseflow percentages, leading to ephemeral streams, unlike Oak catchments with sustained baseflow (18.54%). Oak forests exhibit stricter transpiration down-regulation during dry periods, aligning tree-level and stand-level water fluxes, while Pine forests demonstrate less conservative water use. Strong agreement between sap flux and Bowen ratio estimates underscores their reliability for multi-scale water flux assessments. All measurements confirm higher evapotranspiration in Pine forests and stricter down-regulation in Oak during dry periods. Observations parameterize vegetation in the Ocean-Land-Atmosphere Model, enabling high-resolution simulations of regional hydro-climatic conditions under varying forest covers.

Keywords: Evapotranspiration, Transpiration, Bowen ratio, down-regulation, Hydro-climatic

Impact of Chill and Heat Accumulation on Fruit Flowering in the Northwestern Himalayas

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The Himalayan region of India is facing warmer winters and hotter summers. These changes are reducing yields and putting traditional fruit crops at risk. To study the growing conditions, chill and heat accumulation were calculated. Chill was measured using the Dynamic Model, while heat was measured using the Growing Degree Days (GDD) method. Hourly temperature data from the ERA5 dataset (1940-2023) was used. The results showed that fruits like citrus, almonds, and temperate crops have clear elevation ranges. Areas between 1000-2000 m were found most suitable for fresh



fruits, as more than 70% of the Chilling Portion (CP) values were above 60. To see the orchard-level effect, three locations in Kullu district were studied: Jagatsukh (1867 m), Chansari (1432 m), and Chinjra (1368 m). These sites showed clear differences in flower timing and quantity. The variation was linked to the amount of chill and heat received at different heights. This shows that altitude plays a strong role in fruit flowering and production under changing climate conditions.

Keywords: Climate change, Thermal growing condition, GDD, CP, Winter chill, Temperate fruit

Groundwater (ICGW)

Advancing Hydrogeochemical Modeling and Sustainable Water Resource Management: Insights into Pyrite Oxidation, Contaminant Transport, and Urban Stormwater Systems

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Hydrogeochemical modeling is a useful tool for analysing the movement and degradation of pollutants in different ecological systems. This present study looks into pyrite oxidation in the unsaturated zone and the transport of multi-component pollutants via various soil textures, such as clay, loam, and sand. A computational model that combines unsaturated flow and multi-component transport processes is developed as an initial framework for evaluating the transport and interactions of pyrite oxidation ions (Fe^{2+} , Fe^{3+} , and SO_4^{2-}). The simulation show that ion transport is significantly influenced by the porosity, water content, and texture of the soil. In clay-dominated profiles, lower porosity level affects pyrite oxidation rates and limits the depth of oxygen diffusion, which restricts ion mobility. Sensitivity study shows that higher water content increases ion mobility, especially in clay and loam soils, where higher water concentrations result in higher sensitivity indices. On the other hand, the low water retention of sand restricts ion interactions, thereby restricting the transport of pollutants. Contour profiles indicate that as porosity increases, ion concentrations fall, which suggests that oxidation events are slower, and pollutants are less mobile. These findings emphasize how important soil features are in controlling the movement of contaminants in both mine waste environments and natural soil systems. The study offers important information about hydrogeochemical processes that affect the movement of pollutants, which can help in the generation of sustainable methods for managing water resources. This study establishes a strong foundation for predicting how contaminants behave in different hydrogeological environments by integrating sensitivity analysis with validated models. The results can be used to develop strategies for improving runoff management, preserving groundwater resources, and creating viable remediation methods for contaminated sites. It is important to understand these processes in order to reduce the environmental risks that are connected with mining activities and to ensure that water management methods are sustainable in the long run.

Keywords: Hydrogeochemical modeling, Pyrite oxidation, Contaminant transport, Unsaturated zone, Sustainable water management.

Groundwater remediation through engineered injection-extraction systems: The effect of random perturbations on mixing enhancement

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Groundwater remediation is often limited by mixing between the contaminant and a treatment solution. Engineered injection-extraction systems are interesting solutions to speed up the process. In these systems, mixing may be enhanced by chaotic advection, where stretching and folding contribute to the increase of the solute-solvent interface available for diffusion. However, if the chaotic flow field contains Kolmogorov-Arnold-Moser (KAM) islands, non-mixing regions that limit the chaotic area in the domain, the process of reaching complete mixing in the treated area is limited by diffusion. Therefore, to effectively engineer injection-extraction systems for groundwater remediation, it is crucial to identify and reduce KAM island structures. In this work, we analyze the potential to reduce KAM islands by applying random perturbations to the chaotic flow fields and evaluating the resulting mixing enhancement. We use Lagrangian particle tracking to capture the delicate plume structure due to chaotic advection while minimizing numerical diffusion. Considering various configurations of the rotation angle and the time between rotations of the rotated potential mixing (RPM) flow, we analyze mixing by computing the dilution index. We introduce randomization by periodically applying random perturbations to these two parameters and evaluate the effect on the mixing potential. For different choices of the model setup, we compute the size of the particle-free region in our domain over time and assess their sensitivity by computing Sobol indices. Our results show that the sensitivity for the width of the parameter ranges increases over time as the KAM islands are reduced significantly due to higher randomization. We demonstrate that by applying randomization, we can effectively avoid the diffusion limitation on chaotic mixing and reach complete mixing significantly faster than by using a fixed flow field.

Keywords: Groundwater remediation, Mixing enhancement, Chaotic advection, Sensitivity analysis

Probabilistic groundwater flood maps for improved risk assessment

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The increased frequency of extreme meteorological events has raised the need to investigate different kinds of floods and related risks. Among these, groundwater flooding, which is the rising groundwater level reaching the ground surface or the foundation of buildings, is particularly challenging and less investigated than surface floods. Groundwater flooding is difficult to predict and mitigate due to the complex subsurface processes and the limitations of traditional subsurface flooding assessment tools. Deterministic numerical models rarely account for uncertainty and parameters equifinality, leading to unreliable predictions.

To address this gap, in the framework of the URGRUND project, we propose a probabilistic approach to i) develop risk maps for the assessment of groundwater flooding and ii) evaluate the vulnerability of residential areas when implementing different technical measurements such as drainage systems, wells and storage tanks. The method consists of 1) using the Elementary Effects method to identify influential input factors and reduce dimensionality, 2) applying Bayesian inference using the Differential Evolution Adaptive Metropolis (DREAM) algorithm to estimate the statistical distributions of uncertain parameters and quantify uncertainty, and 3) studying the posterior distributions to assess susceptibility to groundwater based on exceedance probabilities. This framework is tested on a groundwater event in Garching bei Muenchen, Germany, in December 2023, which caused the groundwater flooding of several cellars with consequent economic damage. The probabilistic approach is tested considering MODFLOW-NWT as deterministic distributed model and Flopy as script-based user interface. Our approach enables us to determine the spatially distributed probability that the groundwater level rises above a certain threshold under different flow conditions, i.e., before the flood, during peak flow, the recession phase and after the flood. Probabilistic groundwater flood maps can support the development of guidelines for early warning systems, thereby enhancing risk assessment.

Keywords: Groundwater flood, risk assessment, probabilistic maps

Assessing potential of crop switching to check groundwater depletion in north-west India

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North-west India is a critical region for national food security as it contributes significantly to the nation's total agricultural production of wheat and rice. The high cropping intensity in this region has been largely supported by groundwater irrigation. Excessive pumping of groundwater to meet irrigational needs over the past few decades has led to drastic declines in groundwater levels turning this region into a global groundwater depletion hotspot. The situation is expected to worsen with the changing climate and there is a need to arrest the rapid fall in groundwater levels. One possible solution is to design irrigation strategies in a manner that increases the water use efficiency (WUE) while ensuring that agricultural productivity does not suffer. We carry out a multi-year multi-objective modeling of agricultural revenue and irrigation requirements by using a combination of biophysical model and regional optimization model for this purpose. This model takes into account climate variability, soil and crop characteristics along with field and irrigation management practices. We demonstrate this methodology for two districts in Southern Haryana which are highly water stressed with groundwater levels fallen to 30 m b.g.l. or lower in some blocks. We quantify the water savings by using crop switching and deficit irrigation. We also investigate the reduction in irrigation water requirement by growing the share of millets in the total cultivated area.

Keywords: Groundwater depletion, crop switching, sustainability, food-energy-water nexus, water use efficiency

Rapid Land Use Changes Driving Groundwater Dynamics in Tropical Coastal Regions: Hydrochemical and Remote Sensing Insights

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Rapid urbanization and industrialization in coastal regions have stressed global groundwater reserves, resulting in salinization and acute water crises, particularly in India's coastal districts. This study investigates the impact of Land Use and Land Cover (LULC) changes on groundwater quality in Odisha's coastal regions using 365 groundwater samples collected from the Central Groundwater Board (CGWB) between 2015 and 2021. Samples were analyzed for 14 hydrochemical parameters, validated via ionic balance error, and assessed using Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), Hydrochemical Facies Evolution Diagram (HFE-D), Standardized Precipitation Index (SPI), Seawater Mixing Index (SMI), Groundwater Quality Index (GWI), and GIS-based interpolation. LULC analysis revealed increased agricultural land (36% to 43%) and built-up areas (4% to 13%). Hydrochemical facies shifted from Na⁺-Cl⁻ to Mg²⁺-HCO₃⁻, indicating mixed environments influenced by rock-water interactions, seawater intrusion (SWI), and anthropogenic activities. The SMI model highlighted a temporary decline in SWI in 2018, followed by a slight spatial resurgence in 2021, indicating partial recovery from salinization compared to 2015. HFE-D indicated fluctuating freshening and salinization trends: freshening increased from 47.8% (2015) to 66.6% (2018) but declined to 36.4% (2021). Despite significant rainfall, groundwater levels fell (0-2 mbgl) due to over-extraction. Nitrate (NO₃⁻) levels increased from 1-66 mg/L (2020) to 1-99 mg/L (2022), linked to fertilizer use and sewage contamination. GWI classified 50% of the region as "poor" to "unsuitable" for drinking. Correlation analyses showed a strong relationship between Total Dissolved Solids (TDS) and Total Hardness (TH) ($r=0.77$), as well as TDS with Na⁺ and Cl⁻ ($r=0.8$), confirming worsening salinity and brackish-hard groundwater quality. PCA identified positive GWI and negative LULC loadings, linking urbanization and agricultural expansion to groundwater quality degradation. This study underscores the critical need for sustainable water management strategies to mitigate salinization, control pollution, and ensure groundwater sustainability in coastal regions.

Keywords: Coastal regions, Hydrogeochemical facies, Groundwater quality, Landuse and land-cover, Seawater Mixing Index

Trace metal anomalies in groundwater of hard aquifer of Northern Odisha: Sources, Governance and its health impacts

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Groundwater contamination by trace metals is a major concern in mining-dominated regions like Keonjhar, Northern Odisha, though systematic studies in this region are limited. An integrated study on health risk assessment, pollution indices, and statistical analysis has been carried out to assess the heavy metal pollution and its sources in the groundwater. A total of 40 groundwater samples were collected based upon geology, land cover patterns, and its spatial distribution. The collected samples were analysed for heavy metals like lithium (Li), boron (B), magnesium (Mg), aluminum (Al),

chromium (Cr), manganese (Mn), iron (Fe), copper (Cu), arsenic (As), cadmium (Cd), and lead (Pb). The study findings reveal significant contamination, with Mn, Fe, and Cu concentrations exceeding the drinking water standards set by the Bureau of Indian Standards (BIS) and the World Health Organization (WHO). The contamination by trace metals such as arsenic (As), cadmium (Cd), and lead (Pb) is comparatively lower. The high concentration of these above-mentioned trace metals may be due to mining activities and anthropogenic inputs. The health risk assessment inferred that out of these three age groups, like Infant, children and adults, the most vulnerable population is infants, whose higher exposure has been connected to possible neurological impairments and developmental abnormalities. The study highlights the dual influence of natural and human-induced factors on groundwater quality and emphasizes the importance of addressing contamination to safeguard public health and ensure the sustainability of groundwater resources.

Keywords: Trace metal, groundwater quality, pollution, mining activities, human health

Geochemical and isotopic characterization of geothermal fluids in the West Coast Geothermal Province, India

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The West Coast Geothermal Province (WCGP) in Maharashtra, India, represents one of the most promising low-enthalpy geothermal systems along the Western Continental Margin of India. Spanning a ~350 km long geothermal belt, this region hosts about 60 thermal springs that predominantly emerge from the contact zones between dykes and basaltic rocks of the 65 million year old Deccan Flood Basalt (DFB) formation. The spatial distribution of these springs is largely governed by NNW-SSE trending lineaments. The present study examines the geochemical and isotopic characteristics of geothermal waters from 14 thermal springs, with discharge temperatures ranging from 38°C to 70°C, to unravel the origin and reservoir properties of these fluids. Stable water isotope ratios indicate that the geothermal system is predominantly recharged by meteoric water originating from 200 to 550 m elevations in the Western Ghats. Ionic ratios, such as Cl/Na and Cl/Br, reveal a seawater influence in all springs except the Rajapur spring. Trace element data suggests significant interactions with mafic minerals, particularly in the central and northern sectors, consistent with the increasing basalt thickness from south to north. Multicomponent geothermometry estimates reservoir temperatures ranging between 92°C and 134°C at depths of 1.3 to 2.2 km, with reservoirs predominantly hosted in Precambrian crystalline rocks. Tritium analyses indicate a higher proportion of modern water in the southern sector (37-62%) compared to the central and northern sectors (3-36%). Stable carbon isotope ratios (δ¹³C) in dissolved inorganic carbon (DIC) suggest open-system behaviour, while corrected radiocarbon (¹⁴C) ages point to increasing groundwater residence times from 3.4 to 15.8 ka towards the north. This trend is attributed to slower infiltration through the progressively thickening basalt, resulting in extended flow paths and longer residence times.

Keywords: Geothermal spring, geothermometry, isotope, radiocarbon, West Coast, India

Comprehending Managed Aquifer Recharge (MAR) dynamics using high resolution hydro-geophysical methods in granitic terrain, Southern India

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Managed Aquifer Recharge (MAR) has emerged as a pivotal strategy to augment groundwater resources in crystalline hard rocks that often experiences an erratic rainfall patterns in semi-arid climatic zone. To adapt MAR practices in such environs, it necessitates to understand the litho-settings and dynamics of vadose zone through comprehensive high-resolution hydro-geophysical investigations. We employ electrical resistivity tomography (ERT), water level monitoring and water chemistry analysis, and soil characterization in crystalline hard rocks, near Hyderabad, India. The experimental site (40 ha) is located downstream of the MAR tank (1.74 ha) beset over Archaean granites and belong to semi-arid climate with an erratic rainfall of 800 mm annually. This field scale experiment mainly focusses to understand the impact of the MAR tank, and associated hydrodynamic and hydrochemical processes in such a hydrogeologically challenging environments.

The ERT profiles were carried out using Schlumberger array with maximum profile length (AB) 56 m in the experimental site. A total of 13 observation wells were monitored for water level and water samples analysis for major ion chemistry including pH, TDS and trace elements. Depth wise soil samples were collected to determine soil moisture, permeability, and grain size. The resistivity profiles reveal distinct litho-units comprising sandy regolith that enhance infiltration and deeper laminated layers potentially impeding downward water percolation. The study evaluates resistivity variations 23-100 ohm m that correlate with subsurface heterogeneity, influencing water retention and movement in the aquifer matrix that played a key role in MAR efficiency and groundwater recharge. The primary findings show a significant improvement in groundwater quality owing to dilution of contaminants, natural filtration processes (ion exchange) within the granitic aquifer systems. This study establishes the guidelines tailored for sustainable MAR implementation in similar hard rock settings, contributing crucial insights to hydrogeological management practices globally.

Keywords: Managed Aquifer Recharge (MAR), Hydro-geophysics, Soil permeability, Groundwater quality, Hard rock aquifers, Southern India

Sequential Gaussian Mixtures for Transient Hydraulic Tomography Inversion in Fractured Aquifers: A Laboratory Study

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Fractured aquifer parameters are expected to have intricate spatial heterogeneity that often follow non-Gaussian distributions. Gaussian Mixture models (GMMs), recognized for their ability to represent complex distributions effectively, offer a promising approach to capturing the spatial heterogeneity of fractured geologic settings. Nonetheless, their application in these settings is largely uncharted and has so far been confined to unconsolidated formations, mainly in the context of

steady-state hydraulic tomography. Therefore, in this study we advance the application of Gaussian Mixtures by employing a novel sequential Gaussian Mixture inversion algorithm for transient hydraulic tomography in a laboratory-based fractured environment. We further examine the impact of number of Gaussian components, different parameter initialization strategies and the amount of pumping data on the performance of the sequential GMM. Results demonstrate that GMM with an optimal number of Gaussian components, effectively delineates high and low conductivity zones, captures fracture connectivity, and provides reasonable drawdown predictions ($R^2 = 0.61$) for independent events not used in the inversion process. Stratified (Latin Hypercube) initialization of GMM parameters ($R^2 = 0.74$, average RMSE_{median} = 9.89 mm) outperforms other strategies like random ($R^2 = 0.61$, average RMSE_{median} = 20.64 mm), uniform ($R^2 = 0.64$, average RMSE_{median} = 11.70 mm) and quasi-random initialization ($R^2 = 0.67$, average RMSE_{median} = 11.40 mm) in mapping the fracture connectivity and parameter distribution. These findings underscore the importance of selecting the appropriate number of Gaussian components and parameter initialization for the effective application of sequential GMM in THT inversion. Overall, our findings suggest that the sequential GMM combined with optimum Gaussian components and stratified parameter initialization is able to capture the spatial heterogeneity of aquifer parameters in fractured media and has potential for extension to field-scale studies

Keywords: Gaussian Mixture Model, Transient Hydraulic Tomography, Fractured aquifers, Stratified initialization, Gaussian components, Information

Unveiling the Drivers of Groundwater Resilience: Hydrogeology and Aridity

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During climate extremes such as droughts, groundwater systems are crucial for sustaining water supply. However, decreased recharge coupled with the increased abstraction disrupts the natural aquifer feedback mechanisms, which exceed resilience thresholds and cause potential regime shifts. This study introduces the Endurance, Recovery, and Resilience (ERR) framework to comprehensively assess groundwater resilience by integrating both engineering and ecological perspectives. The ERR framework is applied to the groundwater level and rainfall time series of 19 subbasins of the Ganga Basin. Using the signal processing technique, groundwater fluctuations caused by rainfall are isolated, and the Groundwater Sensitivity to Rainfall (GSR) time series is derived. Finally, the Dynamic Resilience Indicator (DRI) is computed using GSR as the state variable and integrating the recovery and endurance metrics. Key findings reveal hydrogeology and aridity as primary drivers of groundwater resilience. Unconsolidated sedimentary aquifers in humid regions, with high specific yield and permeability, exhibit high resilience, maintaining stable GSR and minimal regime shifts. In contrast, crystalline aquifers in arid and semi-arid regions, with low specific yield and permeability, demonstrate low resilience, frequent regime shifts, and weak recovery. It indicates that high water-bearing and permeable aquifers in wet climates are naturally better equipped to absorb disturbances, while less water-bearing and impermeable settings in dry climates have limited endurance. It also highlights the limitations of focusing solely on recovery and advocates for a broader resilience assessment incorporating endurance metrics. The ERR framework offers valuable insights for adaptive water management to enhance groundwater sustainability and mitigate vulnerability under climatic stress.

Keywords: Groundwater Resilience, ERR Framework, Hydrogeology, Aridity

Characterization of Hydrogeological Attributes for Springsheds with Groundwater Aquifers using Hybrid Geospatial-AHP-Fuzzy Logic Techniques

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Understanding the complex interactions between springsheds and groundwater aquifers is critical for implementing sustainable springshed management techniques. Hydrogeological and morphological factors of springsheds as altitude, slope gradient, slope shape, relative relief, flow accumulation, drainage density, geology, lineament density, land use and vegetation density are considered in assessing springshed potential zones with groundwater aquifers (Ghimre et al., 2019). This study investigates the integration of hydrogeological attributes using Analytic Hierarchy Process (AHP) and Fuzzy Logic (FL) techniques aided by geospatial procedures to interlink these attributes to predict potential springshed zones (SPZ) in selected district sites of Manipur. Using the AHP technique, we compared the criteria in pairs to assess based on the pairwise comparison matrix. For FL approach, the relevant membership functions are applied to convert the criteria values into fuzzy membership values. Field investigations were conducted at routine intervals during the lean seasons of 2023 and 2024 to affirm the findings of the study. The assessment of SPZ showed that approximately 11.87% of the total area falls within a Low Potential Zone, where groundwater availability is limited. In contrast, about 6.11% of the region is classified as a High Potential Zone, indicating areas with substantial water reserves. Notably, the largest portion of the study area 82.02% falls under the Moderate Springshed Potential Zone, signifying stable but not excessive groundwater availability. Among the spring locations identified, 30% of the spring location including Khamason, Huishu, and Phungrei in Ukhrul district are situated in High Potential Zone, indicating significant groundwater aquifers availability, while the remaining 70% (Sihai and Khamason) are located in Medium Potential Zone. The study showed that geology, geomorphology, lineament density, and drainage density are the dominant criteria of the prediction model, and should provide a viable interface for water resources planners to undertake effective springshed rejuvenation measures with site precision.

Keywords: RS and GIS, lineament density, geomorphology, lithology, Springshed Potential Zone, pairwise comparison matrix, membership, rejuvenation, precision

Effects of groundwater transient boundary conditions generated by anthropogenic factors on mixing enhancement: Laboratory and model-based evidence

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Aquifers are affected by transient boundary conditions generated by both natural and anthropogenic processes. This study focuses on anthropogenic drivers leading to highly-transient flow regimes, particularly on the hydropeaking phenomenon and Engineered Injection and Extraction Systems (EIE). Hydropeaking is a sequence of rapid and abrupt water table fluctuations in rivers generated by the release and storage of water for hydropower production. An EIE system is a groundwater remediation technology that consists of a sequence of injection and extraction of water through a system of wells. Even though these two processes have different anthropogenic origins, they both alter the groundwater flow velocity in time and space. In this work, we provide experimental evidence with a model-based interpretation of the effect of hydropeaking and EIE systems on plume spreading and mixing enhancement. We perform laboratory experiments in a quasi-two-dimensional setup reproducing a vertical cross-section of an unconfined homogeneous aquifer. To simulate the hydropeaking phenomenon, in the first experiment, the water table in two rivers connected to the aquifer is changed, mimicking river stage fluctuations occurring during hydropower production. To replicate the EIE system, in a second experiment, a two-dimensional flow-through system is equipped with four wells connected to a peristaltic pump. We inject a conservative dye tracer in the setups, and we apply a high-resolution image analysis technique to track the plume concentration. To estimate the plume spreading, we compute the second spatial moments, while to quantify the plume mixing, we calculate the plume area and the dilution index. In both experiments we observe mixing enhancement when simulating hydropeaking and the EIE system in comparison to steady-state experiments. We demonstrate that highly transient boundary conditions are relevant and have to be considered in order to properly capture contaminant transport in the subsurface.

Keywords: Hydropeaking, Engineered Injection and Extraction Systems, Flow-through experiments

Modelling of Groundwater Aquifer under MAR

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Managed Aquifer Recharge (MAR) is the process of recharging an aquifer for future use and/or environmental benefits, serving as an important strategy for sustainable water resource management and adapting to the increased vulnerabilities in water supplies. MAR has many forms, ranging from infiltration basins and injection wells to managed release from reservoirs coupled with stream channel modification or introduction of recharge especially in arid regions. Groundwater modelling is an important method for knowing the behavior of aquifer systems and to detect groundwater head under different hydrological stresses. This study develops flow and transport models using MODFLOW to assess the feasibility and performance of MAR systems. MODFLOW is a widely used numerical code based on the Finite-Difference-Method technique. Key modeling objectives include optimizing MAR implementation as well as understanding geochemical interactions during injection, storage and recovery. The research also aims to evaluate water recovery efficiency and the effects of injected water on the surrounding groundwater considering heterogeneous hydrogeological conditions like transmissivity, porosity and storativity and unsteady flows in unconfined aquifers governed by the nonlinear Boussinesq's equation that have been seldom incorporated in MAR models but are essential to better stimulate realistic recharge scenarios. Moreover, sensitivity analyses will be conducted to gauge the impact of different recharge rates and boundary conditions, ensuring improved groundwater management strategies.

Keywords: Managed Aquifer Recharge, groundwater modelling, hydrogeology, unsteady flows, unconfined aquifers, Finite Difference Method, Boussinesq's equation

Hydrochemical characteristics of groundwaters by multivariate analysis the from Takisaka Landslide, Japan

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The Takisaka landslide, located in the westernmost part of Fukushima Prefecture, is one of the largest active landslides in northeastern Japan. The bedrock of this landslide consists of Cretaceous granodiorite, Early Miocene granitic sandstone, and Early to Middle Miocene sandy tuff and mudstone in ascending order. Although recent activity has subsided partly due to groundwater drainage works, the hydrogeologic structure of this landslide is still unknown. The goal of this study is to elucidate the hydrogeological structure. Therefore, our objectives are to reveal (1) the hydrochemical characteristics and (2) the formation process of the groundwater. 117 groundwater samples were

collected for hydrochemical analysis. In addition, multivariate analysis was performed on 712 hydrochemical data. Each sample was classified into eight types, A to H. Regarding water-rock interaction and bedrock geology, type B is formed in weathered soil layers, type C in fresh granite, and types A and D in mudstone below the oxidation/weathering front. Type G and parts A and D are formed in sandy tuff below the oxidation front, and types E and F are formed in sandy tuff under reducing conditions. Type H, only one sample, contains a sodium chloride component. The construction of the drainage tunnel caused a significant lowering of the water table in the landslide mass. Types A through D and G are widely distributed within the landslide area and are found in observation wells and many groundwater drainage pipes. In contrast, types E and F are formed under reducing conditions in the deep zone around the landslide surface and discharged from drainage pipes inside the tunnel. Given the recharge area and residence time of these deep groundwaters, it is most appropriate to evaluate the effect of deep groundwater drainage on landslide stabilization.

Keywords: groundwater, hydrochemistry, multivariate analysis, water-rock interactions, landslides

An integrated approach to determine the groundwater recharge in the coastal regions of North-eastern Odisha, India

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The recharge in coastal aquifers is critical as they are fragile and are affected by the land use pattern of the region and adjoining seawater dynamics. The nature of groundwater recharge is studied in the Matei River sub-basin, located in the Bhadrak district in the north-eastern part of Odisha. The region is reflected with multiple land use practices and is composed predominantly of alluvium. Eighty samples from different parts of the study area were collected during the pre-monsoon and post-monsoon periods. The samples were studied for the major and minor ions along with stable isotopes of d18O and d2H. Seasonal geochemical data indicate that high electrical conductivity (EC) is recorded in the area's central and coastal regions during pre-monsoon. Agriculture is the predominant land use in the region, with prawn cultivation and other anthropogenic activities contributing to the elevated salinity observed in the central part of the region. The dominant water types of the region are Ca-Na-HCO₃ and Na-Cl types, samples with higher EC are observed to be of Na-Cl type. The Spearman correlation analysis and the Principal component analysis of the data suggest that weathering, anthropogenic activities, and the influence of saline water are the primary factors affecting the groundwater chemistry of the region, irrespective of the season. The isotopic signature reveals that the main recharge sources are precipitation, surface, and the interplay of saline water ingress. Thus, the regions and sources of recharge were demarcated, and management strategies were suggested.

Keywords: groundwater recharge, seasonal, agricultural, isotope, geo-statistical, salinity

Assessment of Groundwater Dynamics in Agro-Climatic Zone of Eastern India using Data-driven approaches

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Groundwater is a valuable resource which enables a populous country like India to maintain its food security. Its major portion is utilized for irrigation and its regulation remains unaccounted, mainly due to unavailability in its quantification. Therefore, Groundwater Level (GWL) prediction becomes a necessity and in recent years Machine Learning (ML) has proven to be a reliable tool. This study focuses on analysis of Agro-Climatic Zone (ACZ) for the first time in eastern India. Our zone of interest is Lower Gangetic Plain Region, comprising West Bengal, with an approximate area of 63,752 km². We have developed a ML framework which discovers the relationship between the predictors namely, precipitation, temperature, and Gravity Recovery and Climate Experiment (GRACE) derived groundwater storage change (GWS) data, with the predictand GWL. A Long Short-Term Memory (LSTM) model for 21-year period, 2002 to 2022 has been developed. The aim of the model is to evaluate seasonal GWLs using a grid-based approach on a spatial resolution of 0.25°0.25°. To evaluate its performance, three metrics were used namely, correlation coefficient (r), Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE). Training, testing and validation is performed using in-situ groundwater level from India-WRIS website. The finding of this study tells that the LSTM model provide satisfactory results in predicting seasonal GWLs. Performance metrics were well within the range for major portions of the study area. Overall, this method is fast and efficient in predicting GWLs compared to physics-based methods and can be implemented in other regions in the world. Furthermore, the quantified GWLs will be useful in developing policies for sustainable usage of groundwater.

Keywords: Groundwater dynamics, Agro-Climatic Zone, GRACE, Long Short-Term Memory, Grid-based, Seasonal

Submarine Groundwater Discharge: A Hidden Water Pathway

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Submarine Groundwater Discharge (SGD) is a significant yet often overlooked hydrological process, where groundwater seeps from terrestrial aquifers into the ocean, influencing coastal water quality, nutrient fluxes, and coastal dynamics. Understanding SGD is crucial for effective groundwater resource management, particularly in India, where water scarcity remains a pressing issue.

This study, led by the National Centre for Earth Science Studies (NCESS), identifies SGD along the Indian coastline using a multi-proxy approach that integrates geophysical surveys, remote sensing, field measurements, and numerical modeling. To address key research questions related to SGD flux, sustainable utilization, and associated biogeochemical processes, NCESS has initiated a National Network Program involving 14 institutes across India. Approximately 1,200 km (22%) of India's 5,400 km mainland coastline has been identified as potential perennial SGD zones. Nine significant

SGD hotspots have been verified along 106 km of the southwest coast of India. This research employs groundwater level analysis, electrical resistivity tomography, thermal infrared satellite imaging, radon assessments, and UAV-based thermal imaging to locate SGD flux. High-resolution sampling at 500-meter intervals confirmed nine perennial SGD hotspots along a 641 km stretch from Mangalore to Kanyakumari. Numerical modeling of coastal catchments in Kerala-Kadinamkulam, Varkala, and Adimalathura-estimated that 4.3%-6.4% of annual rainfall is lost through SGD. These models integrate geology, topography, and aquifer characteristics, using partial differential equations and mass balance techniques to quantify SGD flux.

Through comprehensive SGD characterization, advanced numerical modeling, and interdisciplinary collaboration, this study establishes a robust scientific foundation for managing SGD as a critical component of India's hydrological and coastal resource framework. Future research at NCESS will refine SGD quantification, assess nutrient fluxes, and explore biogeochemical interactions, contributing to sustainable coastal groundwater management.

Keywords: Groundwater, Submarine Groundwater Discharge, Coastal Hydrology

Hydropeaking affects groundwater flow and transport processes: a multiple spatial and temporal analysis

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Groundwater flow and transport are not only controlled by the properties of the porous media, but also by the boundary conditions of the system. In this study, we consider the case where the river is a highly transient system affected by hydropeaking, a flow regime characterized by sharp and frequent fluctuations due to the operation of hydropower plants upstream. We investigate this problem at the laboratory and at the field scale. At the laboratory scale, we perform flow-through experiments mimicking the cross-section of a homogeneous aquifer in hydraulic contact with two hydropeaked rivers and provide a model-based interpretation of the system. We study the flow topology and track the evolution of an injected tracer plume to analyze dilution and mixing processes. At the field scale, we consider the case study of the Adige aquifer, an alpine valley crossed by rivers under different hydropeaking regimes. We collect data from gauging stations and groundwater piezometers, and apply timeseries analysis (i.e., wavelet transform) to identify the propagation of hydropeaking into the aquifer and evaluate the strength of the impact of surface water alterations. Finally, we model the aquifer to map the area affected by hydropeaking. Ecohydrological indicators reveal that the aquifer can be similarly impacted as the river. This study therefore highlights the importance of considering the surface water-groundwater continuum in the assessment of hydropeaking impacts on the environment.

Keywords: Okubo-Weiss parameter, continuous wavelet transform, wavelet transform coherence, dilution index

Groundwater potential zone identification in a coastal region using AHP and ML technique

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In coastal regions, due to the over-extraction of groundwater, the regions are facing the issue of seawater intrusion, which causes depletion of fresh water and degradation of groundwater quality. Therefore, the availability of water for drinking and irrigation is reduced. In the present study, the Analytical Hierarchical Process (AHP) and Machine Learning technique are used to identify the potential zones for groundwater which will be useful for the development of effective strategies for effective water conservation and recharge as well as ensuring a reliable and uncontaminated water source for local communities. The study was conducted in the Baleswar district which is a coastal region of Odisha. The study integrates multiple hydrogeological, topographical, and climatic factors, including rainfall, land use/land cover (LULC), drainage density, slope, soil type, geology, and groundwater level. AHP is employed to assign weights to the influencing factors, while the machine learning (ML) model Random Forest (RF) is used for automated classification and prediction of groundwater potential zones. The results are validated using field data and the statistical index correlation coefficient. The comparative study will be useful for sustainable management of water resources.

Keywords: Analytical Hierarchical Process, Machine Learning, GW potential zone

Prediction of Groundwater Fluoride Contamination Based on Machine Learning Techniques in the Arid Region of Rajasthan

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Estimation of fluoride contamination in groundwater and its vulnerability is essential to understand contamination prevention mechanism and to minimize the health risks. The primary objective of the present study is to accurately predict groundwater fluoride contamination (GWFC) based on machine learning (ML) algorithms for systematic assessment of fluoride contamination to minimize the health hazards in arid region of Rajasthan. In this study, we propose ML techniques based on a chi-square automatic interaction detector (JCHAIDStar) and random forest (RF) models. The groundwater quality (GWQ) data sets of 132 well locations for eight years from 2015 to 2023 in Jaisalmer district have been collected from State Groundwater Department in Rajasthan. The ML model considers pH, EC ($\mu\text{S}/\text{cm}$ at 25°C), TDS (mg/l), Total Hardness (mg/l), rainfall (mm) and Chloride (mg/l) as input of proposed algorithms for prediction of GWFC. The model utilizes six-year data sets for model calibration and the two-year data sets for model validation for proposed algorithms. The ML model's performance is evaluated by considering four statistical indices CC, NSE, RMSE and nRMSE. It has been observed that the RF model gives superior results as compared to JCHAIDStar in both cases of model calibration and validation. This study may be more beneficial for the risk analysis of groundwater contamination and for minimising the water-based health risks in the study area.

Keywords: GWFC, ML, JCHAIDStar, RF & Statistical Indices.

Assessment of hydrogeochemical characteristics and seawater Intrusion using geostatistical techniques: A case study from Eastern Coastal Aquifer, Odisha, India

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Coastal aquifers undergo the environmental challenge of seawater intrusion (SWI), which diminishes the availability of potable groundwater. This issue has severely impacted large coastal regions due to the overuse of groundwater for industrial, agricultural, and drinking purposes, along with pervasive urban expansion. The present study identifies groundwater quality issues and investigates the geochemical processes that regulate seawater intrusion by utilizing a variety of ionic ratios, hydrogeochemical facies evolution, and geostatistical techniques. Groundwater samples collected from different sources were examined for major physicochemical parameters. The analytical results reveal that dominant cations and anions are in the sequence $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ respectively with high Electrical Conductivity (EC) values. Water Quality Index (WQI) values have classified 42% of water samples as excellent water and 58% as poor water. The concentrations of Na and Cl are strongly correlated with EC, indicating the influence of seawater intrusion on water quality, as further demonstrated by elevated molar ratios of $\text{Mg}/\text{Ca} (>1)$ and $\text{Cl}/\text{HCO}_3 (>1)$ in numerous samples. Results from the hydrogeochemical facies evolution and the piper diagram illustrates that the most prevalent forms of water composition are Na-Cl, followed by mixed Ca-Na- HCO_3 and Ca- HCO_3 types. Evaporation followed by rock-water interaction are the principal natural mechanisms that control groundwater hydro geochemistry, as shown in the Gibbs plot. The saturation index indicates the precipitation of calcite and dolomite phases, as well as the dissolution of gypsum and halite phases in groundwater. PC1 (Na^+ , Cl^- , SO_4^{2-} , Mg^{2+} , and K^+) is considered as dominant salinity process. The results of the geostatistical analysis represents that the salinisation processes are influenced by seawater intrusion, mineral dissolution and anthropogenic contamination. This research will be beneficial to decision-makers in their efforts to resolve groundwater salinity concerns in coastal regions.

Keywords: Coastal aquifers, Seawater intrusion, Water quality Index, Molar ratios, Hydrogeochemical facies evolution, Geostatistical analysis

Water from Everest: Using a Mixed-methods Approach to Understand Alternative Potable Water Groundwater Zones and Resource Management Techniques Using Indigenous Knowledge

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Sagarmatha National Park (SNP), Nepal - home to Mount Everest - has become an increasingly booming tourist attraction in recent decades. Between the massive influx of visitors, climate change, and lack of consistent resource management, the SNP region currently experiences increased pressures on potable water resources for locals and visitors. In previous years, Electrical Resistivity Tomography surveys (ERT) have shown evidence of fracture-zone aquifers with the potential to produce alternative freshwater resources in the village of Phortse, SNP. An additional aim of this research seeks to address social dynamics related to natural resource allocation among residents and visitors within Phortse and the greater SNP region. In 2022 and 2023, nine semi-structured interviews were conducted with residents, including teahouse/lodge owners, park workers, expedition/trekking guides, and others to gauge public perception regarding the successes or shortcomings of the Nepali government's chosen water management framework IWRM (Integrated Water Resource Management - promoted by the United Nations for 30+ years). ERT data provided detailed information about groundwater flow patterns, and interviews captured relevant and timely data as residents live through changes in the quality, quantity, and availability of freshwater resources; trust in governing bodies; and climate change awareness and resilience. Common themes that arose from respondents' answers included anxieties about climate change (melting glaciers and increasingly unpredictable farming seasons) and added pressure on resource availability due to growing numbers of tourists, concerns about environmental education in the region, but overall satisfaction with shifting towards a tourist-driven economy and the way of life that comes along with it. In May 2025, a gravity survey will be conducted in order to provide ground-truth validity to ERT survey results. Results are continuously shared with communities where research is conducted.

Keywords: Geophysics, Electrical Resistivity Tomography, Semi-structured Interviews, Indigenous Knowledge, Gravity Survey

Spatiotemporally Non-Stationary Evolution of Groundwater Levels in Poyang Lake Basin Driven by Meteorological and Hydrological Factors

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The complex relationship between wet-dry transition in the Poyang Lake basin and groundwater storage significantly affects the lake's hydrology, downstream ecological state, and overall security along the Yangtze River in China. There is, however, a notable lack of systematic exploration

into how various factors drive spatiotemporal variability in groundwater level (GWL). Using local indicators of spatial association (LISA), spatial non-stationarity models, and multi-source data, our analysis explores the spatial distribution of GWL and quantifies the influence of driving factors on its spatiotemporal non-stationarity at annual and monthly scales. We also compare driving factor contributions in hilly, plain, and local areas within the Poyang Lake basin. Our findings reveal significant local clustering of GWL, indicating substantial spatial autocorrelation and geographic heterogeneity in GWL. Influencing factors exhibit non-stationary effects on GWL at spatial and temporal scales, with precipitation (P), ground surface elevation (GSE), and soil moisture (SM) being primary contributors, generally exerting positive effects. SM contributes most during dry years and normal periods. P and the Palmer Drought Severity Index (PDSI) have greater impacts in hilly areas, while GSE shows the opposite trend. Rainfall is a source of groundwater recharge, with a lagged response observed in GWL to rainfall in this basin. The lag time is about 1-2 months. Evapotranspiration is not the dominant discharge pathway. The decrease in GWL during the dry season is mainly due to reduced precipitation recharge and increased lateral groundwater discharge from areas of high hydraulic head to areas of low hydraulic head.

Keywords: Groundwater level, Influencing factors, Non-stationary model, Hilly areas, Poyang Lake basin

Machine Learning Approaches for Groundwater Forecasting in the Eastern Mitidja Aquifer, North Algeria

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Accurate groundwater level forecasting is essential for sustainable water resource management, particularly in semi-arid regions like the Mitidja aquifer, where increasing water demand and climatic variations pose significant challenges. This study applies machine learning techniques to predict groundwater fluctuations in the Eastern Mitidja aquifer from 2005 to 2022, using biannual measurements.

The models incorporate historical groundwater level data alongside key environmental variables, including precipitation, evapotranspiration, land surface temperature, and vegetation indices EVI. To assess the potential impacts of climate variability on groundwater resources, projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are incorporated into the analysis. Performance evaluation using Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2) indicates that LSTM achieves the best predictive accuracy, with an RMSE of 0.40 m, an MAE of 0.32 m, and an R^2 of 0.83. The integration of remote sensing and climate data enhances predictive accuracy, highlighting the effectiveness of AI-based models in groundwater resource assessments.

The results suggest a gradual depletion trend in groundwater levels over the study period, primarily attributed to increased extraction and reduced recharge. These findings underscore the necessity for adaptive water management strategies to mitigate depletion risks and optimize aquifer sustainability under evolving climatic and anthropogenic pressures.

Keywords: Groundwater Modeling, Mitidja Aquifer, Machine Learning, Climate Change, CMIP6, Water Resource Management.

Health Risk Assessment and Contaminant Monitoring of Groundwater in the Khetri Copper Mining Region

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Water is the essential resource for lives and mainly altered by the interaction with surrounding environment. Mine tailings and mining operations can contaminate ground and surface waters, which can substantially alter water quality. Present work explores the hydrogeochemical monitoring of the Khetri copper mining region of Rajasthan, India focusing on extent of groundwater contamination. Total sixty groundwater samples were collected in monsoon and post monsoon seasons and analyzed to determine the concentrations of heavy metals, including Pb, Cu, Cd, Cr and Fe using AAS. The groundwater exhibited elevated levels of TDS and EC, which are indicative of increased salinity and mineralization. Furthermore, it was determined that the concentrations of heavy metals, including Pb, Cd, Fe, and Cr exceeded the permissible limits established by the WHO in both seasons. The concentrations were comparatively higher during the post-monsoon period. These results suggest that the region is affected by a persistent source of heavy metal contamination.

The hydrogeochemical facies analysis was conducted using Durov and Piper diagrams to obtain a more comprehensive analysis of the characteristics of groundwater and the contaminants distribution. The results of this analysis indicated that chloride and sulphate were the primary elements in the groundwater.

All metals, with the exception of copper, exhibited hazard quotients (HQ) exceeding 10, indicating a high noncarcinogenic risk for both adults and kids. The safety of groundwater for consumption purposes is a significant concern. The study underscores the importance of ongoing surveillance and evaluation in mining regions to protect public health.

A remediation strategy is proposed in accordance with these findings, with a particular emphasis on the utilization of acid-resistant materials, like tailings, to directly absorb mine leachates at the source. This method aims to reduce the leaching of heavy metals into groundwater, which is a significant contributor to water contamination in the region.

Keywords: Health Hazard, Groundwater, Heavy Metals, Mining

Impact of model selection on groundwater level time series modelling for drought monitoring

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Groundwater level time series models are used for gap filling and forecasting, in applications such as aquifer monitoring, and to study the impacts of drought or over-abstraction. The available models have different levels of complexity and performance and can be broadly categorised into linear and non-linear types. Selecting models from either group requires balancing model fitting and parsimony, which becomes challenging when many options are available. We explore the performance of linear and non-linear groundwater level time series models for simulating groundwater levels in the Netherlands, focussing on regions prone to drought (east and south). Observed groundwater level time series with suitable data characteristics for modelling (e.g. daily records) were downloaded for 5,843 locations. For a sample of ~25% (1,500) of the original locations, 7 models (2 linear and 5 non-linear) and 3 model additions (trend, noise, and threshold) were evaluated, leading to 19 potential combinations (one non-linear models doesn't allow for trend or threshold addition) for each location. The best linear and non-linear models were then fitted to the entire dataset to test their predictive capabilities and produce maps of the 2018 drought for visual comparison. The sample analysis showed that the noise model employed (AR(1)) often resulted in worst fitting (R²) and parsimony (AIC), while the addition of a trend or threshold had either a positive or negligible effect. The non-linear FlexModel and the linear transfer function noise model (TFN) using two gamma distributions as an impulse response function showed the best performance and had very similar results in terms of spatial visualisation and predictive power. This analysis provides valuable insights into model fitting for large datasets and the application of time series modelling for groundwater monitoring at regional and national levels.

Keywords: time series modelling, groundwater, drought, monitoring, regional, national

Assessing Data-Based Global Groundwater Use for Irrigation in CLM5: Hotspots and Sustainability Implications

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Irrigation is the largest sector for water withdrawal, making a reliable water supply essential for crop production and commonly represented through empirical modeling based on observed practices or by estimating water supply and demand in land surface models. The Community Land Model (CLM5) within the Community Earth System Model (CESM) includes a global irrigation map with 64 crop functional types (CFTs) to simulate irrigation demand and estimate water withdrawal from various sources. Groundwater withdrawal from aquifers is vital for irrigation in CLM5, yet unregulated abstraction in many basins over decades has threatened sustainability. Current CESM simulations inadequately capture actual groundwater use, posing challenges for effective management. To address this, we integrated global datasets of observed groundwater consumptive use into CESM coupled with CLM5. These datasets, covering 15,038 global administrative units, were reconstructed at 0.5° resolution. We validated our model against authoritative datasets for India and the US. In the US Central High Plains, controlled simulations estimated groundwater use at 10 km³, while experimental results showed 16.5 km³, compared to the USGS-reported 18 km³ in 2015. Our simulations revealed a 28% increase in groundwater use over 2001-2015. We identified 20 major hotspot basins to simulate an optimized groundwater use for irrigation by replacing the crops in each grid. Our findings offer valuable insights into groundwater depletion in hotspot basins, and sustainable water management for irrigation and highlight the intricate connections between climate, water

resources, and irrigation.

Acknowledgment

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Keywords: Groundwater withdrawal, Land surface models, Controlled simulations, Sustainability

Coupled hydrological modeling with SWAT-MODFLOW using heliborne data in the Ankasandra watershed, Karnataka, India

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Integrated surface water and groundwater modeling is vital for understanding hydro-dynamics and ensuring sustainable water resource management. This study employs a coupled SWAT-MODFLOW modeling framework in the Ankasandra watershed, Karnataka, India, covering ~380 km². The region, characterized by crystalline hard rock aquifers, semi-arid climatic conditions, and significant groundwater dependence for agriculture and domestic use, provides an ideal case for analyzing surface-groundwater interactions. The SWAT model captures spatial and temporal variability in surface hydrological processes, including runoff, evapotranspiration, and recharge, while MODFLOW simulates groundwater flow and aquifer dynamics.

To enhance the accuracy of aquifer characterization, high-resolution heliborne transient electromagnetic (HTEM) was incorporated into the study. These datasets provided detailed insights into aquifer geometry, such as depth, thickness, and spatial heterogeneity, enabling the delineation of recharge zones and preferential groundwater flow paths. This refined understanding was crucial for improving model accuracy and simulating hydrological processes effectively. Historical streamflow and groundwater level data (2010-2023) were used for calibration and validation, achieving satisfactory results. The study highlights the critical role of stream-aquifer interactions, where changes in recharge rates or groundwater extraction significantly affect streamflow patterns and groundwater storage. By integrating advanced geophysical datasets, this research demonstrates the applicability of SWAT-MODFLOW for addressing water scarcity, guiding agricultural planning, and assessing climate change impacts in semi-arid regions.

Keywords: SWAT-MODFLOW, Ankasandra watershed, heliborne data, aquifer geometry, groundwater recharge, hydrological modeling

Fluoride Mobilization in Groundwater: Role of Lithology and Weathering in Pali District, Rajasthan, India

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Fluoride contamination in groundwater is a pressing issue in many arid and semi-arid regions, particularly in Rajasthan, where prolonged water-rock interactions significantly influence groundwater chemistry. This study investigates the geological and geochemical controls on fluoride mobilization in the groundwater of Pali District by analysing 250 samples from various lithological formations. The primary objective is to assess the role of lithology and weathering in fluoride enrichment, providing insights into fluoride dynamics and potential mitigation strategies. Groundwater chemistry was evaluated based on pH, total dissolved solids (TDS), and fluoride concentrations, which ranged from 6.8 to 9.6, 199 to 21,372 mg/L, and 0 to 12.4 mg/L, respectively. To understand fluoride variability, groundwater samples were categorized according to geological formations, and statistical comparisons were made. The fluoride concentrations in groundwater vary across different lithologies, with the highest levels observed in granitoids, followed by volcanic rocks, sedimentary rocks, and the lowest concentrations found in metamorphic rocks. This distribution suggests that fluoride sources are predominantly linked to the mineralogical composition of metamorphic and granitic formations. Hydrogeochemical facies analysis indicates that Na-HCO₃-type groundwater exhibits the highest fluoride concentrations, whereas Ca-HCO₃-type groundwater contains the lowest levels. The inverse relationship between calcium and fluoride activities highlights the control exerted by fluorite (CaF₂) equilibrium, where fluoride concentrations are regulated by calcium availability, influencing precipitation or dissolution reactions. Furthermore, ionic interactions reveal that fluoride enrichment is associated with sodium release and calcium depletion, emphasizing ion-exchange processes. These findings suggest that geological sources play a dominant role in fluoride contamination, and managing groundwater fluoride levels may require strategies that enhance fluorite precipitation through calcium supplementation. This study provides crucial insights into fluoride behavior in groundwater, contributing to improved water quality management and mitigation measures in fluoride-affected regions of Pali District, Rajasthan.

Keywords: Fluoride contamination, Groundwater chemistry, Weathering, Hydrogeochemical processes, Granitoids, Fluorite equilibrium, Ion exchange, Pali District, Rajasthan.

Modelling colloid-facilitated contaminant transport in unsaturated porous media

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In this paper, we aim to analyze the flow and colloid-facilitated contaminant transport in the unsaturated subsurface porous media. The unsaturated subsurface flow and contaminant transport is governed by Richard's and colloid-facilitated contaminant transport equations. The governing equations of the considered physical system is solved numerically. The spatial variations of the flow parameters, such as pressure head, flow velocity, moisture content, and dispersion coefficient, has been analyzed in detail. Moreover, the study offers understanding on the distribution of contaminants in unsaturated porous media. The predictions of the present study are congruent with the existing experimental observations.

Keywords: Colloid-facilitated contaminant transport, Unsaturated subsurface flow, Porous media

Prediction of Nitrate Concentration throughout California, USA using Machine Learning Model

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Groundwater is a vital resource for domestic, industrial, and agricultural sectors worldwide. However, its sustainability is increasingly threatened by contamination and overuse. In California's Central Valley, rising water demand and increasing nitrate concentrations pose significant environmental and public health risks. Nitrate pollution, primarily from agricultural runoff, septic systems, and industrial discharges, is associated with severe health conditions such as methemoglobinemia ("blue baby syndrome") and other chronic diseases.

This study leverages artificial intelligence (AI) and machine learning (ML) to predict nitrate concentrations in California's groundwater, improving water quality management strategies. Data spanning 28 years was compiled from sources including the California State Water Resources Control Board (CSWRCB), the California Department of Water Resources (CDWR), and the United States Geological Survey (USGS). Key parameters include spatial coordinates, slope, soil composition, groundwater levels, screen depth, nitrate concentration readings, proximity to rivers, and meteorological data.

Three ML models-Artificial Neural Networks (ANN), Gaussian Process Regression (GPR), and Support Vector Regression (SVR)-were trained and validated using cross-validation techniques. Model performance was evaluated using R-squared (R^2), Nash-Sutcliffe Efficiency (NSE), and Root Mean Square Error (RMSE). An 80/20 train-test split provided the most accurate predictions compared to 70/30 and 90/10 splits. The best-performing model forecasts a 0.0545 mg/L/year increase in nitrate concentration over the next decade.

These findings offer critical insights for policymakers and water resource managers, enabling strategic planning to mitigate nitrate pollution risks. By integrating advanced predictive models, this study

enhances our understanding of contamination patterns and supports sustainable groundwater management efforts in California.

Keywords: Groundwater contamination, Nitrate pollution, Machine learning (ML), Predictive modeling and Water quality management

Understanding Aquifer Dynamics of Springs in the Tawi River Catchment, Jammu & Kashmir UT, Western Himalayas

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Mountain aquifers are strategic resources for local populations. The Tawi River catchment contains over 350 springs that maintain the river's base flow. However, the lean season discharge of the Tawi River, which sustains 20% of Jammu & Kashmir's population (3 million), is declining. Spring flows have decreased by 0.639 cumecs annually due to anthropogenic activities and climate change. This study aims to understand the aquifer dynamics and recession characteristics of springs in the Tawi River catchment. The objectives include analyzing spring discharge patterns, determining aquifer properties, and identifying factors controlling spring flow behavior for effective springshed management. We analyzed recession behavior in eight perennial springs in the Western Himalayas, India. These springs drain sandstone, shale, and meta-sedimentary aquifers in Shivalik and Murree lithological formations. Seven springs discharge from depression/fractured typology, while one flows as a contact spring from the Chinji formation.

The analysis revealed distinct recession patterns. Chak Rakhwal spring ($a = -0.078 \text{ day}^{-1}$) and Ud-hampur springs (Near Highway and Shani Mandir, $a = -0.022$ and -0.048 day^{-1} , respectively) showed wide recession envelopes, indicating shallow recharge areas and rapid aquifer emptying. Pangara Jagir, Chenani, and Mantalai springs exhibited low recession coefficients ($a = -0.024$, -0.031 , and -0.011 day^{-1}), suggesting diffused fracture systems. Paap Nashni Sudhmahadev ($a = -0.018 \text{ day}^{-1}$) and Shani Mandir (-0.048 day^{-1}) demonstrated balanced groundwater flow characteristics. All recession curves were fitted by functions with exponential terms. Higher coefficients represented fast flow through cracks (quickflow), while lower coefficients indicated slow flow through porous media (baseflow). These coefficients vary based on storage properties and media types (porous, fractured, cracked lithologies, or karst) for each spring, reflecting the hydraulic conductivity of different groundwater flow paths.

This investigation of vulnerable springs has high societal importance for identifying springshed areas and discharge potential to carry out efficient springshed management activities in the area.

Keywords: Spring, springshed, Tawi River basin, recession curve, mountain aquifer, Western Himalayas

Groundwater Quality Assessment Using MCDM Models in Nadia, West Bengal

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Groundwater, the primary supply of potable and irrigation water in developing nations, is crucial for sustaining public health and agricultural output. However, in the Nadia district of West Bengal, India, groundwater quality is frequently compromised, and geological aquifers that comprise this valuable resource are susceptible to contamination by emergent pollutants and arsenic, posing severe health risks to local communities. Hence, for sustainable and socioeconomic development, it is important to map and control groundwater resources. This study attempted to develop the groundwater quality index for the Nadia district using the Multi-Criteria Decision-making Models (MCDM), i.e., Analytical Hierarchy Process (AHP) and Entropy. For this purpose, this study has used water quality parameters, which include the pH, Fluoride, Chloride, Bicarbonate, Sulphate, Nitrate, Phosphate, Arsenic, Total Dissolved Solids, Total Hardness, Calcium, and Magnesium. The result shows that the majority of the blocks in Nadia district are arsenic-contaminated with varying concentrations. The groundwater quality index indicates that most of the study area is contaminated and cannot be recommended for drinking. The result of this study can be used to identify suitable locations for bore wells and tube wells for drinking and agricultural purposes and to make people aware of the future health risks caused by arsenic and other pollutants in the groundwater.

Keywords: Groundwater Quality, MCDM, AHP, Entropy, Arsenic Contamination

Recharging Tradition, Ensuring the Future: The Impact of Minor Irrigation Tank Rehabilitation on Groundwater in Andhra Pradesh

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Minor irrigation tanks have long been a foundation of Indian agriculture, particularly for small farmers. However, their share of irrigation has declined due to poor maintenance, resulting in heavy siltation, weed infestation, and damaged infrastructure. To address these challenges, the Andhra Pradesh Integrated Irrigation and Agricultural Transformation Project (APIIATP) rehabilitates and modernizes 1,000 minor irrigation (MI) tank systems, aiming to bridge the gap ayacut, improve cropping intensity through conjunctive use, and enhance water use efficiency and climate resilience. Several large-scale initiatives around the globe, including Mission Kakatiya in Telangana, India, and the Village Irrigation Rehabilitation Project (VIRP) in Sri Lanka, have employed structured methods to rehabilitate minor irrigation tanks and evaluate their impact on groundwater recharge. A core component of APIIATP is participatory groundwater management, which involved installing piezometers in select tank command areas and regularly monitoring groundwater levels and well discharges. This data provided insights into tank-induced recharge and its influence on the local aquifer. Analysis using a

groundwater model (AMBHAS-1D) indicated that typical rainfall recharge in these semi-arid, hard-rock aquifer regions is 7.4-16.6% of annual rainfall. In contrast, induced recharge generated by rehabilitated MI tank areas is estimated at two to three times the natural rainfall recharge rate. Field data further showed that previously depleted aquifers, post rehabilitation of MI tanks exhibited stable groundwater levels throughout the dry season, creating a reliable buffer against erratic rainfall. These findings underscore the potential of rehabilitated MI tanks to significantly bolster groundwater storage, enhance cropping intensity, and reduce the irrigation gap ayacut. By capturing excess water in wet years, MI tanks help mitigate drought impacts and foster climate resilience. Overall, the APIIATP experience highlights that strategic rehabilitation of minor irrigation systems can be a transformative pathway to sustainable agriculture, benefiting both farmers and the broader rural economy.

Keywords: Groundwater Recharge, Sustainable Agriculture, Tank Rehabilitation, APIIATP, AMBHAS-1D

Groundwater Quality Degradation from a Closed Landfill: The Persistent Threat of Antibiotic Resistance Genes.

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Introduction: Even after closure, landfills can continue to contaminate groundwater by leachate release. This study examines the long-term effects of the closed Vilappilsala landfill on groundwater quality specifically focusing on the release of antibiotic resistance genes (ARGs), which are often linked to microplastics, and their potential to harm human health.

Aim and Objectives: Assessing the long-term fate and transportation of ARGs from the Vilappilsala landfill as well as the related groundwater hazards are the objectives of this study. The targets are: (1) measuring ARG concentrations in groundwater before, during, and after closure; (2) creating an integrated MODFLOW-Agent-Based Model (ABM) to model ARG migration and evolution; (3) comparing observed ARG concentrations with data on local disease incidence; and (4) advising mitigation plans.

Methods: ARG concentrations and other groundwater quality data will be examined. ARG dynamics will be realistically represented by simulating ARG migration and evolution using an integrated MODFLOW-ABM framework. Possible connections between local disease incidence and ARG concentrations will be investigated using statistical correlation analysis.

Results: The results will show patterns in ARG pollution on groundwater over time. The comprehensive model will offer, insights into the long-term fate and movement of ARGs from landfill to groundwater system. Correlation analysis with disease data of people residing nearby will examine possible health concerns from ARG exposure.

Summary: This study highlights the persistent threat of ARG contamination on groundwater. An effective tool for simulating ARG dynamics is provided by the integrated modeling approach. Possible health effects will be investigated using correlation analysis.

Conclusion: The results will help us comprehend the long-term hazards associated with ARG contamination on groundwater. This study will direct to develop best remediation strategy to safeguard groundwater and public health. Long-term groundwater conservation requires ongoing monitoring of closed landfills, even decades after closure

Keywords: Groundwater contamination, Antibiotic Resistance Genes, landfill leachate, modeling, public health.

Machine Learning-Based Prediction of Groundwater Salinization Across Indian States

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Groundwater salinity, influenced by both natural processes and human activities, poses a significant challenge to water quality, agriculture, and ecosystem sustainability. Natural causes include geochemical and hydrological processes such as rock weathering, evaporation, and seawater intrusion, particularly in overexploited coastal regions and areas affected by climate change. Predicting groundwater salinity is crucial in terms of water quality management, agriculture sustainability, ecosystem preservation, and climate change adaptation. Machine learning (ML) improves groundwater salinity prediction by identifying patterns and relationships that may not be immediately apparent. This study leverages a few ML techniques: Random Forest, Gradient Boosting, Logistic Regression, and Gaussian Process, to predict groundwater salinity across selected Indian states. Electrical Conductivity data from the Central Ground Water Board (CGWB) was used as the salinity indicator, while predictors included land use and land cover data, elevation, slope, climatic data, and proximity to water bodies. The data collected were pre-processed using lagging and rolling techniques prior to analysis. Among the models adopted, Random Forest achieved the highest test accuracy of 80.09% for groundwater salinity prediction in this study, followed by Gradient Boosting with 79.40%, demonstrating strong predictive capabilities. The Gaussian Process model performed well in Maharashtra and Rajasthan but showed moderate accuracy in Andhra Pradesh, West Bengal, Assam, and Kerala, highlighting the need for improved generalization. The analysis reveals the promising results of AI-driven models in predicting groundwater salinity while indicating areas for data improvement and model refinement, offering valuable insights for future research in reliable assessment of salinity for sustainable management of water resources.

Keywords: Machine Learning, Groundwater Salinity, Electrical Conductivity, Random Forest, Gradient Boosting

Integration of Machine Learning Approach with Hydro-Geochemistry for Groundwater Quality Assessment and Contamination Mapping in Kishangarh, Rajasthan, India

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Groundwater contamination and its adequacy for various uses remain primary concerns in semi-arid regions, especially regions suffering from rapid urbanization and industrialization. This study inspects the groundwater chemistry and the main contributing sources of contamination in groundwater in Kishangarh, Rajasthan, India. It also integrates conventional hydrogeochemical techniques with advanced machine learning models, i.e., Artificial Neural Networks (ANN) and Extreme Gradient Boosting (XGBoost). We have collected 30 groundwater samples from various sites and examined various physicochemical parameters, major anions, and cations to identify the contamination trend. The results show that the main hydrogeochemical facies were Na-HCO₃ and Na-Cl, which indicates the dominant effect of rock-water interactions, silicate weathering, and evaporative processes. The groundwater pollution index evaluation identifies that 3.33% of the total samples exhibit a very high risk of Pollution, while 16.67% lies within the moderate range, mainly due to industrial and agricultural activities. Groundwater suitability index (GSI) for drinking, irrigation, and industrial purposes were calculated using water quality indices, which indicates that 43.33% of the total samples were not found to be suitable for drinking purposes due to increased concentration of total dissolved solids (TDS), nitrate (NO₃⁻), and fluoride (F⁻). Machine learning models (ANN and XGBoost) exhibit high predictive accuracy in contamination mapping providing an understanding of spatial distribution patterns which identifies the northern region as a pollution contamination hotspot in our area due to high TDS, F⁻, SO₄²⁻ and nitrate levels which may be due to the geogenic minerals, industrial discharge and agricultural waste. Integrating geospatial machine learning with hydrogeochemical analysis provides a use one effective as it is repetitive groundwater governance, assisting policymakers in addressing pollution challenges and enhancing resource allocation in water-scarce areas.

Keywords: Groundwater quality, ANN, XGBoost, Contamination mapping, Hydro geochemistry, Groundwater suitability

Large-scale landslides influenced by saline water plume intrusion - An example of the Okimi landslide in Central Japan -

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Large-scale landslides with volumes ranging from tens to hundreds of millions of cubic meters are scattered throughout Niigata Prefecture, Central Japan. Highly concentrated Na-Cl type groundwater (hereinafter "saline water") has been found in large-scale landslides in Niigata Prefecture. In addition, these saline waters are artesian groundwaters. We also pay special attention to the distribution of landslide-prone areas and oil and gas fields in Niigata Prefecture, which generally overlap, and saline water from landslides is originally fossil seawater such as oil-brine based on geochemical characteristics. On the other hand, anomalous high-pressure reservoirs at depths of more than 1,000 m in oil and gas fields have been known since the 1960s and are possible saline water sources. We focus on the behavior of saline water as the key to solving the mechanism of large-scale landslides. Our research area, the Okimi landslide, is located in the western part of Niigata Prefecture, Japan. The aspect of the active body is about 500 m wide and 1,500 m long. The bedrock geology is mainly Neogene unconsolidated mudstone. According to previous studies, saline water has been detected in observation wells at the head of this landslide. Since the geological formation containing saline water has a significantly low resistivity value (= 2.0 Om), the CSMT method is best suited for electromagnetic exploration to visualize the resistivity to a depth of 1,000 m. The survey results confirm a saline water plume rising from a "saline water chamber" located 100 to 300 m below the western side of this landslide to the base of this landslide (at a depth of approximately 30 m). The presence of the saline water plume suggests that upwelling from the anomalous high-pressure reservoir (saline water chamber) is closely associated with several large landslides.

Keywords: large-scale landslides, groundwater, saline water plume, oil brine, fossil seawater

Groundwater Storage Estimation in Uttar Pradesh by GRACE/GRACE-FO using Geospatial technology and Google Earth Engine

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Groundwater is essential for the sustainability of agriculture and industry worldwide, as well as the provision of potable water to billions of individuals. The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On, employ satellite derived datasets to assess the trends in groundwater levels and the fluctuations in Total Water Storage (TWS) in the most populous state, Uttar Pradesh of India. From the GRACE TWS anomalies, changes in groundwater storage were computed by subtracting the summation of GLDAS-derived Soil Moisture and Canopy Water Storage. The calculated groundwater levels were then compared with GLDAS TWS data to

validate the observed patterns. Since GLDAS TWS disregards groundwater levels, the study deducted GLDAS TWS from GRACE TWS to derive groundwater storage estimations. This indicates that the groundwater data obtained is reliable, as evidenced by the consistent patterns between the two methodologies.

Examining Land Use Land Cover (LULC) between 2005 and 2024, NDVI and LST data from 2000 to 2024 shows built-up areas and agricultural land have increased. The spread of urbanized areas reduces water infiltration, influencing groundwater recharge. Agricultural growth indicates increased groundwater extraction for irrigation. NDVI increment designate a drift towards intense farming and growing multiple crops at a time and, the rising LST indicates the problems like exposed soil, deforestation, and groundwater loss, showing agricultural growth, land degradation, and changing land use patterns all affect each other in complicated ways. Furthermore, The GRACE-derived groundwater storage has been compared with groundwater level data from wells in Uttar Pradesh and Rainfall data for same years. The Well data indicate the identical trend of declination of groundwater level and, Rainfall data shows a marginal decrease during the same timeframe. The relationship between reduced rainfall and falling groundwater levels emphasizes the impact of decreased recharge rates on groundwater depletion.

Keywords: GRACE, GRACE -FO, Soil Moisture, Canopy Water Storage, GLDAS-TWS, Well data

Design of a cost-effective pressure plate apparatus for measuring pressure-saturation relationship in a range of plant-available soil moisture

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Understanding soil water retention within the range of soil moisture available for plant uptake is crucial for improving crop productivity. Commercially available setups like HYPROP and WP4C are cost-intensive, and the mass balance of soil moisture within the cores at different pressures cannot be established using these setups.

This research aims to design, fabricate, and test a low-cost pressure-plate device that can measure pressure and saturation in a soil core in small steps of pressure in the saturation range of field capacity to the wilting point while maintaining mass balance at each pressure step. The setup consists of stainless-steel top and bottom flanges, holders for soil cores of diameter 45 mm, and lengths of 25, 50, and 100 mm. The ceramic plates and cellulose membranes for 3, 5, and 15 bar entry pressures were procured from Soil Moisture Corp., USA. The setup operates in two distinct modes: 1) conventional pressure plate system with a burette for measuring exuded soil moisture with 0.1 mL accuracy at each pressure, and 2) Tempe cell setup, enabling the collection of exuded water for transport-related studies. The system allows easy interchangeability of ceramic plates and cellulose membranes by switching soil cores and incorporating a supporting wall to prevent membrane deformation.

The setup was tested with sandy soil and silty loam soil from an agricultural field. The data shows high-resolution measuring ability (with mass-balance) of the pressure-saturation relationship in the range of field capacity to the wilting point, unlike HYPROP and WP4C, which show reduced accuracy in this range. A comprehensive soil water retention curve can be obtained by integrating data from this device with HYPROP for high moisture conditions and WP4C for dry conditions. Ability to sample exuded soil moisture with mass balance makes it a potential tool for transport studies in the root zone.

Keywords: Soil water retention, Pressure-plate apparatus, Soil moisture measurement, Soil hydraulic properties

Hydrogeochemical evaluation of groundwater resources around Raichur Thermal Power Plant, Karnataka, India, with emphasis on fluoride and nitrate contamination

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INTRODUCTION:

Fluoride and nitrate contamination in groundwater is one of the major emerging problems in northern part of Karnataka region, India due to industrial and agricultural practices.

OBJECTIVE:

The present study has been carried out to identify the hydrogeochemical characteristics of the groundwater and assess its quality with reference to drinking, domestic purposes.

METHOD:

In the study area, 65 groundwater samples were collected around Raichur Thermal Power Plants (RTPPs) and analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, F⁻, Cl⁻, HCO₃⁻, SO₄²⁻, NO₃⁻, Ca²⁺, Mg²⁺, Na⁺, and K⁺. The analytical results show alkaline nature of the groundwater in the study area. Na⁺ and Ca²⁺ are the dominant cations, while anion chemistry is dominated by Cl⁻ and HCO₃⁻.

RESULTS:

The results indicate that fluoride (F⁻) concentrations exceeded the Bureau of Indian Standards (BIS) and World Health Organization (WHO) permissible limit of 1.5 mg/L in 6% of the samples, while nitrate (NO₃⁻) levels surpassed the BIS and WHO guideline of 45 mg/L in 24% of the samples. Elevated fluoride levels pose health risks such as dental and skeletal fluorosis, while excessive nitrate concentrations contribute to methemoglobinemia and other waterborne diseases.

CONCLUSION:

The present study suggested seasonal variation of groundwater and health risk assessment study is crucial to protect the human health

Keywords: Fluoride and Nitrate, Thermal Power Plant, Groundwater, Drinking water, Raichur, India

Estimation of aquifer recharge of the semi-arid Konya Closed Basin in Türkiye under climate change

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The net recharge is a primary component of an aquifer's water budget and a critical parameter for the sustainable use of groundwater resources. The estimation of aquifer recharge is a challenging task particularly for large watersheds such as the Konya Closed Plain, one of the major agricultural regions of Türkiye, associated with uncontrolled extraction for irrigation. In this paper a coupled unsaturated-saturated water flow model, based on the MODFLOW/UFZ computer program, is developed for the Konya Closed Basin to estimate the impact of different agricultural practices and climate change on the basin's water resources. Groundwater levels in this semiarid basin have experienced rapid decline in recent years due to excessive over-exploitation. The model, covering an area of about 5,0000 km², simulates unsaturated vertical flow through the vadose zone and groundwater flow through the underlying aquifer system. Because extraction wells in basin are unmetered, groundwater extraction data were estimated from historical agricultural yields and crop water demands. The model was calibrated based on long-term groundwater level monitoring data. Future climatic conditions were simulated based on seventeen regional climate models under two climate pathways (RCP4.5 and RCP8.5) developed within the EURO-CORDEX framework. Results show that the model was able to reproduce the observed historical groundwater level trends. Recharge areas are mostly located in the higher elevation regions of the basin with water flowing towards the central portions of the plain where intensive irrigation is located. Uncertainty of recharge rate is seen to be strongly influenced by the variability between climatic projection models. The modeling results also underscore the impact of expanding irrigated lands and the adoption of more efficient irrigation technologies on the basin's overall water budget.

Keywords: groundwater flow modeling, aquifer recharge, saturated unsaturated flow, irrigation, climate change

Spring Water Mass Quantification Through End Members mixing Employing Biogeochemical Tracers in Southern Western Ghats, Kerala, India

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Spring water, a significant form of groundwater, requires thorough investigation, particularly in light of the rapid environmental degradation occurring worldwide. India, with its extensive hydrogeological network, is home to approximately 5 million spring water systems, making their study essential for sustainable water resource management. This research examines the origins and formation processes of spring water in the southwestern coastal regions of the Indian subcontinent. To achieve this, a comprehensive analysis was conducted, involving the collection and examination of spring water, groundwater, and rainwater samples, along with the assessment of biogeochemical tracers. The findings reveal that the springs in this region exhibit cold temperatures ($\leq 29.5^{\circ}\text{C}$), acidic pH (3.4 - 6.8), a dominance of freshwater characteristics (chloride concentration: 10.10 - 43.67 mg/L),

and moderate oxygenation (DO: 5.08-9.43 mg/L). A binary and ternary mixing model, incorporating biogeochemical tracers such as total alkalinity and chloride concentration, was employed to determine the relative contributions of different water sources. The results indicate that precipitation and groundwater are the primary contributors to spring water, with seawater also playing a role, particularly in coastal areas. The model estimates that precipitation accounts for a major portion of spring water composition (85-100%), while groundwater contributions range from 0% to 68%. Furthermore, basin-wise variations in water source contributions highlight the spatial heterogeneity of precipitation's influence. This variability suggests that precipitation not only serves as the dominant driver of spring water formation but also interacts with geochemical processes governed by the hydraulic gradient between the spring and groundwater systems. These findings emphasize the complex hydrological and geochemical interactions that regulate spring water formation and underscore the need for a deeper understanding of this precious resource, particularly in the face of growing environmental challenges.

Keywords: Spring water, End member mixing model, Quantification, Chloride, Western Ghats

Fate and transport of pharmaceuticals and personal care products from Delhi NCR surface waters into the subsurface.

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Introduction -

Pharmaceuticals and personal care products (PPCPs) have emerged as significant environmental contaminants due to their extensive usage and subsequent disposal into natural water bodies. These contaminants pose various risks, including persistence and potential transformation into more hazardous compounds. The National Capital Region (NCR) of Delhi, India is heavily impacted by untreated wastewater and industrial effluents, which exacerbate the contamination levels.

Aim and Objectives

The study aims to fill the knowledge gaps about the transport processes that govern the flux and fate of 30 target PPCPs, including antibiotics and estrogenic compounds, from surface water to groundwater in the NCR. Three surface water bodies are studied to investigate the movement of PPCP through the subsurface into the groundwater using field and laboratory studies.

Methodology:

(1) Installation of piezometers at 3 sites: (A) Locations: Yamuna, Shahdara Drain, Sanjay Lake. (B) Analysis for PPCPs of soil cores collected at different depths

(2) Periodical sampling and analysis: Surface water, Groundwater

(3) Leaching tests: Conducted on soil cores

(4) Batch tests: (A) Sorption characteristics, and, (B) Aerobic and anaerobic biodegradation of PPCPs

- (5) Column experiments: To Investigate vertical transport of PPCPs in the subsurface
- (6) Robust and validated LCMS method: For quantification of PPCPs

Conclusion:

This study delves into India's pressing environmental issues, focusing on the presence of emerging contaminants, particularly pharmaceuticals and personal care products (PPCPs). These contaminants pose significant risks to the environment and public health. By investigating the vertical transport and fate of PPCPs, the research aims to identify critical gaps in current knowledge. The findings will provide valuable insights for policymakers, helping them to better understand the extent of contamination and develop effective mitigation efforts. Ultimately, this study aims to bridge the gap between scientific research and policy implementation, fostering a more informed approach to tackling India's environmental challenges.

Keywords: PPCPs, groundwater, surface water, subsurface, NCR

Chlorinated solvents in UK Groundwater: A Data-Driven Analysis of Long-Term Trends and Occurrence Prediction

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Chlorinated solvents were extensively used across the UK in the last century, leading to widespread groundwater contamination through inadequate disposal and industrial spills. Their high density and low solubility enable them to sink through aquifers, creating complex multiphase contamination that is difficult to detect and remediate. Despite strict regulations, the legacy of these chlorinated compounds remains significant.

This study leverages historical groundwater monitoring data from the England's state water monitoring network, dating back to 1980, to assess the current status of chlorinated solvent contamination. Three families of chlorinated solvents-ethenes, ethanes, and methanes-are analysed for their long-term spatio-temporal trends. This analysis identifies historical contamination hotspots, evaluates contamination persistence, and assesses degradation timeframes.

In addition, we develop a predictive model for chlorinated solvent detection in groundwater using eXtreme Gradient Boosting (XGBoost), a robust ensemble tree-based method. The model incorporates hydrochemical data alongside hydrogeological variable predictors such as aquifer type, depth to the water table, bedrock depth, and recharge rates. XGBoost's ability to handle missing data and outliers makes it well-suited for this large, heterogeneous dataset. The model is trained on a subset of state monitoring data, where parent and metabolites solvents are converted to a binary variable (detected/non detected) to model detection of any chlorinated solvent.

This research provides the first comprehensive update on chlorinated solvent groundwater contamination in England since 1990, offering insights into their persistence and degradation across different aquifers. By identifying key predictors of solvent detection, our findings provide more understanding of their intermittent detection of chlorinated solvents.

Keywords: chlorinated solvents, groundwater, DNAPL, degradation timeframes, prediction of detection, XGBoost, long-term monitoring

Assessing Coastal Groundwater Vulnerability Using the DPASTIC Model: A GIS-Based Modification of DRASTIC in Tropical Coastal Regions

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Groundwater vulnerability assessment is crucial for sustainable water resource management, especially in coastal regions facing growing threats from anthropogenic contamination, agricultural runoff, and seawater intrusion. This study introduces the DPASTIC model, a novel modification of the traditional DRASTIC framework, specifically adapted to the hydrogeological conditions of coastal Odisha, India. A key innovation of DPASTIC lies in replacing the Net Recharge parameter with the Percolation Index (PI), derived from hydrological soil group classifications and regional rainfall data. The PI serves as a more representative indicator of contaminant percolation potential in coastal aquifers.

Seven thematic layers were used: Depth to Groundwater, Percolation Index, Aquifer Media, Soil Type, Topography, Vadose Zone Impact, and Hydraulic Conductivity. These were developed through Geographic Information System (GIS) techniques and integrated to generate a spatial groundwater vulnerability index. The resulting vulnerability map categorizes 12.70% of the study area as Very High, 41.25% as High, 32.60% as Moderate, and 13.45% as Low vulnerability. Low vulnerability zones are primarily located in the northwestern and southwestern regions, characterized by dense vegetation, steeper slopes, and higher recharge. In contrast, High and Very High vulnerability areas are concentrated in the eastern coastal belt, near urban settlements, intensive agriculture, and industrial clusters, where seawater intrusion and deep groundwater levels exacerbate contamination risks.

Validation using Total Dissolved Solids (TDS) data from 128 monitoring wells revealed a strong correlation with the computed vulnerability index (Pearson's $r = 0.733$; Distance correlation = 0.702). The DPASTIC model demonstrates improved predictive performance and offers actionable spatial insights for groundwater protection and contamination mitigation in vulnerable coastal environments.

Keywords: DPASTIC Index, Groundwater vulnerability, Seawater Intrusion, Coastal regions

Microplastic concentrations in groundwater - A worldwide assessment

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Microplastic particles (MPs) are emerging contaminants that are potentially harmful to groundwater ecosystems and human health. MPs are assumed to be transported to groundwater bodies by agricultural or recharge water, as leachate at landfill sites, through groundwater-surface water interactions, as well as at water supply or managed aquifer recharge sites through injection/abstraction wells and boreholes. Although a handful of studies have identified MP contamination in aquifers, data on global groundwater contamination by MP are still scarce. However, such baseline information is required to properly assess the potential threat MPs pose to worldwide groundwater resources

and to develop appropriate mitigation strategies where necessary.

Here we share results of a global groundwater sampling campaign undertaken by the scientific community. Groundwater was collected around the world via accessible boreholes, monitoring wells, surface springs and caves. A standardised sampling protocol focussing on a low-cost and easy-to-execute sampling procedure was used to ensure widespread participation in sampling and comparability among field sites.

About 300 L of groundwater were collected and filtered on-site through a series of metal sieves (123 and 25 μm mesh size) while for quality control, passive air samples (25 μm mesh) were collected at each site. Filtrates and meshes were then stored in glass vials. Samples were processed in the lab using digestion with Fenton reagent to remove organic matter, density separation in glass separation units using zinc chloride, and MP staining with Nile Red dye. Fluorescence-guided Raman spectroscopy combined with a newly developed spectral library and post-processing routine were used to identify different polymers. First results indicate a lower presence of fibres than fragments and of MPs larger than 123 μm than MPs of 25-123 μm size. Identified concentrations ranged from 0.01 to almost 6 particles per litre.

Keywords: Emerging contaminants, groundwater, microplastics

Leveraging water quality data to reduce uncertainty in mountain aquifer modeling

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Mountain regions represent crucial resources of high-quality freshwater, primarily due to their unique geological and hydrological characteristics. However, despite groundwater's critical role within mountainous regions, systematic monitoring remains limited. Consequently, groundwater models frequently suffer from insufficient datasets, making it challenging to accurately determine system parameters. This data scarcity often results in considerable uncertainty, with multiple parameter combinations able to yield similar modeling outcomes.

This research specifically evaluates the uncertainty inherent in flow and contaminant transport modeling for a lowland aquifer located in Italy's lower Chiese Valley. The aquifer is characterized by intense groundwater withdrawals primarily for fish farming activities and faces contamination threats originating from nearby industrial zones. The modeling framework involves four key parameters: the hydraulic conductivity of the aquifer, the conductance of the Chiese River's bed, and mountain recharge fluxes from the eastern and western slopes. Available observational data include groundwater levels from 21 wells and piezometers, chemical composition measurements from three piezometers, and contaminant concentrations measured at seven critical locations.

A Bayesian calibration methodology was adopted, progressively incorporating different observational datasets. Results clearly demonstrate that relying solely on groundwater head data inadequately constrains the parameter distributions, leaving uncertainty largely unchanged from initial assumptions. In contrast, introducing chemical and contamination data significantly reduced model uncertainty. Specifically, the space of hydraulic conductivity clearly converges to approximately 10^{-1} m/s, indicating sandy-gravel deposits consistent with local geological observations. Nevertheless,

uncertainties in parameters related to mountain recharge and riverbed conductance, although notably reduced, remained relatively broad even with the comprehensive dataset.

The findings underscore the continued challenge in precisely characterizing interactions between mountain recharge, river-aquifer exchanges, and downstream groundwater flow without enhanced monitoring networks. Despite focusing on the lower Chiese aquifer, the modeling framework is broadly applicable to other comparable hydrogeological settings, both morphologically and hydraulically.

Keywords: groundwater modeling, mountain aquifers, uncertainty, interaction SW-GW, bayesian methods

Emerging trends in terrestrial water storage of the global key hotspot regions

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The Gravity Recovery and Climate Experiment (GRACE) satellite mission and its successor, GRACE Follow-On (GRACE-FO), have provided a paradigm shift in near-continuous Earth mass observations since 2002. It measures temporal variations in the gravity field, which can be used to estimate changes in terrestrial water storage anomalies (TWSA). Rodell et al. (2018) identified 34 key hotspot regions exhibiting statistically significant TWSA trends from April 2002 to March 2016. Here, we compare emerging GRACE TWSA trends (April 2002-January 2021) with R34 trends both spatially and temporally and attribute them to the climatic and anthropogenic factors. Our results revealed significant differences between the two datasets in terms of magnitude and direction. The trend values are declining in 16 regions, the majority of which are in Africa, North and South America. In contrast, trend values are rising in 18 regions, the majority of which are in Asia. In R5 (Northern North America) and R6 (Northern Eurasia) regions, the trend direction is changed from positive to negative, and interestingly, in R30 (Northern Congo) region, the trend direction is changed from negative to positive. Regions such as R26 Eastern Brazil, R12 North China Plain, R7 North India, R19 Central Canada, and R32 North Africa are showing multi-fold increasing trends. Conversely, areas such as R29 Tropical Western Africa, R10 Tibetan Plateau, R28 Nile Headwaters, R23 Patagonian Ice Fields, R24 Central Argentina, and R9 Eastern Central China show nearly comparable declining trends. We further attribute these divergent changes to the shift to a warming climate, rising groundwater extraction, and policy interventions. Our findings on the recent trends provide a thorough understanding of how the trends are evolving and emphasize the critical need for immediate attention to water resource management, and will be useful in promoting policy action discussions and improved multilateral cooperation for a sustainable future.

Keywords: Terrestrial water storage anomaly (TWSA), GRACE, Climate change, Policy interventions

Quantifying geogenic and anthropogenic contribution to groundwater pollution using APCS-MLR receptor model

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The dependence on groundwater in the arid regions is high for both agriculture and domestic needs, however its quality is threatened by both natural and anthropogenic factors. In this study, receptor model Absolute Principal Component Scores-Multiple Linear Regression (APCS-MLR) was developed to qualitatively identify the sources of groundwater pollution and quantitatively evaluate the contribution of each source to groundwater quality. A total of 428 groundwater samples were analysed across 15 districts in the arid northwestern part of India in 2023. Hydrochemical analysis revealed two predominant groundwater types: NaCl and Mixed type, mainly influenced by evaporation-rock weathering-anthropogenic influence. The median NO₃ concentration was 40 mg/L. Natural Background Levels of Nitrate were determined through cumulative distribution function. Two thresholds identified at 16.2 mg/L and 162.4 mg/L indicates multiple local events of nitrate contamination in groundwater. The order of groundwater nitrate concentration in different land-use types was as follows: agriculture land, urban land and wasteland. The contribution rate of four distinct sources to groundwater pollution were salinity factor (43.8 %), natural sources (34.4 %), fluoride enrichment factor (13 %) and agriculture activities (8.9%). Agriculture practices significantly influenced NO₃ (36.69 %) and K (31.81 %) concentration likely due to overuse of fertilizers through leaching and runoff. Salinity is mainly geogenic, resulting from evaporation, saline sediments (e.g., gypsum, halite), and long water residence. The high adjusted mean R² value (0.82) confirms the robustness of model in quantifying source contributions. Groundwater irrigation suitability was assessed using Sodium Adsorption Ratio (SAR) and Percent Sodium (%Na) indices. Based on these parameters, 17% of the samples were classified as unsuitable according to SAR, while 74% were found to be unsuitable based on %Na, indicating a significant risk to soil permeability. This comprehensive source characterization provides a scientific foundation for pollution source management in arid regions globally.

Keywords: Receptor modeling, Source Apportionment, APCS-MLR, Arid region

Assessing the Porous-media clogging by Micro-plastics contaminated filtrate media

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Microplastics are small plastic particles with a size ranging from 1 micron to 5mm. When they migrate with surface or groundwater, these particles get clogged in the porous media, altering the properties of the aquifer media, which in turn changes the flow pattern. The micro-plastics are neutral and non-decomposing particles; this distinguishes them from the fine sediments and thus,

the clogging effect in the porous media. In this study, the constant head permeameter installed at the hydraulic lab of IIT Roorkee was used to evaluate changes in the hydraulic conductivity and porosity due to variations in flow, micro-plastic concentration and time of experiment. Results show that microplastics get clogged primarily on the upper layers of the porous media, and the percentage of clogging is affected by flow rate, size and concentration of both the porous medium and the microplastics. The experiments reveal that the higher-density microplastics deposit faster and clog up at the interface, whereas the smaller particles result in interstitial depositions.

Keywords: Microplastics, Porous media, clogging and Hydraulic properties

A DPSIR approach to arsenic and other geogenic contaminants in global groundwater

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Occurrence of geogenic contaminants (GCs), in groundwater particularly arsenic, fluoride, selenium, and uranium has reduced its availability for consumption by 60%. Ineffective mitigation measures resulting from the lack of knowledge of the relationships between local scale heterogeneities and global scale driving forces, has endangered the lives of 300- 500 million people. The work presented here attempts to bridge this gap by organising the problem of geogenic contamination into the Drivers-Pressures-State-Impact-Response (DPSIR) framework, such that efficient mitigation strategies, custom-made for the affected population can be provided.

Driving the contamination cycle are magmatic processes at active plate boundaries which bring up GCs from the deep sub surface. Denudation and transportation of these igneous and hydrothermal sources supply GCs laden detritus and solutions to adjacent sedimentary basins, which eventually act as clastic aquifers for groundwater exploitation. Once within the aquifer the GCs can be liberated from their carrier phases via any combination of hydrolysis, redox, sorption and ion exchange reactions depending on local climatic and flow conditions. Patchy distribution of organic matter and suitable organic and inorganic oxidisers, competitive ions, and sub surface aquifer framework give rise to high spatio-temporal variability in GCs distribution and severity. Stressing the naturally contaminated system are anthropogenic pressures of intense groundwater pumping and land use land cover changes, that bear the capability to alter GC distribution patterns, coverage and degree of contamination. This results in extensive occurrence of GCs (either singly or together) in exploited aquifers (state), putting the lives of 300-500 million people at risk through its usage(impact). Response to the situation involves rigorous and high-resolution monitoring using real time sensors and data sciences backed-predictive modelling, adoption of effective remediation strategies (both in-situ and ex-situ) that are socio-economically feasible and acceptable, and exploration of supplementary sources of safe drinking water, to attain sustainable development goals.

Keywords: DPSIR, groundwater contamination

Identifying Groundwater Storage Potential Zonation in an Arid Cratonic Region

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Identifying Groundwater Storage Potential Zones (GWSPZs) in environmentally stressed arid Cratonic regions presents significant challenges due to limited subsurface data and the complex geological and hydrological characteristics of these regions. Integrating heterogeneous and intricate subsurface behavior into decision-making processes poses further challenges. This research addresses these challenges through the integration of the Analytical Hierarchy Process (AHP), Boolean Logic Analysis (BLA), Very Low Frequency Electromagnetic (VLF-EM) technique, and Electrical Resistivity Tomography (ERT). These techniques enable the systematic and comprehensive integration of subsurface geophysical data with remotely sensed information into decision-making models. The methodology covers nine thematic parameters that influence groundwater storage potential, including geomorphology, drainage density, slope, lineament density, soil type, rainfall, elevation, geology, and land use/land cover (LULC). AHP techniques were used to assign relative weights and rankings to these parameters, while BLA helped to identify feasible artificial recharge zones in the arid region. The reclassified thematic layers were integrated into a Geographic Information System (GIS) to delineate the GWSPZs. The resulting GWSPZ map categorizes the study area into five categories: very high (2.63%), high (16.41%), moderate (42.36%), low (30.86%), and very low (7.74%). ERT profiles revealed lower resistivity values in regions, and VLF-EM indicates the high current density responses with high lineament density and low drainage density, suggesting increased infiltration and reduced surface runoff. The GWSPZ map was validated using seven VLF-EM and eight ERT profiles, along with borehole yield data from seven locations collected through field surveys. This validation process resulted in an accuracy of 85.7%. Key factors contributing to enhanced groundwater storage potential include moderately to deeply weathered pediments and pediplains, high lineament density, alluvial geology, gentle slopes, coarse-textured soils, and abundant rainfall.

Keywords: Arid Cratons, Groundwater storage potential zones (GWSPZs), Analytical hierarchy process (AHP), Boolean logic analysis (BLA), Electrical resistivity tomography (ERT), Very low frequency-electromagnetic methods (VLF-EM)

Spatio-Temporal Variation of Groundwater Isotopes and Monsoonal Recharge Studies associated with extreme climatic events in Chalakudy Basin, Southern Western Ghats, India

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The present study investigates the spatiotemporal variations in the stable isotopic composition of oxygen ($d^{18}O$) and hydrogen (d^2H) in shallow groundwater aquifers of the Lower Chalakudy River Basin (LCRB) in Southern Western Ghats, India. A total of 60 groundwater samples were collected from 20 sites during three distinct hydrological periods: pre-monsoon, extreme monsoon, and post-monsoon, and with corresponding rainfall isotope data. The $d^{18}O$ values ranged from -2.90‰ to -0.97‰ (pre-monsoon), -2.75‰ to -1.93‰ (monsoon), and -3.17‰ to -2.27‰ (post-monsoon), while d^2H values varied from -13.54‰ to -0.65‰, -6.23‰ to -15.74‰, and -9.95‰ to -16.79‰, respectively. Seasonal comparison indicates a higher isotopic depletion during the post-monsoon period (average $d^{18}O$: -2.72‰), relative to the monsoon (-2.40‰) and pre-monsoon (-2.09‰) seasons. This pattern suggests that intense monsoon events causing for a quick groundwater recharge in the shallow groundwater regime. The observed data is very much significant with respect to the already reported studies from the Western Ghats. Despite the seasonal shifts, only minimal isotopic variation (~0.31‰) is observed across the sampling periods, indicating relatively stable recharge processes. The contribution of rainwater to groundwater recharge in the Lower Chalakudy River Basin was quantified using a two-component isotope mass balance approach based on $d^{18}O$ values. Spatio-temporal variations in the isotopic composition of both rainwater and shallow groundwater were analyzed to assess seasonal recharge dynamics and aquifer responses. The $d^{18}O$ signatures indicate a significant influence of monsoonal rainfall, and about ~48 % of the post-monsoon groundwater is derived from recent rainwater infiltration. These findings highlight the substantial role of extreme monsoon events in recharging lowland aquifers. Overall, the isotopic evidence confirms that groundwater recharge in the region is predominantly controlled by meteoric sources, offering valuable insight into hydrological processes under varying seasonal conditions.

Keywords: Groundwater, Isotopes, Western Ghats,

Assessing Groundwater Vulnerability in the Sundarban Aquifers using Geochemical Analysis

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Hydrological calamities, enhanced by anthropogenic stresses, such as saline water intrusion, climate variability, over extraction and pollution, have threatened groundwater vulnerability in the deltas for decades. This study integrates detailed hydrostratigraphic characterization with geochemical analysis of groundwater to assess aquifer vulnerability across shallow (<150m), intermediate (150-250m), and deep (>250m) depths. Cross-sectional diagrams from lithologs reveal a vertically heterogeneous aquifer system, where variation in occurrence and thickness of sand and clay design

the hydraulic integrity of the delta. Shallow aquifers are distinguished from deep aquifers by distinct geochemical and stable isotope signatures as deeper groundwater is enriched in Na⁺, dD and d18O values while shallow groundwater is characterized by high Ca²⁺, Mg²⁺ and K⁺ with relatively higher conductivity values. Intermediate aquifers lying between these two show a mixed signature, probably a result of vertical connectivity between the aquifers evident from the constructed hydrostratigraphic diagram. Coastal aquifer characterization across multiple depths (D1:15-25m, D2:30-50m, D3: 115m and D4:333m) reveal that deep coastal aquifers have similar signatures as inland deep aquifers, however their age varies significantly. The shallow coastal aquifers are the most vulnerable due to their established connection with the seawater and display completely distinct geochemical signature. Further, spatial maps, graphical and statistical multivariate analyses reveal the dominant geochemical processes - silicate weathering, carbonate dissolution and cation exchange that shape the water quality of the region. Depth-specific groundwater quality comparison in both inland and coastal aquifers aids in understanding their vulnerability for future groundwater use. Shallow aquifers being most exposed to the surficial processes must be monitored thoroughly as weak stratigraphic confinement might affect localized degradation of deeper aquifers and affect long term groundwater security for future use. The study highlights zones at critical risk, emphasizing the need for sustainable groundwater governance involving depth-specific abstraction guidelines and community-level aquifer management in the Sundarbans.

Keywords: Groundwater vulnerability, Aquifer characterization, Hydrostratigraphy, Groundwater geochemistry

Science-Based Site Suitability Analysis for Groundwater Recharge: A Case Study of Chittharagi Sub-watershed, Karnataka, India

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Groundwater is a very important source in agricultural activities and overall societal demands, but management is strained by climatic variation and increasing demand. In semi-arid areas, like the Chittharagi sub-watershed in Bagalkot, Karnataka, India, frequent drought has caused water scarcity. This research work, sponsored by the REWARD project implemented by the Watershed Development Department, Government of Karnataka and the World Bank, tries to meet this challenge by combining hydrogeological and geophysical studies to enable the most appropriate selection and verification of best sites for groundwater recharge structures.

The aim was to offer a scientific ground through combination of multi-criteria analysis in conjunction with geophysical surveys. We applied a detailed study of the major hydrogeological parameters, such as hydrometeorology, soil, lithology and geomorphology, so as to evaluate the groundwater potential of the area. We adopted Groundwater Potential Zone Mapping procedure with weighted overlay analysis for influencing parameters to identify feasible sites, and these sites were validated using Electrical Resistivity Tomography (ERT) surveys.

These findings imply that June to October, when the actual evapotranspiration is low, is the most convenient period to save water. The results of the ERT surveys verified the layering of the sub-surface with weathered and fractured layers. These zones with low resistivity show that they have



more moisture and permeability and thus are susceptible to groundwater recharge. Pumping tests and theoretical estimates proved the ability of the sub-surface to receive and store water.

In summary, this work proposes a scientifically tested approach for the implementation of groundwater recharge structures. Hydrogeology and geophysics are two important areas in which integrated information is fundamental to the conservation of water. All these results of the geophysical surveys, combined with the pumping tests, reinforce the viability and effectiveness of the recharge shafts proposed.

Keywords: Groundwater Recharge, Hydrogeology, Geophysical Investigation, Watershed Management, Site Suitability Analysis

Human-Water Feedbacks (ICHWF)

Understanding the Spatial Patterns of Himalayan Ecosystem Services and their Valuations using a Systematic Literature Review and Meta-Analysis

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The Himalayan Mountain ecosystem provides numerous Ecosystem Services (ES) that support the well-being and livelihood of millions in the region. However, an uneven spatial distribution of these ES often causes a disparity in resource availability and values. Therefore, it becomes necessary to understand the spatial patterns of ES and its value across the Himalayan region. This study conducts a systematic literature review and meta-analysis to examine ES distribution, economic valuation, and knowledge gaps across the Himalayas. ES across the Himalayan region were identified from the literature review and were standardised into 31 unique Common International Classification of Ecosystem Services (CICES) classes. It was observed that while the distribution of reviewed literature was balanced (Western: 30.26%, Central: 32.89%, Eastern: 36.84%), there exists a bias towards Provisioning ES (PES) - 43.54%, indicating the need for increased research focus on Regulating ES (RES) - 36.48% and Cultural ES (CES) - 19.98%. A higher economic valuation was given to RES with the value of 1128.81 USD/ha/year, while values of PES and CES were 446.75 USD/ha/year and 457.51 USD/ha/year, respectively. The ES were ranked based on the frequency with which they were identified across the Himalayas, and water-related services-specifically PES9 (surface water for non-drinking uses) and PES8 (drinking water)-consistently rank highest across the Himalayas yet remain under-studied in terms of quantification and valuation. Furthermore, while most literature focused on the identification of ES (73.68%), there is a significant lack of attention to quantification (39.47%) and valuation (23.68%) of ES in the region. This underlines the need for a more balanced research approach that includes identifying and thoroughly quantifying and valuing all types of ES in the Himalayas.

Keywords: ecosystem services, ecosystem, Himalayan region, climate change, freshwater, terrestrial

Using Agent-Based Modeling to understand changing floodplain dynamics in Indian context

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The "levee effect" phenomenon suggests that constructing levees designed to protect areas from flooding can increase flood risk by giving a false sense of security, increasing population growth and socio-economic activities in levee-protected regions. While many studies have identified and analyzed the "levee effect" using flood risk and vulnerability frameworks that integrate multiple geospatial

variables, these approaches may often overlook the individual-level factors influencing responses to flood risks.

This study proposes that individual responses to flood damages are not constant and vary significantly based on factors such as education, livelihood, and prior flood experiences. We explore this idea by developing an agent-based modeling (ABM) approach, creating diverse agents that reflect these individual characteristics. Using this conceptual ABM framework, we simulate the levee effect in Indian floodplains to evaluate the long-term efficiency of structural flood protection measures. Moreover, this study seeks to contribute insights into community-based flood management practices and inform policies aimed at disaster resilience.

Keywords: Levee-effect, Flood Risk Management, Agent-based model (ABM)

Understanding Human-Water Interactions and their Health Implications Under Changing Climate

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Human interaction with the hydrological cycle, particularly under the changing climate is investigated inadequately despite of critical role in shaping water availability, distribution, and quality for human habitat.

This study investigates how human-driven water usage, such as agricultural irrigation, domestic consumption, and groundwater abstraction, interacts with five major extreme weather events (EWEs) (heatwaves, cold waves, floods, droughts, and tropical cyclones) and their impact on human health across the Pan-India region.

Using a socio-hydrological framework, feedback mechanisms between water demand, hydrological changes, and shifting patterns of climate variability are analyzed. A combination of remote sensing, hydrological modeling, and socio-economic surveys is employed to assess the spatial and temporal variations in water stress and their cascading effects on waterborne diseases, heat stress, and access to clean water. Furthermore, the study examines how extreme climate events exacerbate groundwater depletion and water contamination, further affecting public health and community resilience.

The analysis reveals that hydrological data influenced by climate change-induced EWEs follows a skewed distribution, indicating shifts in water availability patterns and uncertainty in resource management. These findings highlight the need to integrate human-induced changes in the hydrological cycle into water resource assessments. By understanding the policy-linked intricate relationships between water use behaviors, climate extremes, and hydrological changes, this study provides valuable insights into developing sustainable water management strategies to mitigate health risks and improve water security programmes in India.

Keywords: Human-water interactions, socio-hydrology, hydrological cycle, climate change, extreme weather events, groundwater depletion, waterborne diseases, skewed distribution, India.

Can satellite data validate socio-hydrology models? Insights from a model application to a large reservoir

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Socio-hydrologic models have emerged as useful tools for understanding the linkage between human and water systems. However, it is often challenging to validate the model structures and/or their output variables due to a lack of detailed information regarding the region of application. Here, we explore the use of satellite data in validating output from a socio-hydrologic model developed for the Nagarjuna Sagar command area. A previously developed socio-hydrologic model was used to simulate the water use behaviour of farmers in the reservoir command area. The model is composed of a reservoir water balance module, a groundwater module, and a consumer module. Each module has both physical processes and human related decisions built into them. We test the applicability of two satellite products in validating the simulations of water used for agriculture: the Leaf area index (LAI) and normalized difference vegetation index (NDVI). The modelled time series of farmer water use by three model variants is used as a proxy for cropped areas within the reservoir's command area. These time series are then compared against spatially averaged LAI and NDVI across the command area. The analysis spans from 2001 to 2013, including two major drought events, providing an opportunity to evaluate how well the model captures the hydrological and behavioural response to extreme climate conditions. We employ the Bayes theorem to assign likelihood to each of the three model variants based on each satellite product. The posterior probability for each model variant is estimated and assumed to indicate the model's ability to reproduce command area farmer water use behaviour. Preliminary findings suggest that LAI may serve as a useful indicator of post-drought changes in farmer water use, offering valuable insights into how cropping patterns and irrigation behaviour shift in response to water scarcity.

Keywords: Socio-hydrologic model, Satellite data, Bayes theorem

Quantifying the impact of conjunctive use of groundwater and surface water on baseflow in the command area of a large reservoir

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Baseflow plays a vital role in sustaining aquatic ecosystems. Thus, quantifying the changes in baseflow due to human activities is necessary to understand how activities such as groundwater pumping may impact aquatic ecosystems. This study aims to evaluate the effect of conjunctive use of surface water and groundwater on downstream baseflow in the command area of the Nagarjuna Sagar Reservoir (NSR) located on the Krishna River in southern India. NSR supplies water for agriculture, hydroelectricity, and domestic use. The farmers in the command area of the reservoir extract groundwater when surface water supplied by the reservoir does not fully satisfy their water demands. This conjunctive use of groundwater and surface water changes with varying water

availability in the NSR as well as farmers adaptation response to dry years. We use a previously developed socio-hydrological model (SHM) for this reservoir, including a reservoir water balance module, a groundwater module, and a farmer demand adaptation module. We construct an estimated water demand time series using existing reports on the reservoir's cropping pattern and cropped area since the inception of its operations from 1968 to 2016. We calibrate four groundwater parameters using groundwater well levels from 2007-2016. The farmer demand adaptation module was developed based on stakeholder interviews and validated with independent data on reservoir storage, groundwater levels, and relative use of surface water and groundwater in the command area. We then hindcast the baseflow (outflow) from the groundwater storage, assuming changing water demands within the command area between 1968-2016. We found an average annual reduction of 188 MCM in the baseflow due to the abstraction of GW in the command area of the NSR from 1968 to 2016.

Keywords: Human-water feedback, Sociohydrology, REGSim, Anthropogenic, Water management, Drought, Climate change, Irrigation, System dynamic model

Development of climate, catchment, and human action-informed model for forecasting seasonal flood probabilities

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Flood risk is an act of humanity. Seasonal extreme event forecasting and warning systems are one of the most effective flood risk management tools. The imperfect model structure and inherent uncertainties in hydrological forecasting might lead to missed events or false alarms, limiting its reliability. Past studies have explored several regression-based and machine-learning models in the context of streamflow forecasting. One main limitation of these studies is that these models are single-value forecasting models. The uncertainty associated with these models can limit their effectiveness in reducing flood risk. Additionally, most models focus primarily on hydrological and meteorological drivers, overlooking the influence of anthropogenic activities in forecasting extreme events. However, extreme events are shaped by several hydrological, meteorological, and anthropogenic factors, such as catchment and atmospheric and reservoir conditions. The present study addresses these gaps by developing a probabilistic forecasting framework that integrates copula with the generalized additive model for location, scale, and shape (GAMLSS) by considering hydrological, meteorological, and anthropogenic covariates. The copula model will capture the combined influence of multiple factors shaping extreme events and provide joint probability distribution of these factors. GAMLSS, as a regression framework, will then model the distribution parameters as functions of these joint probabilities. The proposed model provides a more comprehensive representation of flood extremes. Preliminary results highlighted the significant role of past season reservoir conditions in shaping forecasted extreme events. The expected results will provide insights into the contribution of each covariate in forecasting seasonal extremes. Particularly addressing to what extent, the reservoir conditions influence the extreme event occurrences. This work aims to enhance seasonal flood prediction accuracy, ultimately contributing to more effective flood risk management strategies.

Keywords: Extreme event forecasting, GAMLSS, Copula, Anthropogenic

Understanding the failure risk of dual-dam system and its downstream impact: A case study of Tuirial Reservoir

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Dams, as hydraulic structures, are major facilities that regulate water for various purposes such as water supplies, irrigation, flood prevention, and hydroelectric energy. However, the potential failure of such structures can have disastrous consequences for downstream communities, necessitating extensive safety assessments and flood risk modelling. This study quantifies the risk of sequential dam failure for the Tuirial Dam and its associated Saddle Dam on the Tuirial River in Mizoram, India. A two-dimensional dam break model was developed using HEC-RAS to route the dam break outburst flood up to 84 km downstream of the confluence of the Tuirial and Barak rivers. Simulations were conducted for a complete breach with different failures (overtopping and piping) and inflow conditions (PMF and 100-year return period flood) to identify the worst-case scenario among various failure cases. Five probable breach scenarios were analyzed to determine peak flow rates and the resulting flood wave propagation. When the main dam failed due to piping and the saddle dam due to overtopping, is identified as the worst case. The hydrograph is generated at various locations downstream for the worst case identified, i.e., when the main dam failed due to piping and the saddle dam failed due to piping, and the peak flow obtained near the dam site is 38373.84 m³/s attenuated to 3035.34 m³/s near the confluence. The results highlight substantial flood hazards and risks posed to downstream areas, with potential inundation reaching significant depths across critical infrastructure. Findings from this study underscore the need for early warning systems and targeted emergency action plans to mitigate the impacts of such events. The generated flood hazard and risk maps will aid local and disaster management authorities in prioritising at-risk areas, optimising resource allocation, and enhancing preparedness efforts for flood mitigation and recovery.

Keywords: Dam safety, dam breaks, Flood risk assessment, Hydrodynamic modelling, Emergency action plans (EAPs), Flood hazard mapping

Integrating Reservoir Management into Hydrological Modeling: Advancing Streamflow Simulations in South Asia's Major River Basins

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Accurately modeling streamflow dynamics in regions like India, where complex reservoir operations and data scarcity prevail, poses significant challenges. Most large-scale hydrological models do not sufficiently account for reservoir impacts, thus failing to accurately depict human interventions on streamflow. This study integrates the Noah-MP land surface model with the mizuRoute hydrodynamic model to simulate regulated streamflow across 18 major river basins in South Asia from 2000 to 2022, incorporating over 223 reservoirs. Utilizing high-resolution river networks from MERIT Hydro and reservoir data from GRanD v1.3, our framework enhances the representation of reservoir-regulated streamflow. We apply the Gini coefficient to measure streamflow inequality across 99 gauge stations. Preliminary results indicate a significant reduction in streamflow variability due to reservoir management, particularly noticeable in seasonal and interannual flows. The framework achieves high modeling accuracy with Kling-Gupta Efficiency (KGE) values reaching up to 0.87. Comparative analyses suggest that including reservoirs reduces streamflow inequality by up to 15%, underscoring their utility in hydrological extremes mitigation. This integration of reservoir dynamics into hydrological modeling marks a crucial step towards improving predictions and informs strategies for optimal reservoir operations, flood mitigation, and climate adaptation in regulated basins

Keywords: Noah-MP, MizuRoute, Reservoirs modelling, Streamflow

Tracing unintended consequences of interventions in coupled human-water systems using critical pathway

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In real-world water management, interventions are taken for changing the dynamics of coupled human-water system (CHWS) and addressing water-related issues such as flood, drought, agricultural water use, transboundary water conflict, etc. However, due to the complexity of CHWS, these interventions can bring unintended consequences which instead exacerbates the issues to be solved. Our study carried out meta-analysis on real-world case studies to reveal the formation process and mechanism of unintended consequences that emerged in a variety of CHWS. A multilevel and nested framework including first-level core subsystems and second-level variables was first developed, representing the "common anatomy" across different types of CHWS. Critical pathways were then determined between variables by summarising the storyline of each case study and carrying out frequency analysis, with key variables that foremost leading to unintended consequences identified. Compared to the causal loops proposed based on system dynamics archetypes,

the critical pathways can be seen as a subset of system behaviours which trace the strongest path along which the perturbation brought by human intervention propagates throughout the system. The critical pathways and key variables obtained in this study provide a more intuitive guidance for addressing the unintended consequences in real-world water resource management, with recommended primary entry points.

Keywords: Coupled Human-Water System, Unintended consequences, Sociohydrology, Meta-analysis, Critical pathway

Embedding land and water planning practices in context: A diagnostic contribution from sociology

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The pace, scale and frequency of climate impacts on land and water systems experienced across world's basins demands stepping up the planning and implementation of innovative land and water management measures that maximize adaptation benefits, minimize trade-offs and maladaptation risks, and enhance the functioning and resilience of land and freshwater ecosystems. In this respect, growing number of reports and articles from the adaptation and ecosystem services community scientific community are sharing empirical evidence on the value of ecosystem-based measures (e.g. to restore soils, wetlands, landscape and hydrological connectivity) to achieve many of those objectives while suggesting step-wise guidelines and/or conceptual frameworks. As most of this knowledge is based on fragmented and empirical understanding from planning cases and experiments across the globe its capacity to provide universal lessons and diagnostic tools to understand context-specific social and technical barriers, adaptation problems, trade-offs and synergies is limited. This also means that it does not provide guidance on how to embed planning innovations from experiments in existing planning cultures, institutions and governance arrangements in different contexts.

Drawing from the sociology of practices and with the aim to fill that knowledge gap, I propose a diagnostic approach focusing attention on the context-specific material elements used (e.g. information tools, models, legal frameworks and formal policies), the competences used in and the (culturally-mediated) meaning attributed to different planning activities (e.g. using models, dealing with trade-offs, engaging stakeholders, navigating existing governance arrangements, etc.). An integrated water management case from drylands in Latin America will showcase the use of this diagnostic tool to understand contextual dimension of land and water planning practices and how planning innovations (e.g. using innovating information platforms, opening spaces for public participation, etc.) can be nudged and become routinized in local context beyond the life of land and water systems planning experiment.

Keywords: land and water planning practices, ecosystem-based measures, drylands

Simulating human-water feedbacks for climate extreme resilience in the Dutch context

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The Netherlands has experienced extreme climatic patterns recently, with record dry and wet years. This situation poses challenges for adaptation, especially when considering that some strategies to deal with one extreme (e.g., drought) can increase the risk of occurrence of the other (e.g., floods). Our main goal is to find social dynamics and landscape configurations that offer the highest resilience to climate extremes in the sandy landscapes of the Netherlands (east and south of the country). To this aim, we built a socio-hydrological agent-based model emphasising the interaction between the human and groundwater systems. The model focuses on the relationship between farmers and water authorities in the rural context of the sandy soil region. From a behavioural point of view, farmers can adapt in different ways (irrigate, install weirs, change crops, or sell their land) and comply with water abstraction bans by the water authority to different extents based on the protection motivation and grid-group theories. Water authorities (modelled as rational) can put in place fines and monitoring to enforce water use restrictions. Farmers' behaviour was predominantly conceptualised through interviews conducted in the east of the Netherlands in 2024. The dynamics between the agents involved were derived from interviews with water authorities and experts who are involved in water management and research. The hydrological component of the model has been built in MODFLOW 6 and loosely coupled to the social behavioural system. This modelling approach is relevant for water authorities and stakeholders involved in landscape configuration to evaluate options that can improve resilience to climate extremes.

Keywords: Agent-based model, groundwater model, climate extreme, adaptation, rural context

Bridge constructions and riverscape dynamics in geo-spatial lens

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The study of riverscape dynamics in connection to human impacts, especially bridge construction, has grown increasingly interactive in recent years. The study includes the hydro-sediment features brought about by the building of bridges for road-stream and railway-stream crossing locations, the likelihood of flooding in upstream and downstream areas as a result of bottleneck conditions. The far upstream reach (L2 section) from the rail bridge, the width of the river Lish increased ~ 496 m between 1965 and 1984. Between the rail and road bridge (L4 section), the width has drastically shortened ~175 m since 1965. Width of river Gish expanded between 1913 and 1936, the notable rise in width ~1088.67, ~1061.69, and ~604.06 m, respectively in the downstream G5, G6, and G7

sections. The width appears to have shrunk between 1965 and 1984 (246 and ~142 m, respectively) in the river Chel. Again, between 1984 and 2008, a substantial increase in width is noted in the section (C5) 419 m and ~324 m, respectively. A notable bottleneck condition is found to be developing in the Gish River. The HEC RAS model defines that the flood coverage area decreases if the bridges are reframed according to the width of the riverbed. It is noted that the velocity, which is maximum near the bridge piers in the River Chel with the bridges, decreases considerably with reframed bridges. The reframing of the bridge will increase the velocity in the Lish pier minimising sediment aggradation and vertical depth between the riverbed and the bridge. The study reveals that the Gish is experiencing bottleneck conditions. The HEC RAS modelling discloses that reframing of the river width is the most applicable mitigation to minimise flood probability in the downstream rather than relocating or without a bridge condition.

Keywords: Channel evolution, bottle neck condition, HEC RAS modelling

Geospatial Assessment of Cocoa-Driven Nature Loss and Water Consumption in the Pra Basin in Ghana

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Cocoa production in Ghana has historically been linked to deforestation and encroachment into protected areas, yet its water consumption patterns is understudied. While data on cocoa yields and cultivated areas are accessible, detailed information on water usage by cocoa plantations remains scarce. This study, conducted under the Transforming Agrifood Systems in West and Central Africa (TAFS-WCA) initiative by CGIAR, presents an innovative modeling framework to bridge this knowledge gap. By integrating open-access Earth observation data, global geospatial datasets, and the Water Accounting Plus (WA+) framework, the study quantifies water availability and water consumption linked to cocoa production and encroachment-driven activities in the Pra Basin, Ghana's largest southwestern river basin and a critical cocoa production zone spanning approximately 23,200 km² across five regions.

Over the 2004-2020 period, the basin received an average annual rainfall of 1,430 mm, with 88% consumed as evapotranspiration, amounting to a total water consumption of 29 km³/year. Cocoa production accounts for 30% of this total, with monoculture cocoa dominating (84%), agro-protected cocoa contributing 14%, and shaded cocoa consuming just 2%. Notably, agro-protected cocoa, which encroaches on protected areas, constitutes 24% of water consumption in these sensitive zones, with 1.22 km³/year of unauthorised water consumption, posing significant threats to biodiversity conservation. Cocoa water productivity ranges from 0.019 kg/m³ to 0.061 kg/m³, highlighting variability across regions.

These findings underscore the critical implications of agricultural-driven nature loss on water resources and biodiversity, emphasizing the need for sustainable cocoa production practices. The study provides actionable insights to inform policy and guide decision-makers in balancing agricultural development with environmental conservation.

Keywords: Water use, deforestation, agriculture, cocoa, Ghana

Deciphering the roles of climate and land-use changes on water resources in India

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Understanding the complex interactions between climate variability and land-use change in shaping water resources remains a fundamental challenge in hydrological research. This study presents a novel approach for quantifying the relative contributions of these drivers to changes in water availability in India. We use a simple yet effective Budyko-based framework combined with counterfactual analysis over the period 1980-2020 at a $1^\circ \times 1^\circ$ spatial resolution on a 5-year running mean across the country. The catchment parameter (?) in the Budyko model is allowed to vary with multiple environmental variables in a generalized linear model. The evolution of water availability in the actual conditions is compared against that in counterfactual scenarios that maintain historical land-use or climate patterns. The results reveal that land-use modifications have substantially influenced both evapotranspiration and water availability, with marked spatial heterogeneity in impacts across the country. Regions in Punjab, Haryana, and Uttar Pradesh in northern India - the country's primary bread basket - show that land-use changes have increased mean evapotranspiration by upto 20%. This has implications on both water and food security in India. The proposed framework can be further used to estimate future water resources in the country under climate change.

Keywords: Budyko Framework, water availability, land-use changes, climate variability

Controlling the Atreyee by Impoundment Structures in Bangladesh and India

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A dam is a barrier that interrupts the natural flow of a river. It interferes with its dynamic equilibrium and also affects the floodplain ecosystem. This work assessed the impact of the 2012 Mohanpur Rubber Dam (MRD) in Bangladesh on the Atreyee River just upstream of its entrance to India. To combat its adverse effect, the Indian Government obstructed the Atreyee near the river's re-entry into Bangladesh by constructing an overflow dam in 2023. This ensured a minimum requirement of water could be maintained in the Indian portion of the Atreyee basin to restore the ecosystem and recharge the groundwater. Recently in February 2025, the overflow dam constructed by INDIA near Balurghat town was broken down and emerged the probability of serious hydro-meteorological hazed. Though the barrage has been started re-constructing, a detailed review on its construction and the probable causes of its failure should be carried out which this study has taken care of. Using satellite images of 2001, 2011 and 2021 besides other primary and secondary data, this

study conducted a spatiotemporal analysis of the changing planform of the Atreyee during pre- and post-MRD and compared it with the overflow dam impacts. Temporal land use land cover data as well as groundwater data were compared to analyse the overall impact of the two impoundment structures. In the down-MRD Dakshin Dinajpur District of West Bengal, changing riverbed, the surface and groundwater volume and the ensuing alterations in agrarian land use were the main effects observed.

Keywords: Atreyee River, Mohanpur Rubber Dam, overflow dam, changing planform, dam impacts, agrarian land use, restore the ecosystem.

Unravelling the interplay of hydrological extremes and socioeconomic inequalities

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Hydrological extremes, such as floods and droughts, can exacerbate socioeconomic inequalities, as poor communities are often disproportionately affected and have fewer resources for recovery. In turn, socioeconomic inequalities can exacerbate the impacts of hydrological extremes, as more unequal societies often suffer more severe consequences. These interconnected dynamics can create vicious cycles in which escalating inequalities and worsening impacts reinforce each other. However, hydrological extreme events can also serve as catalysts for transformative change, offering opportunities to alleviate inequalities. By seizing these moments, it becomes possible to break vicious cycles. This work aims to unravel the complex interplay of hydrological extremes and heterogeneous societies, and uncover the mechanisms underlying (the breaking of) vicious cycles across multiple scales. Mathematical models, case studies and global analyses are combined to explore the role of: i) power relations and asymmetries; ii) the intersection of socioeconomic status, gender, race and ethnicity; as well as iii) human behaviour, including cognitive heuristics in the decision-making process. By combining theoretical and empirical work, this work presents an initial attempt to address major knowledge gaps and provide novel insights about the fundamental processes shaping the distribution of risk across segments of society.

Keywords: Sociohydrology, poverty, inequalities, disasters, floods, droughts, feedbacks

Incorporating community knowledge and values within urban river restoration visions

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Anthropogenic transformations to rivers have negatively impacted people and freshwater ecosystem health globally. Restoration practices aim to enhance the ecological integrity of watercourses by promoting natural processes, but such interventions often overlook community engagement within both their design and appraisal. Such oversights can lead to local communities not benefiting from environmental improvements in their local green or blue spaces. Further still, limited or no public engagement can lead to communities resisting restoration works, particularly where such actions threaten attributes of societal importance. In this project, we aimed to ascertain the plural forms of knowledge and values held by local volunteer groups towards a 5km stretch of the River Cole - an iconic, highly urbanised river in the English Midlands (UK). This was achieved via walking interviews (e.g., emotive, sensory knowledge) and a community workshop (e.g., instrumental knowledge). Our results indicated that communities are interacting with the Cole in various ways, including foraging, nature engagement and family-orientated recreation. A recurring theme was how the local waterway depicted a vital green / blue space where people can relax by enjoying sights, sounds and smells (e.g., wild garlic, flowing water) and feel like they are away from the city. Participants expressed mixed views on the health of the Cole, with positive perceptions held towards faster flowing stretches exhibiting clear waters, but a wider recognition that pollution and litter is degrading its ecological integrity. Communities were broadly in favour of restoration actions promoting natural functions and features, but favoured preserving iconic 'stepping stones' on top of weirs due to their heritage value and role as a key access point. The suite of community engagement activities undertaken in this project formed part of a Cole restoration vision, and showcases how 'people friendly' river restoration solutions can be co-created alongside engaged community members.

Keywords: societal, people-friendly, engagement, river, rehabilitation,

Navigating Jordan's Water Resources Futures: Regional Hydrological Modelling Under Socio-Economic Developments and Climate Change

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Jordan faces increasing water scarcity as climate change and socio-economic development place greater pressure on its already limited water resources. This study examines the potential impacts of climate change and socio-economic pathways on the country's water availability by 2050 using the Community Water Model (CWatM). Through scenario analysis, it assesses how projected changes in precipitation, evapotranspiration, and groundwater depletion will influence future water resources and evaluates the potential gains of a 15% improvement in irrigation efficiency.

Findings indicate that Jordan's water deficit is expected to rise significantly, reaching an average of 1,100 - 1,400 Mm³/year between 2025 and 2050, compared to 567 Mm³/year between 1980 and 2014. Enhancing irrigation efficiency could contribute to improved water availability, adding approximately 70-100 Mm³/year over the same period. However, to achieve long-term water security under climate change, additional measures such as seawater desalination and expanded reuse of treated wastewater will be crucial. While irrigation efficiency improvements support the optimal use of available water resources, integrated strategies combining supply augmentation and demand

management are necessary to ensure sustainable water management in Jordan's arid climate.

Keywords: Climate change, Anthropogenic activities, Water Management

Modeling Hydrological Droughts in Alpine Hydropower-Influenced Basins

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This work offers a renewed outlook on modeling hydrological droughts by underlining the pivotal influence of hydropower operations in shaping drought dynamics. Although model structure remains a key component in representing the catchment's response to climatic drivers, our analysis demonstrates that achieving reliable drought simulations requires an explicit and realistic integration of reservoir management strategies.

Using the Adige River basin-an intensively regulated Alpine watershed-as a case study, we employ the distributed hydrological model HYPERstreamHS, which incorporates interactions between natural processes and human interventions. We explore the impact of three distinct hydropower management scenarios on drought characterization: NAT (absence of infrastructure), MAX (constant operation at maximum flow), and FULL (implementation of detailed operating policies).

Our results reveal that only the FULL scenario, which mirrors real-world hydropower operations, succeeds in replicating observed drought features such as the relationship between severity and duration, and the frequency of extreme events. In contrast, the NAT and MAX setups, despite their widespread use due to their simplicity, consistently underestimate drought severity and fail to capture the dynamics of drought evolution through the river network.

A bivariate copula-based analysis further confirms that only the FULL configuration accurately reflects the observed interdependence between drought severity and duration, a key factor in understanding drought propagation under anthropogenic influence. These outcomes highlight the added complexity of drought assessment in mountainous basins, where human interventions significantly alter flow connectivity and low-flow regimes.

By stressing the necessity of representing hydropower operations in detail, this study enhances current capabilities in drought modeling and offers valuable insights for planning and managing water resources in regulated high-altitude catchments. It supports integrated approaches to climate resilience, operational planning, and sustainable water governance under evolving hydroclimatic pressures.

Keywords: Hydrological drought modeling, Reservoir operations, Human-natural systems coupling

Identification and Mapping of Paleochannels for Water Resource Management

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Small river or tributaries are most significant to a river system as the small river are the major contributor of the water demand of a large river system. However, these rivers are fragile towards, global climatic change, tectonism and anthropogenic activities. The study focuses on the Assi River in Varanasi, now reduced to a 7 km stretch and functioning as a sewage drain. Nonetheless, it is believed among commoners that the Assi River is way older like Ganga. The study has been started with the detailed literature survey, followed by remote sensing analysis followed by geophysical (Transient Electromagnetic survey) and geotechnical investigations. The reconnaissance survey by remote sensing analysis, provides ~450 km of Paleo-channel in the upstream of the present channel and provides a zone of further investigation. While, further exploring with the Transient Electromagnetic (TEM) survey and geotechnical investigation a long paleochannel ~170km length in the upstream of the current Assi River stretch with a width of about 45-70m along with associated riverine features like oxbow lake, meander scars and scroll bars etc was depicted. The channel has its connection of the Ganga River in Prayagraj District and 'flowing as a chute channel of the major river (Ganga). The channel has a characteristics resistivity signature of 30-55 ohm.m has been designated by non-plastic silt and coarse silt with granules. Furthermore, there was a neotectonic activity as reactivation of Allahabad-Azamgarh Fault in the upper reaches of the paleo channel and anticipated as one of the key reasons of its decline. In order to rejuvenate the small river like Assi these Paleo-channel will have a vital role to play as it stores a good amount of water at a depth of 6-8m bgl and has a vast catchment (~900 sq. km) to feed the current Assi River.

Keywords: River rejuvenation, Groundwater recharge, Alluvial River, Neotectonics, River Piracy

Remote Sensing (ICRS)

A change in the peak timing of Indian summer monsoon rainfall due to a shifting climate: observational evidence

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Global warming has become a significant driver of increased extreme precipitation events and a notable variability in rainfall patterns worldwide and altering the timing of peak rainfall occurrences and exerting substantial changes on the hydrological cycle in various evolving climatic conditions. This study focuses on analyzing the spatial trends of rainfall across India during the Indian Summer Monsoon (ISM) period, specifically from the years 2001 to 2020, utilizing data from the Global Satellite Mapping of Precipitation (GSMaP-ISRO) initiative. The analysis reveals a significant increase in rainfall, specifically an average rise of 2 mm per day over the region of west central India between the years 2011 and 2020. Furthermore, an in-depth investigation into the timing of the peak rainfall events indicates a shift towards earlier peaks in recent years over the Indo-Gangetic Plain, located in central India. Additionally, an investigation into the timing of peak rainfall demonstrates an early (late) peak over the Indo-Gangetic Plain (central India) in recent years. This trend contrasts with later peaks observed previously, suggesting potential influences from changes in aerosol loading and other anthropogenic factors. The findings of this study underscore a significant shift in the timing of peak rainfall, which could have profound implications for various sectors, including agriculture, hydrology, and disaster management. This shift may affect crop yield timings, water resource management strategies, and the planning and response mechanisms to natural disasters linked to rainfall variability. Understanding these trends is crucial for developing adaptive strategies to mitigate the impacts of climate change on regional climates and communities.

Keywords: Rainfall, Peak time, Indian Summer Monsoon, GSMaP-ISRO

Identifying groundwater drought risks in major agricultural regions of China: A combined perspective of GRACE- and groundbased observations and modeling

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With the challenges of climate change and increasing food demand, North China has produced more than 65% of cereal productions of China, and is of great importance in food security. However, North

China is facing with significant ecological degradation subsequent to water withdrawal for irrigation. As a result, lots of rivers run drying-up and groundwater table declined fast in the past several decades. There is a observed positive precipitation trend in past 2 decades over North China, and most rivers' flow has been measured increasing, accompanied with vegetation revigorous, i.e. increase in vegetatoin cover. Under this background of climate and land cover change, we find groundwater continued to subject overpumping and has played a key role to support the gain of food production and vegetation restoration during this period. In this study, we will present the results in detail to use combined method of ground-based and GRACE observations to screening up groundwater drought risk under the increasing precipitation or wetting background. Using some machine learning algorithms, we extropolated the GRACE observed Terrestiral Water Storage (TWSA) and Groundwater Storage (GWSA) back to 1960s, and proposed a groundwater drought index (GDI) to investigate the groundwater drough characteristics under the effects of climate change and human exploitation. And we found that in major basins across North China, such as Tarim River Basin, Yellow River Basin, Hai River Basin, and Songhua River Basin, groundwater experienced more frequent and severe drought in recent 20 years, than it was in the past 4 decades before 2000. This is mainly caused by agricultural withdrawal and vegetation restoration. And in future, groundwater would be likely encounter with more severe drought threats.

Keywords: GRACE, groundwater depletion, North China, Agricultural withdrawal, Drought risk.

A study of hydrological extremes from space

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Land surface hydrology is a collection of complex processes. The spatial variability both the land surface properties (soil and vegetation) as well as the meteorological inputs (precipitation and radiation) play an important role in hydrology. Satellite remote sensing has a broad spatial and repeat temporal view of the land surface and is able to provide observations for use in hydrology such as soil moisture, surface temperature and vegetation density. The variability of the water cycle causes extremes such as droughts and floods and these have an impact on society. In addition, landslides, permafrost thaw and wildfires are the three other hydrological extremes that impact society. In the past two decades with the advent of improved satellite sensors, modeling and in-situ observations, quantification of the water cycle and its extremes has become possible. These satellite sensors include - microwave observations for soil moisture and precipitation; visible/near infrared for vegetation and evapotranspiration, gravity for groundwater/total water and thermal observations for surface temperature. In this talk I will focus on using models, satellite and in-situ observations for hydrological variability specifically as they relate to hydrological extremes.

Keywords: earth observations, hydrological extremes, water crises

Mapping and assessing the impacts of crop-weed competition in neglected and underutilized crops

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In light of a growing population and climate change compounding existing pressures on the agri-food system, there is a growing need to diversify agri-food systems and optimize the productivity and diversity of smallholder farming systems to enhance food and nutrition security under climate change. Subsequently, there has been an increase in the promotion of neglected and underutilized crops (NUCs) for smallholder farms. In this context, improving weed management takes on added significance, since weeds are among the primary factors contributing to crop yield losses for smallholder farmers. Adopting remote-sensing-based approaches to facilitate precision agricultural (PA) applications such as integrated weed management (IWM) has emerged as a potentially more effective alternative to conventional weed control approaches. However, given their unique socio-economic circumstances, there remains limited knowledge and understanding of how these technological advancements can be best utilized within smallholder farm settings.

As such, this study aims to accurately identify and map the spatial distribution of weeds as well as understand and quantify the impacts of weed water use on crop health, quality, yield and available water resources. It is envisaged that this information will then serve to guide more effective weed management in the future. The study first used a systematic scoping review and attribute analysis to gain further insight into remote-sensing-based IWM approaches and identify which are potentially best suited for smallholder farm applications. The findings of this review revealed that unmanned aerial vehicles (UAVs) are the most frequently utilized remote sensing platform for IWM applications and are also well suited for mapping and monitoring weeds within spatially heterogeneous areas such as smallholder farms. Following this, the study utilized UAVs, and open-access cloud computing platforms [GEE] to demonstrate the potential of improving farming practices through PA. Subsequently, this study used taro (taro is among the NUCs typically grown by smallholder farmers) and weed interaction as proxies to develop a model that utilizes available technological infrastructure to enhance farming productivity. A total of three supervised classification techniques were tested on multispectral images, namely the traditional pixel-based image, and two object-based image analysis approaches. The study revealed that the multispectral UAV imagery processed using GEE can provide reliable prescription maps for smallholder farms which can assist with the implementation of sustainable management practices.

Keywords: remote sensing, agriculture, food insecurity, smallholder farmers, UAVs, drones

The Application and Assessment of Satellite based remotely sensed Rainfall Data in the ACRU Hydrological Model: Case study in selected catchments in South Africa

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In-situ rain gauge networks are diminishing, especially in southern Africa, resulting in sparse networks whose records give a poor representation of rainfall occurrence, patterns and magnitudes. Hydrological models are important tools used to generate information for water resources management decisions. However, model performance is directly linked to the quality of input data used to drive the model, such as rainfall. The use of satellite-derived remotely sensed rainfall is increasingly being advocated as a viable alternative or supplement to existing rainfall data. The aim of this study was to evaluate the representativeness of satellite-derived rainfall and assess its applicability for use in the ACRU agro-hydrological model to simulate stream flow magnitudes, distributions and patterns. The satellite-derived rainfall products selected for use in this study included TRMM3B42, FEWSARC2.0, FEWSRFE2.0, TAMSAT3.0 and GPM-IMERG4. The satellite rainfall products were validated against available historical observed records and then were used to drive simulations using the ACRU hydrological model in selected catchments in South Africa. At the daily timescale, satellite-derived and observed rainfall were poorly correlated and variable among locations. However, monthly, seasonal and yearly rainfall totals and simulated streamflow volumes were in closer agreement with historical observations than the daily correlations; in the upper uMngeni and uThukela than in the upper and central Breede (e.g. FEWSARC2.0 and FEWSRFE2.0, produced relative volume errors in the range of -5% to 4%). Overall the ACRU model was able to successfully simulate flows using the satellite derived rainfall data sets however further studies need to be undertaken to improve the satellite vs observed at a daily timestep and investigate the use of Bias correction and downscaling for improved daily rainfall estimates.

Keywords: Satellite Rainfall, Hydrological Modelling, Remote Sensing

Estimating river bathymetry from spaceborne LiDAR data and curve-fitting method

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River bathymetry data is essential for estimating river discharge and supporting various hydrodynamic applications. However, surveyed bathymetric data is often available only at a limited number of locations, even for major rivers. Accurate characterization of river bathymetry, particularly in sparsely monitored basins, is crucial for developing reliable hydrodynamic models. Remote sensing technologies, especially laser altimeters, offer a promising, non-invasive, and efficient approach to approximating river bathymetry. This study focuses on developing an algorithmic framework to approximate river bathymetry along the Ganga River using spaceborne ICESat-2 LiDAR data. ICESat-2 operates in the green band, enabling it to penetrate the water surface. However, this capability is highly dependent on water clarity and the coefficients of absorption and scattering. As a result, only a limited subset of the data can be used to approximate the entire river cross-section, encompassing both dry and wet bathymetric sections. The underutilized data, however, presents an opportunity to observe the dry bathymetric section, which can be used to extract height-width pairs. We used a height-width relationship to predict the unknown bathymetry using the nonlinear slope break (NLSB) method. The NLSB method predicts the bed elevation and low-flow area, allowing the densification of river bathymetry approximations at additional locations. Furthermore, the proposed

algorithmic framework can also be utilized to infer bathymetry from SWOT satellite-observed water surface elevation and river width data.

Keywords: River bathymetry, ICESat-2, Remote Sensing, Curve-Fitting, LiDAR

Atmospheric Moisture Budget and Its variability over the Indian Subcontinent

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The transport of atmospheric moisture plays a fundamental role in the global water cycle, directly influencing climate patterns and regional weather systems. This study provides a detailed assessment of atmospheric moisture availability, employing high-resolution moisture budget equations to capture spatio-temporal variations. Using ERA5 reanalysis data from 1990 to 2023, we estimated the atmospheric moisture budget to understand its role in shaping climate variability. Horizontal moisture advection modifies regional humidity conditions, while vertical transport affects convection and precipitation processes. To identify key moisture sources and sinks across oceanic and terrestrial regions, we analyzed seasonal variations in E-P (evaporation minus precipitation) and vertically integrated moisture flux divergence. The Mann-Kendall trend test was applied to assess long-term trends in daily and monthly mean atmospheric water availability. The results highlight a significant positive E-P trend over the Western Ghats and the equatorial Indian Ocean, indicating an increase in moisture supply may be due to land-sea-atmosphere interaction. However, a negative E-P trend over the Western Ghats suggests intensified moisture recycling, potentially linked to a "capacitor effect," where soil moisture, evapotranspiration, and precipitation feedback mechanisms become more prominent during weak monsoon phases. These findings have critical implications for climate adaptation strategies, particularly in the context of energy and food security. Understanding variations in atmospheric moisture availability is essential for managing water resources, mitigating extreme risks (like floods and droughts), and ensuring sustainable agricultural practices in the Indian monsoon region. This research enhances our ability to predict hydrological extremes and their socio-economic consequences in a changing weather.

Keywords: Atmospheric moisture transport, Atmospheric water availability, Atmospheric Moisture Budget, Mann-Kendall Trend-test, Vertical Moisture Transport.

Exploring Differences in Soil Moisture Selection Maps: A Comparison of Triple Collocation and Mutual Information Methods Across Climates and Land Covers

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Soil moisture information is vital in water resources management, disaster monitoring, and various hydrological applications. With the advancement in remote sensing technologies, it became possible to obtain global-scale soil moisture measurements with a high temporal resolution. Nevertheless, the validation of remotely sensed soil moisture remains constrained by the sparse network of in-situ monitoring stations. To address this, techniques based on triple collocation and mutual information have been developed to validate satellite-based data without needing ground truth observations. However, limited efforts have been made to explore the differences in the soil moisture choice map and provide insights into the optimal utility of the existing validation techniques. In this study, we have analyzed the relative strength of the three passive soil moisture products using triple collocation and mutual information analysis. The results indicate that the selection of the optimal soil moisture dataset varies across approximately 50% of the analyzed grids. SMAP emerged as the dominant choice based on triple collocation analysis, whereas AMSR demonstrated superior performance when compared to other soil moisture datasets in the best-choice map. To further contextualize these findings, the best-choice map was integrated with climatic zone classifications and land use/land cover (LULC) data. This integration provided valuable insights into the specific conditions under which each soil moisture product performed optimally. Overall, the study offers critical guidance to hydrologists and researchers for selecting the most suitable soil moisture dataset for diverse hydrological applications across varying climatic and environmental conditions.

Keywords: Soil Moisture, Triple Collocation, Mutual Information, LULC, Climatic Zones

Investigating lower-than-expected urban flood peaks through field investigation, remote sensing and machine learning

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Like many other developing countries, South African cities have expanded considerably in recent years, increasing flooding risks in both formal and informal settlements. Previous studies have shown that while flood volumes increase with urban development, catchment response times don't decrease, and peak flow rates don't rise as expected. This study investigated two key factors behind these unexpected hydrological responses: (i) levels of imperviousness and (ii) connectivity of

impervious areas to drainage systems.

Measuring imperviousness at the catchment scale is challenging, especially in developing countries with limited data. The study used remote sensing, machine learning, and field verification to identify significant differences in Median Total Impervious Area percentages (μ TIA) across urban land cover types: residential (μ TIA=38%), commercial (μ TIA=81%), and industrial (μ TIA=89%). Furthermore, μ TIA varies significantly between different formal residential classes (17%-61%) and different informal residential classes (14%-43%). Based on the results, Total Impervious Area percentages for model parameter estimation are recommended for any urban area in the South African National Land Cover dataset. The methodology applied could be used in any region with a land cover dataset that differentiates between a range of urban land cover classes.

The study also explored the connectivity of impervious areas to drainage systems, a complex task. Field testing was applied at sample sites to assess the Directly Connected Impervious Area (DCIA). Three methods were tested to predict DCIA: existing relationships, linear regression models, and median DCIA values for each land use class. Existing equations performed poorly, particularly for residential areas ($0.12; R^2; 0.44$). However, predictions for industrial and commercial areas were more accurate ($0.80; R^2; 0.93$). The study suggests that in developing countries, rainfall-runoff modelling can be improved by assuming zero connectivity in informal settlements, using median DCIA percentages for formal residential areas, and a derived relationship for industrial and commercial areas where direct measurements are unfeasible.

Keywords: GIS, impervious, land cover, remote sensing, machine learning, developing countries, runoff, flood

Satellite- based Flood detection in Arid regions using Sentinel-1 Synthetic Aperture RADAR

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Flood events represent one of the most prevalent and devastating natural disasters, necessitating rapid and accurate mapping of inundated areas for effective emergency response. Satellite remote sensing has emerged as a cost-effective tool for near real-time flood surveillance. While traditional optical satellites can distinguish water from land, their effectiveness is limited by cloud cover during flood events. Synthetic Aperture Radar (SAR) technology overcomes this limitation by providing cloud-penetrating imagery, making it invaluable for operational disaster response. However, SAR-based flood detection in arid regions presents unique challenges, as sand surfaces frequently produce water-like signatures, leading many operational services to exclude these regions entirely from their analyses.

We present a methodology combining SAR amplitude data with interferometric coherence information. Our approach employs Random Forest classification to analyze multiple SAR features, with results validated against flood masks derived from cloud-free optical imagery. Testing across multiple case studies in Iran, Turkmenistan, and Pakistan revealed that integrating coherence data with

amplitude measurements improved flood mapping accuracy by 50% compared to traditional methods. Through permutation feature importance analysis, we identified key parameters that maintain accuracy while reducing processing time by 33%-a crucial advantage for emergency response operations. The model demonstrated robust performance across diverse geographical settings without site-specific retraining, indicating its potential as a standardized flood detection system for arid regions.

The increasing availability of open-access SAR data and advances in cloud computing have made handling and computing calculations of SAR data more feasible. With multiple space agencies launching new SAR missions, there are opportunities to test and adapt this methodology across different sensors and integrate it into operational flood mapping systems.

Keywords: Flood mapping, SAR, Machine learning, Remote sensing, Coherence, Disaster management

Identification of Groundwater Potential Zone in Lower Gangetic plain

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Groundwater is considered as the most reliable source of freshwater that can boldly meet the need in various sectors. Since last few decades, population growth and subsequent urbanization has increased groundwater demand and resulted in a long-term crisis in availability of groundwater resources. Birbhum is one such district in Gangetic West Bengal that, in recent decades, has witnessed rapid urbanization, giving significant reduction in groundwater level throughout the district. Surprisingly, the annual average rainfall has shown a gradual increase from ~1200 mm in 2014 to ~2100 mm in 2023 (rise of 75%) over the entire region although it is not translated into groundwater recharge. Isohyetal maps show a concentration of highest rainfall depth in the south-western part of the district. The prime focus of this study is to investigate groundwater potential zones to safeguard the valuable resource at risk and to identify the favourable location for groundwater recharge within the study area by employing Multi-Criteria-Decision-Analysis based Analytic Hierarchy Process combined with Geographic Information System. Based on groundwater potential index, an area of 11.68%, in the south-eastern part of the study area, is categorised as very high groundwater potential zone. The region covering almost 51.12% area is categorized as high groundwater potential zone which is observed in majority of the central portion of the district. These zones are identified in the plain regions (~slope 0.50%) with high annual average rainfall (~1470 mm.) corresponding to higher rate of infiltration. This is consistent with the presence of relatively permeable quaternary sediments in the subsurface. The need for managed use of groundwater is validated with the declining trend in groundwater level by the help of Central Ground Water Board year-book data. Field validation is required for better understanding of the results and making vital decisions to enhance the groundwater level in the study area.

Keywords: Groundwater, Urbanization, Isohyetal maps, Analytic Hierarchy Process, Groundwater potential

Recent progress and future opportunities in monitoring evapotranspiration from High Resolution Thermal InfraRed Remote Sensing in the context of the TRISHNA, LSTM and SBG satellite missions

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Even though Thermal InfraRed Remote Sensing has been used for Evapotranspiration (ET) monitoring for several decades, its widespread development both for scientific and practical applications has been hampered by either the low resolution of the platforms with daily revisit, or the low frequency of acquisition of the high-resolution sensors, in particular those with pixel size of the order of one hectare, a satisfying target for agriculture. This is about to change with the arrival of the sequel of space missions such as ECOSTRESS, TRISHNA, LSTM, SBG or many projects of the New Space. TRISHNA will provide a daily evapotranspiration product on all continental surfaces on a clear sky day of acquisition (L2) as well as a temporally gap-filled product (L3), LSTM will only provide Land Surface Temperature (LST). Since ET retrieval of TIR data depends on auxiliary data such as meteorological data (at least incoming solar radiation) as well as a vegetation development (or a proxy thereof), designing a robust product is particularly challenging, those data being not routinely available at high resolution every day. However, the availability of local data, such as a meteorological tower or detailed UAV cover of vegetation features, enable the use of more complex algorithms. Here we present the recent advances in both areas: how we build the L2 and L3 product for TRISHNA and their expected limits and uncertainties, with respect notably to existing low resolution ET products, and how one can tailor more precise algorithms accounting for canopy and sun-target-sensor geometry to fit precision agriculture needs. Current progresses in applications such as stress detection and monitoring or evaporation/transpiration partitioning are also presented. Those will have great impacts in sensitive areas in applications to agro-eco-hydrology, such as irrigation scheduling, forest fire early warning etc etc.

Keywords: evapotranspiration, TIR remote sensing, water stress

A New Approach for Enhancing Reservoir Surface Water Mapping Using SAR-Assisted Correction of Cloud-Contaminated Optical Scenes

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Understanding reservoir surface water dynamics is essential for estimating volumetric variations and reservoir storage. However, assessing these dynamics remains challenging due to environmental complexities and seasonal fluctuations. Optical remote sensing datasets, such as Sentinel-2 and Landsat series, are widely used for surface water mapping but often suffer from temporal gaps caused by cloud cover contamination. Traditionally, this contamination is corrected using historical water probability scenes, which may fail to capture real-time water spread accurately.

This study introduces a new approach to generating a time series of surface water dynamics by effectively correcting cloud-contaminated optical scenes. Instead of relying on multiple stacked historical water probability maps, the proposed method utilizes the nearest available Synthetic Aperture Radar (SAR)-derived water spread scene. The approach was implemented as a pilot study over the Yeldari Reservoir in India using freely available high-resolution Sentinel 1 and 2 datasets on the Google Earth Engine (GEE) platform. It effectively corrected Sentinel-2-derived optical water spread scenes for instances when cloud cover ranged between 1% and 30% using the nearest Sentinel-1-derived SAR water spread scene. As a result, 16 Sentinel-2 optical scenes from 2023-2024 were corrected, resulting in approximately 20% increase in the number of valid optical scenes in the water-spread time series. The accuracy of the corrected water spread areas was evaluated against bathymetry-derived water spread areas at corresponding water levels, with deviations ranging from ± 0.66 to 4.09 square kilometers.

A detailed comparison with traditional methods is currently in progress. Preliminary observations suggest that the proposed approach has the potential to enhance the accuracy of surface water mapping in cloud-contaminated areas compared to conventional methods, but further analysis is needed to confirm its effectiveness.

Keywords: Synthetic Aperture Radar, Google Earth Engine, Time series, Bathymetry, Cloud-Contaminated

"Seasonal Variations in Water Resources, Vegetation Health, and Turbidity along the Yamuna River Mathura: A Geospatial Analysis"

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The study investigates seasonal variations in water resources, vegetation health, and turbidity along the Yamuna River in Mathura, India, using geospatial analyses of NDWI (Normalized Difference Water Index), NDVI (Normalized Difference Vegetation Index), and NDTI (Normalized Difference Turbidity Index) maps for 2024. The stretch in Yamuna River Mathura analyzed from the Devraha Baba Temple to Bengali Ghat and Bengali Ghat to Chintaharan Ghat. Pre-monsoon NDWI values

ranged from -0.518519 to 0.0945946, indicating limited water presence, while post-monsoon values improved slightly, highlighting the monsoon's role in replenishing surface water. NDVI analyses revealed robust vegetation health pre-monsoon, with maximum values of 0.638376 and 0.660777 in the respective regions. Post-monsoon NDVI values declined, reflecting vegetation stress caused by flooding and soil erosion. NDTI values demonstrated significant turbidity changes, with pre-monsoon maps indicating lower sediment levels and post-monsoon maps showing elevated turbidity due to monsoonal runoff and sediment transport. The findings emphasize the critical influence of monsoonal rainfall on water availability, vegetation dynamics, and sediment transport. This study underscores the need for sustainable water resource management and vegetation preservation strategies to mitigate environmental stressors in the region.

Keywords: Yamuna River, NDWI, NDVI, NDTI, Geospatial analysis.

Detection of Flood Areas Using SENTINEL Radar Imagery in Urban Environments for Strengthening Flood Early Warning Systems in Abidjan.

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Floods are one of the most frequent, damaging, and deadly natural disasters, particularly affecting developing countries. In Côte d'Ivoire, specifically in the Autonomous District of Abidjan, rapid urbanization and population growth exacerbate vulnerability to urban flooding, amplified by the effects of climate change. Accurate detection of flood-prone areas in this complex urban context is essential to strengthen early warning systems and improve risk management.

Radar remote sensing, particularly SENTINEL-1 imagery, offers significant advantages for flood monitoring, including its ability to acquire data regardless of weather conditions and lighting. However, in urban environments, major technical challenges remain, such as shadows caused by tall structures, confusion between water surfaces and building roofs, and the distinction between natural water bodies and flooded areas. These challenges require a rigorous methodological approach combining multiple techniques and the use of historical in situ data for reliable detection.

In this study, we propose an innovative methodology based on the use of Google Earth Engine (GEE) for processing SENTINEL-1 RADAR images. Our approach integrates rigorous radiometric and geometric calibration, including speckle filtering, Earth curvature correction, and viewing angle distortion correction. To overcome the specific challenges of urban environments, we combine these processes with the use of a Digital Terrain Model (DTM) derived from Lidar data and historical in situ flood data. This combination of methods enables more accurate detection of flood-prone areas, even in dense urban environments.

Preliminary results demonstrate significant improvement in the identification of flooded areas, offering promising prospects for strengthening early warning systems in Abidjan. This study contributes to the scientific literature by proposing a reproducible methodology for flood detection in urban areas, while providing practical tools for risk management in vulnerable regions.

Keywords: Urban floods, Radar remote sensing, SENTINEL-1 imagery, Google Earth Engine (GEE),

Digital Terrain Model (DTM), Flood-prone area detection, Climate change, Early warning systems, Abidjan, Dense urban environments

Remote Sensing for Efficient Irrigation: Monitoring Reservoirs with Sentinel Data

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Rice is the most important irrigated crop in Uruguay, covering 140,000-160,000 hectares annually. Half of the water supply comes from reservoirs, while the rest is drawn from natural surface sources. However, high costs associated with water volume estimation in reservoirs and flow monitoring in channels hinder efficiency, planning, and equitable water distribution.

Satellite imagery, processed through platforms like Google Earth Engine, provides free geospatial data for large-scale environmental analysis with minimal hardware requirements, offering a cost-effective alternative for monitoring natural resources. Water indices such as NDWI and MNDWI, derived from Sentinel-2 (S2) optical imagery, are widely used to measure reservoir water surfaces. However, S2 accuracy is affected by atmospheric conditions. In contrast, Sentinel-1 (S1) radar sensors enable all-weather, day-and-night monitoring.

This study analyzed satellite image collections from 2018 to 2024 of the India Muerta reservoir in the East region of Uruguay. Images were processed using Google Colab Python scripts in combination with Google Earth Engine.

Water surface areas were generated at 20 cm intervals using a digital elevation model and field sensor data. S2 images were filtered for cloud-free coverage, and NDWI thresholds were tested to optimize accuracy. The Otsu algorithm was applied to S1 images to determine reflectance thresholds for water detection.

Results showed that variable S2 NDWI thresholds outperformed the S1 Otsu-based method, achieving higher accuracy and lower errors. These findings highlight the effectiveness of optical remote sensing for reservoir monitoring.

Satellite-based monitoring offers valuable data for policymakers and farmers, enabling better irrigation management, mitigating water shortages, and promoting fair water distribution. By providing a cost-effective alternative to traditional methods, this approach enhances sustainable water resource management and supports long-term agricultural productivity

Keywords: remote sensing, satellite imagery, sentinel, irrigation, water monitoring

Unveiling Methane Concentration Patterns over Wastewater Treatment Plants in Indian Cities Using NDCI and Sentinel-5P TROPOMI Data (2019-2024)

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The global warming measurement for methane (CH₄) remains significantly higher than carbon dioxide (CO₂) because its 100-year potential reaches 28 times greater, and its 20-year potential reaches 84 times greater. The wastewater treatment facilities act as major CH₄ emitters in urban areas involving several biological and chemical processes for the treatment of sewage and organic waste primarily due to anaerobic conditions that arise during wastewater processing and sludge management which is often underrepresented in the national greenhouse gas inventories. The objective of this study is to track CH₄ emissions by analyzing CH₄ concentrations at more than 25 leading WWTPs across major Indian cities throughout 2019 to 2024 through remote sensing analysis using Sentinel-5P TROPOMI satellite data along with the NDCI index parameter using Sentinel-3 OLCI data. Normalized Difference Chlorophyll Index (NDCI) serves as a measure of water quality by indicating cyanobacterial growth and algal biomass that typically develops in stagnant wastewater areas with high nutrient concentrations. These values are monitored biweekly to track the spatial and temporal trends of methane associated with the WWTPs. The correlation between methane concentration and the NDCI is analyzed across temporal and spatial emission patterns, using CH₄ value averages from a 15 km buffer area surrounding each plant. The relationship between CH₄ concentrations and NDCI values is examined to better understand the influence of water quality on greenhouse gas emissions. This research demonstrates the feasibility of remote sensing in urban CH₄ surveillance and delves into how rapidly developing Indian Cities manage wastewater-related GHG emissions. This study is eventually a tool for policymakers and planners for site-specific strategies to decrease emissions in high-density urban areas thereby supporting the mitigation of both climate change and urban sustainability.

Keywords: Methane Emissions, Wastewater Treatment Plants (WWTPs), Normalized Difference Chlorophyll Index (NDCI), Algal bloom, Greenhouse Gas Monitoring,

Assessment of terrestrial water storage distribution of the Ganges River Basin of India using GRACE, GLDAS, and TRMM

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Quantifying the terrestrial water storage over a large region is the key to understanding the availability of water resources and taking countermeasures against potential natural hazards such as floods and droughts. Further, this study will help comprehend the interactions between water storage and human society. This study deals with the spatial distribution of the terrestrial water storage level over the Ganges River basin of India. Gravitational anomaly data from the Gravity Recovery and

Climate Experiment (GRACE) has been used to estimate changes in Total Water Storage (TWS) content. Additionally, the Global Land Data Assimilation System (GLDAS) canopy surface water and soil moisture content have been used to observe how they contribute to total water storage over the river basins. Tropical Rainfall Measuring Mission (TRMM) data, processed by the Global Precipitation Climatology Centre (GPCC) has been used to evaluate annual average rainfall over the study area. This study provides a chronological comparison between the GRACE gravitational-anomaly data, GLDAS model data, and TRMM precipitation data over the major river basins, which will provide a view of India's terrestrial water storage condition.

Keywords: GRACE, Gravitational Anomaly, Terrestrial Water Storage (TWS), GLDAS, Soil Moisture, Canopy Water Storage, TRMM, Annual Rainfall, River basins of India, Groundwater.

Evaluating Large-Scale Recycling of Treated Municipal Wastewater to Address Water Scarcity in Karnataka's Arid Regions Using Earth Observation

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Groundwater depletion and inadequate recharge pose significant challenges to sustainable water management, particularly in drought-prone regions like Chikkaballapur district, Karnataka. To address this crisis, the Government of Karnataka implemented a large-scale water recycling initiative, utilizing secondary treated wastewater to replenish groundwater resources. This study evaluates the impact of this program, focusing on agricultural area, and water availability.

Our analysis relies entirely on remote sensing-based datasets. Key indicators such as variations in water body size, land use patterns, vegetation cover, and crop area were examined by comparing project and non-project areas.

The results indicate a significant positive impact within the project zone. Water bodies and cultivated land expanded notably, leading to improved irrigation and water availability. Enhanced water access contributed to agricultural growth, with farmers increasing cultivated land and adopting more diverse cropping patterns. In contrast, non-project areas continued to face water scarcity, limited agricultural expansion, and minimal growth of surface water bodies, highlighting the benefits of water recycling initiatives.

Despite successes, challenges remain, including health concerns, public acceptance, and equitable access. Policy interventions are needed to ensure fair benefit distribution, especially for marginalized farmers. Future research should address these issues and assess scalability in other drought-prone areas.

In conclusion, this treated water recycling initiative highlights the potential of wastewater reuse for sustainable water management. It serves as a replicable model for addressing water scarcity, boosting agricultural resilience, and promoting ecological recovery. Overcoming health concerns, fostering community support, and ensuring fair access will be crucial for expanding similar initiatives, contributing to long-term water sustainability and food security in India and beyond.

Keywords: water recycling

Land Use Land Cover Classification of an Urban Watershed Using Machine Learning Algorithms

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Accelerated urbanization has profoundly transformed Land Use Land Cover (LULC) patterns, affecting ecological equilibrium, water resources, and sustainable urban development. Accurate classification and monitoring of LULC changes at the watershed scale are crucial for effective environmental management and urban development strategies. Recent advancements in high-resolution satellite imagery and machine learning algorithms have facilitated the efficient classification of various land cover features. However, the accuracy of these classifications depends on input datasets, training samples, and the selection of optimal machine learning models.

This study evaluates four prevalent machine learning algorithms-Random Forest (RF), Support Vector Machine (SVM), categorization and Regression Trees (CART), and Gradient Tree Boost (GTB)-for land use and land cover (LULC) categorization in the Saroor Nagar urban watershed. The models are assessed based on accuracy metrics, including user accuracy, producer accuracy, overall accuracy, and kappa coefficient, to determine the most suitable approach. The classification process is implemented on the Google Earth Engine (GEE) cloud computing platform, ensuring efficient data processing and storage management. The findings of this study provide a reliable LULC classification framework that can support urban planning, resource management, and environmental policymaking through improved spatio-temporal monitoring.

Keywords: LULC Classification, Machine Learning, Remote Sensing, Google Earth Engine, Urban Watershed, Accuracy Metrics

Utility of contextual remote sensing models for mapping evapotranspiration over large areas

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Remote Sensing (RS) based evapotranspiration (ET) models are now widely used for repeated and consistent mapping of ET over different parts of the globe. Among the different RS based ET models, the contextual models have received least attention for practical applications due to the limiting assumptions. Contextual models are semi-empirical models that are based on the relative variation between land surface temperature (LST) and other surface variable such as the Normalized Difference Vegetation Index (NDVI) or surface albedo that can be observed by satellites. In this study, we demonstrate the application of LST-NDVI contextual model for mapping ET across India combining MODIS data with reanalysis data from the Indian Monsoon Data Assimilation and Analysis (IMDAA).

The model was used to map ET across India at 0.05° spatial resolution at 8-day interval and the satellite derived ET was validated using observations from Eddy covariance and Bowen Ratio towers. The ET from the contextual model exhibited an RMSE of 9.4 mm/8-day whereas, the highly used MODIS ET product had an error of about 13 mm/8-day. Further, the spatial patterns captured by the contextual ET agreed well with the landcover and rainfall patterns observed over India which was not reflecting in the MODIS observations. This study has shown the potential of contextual models for mapping ET over large areas and further, this model has been selected as one of the algorithms for the ET product of the upcoming Indo-French thermal satellite mission TRISHNA.

Keywords: Evapotranspiration, Land Surface Temperature

Integrating Multi-Temporal Optical and SAR Data for Large-Scale Flood Monitoring in a Monsoonal River Basin: A Case Study from Northern India

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Floods are among the most destructive natural hazards, causing extensive damage to lives, infrastructure, and livelihoods, particularly in monsoonal river basins. Understanding the long-term flood dynamics in such regions is critical for effective risk assessment and mitigation. This study utilizes multi-temporal Sentinel-1 Synthetic Aperture Radar (SAR) data to analyze flood patterns across a major river system in northern India from 2017 to 2024. SAR's all-weather capability and ability to penetrate cloud cover make it an indispensable tool for flood monitoring when optical imagery is often unavailable. To enhance temporal coverage, SAR data from ascending and descending orbits were normalized and integrated to generate a high-temporal-resolution flood dataset. Flood inundation was mapped using the thresholding approach applied at smaller sub-regions. The accuracy of SAR-based flood maps was validated using Sentinel-2 optical imagery, achieving an overall accuracy of 91.2% and a Kappa coefficient of 0.84, with producer's and consumer's accuracies of 93.6% and 94.1%, respectively. In addition to recent SAR-based flood mapping, this study uses historical flood records from the EC-JRC, which provides optical-derived flood data from 1984 to 2021. By merging SAR and JRC datasets, a composite flood record was developed, significantly improving the spatial and temporal representation of flood events. The results highlight critical flood-prone areas that were previously undetected due to optical limitations, demonstrating the added value of SAR in capturing inundation events. The findings of this study provide valuable insights into the evolution of flood hazards over nearly four decades, offering a more comprehensive basis for flood risk assessment and zoning. The methodology is fully reproducible and adaptable to other flood-prone regions, making it a valuable framework for future flood hazard mapping and disaster preparedness. By leveraging multi-source remote sensing data, this research enhances the understanding of flood dynamics and supports the development of effective flood management strategies.

Keywords: Flood monitoring, Sentinel-1 SAR, historical flood records, multi-temporal analysis, adaptive thresholding, flood risk assessment, northern India, JRC flood data

Sediment transport modelling in a mining impacted ephemeral Himalayan River

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River sand is vital for infrastructure development, particularly in developing countries. However, excessive extraction beyond natural replenishment rates threatens fluvial systems by altering river morphology and degrading riparian vegetation habitat. Selective removal of finer grain-sized particles such as sand leaves behind a layer of coarser particles known as bed armouring which shields the bed from sediment transport and disrupts connectivity. Our study is on the Gaula River, which is an ephemeral Himalayan River, exploited for sand since 1990. This river has a high sediment flux potential from a tectonically active hinterland becoming functionally active only during Indian monsoons when sediments are transported down into the lower reaches of the river, making it appealing for the sand miners. This study integrates a hydrological model (SWAT) with sediment transport modelling (CASCADE and D-CASCADE) to quantify sediment flux and volumes respectively at a network scale under both mining and no-mining conditions in the Gaula River. UAV-based optical granulometry for both the mining scenarios along with other geomorphic inputs such as river width, length, slope, Manning's n , and empirical sediment transport capacity formulas were incorporated in the model. Results show reduced deposited, transported and entrainment fluxes in the mining reaches in the mining scenario. Sediment volumes were compared with observed mining records, showing river reaches experiencing excessive sand extraction.

The proposed modelling framework provides a valuable tool to monitor sand mining and assess sediment connectivity. By identifying vulnerable reaches, this approach supports sustainable sediment management and biodiversity conservation in dynamic riverine environments.

Keywords: Sand Mining, SWAT, CASCADE, Sediment transport, Connectivity

Deep Learning based Quantitative Precipitation Estimation using Dual-Polarization Remote Sensing Radar over Widely Varying Climate Zones

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Real-time observations from dual-polarization weather radar demonstrate its suitability for capturing the wide spatial and temporal variability of precipitation. Dual-polarization weather radars have been utilized to understand the microphysics of precipitation. Quantitative precipitation estimation (QPE) is a key application of dual-polarization weather radars. Accurate QPE is important for mitigating hazardous events, such as flooding. Conventional QPE has been investigated using radar rainfall Z-R relation. However, a fixed Z-R relationship presents challenges in accurately estimating rainfall due to the variability in precipitation. Deep learning techniques have emerged recently as a promising approach for QPE from remote sensing instruments. This study examines applications of deep learning based QPE techniques across widely varying climate zones. Vertical profiles of radar observations are extracted to provide precipitation information to the deep learning model. The deep

learning model estimates rainfall from radar vertical profiles using the rain gauge measurements as a ground truth. Application of deep learning techniques using vertical profiles in different regions is a challenge due to varying climate characteristics. This research presents an application of deep learning based QPE in Florida, United Arab Emirates (UAE), and the San Francisco Bay Area, highlighting the challenges posed by varying climate zones. Florida lies in a near tropical climate zone and the UAE sits in a desert environment and the San Francisco Bay Area is characterized by complex terrain, and effective by atmospheric rivers. Sporadic precipitation in UAE presents a challenge for deep learning, as it can provide insufficient precipitation patterns for effective training. Complex terrain in the San Francisco Bay Area obstructs radar beams, resulting in restricted radar observations, while low temperatures cause contamination of the radar vertical profiles. Different methodologies were employed in deep learning techniques to address the challenges posed by various climate zones across the regions, and a comparative analysis is presented.

Keywords: dual-polarization weather radar, quantitative precipitation estimation, deep learning

Flood inundation mapping and damage assessment: A comparison between Sentinel-1 derived flood extent and large-scale hydrological model derived extent

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Floods are a natural phenomenon in water bodies, playing a vital role in maintaining ecological balance. However, the rising frequency of floods has become a growing concern due to factors such as climate change, shifting rainfall patterns, soil erosion leading to siltation, and the consequences of unplanned development. On October 29, 2024, torrential rain caused by an isolated low-pressure system at high altitudes brought over a year's worth of precipitation to several areas in eastern Spain. The resulting floodwaters led to severe inundation in Valencia province. Accurate flood inundation maps, created using remote sensing techniques, are essential for mitigating the impact of flood disasters. Publicly available Sentinel-1A SAR data, renowned for its all-weather imaging capabilities, offers significant potential for mapping flood inundation. This study utilized temporal dual-polarization Sentinel-1 SAR data for inundation mapping and change detection, which was subsequently applied to assess damage to various socio-economic factors, including land cover and population. The research employs open-source datasets for inundation mapping and damage assessment, with a methodology that can be easily adapted to different study areas depending on data availability. Peak flooding was observed on October 31, with flood extents of 156.33 sq. km, followed by a reduction to 78.32 sq. km on November 3 and 70.48 sq. km on November 6. A large-scale hydrological model also indicated similar inundation extents in the region. Such research is invaluable for policymakers and local authorities, enabling efficient resource allocation and damage assessment in flood-affected areas. The methodology adopted in this study is cost-effective, time-efficient, and easily replicable.

Keywords: Remote Sensing, SAR data, Valencia Flood, Hydrological Model, Damage Assessment

Unleashing the Power of Emerging Datasets for More Reliable Hydrologic Models

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The growing availability of high-resolution Earth system datasets and remote sensing technologies is reshaping hydrologic modeling by offering unprecedented opportunities to enhance predictive accuracy. Traditional models often rely on calibration at discrete watershed points, limiting their ability to represent broader landscape dynamics. This study explores a data-driven approach that integrates diverse biophysical datasets to refine hydrologic and water quality models, capturing the complexity of natural systems more effectively. Focusing on a large watershed in the Southeastern United States, we enhanced the widely used SWAT model by incorporating a dynamic land-use update tool and multiple data sources. Our framework examines the role of tree species distribution and land-atmosphere interactions in shaping streamflow and water quality, particularly in the context of large-scale forest restoration. The results indicate that accounting for forest composition and structural variability leads to substantial differences in water yield, nutrient fluxes, and sediment transport predictions. To further improve hydrologic simulations, we introduce an advanced methodology for modeling forest canopy evaporation using remote-sensing data, enabling more precise parameterization across diverse climatic and geographic conditions. Additionally, we address critical gaps in representing channel morphology in watershed models like SWAT and HSPF. By integrating bankfull channel width estimates derived from satellite imagery, LiDAR, and global datasets, we achieve more accurate high-flow predictions and better alignment with field observations. This study underscores the transformative impact of leveraging multi-source datasets to refine hydrologic models. By enhancing process representation and model reliability, these advancements provide valuable insights for sustainable water resource management, conservation planning, and climate resilience strategies.

Keywords: hydrologic modeling, remote sensing, SWAT, watershed

Machine Learning-Integrated InSAR Analysis for Land Deformation Study in Jodhpur City Using Sentinel-1 SAR and GRACE TWS Data

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The sentinel 1 satellite provides SAR radar data for accurate surface deformation monitoring using InSAR. InSAR techniques analyze phase differences between SAR images captured at different times to detect changes in the Earth's surface. Small Baseline Subset (SBAS), an advanced form of InSAR, involves pairing SAR images based on Perpendicular and temporal baselines. Perpendicular baselines maintain spatial coherence, while temporal baselines ensure sufficient temporal coherence between acquisitions. The GRACE satellite detects variations in groundwater mass by measuring shifts in earth gravity field changes that help identify groundwater reduction in total water

storage (TWS) on a regional scale. The SBAS methodology involves processing the SAR data by applying orbital file correction, Coregistration, and interferogram generation during preprocessing. The post-processing involves steps like phase filtering, phase unwrapping, time series analysis and geocoding. For SBAS methodology, single-look complex (SLC) images were processed from January 2018 to December 2023.

This study used machine learning (ML) techniques to classify the surface deformation trends analyzed using the SBAS methodology. These machine learning algorithms used extreme gradient boosting (XGB) and Random Forest (RF) models to categorize the surface deformation trends into Linear, stable recovery zones and accelerating subsidence. The SBAS's land deformation analysis and Machine learning model were validated using GRACE's TWS and CGWB groundwater level data. This validation confirms a strong correlation between land deformation trends and groundwater variations. Results indicate that Northern and Eastern Jodhpur show long-term subsidence trends, aligning with declining TWS values, whereas Southern and Western Jodhpur exhibit seasonal recharge patterns, with slight recovery post-2022. Future work will discover the integration of multi-source data fusion with GPS data and the integration of Deep Learning (LSTMs, CNNs) techniques.

Keywords: SAR, InSAR, SBAS, Machine Learning, GRACE, Groundwater storage, Land deformation.

Burnt Area Mapping and Greenhouse Gases Emissions Monitoring in Agricultural Landscape

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Burning agricultural fields is a prevalent practice with significant environmental consequences, leading to the emission of pollutants and greenhouse gases into the atmosphere. Accurate and timely monitoring of burnt areas and pollutant emissions is crucial for environmental management and sustainable agricultural practices. This study presents an innovative approach to assess burnt areas in crop fields and monitor methane (CH₄) and carbon dioxide (CO₂) greenhouse gases using satellite imagery from 2019 to 2023. It utilizes Google Earth Engine techniques and data from high-resolution satellite sensors to map CH₄ emissions and burnt areas, enabling the calculation of CO₂ emissions from the burnt area. The proposed method facilitates automated and accurate burnt area mapping with minimal human intervention. Two indices, the Normalized Difference Vegetation Index (NDVI) and the Normalized Burnt Ratio (NBR), are used as numerical indicators for evaluating burned areas to assess the extent of burnt surfaces. By integrating satellite-derived burnt areas, CH₄ and CO₂ emissions were estimated before and after burning events. The results of burnt area mapping indicate a decrease in NDVI values from 0.6 in September to 0.4 in November, along with a simultaneous reduction in NBR values from 0.2 to 0.08 during the same period. This change can be attributed to the maturation and harvesting of crops in October, leading to a decline in NDVI and a still significant value because of the sugarcane plantation. Additionally, burning remaining crop stubble contributes to the decrease in NBR values. Consequently, agricultural practices such as rice cultivation and sugarcane plantation emit more CH₄ emissions in (September 1366 tons) and less in (November 1359 tons), as rice and sugarcane cultivation increase CH₄ emissions through methanogenesis. Furthermore, burning crop residues increases CO₂ emissions from 9658.62 tons

to 11052.14 tons. This approach provides valuable insights into the environmental impact of burning on climate change.

Keywords: Agriculture, Greenhouse Gas Emissions, Burnt Area Mapping, Satellite Imagery, Environmental Impact.

Mapping Irrigation Quantities in Indian Rice Fields Using MODIS and GPM Datasets

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Rice cultivation in India is characterized by extensive irrigation practices that often lead to inefficient water use, thereby driving regional water deficits, impacting food security, and increasing methane emissions. Most studies monitoring irrigation rely heavily on labour-intensive ground surveys and coarse statistical estimates that fail to capture the spatial and temporal variability in rice fields. To improve spatio-temporal resolution of irrigation data, this study quantifies irrigation at a 500 m resolution for rice fields in India during 2004-2021 through a dual-sensor integration of MODIS-derived rice water footprint estimates and GPMv7 precipitation data. Validation against available statistical data indicates that the dual-sensor approach provides irrigation estimates with higher accuracy (R^2 : 0.7), addressing the underestimations observed in previous assessments. The study reveals that the overall irrigation quantities in India increased significantly from 77.25 billion m³ to 139.29 billion m³ between 2004 and 2021. This increase is attributed to two major factors: the expansion of rice cultivation areas and a decline in precipitation. On a regional level, states distant from perennial water sources like Tamil Nadu and Andhra Pradesh, exhibited the most pronounced growth in irrigation. These trends highlight the critical need for improved water resource management in the context of expanding agricultural production and climate variability. The resulting medium-resolution irrigation maps generated from this study offer valuable insights for policymakers aiming to improve water use efficiency in rice-dominated agricultural systems.

Keywords: Irrigation, GPM, MODIS, Rice, Water Footprint

Evaluating the Performance of Satellite-Derived Precipitation and Reanalysis-Based Potential Evapotranspiration in Streamflow Estimation Across Diverse Climatic Zones

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Integrating satellite-derived and reanalysis meteorological data with hydrological models has become a standard approach for streamflow estimation, particularly in regions with limited ground-based observational networks. While these datasets offer extensive spatial coverage and near-real-time availability, their accuracy and reliability in streamflow estimation remain uncertain. Though open-access Satellite Precipitation Products (SPPs) and reanalysed potential evapotranspiration (PET) products have been extensively evaluated, their combined effect on streamflow simulation across different climatic regions remains largely unexplored. Hence, it is imperative to assess the utility of newly released datasets. GPM IMERG recognized as one of the best-performing SPPs, has recently introduced an updated dataset. Similarly, GLEAM offers the longest time series (1980-2023), and its latest dataset features the highest-resolution (0.1-degree) PET data. Therefore, this study aims to evaluate the influence of these products on streamflow simulations in six catchments located across four distinct climatic zones in Australia.

This research employs the GR4J (Génie Rural à 4 paramètres Journalier) hydrological model to estimate streamflow using gauge-based daily precipitation and PET datasets from the Australian SILO network for the period 2006 to 2023. The model was calibrated and validated against observed flow data in six catchments, with performance evaluated using Kling-Gupta Efficiency (KGE). Then satellite-derived and reanalysis datasets were integrated into the GR4J model to assess their influence on streamflow simulations. Streamflow is simulated under three scenarios: using (1) GPM IMERG dataset (2) GLEAM dataset and (3) combining both datasets while maintaining the optimized calibration parameters for all three scenarios.

Preliminary results indicate that the SILO gauge-based dataset achieves KGE values above 0.7 during calibration, while satellite-derived and reanalysis datasets show varying accuracy across different climatic conditions. While the analysis is ongoing, this study could offer better understanding about the applicability of satellite-derived and reanalysed datasets in hydrological modeling across various climatic conditions.

Keywords: Hydrological modeling, Streamflow estimation, Satellite Precipitation Products, Reanalysed Potential evapotranspiration, GPM IMERG, GLEAM, GR4J model, Kling-Gupta Efficiency

Soil Loss Estimation of watershed in eastern Himalayan region of Sikkim.

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Being severe threat to availability and utilization of natural resources, soil erosion remains the significant environmental problem worldwide. In India, different forms of land degradation including soil erosion problems affects annually about 147 million-ha area with erosion by water being the chief contributor. Ranikhola river is a major tributary of Teesta river in eastern Himalaya region of Sikkim, India. The land use and land cover of Ranikhola watershed includes forest areas, urban settlements and agricultural land which experience heavy rainfall in monsoon season on steep hilly slopes making it more vulnerable to soil erosion. Therefore, in the present study, an attempt has been made not only to estimate soil loss in the Ranikhola watershed but also to identify sub-watersheds having higher soil loss necessitating the SWC measures on priority basis. The raster layers in various factors of the RUSLE were estimated by employing freely available datasets like the R factor from IMD gridded rainfall data, the K factor from FAO soil database, and the LS factor from ALOS PAL-SAR DEM. The LULC based C and P factors were estimated by using Sentinel-2 satellite imagery in ERDAS IMAGINE software. The annual average soil loss in the Ranikhola watershed and also in its four sub-watersheds for the years of 2018 to 2020 were estimated by overlaying and multiplying the generated layers pixel by pixel in GIS environment. From the estimated average annual soil loss in the Ranikhola watershed, it is observed that 73% area experiences extremely severe erosion (>80 tonnes/ha-year) followed by very slight (upto 5 tonnes/ha-year) and very severe (40 to 80 tonnes/ha-year) soil loss with corresponding areas of about 13% and 11%. It indicates that sub-watershed level prioritization of region will be helpful to control the erosion challenges.

Keywords: Soil loss, Ranikhola watershed, RUSLE, sub-watershed, GIS.

Enhancing soil moisture and vegetation optical depth retrievals through improved surface roughness parameterization for the upcoming CIMR satellite mission

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Soil moisture (SM) regulates the hydrological cycle by influencing evapotranspiration, runoff, and infiltration. Vegetation optical depth (VOD) reflects vegetation water content, linking plant transpiration to atmospheric moisture fluxes. Accurate retrievals of SM and VOD enhance the understanding of water and energy fluxes in the earth system. In remote sensing-based measurements, particularly in passive microwave radiometry, radiative transfer models (RTMs) are used to derive information about these variables from brightness temperature (TB). However, RTM parameterization, particularly surface roughness (HR) and single scattering albedo (?), introduces uncertainties in retrieval. The upcoming Copernicus Imaging Microwave Radiometer (CIMR) will operate at multiple frequencies with an L-band incidence of $\sim 52^\circ$. Understanding RTM parameter interaction is essential for seamless SM and VOD retrievals from CIMR observations. This study retrieves spatially varying HR under a quasi-CIMR configuration using soil moisture and ocean salinity satellite mono-angular TB data (52.5° , L-band) from 2015-2020. We assumed negligible vegetation effects and focused on bare soil and sparse vegetation (BSV) conditions to retrieve HR. The multi-temporal dual-channel algorithm was applied to retrieve SM and HR, mitigating underestimation issues. The H-Q-N model (Lawrence et al., 2013) was used for HR parameterization, integrating auxiliary datasets from European centre for medium-range weather forecasts, international soil reference and information centre, and global multi-resolution terrain elevation data. Temporal Mean of HR values over BSV, along with soil and terrain properties, were used to train a random forest model. This model was then extrapolated to predict HR globally. These predicted HR values serve as RTM inputs for SM and VOD retrievals from SMOS TB data. The retrieved SM is validated against core validation sites, while VOD is assessed using optical based vegetation index and above ground biomass. This approach enhances HR characterization and is expected to improve SM and VOD retrieval accuracy when adapted for CIMR.

Keywords: Radiative transfer modeling, Soil moisture, Vegetation optical depth, Surface roughness, Copernicus Imaging Microwave Radiometer

GPU accelerated GUI for flood mapping from SAR data

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SAR can penetrate clouds and provide real-time surface information essential for flood mapping. However SAR data is complex and cannot be interpreted with human eyes making flood inundation mapping complex. In this study we develop an automated deep learning based framework that uses SAR data and auxiliary terrain information to map flood inundation. We develop weak training data using concurrent SAR and optical imagery where optical imagery based flood inundation serves as labels. We use maxvit, swin and resnet based encoders and unet, unet++ based decoders. Our models have a state of the art IOU of 0.722 on sen1floods11 test set. The above models are developed into an easy to use GUI which uses cloud computing to fetch the data. The GUI only requires the date and location of the flood to develop inundation maps. The proposed GUI also supports GPU acceleration. We were able to map floods in a area of $1^\circ \times 1^\circ$ in under 1 minute showing its usage in real-time mapping.

Keywords: Deep learning, SAR, Flood inundation

Monitoring of wheat crop and its phenology pattern using UAV Multispectral data

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Wheat is one of the world's most important staple crops which serves as a primary food source. Assessing the health of wheat crops is crucial for maximizing yield and ensuring food security. Optical remote sensing is a reliable technique used for monitoring crop health and helps in the early identification of stress factors. In this study, Unmanned Aerial Vehicle (UAV) based multispectral remote sensing has been used to monitor the crop phenology pattern under varying fertilizer treatments. The experimental study was conducted in the arid region of Uttar Pradesh, India. The experimental setup consists of 9 field plots corresponding to 3 fertilizer treatments in which nitrogen fertilizer was applied at different rates: 150 kg/ha (Plot 1), 120 kg/ha (Plot 2, recommended dosage) and 90 kg/ha (Plot 3). Each treatment had three replications, and irrigation was supplied to all the treatments as 100% ET_c (crop evapotranspiration) using the drip irrigation. The UAV data was processed using the Pix4D fields software and vegetation indices such as Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red-Edge Index (NDRE) were calculated to analyze the temporal variation in crop growth. NDVI and NDRE attained the maximum value during the flowering stage. The peak NDVI and NDRE values obtained for Plots 1, 2 & 3 were (0.86, 0.86 and 0.84) and (0.56, 0.56, 0.54) respectively. The senescence rate obtained as per NDVI and NDRE were (0.76, 0.85 & 1.05) %/day and (0.70, 0.75 & 0.95) %/day for Plot 1, 2 & 3. The senescence rate and grain yield were almost the same in plots having an overdose and recommended dosage of fertilizer. Due to the high senescence rate in Plot 3, there was a significant decrease in grain yield. These results contribute to the understanding of how UAV remote sensing can help in crop monitoring and support sustainable agricultural practices.

Keywords: Unmanned Aerial Vehicle (UAV), Vegetation Indices (VI), Senescence, Phenology, Multispectral, NDVI, NDRE

Beyond Visible Rivers: Integration of RCM SAR Imagery and Machine Learning for Streamflow Estimation in Remote and Data Limited Riverine Systems

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Estimating streamflow in remote riverine systems is challenging as both remote sensing and physical measurement methods are limited due to coarse satellite resolution, narrow river widths, harsh environmental conditions, and inaccessible terrain. Traditional feature extraction techniques, like spectral water indices (NDWI, MNDWI), SAR-based Thresholding, often fail in these environments, as rivers are too small to be directly detected in satellite imagery.

By using RADARSAT Constellation Mission (RCM) imagery, this research extracts zonal statistics of back scatter intensity rather than relying on direct water detection. A Long Short-Term Memory (LSTM) neural network is used to establish correlations between RCM derived Zonal Statistics, meteorological data and observed streamflow data, providing a data driven approach for hydrological modeling. The research methodology includes preprocessing SAR imagery using ESA SNAP, computing zonal statistics over predefined hydrological zones, and integrating these features into the LSTM model for streamflow forecasting.

The results highlight the potential of SAR-derived zonal statistics as an alternative data source for streamflow estimation, particularly in regions with sparse ground-based hydrometric data. This research contributes to advancing remote sensing applications in hydrology, demonstrating how machine learning can enhance streamflow predictions using radar-based spatial statistics.

Keywords: RADARSAT Constellation Mission, Machine Learning, streamflow estimation

Multi-Hazard Disaster Risk Assessment Using Google Earth Engine: An Integrated Approach for Climate Resilience

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India, being one of the most disaster-prone countries in the world, faces recurrent challenges from urban floods, droughts, and forest fires, impacting lives, infrastructure, and ecosystems. Traditional disaster risk assessment approaches often lack real-time capabilities, spatial accuracy, and computational efficiency, leading to delayed responses and ineffective mitigation strategies. The integration of Google Earth Engine (GEE) with machine learning presents an innovative and scalable solution for multi-hazard disaster risk assessment, enabling rapid, data-driven decision-making for both policymakers and the public. This study develops a comprehensive multi-hazard assessment framework using GEE, focusing on urban flood inundation mapping, flood depth analysis, drought monitoring, and forest fire risk analysis across India. High-resolution satellite datasets such as Sentinel-1, Sentinel-2, Landsat, CHIRPS precipitation data, and MODIS fire detection data are utilized for real-time and historical disaster analysis. Machine learning algorithms (Random Forest,

Support Vector Machines, and Deep Learning models) are integrated into GEE for automated feature extraction, pattern recognition, and predictive modeling of disaster risks. Despite advancements in disaster management, India still lacks a unified, cloud-based, and automated multi-hazard risk assessment system that can provide high-resolution, near-real-time insights. This research addresses this critical gap by leveraging GEE's big data processing power, cloud computing capabilities, and AI-driven analytics to enhance disaster prediction and response strategies. The outcomes of this study hold significant implications for government agencies, disaster management authorities, urban planners, and policymakers by providing real-time hazard mapping, risk zones identification, and early warning alerts. This framework can assist in flood mitigation planning, drought adaptation policies, forest fire control measures, and climate resilience initiatives, ultimately reducing economic losses and safeguarding human lives. The proposed multi-hazard GEE-based approach can serve as a scalable model for disaster-prone regions across the globe, reinforcing India's commitment to climate resilience and disaster preparedness.

Keywords: Multi-hazard risk assessment, Google Earth Engine, machine learning, urban flooding, drought monitoring, forest fire analysis, disaster resilience

GIS-Integrated Hydro-Geo mechanical Framework for Predicting Soil Piping-Induced Subsidence in Lateritic Terrains

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¹0 years of climate records, including rainfall, temperature, and humidity, with satellite-derived datasets including NDVI, NDWI, and soil moisture indices are used in the methodology. High-resolution risk maps are produced by layering these inputs and performing a weighted overlay analysis using GIS programs like QGIS and ArcGIS. A weighted sum of variables, including rainfall (0.4), soil moisture (0.3), NDVI (0.2), and land use/land cover (0.1), is used to create the risk index.

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In Kerala for the past few years piping-induced soil subsidence started triggered in lateritic terrain which presents serious problems for environmental management and infrastructure stability. This research examines the subsidence-prone area of Wayanad, Kerala, and uses a novel GIS-integrated hydro-geomechanical modelling technique that evaluates and forecasts subsidence hazards by including geospatial analysis, finite element modelling (FEM), and machine learning.

10 years of climate records, including rainfall, temperature, and humidity, with satellite-derived datasets including NDVI, NDWI, and soil moisture indices are used in the methodology. High-resolution risk maps are produced by layering these inputs and performing a weighted overlay analysis using GIS programs like QGIS and ArcGIS. A weighted sum of variables, including rainfall (0.4), soil moisture (0.3), NDVI (0.2), and land use/land cover (0.1), is used to create the risk index.

The GEOSTUDIO modules SEEP/W and SIGMA/W are used to carry out finite element modelling (FEM). SIGMA/W inspect stress and deformation in lateritic soils under hydrological conditions, whereas SEEP/W models water flow and pore pressure variations. To enhance spatial accuracy and offer comprehensive insights into subsurface dynamics, the outputs are exported as GIS layers.

Predictive capacities are enhanced with the use of machine learning techniques, specifically Random Forest. With field validation data from Wayanad guaranteeing dependability, the model is

trained on a dataset that combines FEM outputs and indices generated from GIS. This method produces predictive maps that enable dynamic risk assessment.

The integration of hydrological, geotechnical, and computational methods is highlighted in this innovative framework. It gives planners and politicians practical suggestion on how to mitigate disasters, plan for sustainable land use, and build resilient infrastructure. The work help to evolve a novel approach to risk mitigation via soil piping, which may find scalable use in other susceptible areas across the globe.

Keywords: Soil piping, Geotechnical Engineering, Hydrological Engineering, Geo Spatial analysis, Modelling, Machine Learning

Groundwater potential zones mapping for Natural Springs: A Geospatial and AHP-Based Study in Manadunga Village, Champawat District, Uttarakhand

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Introduction

Springs are lifeline for mountain communities of the Indian Himalayan Region (IHR) for their daily water needs. The problem of drying of springs has been reported across IHR affecting the water security. Various spring rejuvenation activities are being carried out to revive this precious source. In one such study, the Analytic Hierarchy Process (AHP) and RS-GIS techniques were used to identify groundwater potential zones for targeted recharge intervention works. Geospatial analysis used key thematic layers such as geology, lineament density, geomorphology, LULC, slope, rainfall, soil, and drainage density to map groundwater potential zones and recharge interventions have been implemented for spring rejuvenation.

Methodology

The study adopted a systematic methodology involving geospatial analysis, thematic layer development, and multi-criteria evaluation using AHP and supported by field observations. Groundwater recharge potential zones were divided into five classes, wherein recharge interventions could be targeted.

Result

The groundwater potential varied significantly in space throughout the study area. The high-potential zones covering 47.68% (2.16 km²) of the total area exhibit high recharge potential due to favorable lithology, extensive forest cover, and high lineament density. Moderate potential zones covered 37.75% (1.71 km²) and low-potential zones covered 14.57% (0.65 km²) of the total area. The thematic analysis identified slope, geology, and lineament density as the main determinants of groundwater potential.

Conclusion

The study used a geospatial & AHP approach to identify groundwater potential zones in the Manadunga village cluster in Champawat district of Uttarakhand. Accurate delineation of these zones

ensures the interventions in targeted zones only for its effectiveness. This exercise is useful in planning the recharge interventions in springshed area for the rejuvenation of springs. These findings underscore the importance of considering these aspects when designing spring rejuvenation strategies, and using advanced tools and techniques. This method offered a scientific basis for comprehending spring recharge processes.

Keywords: Springs, Groundwater potential, IHR, AHP, RS-GIS, LULC

Assessing the Impact of Wildfires on Soil and Water Quality Using Hyperspectral Remote Sensing and Field Analysis

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Wildfires significantly alter soil and water quality by increasing runoff, nutrient leaching, introducing pollutants and sediment load into the nearby aquatic ecosystem due to carbon and ash generation. Overall, it has a negative impact on the catchment area of any water body by reducing the forest cover. Traditional studies focus on in-situ measurements. The hyperspectral visible and infrared remote sensing data can provide soil and water quality analysis more efficiently than the traditional approach. The change in the forest ecosystem is very dynamic post-fire because it depends on several components such as vegetative response and soil cover; this is why it is necessary to continuously monitor the forest ecosystem during and post-fire to take responsive action. This research focuses on the integration of advanced remote sensing techniques with field and laboratory analyses to develop a predictive framework for the soil and water assessment post-wildfire. Initially, we are using SMOS (Soil Moisture and Ocean Salinity) data to locate the potential wildfire risk zone in the Uttarakhand state. For the Soil quality analysis, we have collected the Soil and Water samples from the two forest fire locations in the Nainital District of Uttarakhand. We analysed colloidal stability and soil retention capacity and found that the fire-impacted soil has low colloidal suspension stability, but it has higher soil retention capacity than the fresh soil. We are focusing on developing novel remote sensing indices and machine learning models to estimate soil carbon content and post-fire recovery trends by correlating hyperspectral satellite data with field-measured soil organic carbon, nutrient retention, and erosion rates. We leverage Google Earth Engine (GEE) for large-scale data processing and ensemble learning techniques for predictive modeling. These approaches enable early impact assessment, real-time monitoring, and mitigation planning, marking a significant advancement in remote sensing-driven environmental research.

Keywords: Wildfire, Hyperspectral Remote Sensing, Google Earth Engine, Soil and Water Quality

Performance Assessment of IMERG Precipitation Estimates Using MESONET Data in Mumbai

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Accurate precipitation estimates are crucial for hydrological modeling, particularly in flood-prone cities like Mumbai. Satellite-based gridded precipitation products provide large-scale estimates but may suffer from spatial resolution limitations and algorithmic biases. Gridded precipitation estimates like Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG) (0.1° resolution) over India are typically validated using the India Meteorological Department (IMD) gridded dataset (0.25°), but the coarser IMD data may smooth localized rainfall variations, making direct comparisons less ideal. This study critically assesses the IMERG Final run using Mumbai's high-density MESONET gauge network, offering a comprehensive evaluation through qualitative and quantitative approaches. A rigorous quality check of MESONET data ensured reliable daily-scale comparisons. Statistical metrics - Correlation Coefficient (CC), Root Mean Square Error (RMSE), Probability of Detection (POD), False Alarm Ratio (FAR), and Bias score - were employed to quantify IMERG's performance. Results revealed spatial discrepancies in IMERG grids, with better agreement when averaging all gauge stations within a grid rather than comparing individual stations. IMERG exhibited high accuracy in detecting rainfall occurrence but showed reduced performance in estimating actual rainfall amounts. Additionally, the study compared IMERG with the IMD gridded dataset. It also assessed the IMD dataset using MESONET observations to evaluate its accuracy and performance. This study underscores the importance of regional-scale validation, as findings from Mumbai can inform improvements in satellite precipitation estimates for similar flood-prone regions, where high-density gauge networks are lacking, offering valuable insights for enhancing the accuracy of remote sensing products in hydrological applications.

Keywords: IMERG, MESONET, Precipitation Validation, Satellite-Ground Comparison

Climatic shift and human activities have resulted in a loss of 40 Gt water storage from the Helmand River basin over the last two decades

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Conflicts in transboundary river basins are intensifying due to climate change and human interventions. In the Helmand River Basin (HRB) water stress even led to firing of bullets between Afghanistan and Iran. To make informed decisions, attributing the role of climate and human activities is imperative. Here, we investigate the impact of climate change and human activities on water storage in HRB using remote sensing data, hydrological modelling, and wavelet analysis. Firstly, 1998 was identified as change point in the meteorological data with the Bayesian Change

Point Algorithm. Then the Soil and Water Assessment Tool (SWAT) was calibrated and validated with Kling-Gupta Efficiency (KGE) values of 0.64 and 0.53, respectively, for the pre-change period. The soil moisture anomaly data obtained from the model for the post-change period, with the same SWAT model parameters as the pre-change period, was regressed with the Gravity Recovery And Climate Experiment total water storage anomaly (TWSA) to establish a predictive relation between soil moisture and TWSA. The predictive model was used to estimate TWSA for the pre-GRACE period using simulated soil moisture. A prominent shift in precipitation patterns and magnitude was noticed during 1998-2005 drought, while negligible long-term trend exist. The system was unable to recover fully due to several reasons, such as expansion of opium cultivation, urban sprawl, and inefficient irrigation practices resulting in a loss of approximately 40 gigatons of water in the last two decades. The wavelet analysis reveals that the overexploitation of water storage led to persistent dry conditions in the post-change period, triggering a phase shift in evapotranspiration patterns. The findings from this study provide critical insights for optimal decision-making in conflict prevention and sustainable water management.

Keywords: climate change, human activities, water conflict, GRACE, SWAT, wavelet analysis

Permafrost Dynamics in Himachal Pradesh using Integrated PS and SBAS InSAR Approach

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Permafrost in Himachal Pradesh, a vital component of high-altitude cryospheric landscapes, plays a significant role in regional hydrology, geomorphology, and ecological stability. Monitoring the vertical subsidence of these dynamic landforms is essential to understanding their deformation mechanisms, stability, and potential impacts on downstream ecosystems. This study employs an advanced approach integrating Small Baseline Subset (SBAS) and Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) techniques, using data from both ascending and descending passes of Sentinel-1A satellites to estimate vertical and horizontal subsidence in permafrost-affected regions across the area. The combination of ascending and descending SAR passes allows for the decomposition of line-of-sight (LOS) displacement into vertical and horizontal components, providing a detailed and precise assessment of subsidence trends. SBAS is utilized for wide-area coherence and temporal deformation analysis, while PS-InSAR captures high-precision measurements at stable scatterers. The results, derived from multi-temporal SAR data, reveal millimeter-level deformation trends, with a particular emphasis on vertical subsidence influenced by seasonal variations, local geomorphological factors, and underlying cryospheric dynamics. This integrated methodology demonstrates the efficacy of using SAR data from complementary orbits, enabling accurate and long-term monitoring of high-altitude terrains. The findings provide critical insights into deformation processes, aiding in geohazard mitigation and informing sustainable development in these vulnerable mountainous regions

Keywords: InSAR, SBAS, PSI, GMTSAR, Permafrost, Cryosphere

Flood Extent Delineation: Combining Unconventional Remote Sensing and Geospatial Technology with HAND Hydrogeomorphic Approach

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Floods hazard causes the severe damage to lives, property, and the natural environment. The flood extent map needs to be delineated to monitor the existing floods and develop strategies to mitigate future severe floods. It is not always possible to utilize conventional approaches for flood extent delineation in impassable and high-altitude terrain. The present study investigated the utilization of an unconventional approach for flood extent mapping in inaccessible terrains. The study integrates remote sensing and geospatial technology with a terrain-based Height Above Nearest Drainage (HAND) hydrogeomorphic approach to delineate the flood extent. The optical and microwave remote sensing data available for the Jhelum basin 2014 flood events were integrated with the terrain-based HAND to delineate the present and the probable flood extent of recurrence of this event. The optical remote sensing data utilized for this purpose were Landsat-8 and Resourcesat LISS-MX4 of 10th and 19th September 2014. The study has used RISAT-1 C band multi-temporal dual polarized (HH and HV) Synthetic Aperture Radar (SAR) data of 08th, 09th, 10th, 17th, and 21st September 2014 as microwave remote sensing to map the flood extent. The Advanced Land Observing Satellite (ALOS) PALSAR Digital Elevation Model (DEM) has been integrated with the observed stage hydrograph for delineating the present and probable extent of the event using HAND. It was observed from the combined optical and SAR flood extent depicting the flood progression of the 2014 flood event in the Jhelum River basin that maximum flooding occurred on September 10th, 2014, while minimum flooding occurred on September 21st, 2014. The accuracy assessment of flood extent from HAND shows good agreement with the combined flood extent generated using optical and SAR remote sensing. The combined approach would be easily scalable to the other inaccessible regions, along with the regions where data and resources are limited.

Keywords: Flood extent, remote sensing, geospatial, HAND, hydrogeomorphic.

Evaluation of error components in SM2RAIN precipitation products over an Indian coastal state

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Accurate precipitation estimation is crucial for hydrological and climate studies, particularly in regions with limited ground-based observations. The SM2RAIN algorithm, which derives rainfall estimates from soil moisture retrievals, has emerged as a promising approach to improve precipitation

datasets. However, its accuracy remains uncertain due to errors associated with satellite-based observations. This study presents an evaluation of these errors and their decomposition into random and systematic error components for SM2RAIN precipitation products, i.e., SM2RAIN-ASCAT, SM2RAIN-CCI, and SM2RAIN-GPM, over Odisha, India, a region characterized by diverse topography and monsoonal rainfall patterns. The analysis employs gauge-based gridded observation data as a reference to assess the performance of multiple SM2RAIN-derived products. Statistical metrics such as correlation coefficient (R), Root Mean Square Error (RMSE), and Kling-Gupta Efficiency (KGE) are used to quantify the performance of precipitation products. Additionally, an error decomposition approach is applied to distinguish the sources of uncertainty. Results indicate that while SM2RAIN products capture the overall rainfall dynamics well, they exhibit regional and seasonal variations in error magnitudes, i.e., random errors dominate during dry spells. These findings provide insights into the reliability of SM2RAIN precipitation estimates and contribute to the refinement of satellite-based rainfall retrieval techniques. The study underscores the need for localized calibration to enhance the applicability of SM2RAIN products for hydrological applications, particularly over Odisha.

Keywords: Precipitation, Random error, Systematic error, SM2RAIN

Estimation of Evapotranspiration Using the S-SEBI Model and Landsat-9 Data over Asan Barrage

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Evapotranspiration (ET) is a critical component of the hydrological cycle. Accurate estimation of ET supports irrigation scheduling, water budgeting, and drought monitoring, particularly in water-scarce regions. However, traditional point-based methods like Penman-Monteith, lysimeters are limited in capturing spatial variability. Remote sensing (RS)-based approaches address this limitation, offering spatially distributed and temporal measurements. This study focuses on estimating crop evapotranspiration (ET_c) over Asan Barrage. The Simplified Surface Energy Balance Index (S-SEBI) model was employed, utilizing Landsat-9 imagery to derive spatially distributed ET_c. S-SEBI requires limited meteorological input and uses the evaporative fraction (?) calculated from scatter plots of land surface temperature (LST) and surface albedo (a). A Landsat-9 image from February 2nd, 2024, is used and key parameters such as NDVI, a, and e₀ were derived to parameterize the S-SEBI model. The methodology involved the generation of feature space plot between LST and a to identify wet and dry edges, which represent maximum and minimum ET_c, respectively. Instantaneous ? was calculated for each pixel and scaled to daily ET_c values using established empirical relationships. MODIS-derived ET products and local metadata were used to validate the results, ensuring accuracy in the regional-scale ET_c estimates. Results showed a consistent relationship between surface reflectance and temperature, affirming the theoretical framework of the S-SEBI model. Regression coefficients for the wet and dry edges were derived from the feature space plots, to find ?. The comparison of S-SEBI-derived ET_c with MODIS products and meteorological data demonstrated a high degree of correlation, validating the model's performance. This study highlights the capability of the S-SEBI model, coupled with Landsat-9 data, to estimate ET_c over heterogeneous regions. The findings emphasize the importance of ET_c data for optimizing irrigation management and improving

water use efficiency in agriculture.

Keywords: Evapotranspiration, NDVI, S-SEBI, Landsat - 9, Feature space plot

HydroSecure Dashboard: Advancing Climate Resilience through Flood and Drought Monitoring and Management in Africa

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Africa is increasingly vulnerable to climate-induced water risks, with floods and droughts posing significant threats to livelihoods, ecosystems, and economic stability. Addressing these challenges requires an integrated, data-driven approach to risk monitoring and management. The Digital Innovations for Water Secure Africa (DIWASA) initiative, supported by the Helmsley Foundation, introduces HydroSecure: Flood & Drought Dashboard, an advanced Earth Observation (EO)-based system designed to enhance Africa's climate resilience. HydroSecure integrates NASA MODIS, ESA Sentinel-1, and Landsat data, leveraging satellite-derived insights to provide high-resolution, real-time flood and drought assessments across continental, national, and sub-national scales. The flood monitoring framework combines MODIS 8-day composites for large-scale detection with Sentinel-1 SAR data for national-level precision mapping, while continental drought assessments utilize the meteorological (Standardized Precipitation Index) and agricultural drought (Vegetation Health Index) to track vegetation stress and surface moisture dynamics.

By leveraging the AWS Open Data Registry, Digital Earth Africa (DEA), and AWS cloud computing, HydroSecure provides real-time monitoring, early warning, and decision support for governments, relief agencies, and researchers. The dashboard facilitates multi-hazard mapping, vulnerability assessments, and disaster preparedness, ensuring informed decision-making for proactive adaptation planning. This presentation highlights HydroSecure's operational framework, the DIWASA initiative's multi-pillar approach to resilience-building, and the role of EO-powered analytics in strengthening climate adaptation strategies. The HydroSecure platform stands as a scalable, open-access solution for managing Africa's evolving water security challenges, with a vision for broader regional integration and impact

Keywords: Flood and Drought Monitoring, HydroSecure Dashboard, DIWASA, Climate Resilience, Earth Observation, Early Warning Systems, Africa

A Comparative Analysis of Advanced Machine Learning Techniques for Accurate Groundwater Potential Zone Mapping in Haryana, India.

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In the agrarian state of Haryana in north India - groundwater (GW) is a critical resource for agriculture, human consumption, and industrial development. The Gravity Recovery and Climate Experiment (GRACE) satellite data shows that GW volume is declining by -0.819 cm/year from 2003 to 2023, which raises concerns about water security and agricultural sustainability. This requires a detailed understanding of groundwater potential zones (GWPZ) over the region. In this context, a combined geospatial-based machine learning (ML) approach is essential in analyzing the complex pattern of groundwater availability over the state. Here, we compare and integrate three well-known ML (i.e., Random Forest, XGBoost, and Support Vector Machine) techniques along with advanced Multi-criteria Decision Analysis (MCDA) such as Analytical Hierarchy Process (AHP) and Fuzzy-Analytical Hierarchy Process (FAHP) for the precise GWPZ mapping vulnerability assessment. We analyze ten major GW influencing parameters: geology, geomorphology, rainfall, drainage density, lithology, slope, topographic wetness index, topographic position index, and Roughness. The XGBoost model shows the highest accuracy (84.17%) among others by identifying key influencing factors for GWPZ. Further, we classified the GWPZ maps into four classes based on the potential water availability: critical, low, medium, and high. The XGBoost-based observation depicts 1.45%, 35.81%, 57.49%, and 5.23% for critical, low, medium, and high potential zones, respectively. Such predictions aligned well with the groundwater level, incorporating the total annual recharge and extraction rates. Similarly, AHP classified 1.36%, 33.91%, 56.1%, and 8.62%, whereas FAHP classified 4.11%, 54.11%, 35.55%, and 6.19% as critical, low, medium, and high potential zones. The geospatial analysis of GWPZ maps identified the northern districts of Haryana, such as Panchkula, Yamunagar, and Ambala, are safe for groundwater potential recharge. In contrast, Kurukshetra, Fatehabad, Panipat, and Kaithal districts are of medium potential categories, which will be critical if the current extraction rate exceeds natural recharge rates.

Keywords: Groundwater Potential Zones, Machine Learning, Remote Sensing

Spatio-Temporal Investigation of Precipitation Variability and Extreme Rainfall in the Cauvery Basin, Tamil Nadu, India Using CMIP6 data

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Assessing the spatiotemporal distribution of rainfall characteristics is crucial for evaluating water

resource availability within a catchment. Therefore, analyzing variations in rainfall patterns using gridded precipitation data and robust statistical methods is essential for informed decision-making. This study uses the Coupled Model Intercomparison Project Phase 6 (CMIP6) datasets to investigate climate change's impact on hydrological patterns in the Cauvery River Basin, India. A detailed spatiotemporal analysis has been conducted using the key precipitation-related parameters: DR, CWD, D64, RTWD, RXA, RX5D, SDII, and PCI. IMD-observed gridded precipitation data is used along with the EC-Earth3 model to improve accuracy in analyzing climate trends, demonstrating superior performance compared to other models. The analysis revealed significant spatial variability, with higher rainfall intensity and frequency observed near the Western Ghats, while drier trends dominated the eastern and northern regions of the basin. The spatial patterns of the rainfall and rainfall extremes trends in the Cauvery River Basin were analyzed across three-time steps (long-term, pre-, and post) using the Modified Mann-Kendall test, Spearman's Rho, and Sen's slope estimate, revealing shifting precipitation patterns with increasing extreme rainfall events and changes in seasonal distribution. The western part of the basin showed higher precipitation concentration, whereas the eastern regions exhibited more dispersed rainfall patterns. The findings highlight climate-driven hydrological variability, emphasizing region-specific water management. Advanced techniques enhance precipitation analysis and climate projections, supporting sustainable adaptation strategies.

Keywords: Cauvery River Basin, EC-Earth3 model, Extreme Rainfall, CMIP6, Sustainability

Water Extent and Water Level Dynamics of a Tropical Large Hydropower Reservoir for Sustainable Water Management

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Understanding water extent (WE), water level (WL), and their inter-relationship is crucial for sustainable reservoir management. This study aims to understand the surface water dynamics of Maithon, a tropical reservoir in Jharkhand, India. OTSU, a machine learning algorithm, is applied to Sentinel-1 SAR images ranging from 2017-2023 (689 scenes) to extract water extent information using Google Earth Engine. To validate the results, random sampling points are taken over the WE map of the reservoir and compared with the same points taken on raw SAR images for the dry (October-May) season with less precipitation and wet (July-September) season with heavy precipitation. For the wet season, it identifies a large proportion of water bodies (recall 0.79) with a misclassification of 18% (precision 0.82). While for the dry season (recall 0.94), a misclassification of 1% (precision 0.99) is obtained. The lower accuracy and precision in the wet season can be a product of wet soil and marshy areas in the monsoon being classified wrongly as water areas. A 2nd degree polynomial is established between WE and WL ($WE = 0.1468 * WL^2 - 38.179 * WL + 2502.9$) with an R² value of 0.94. This relationship between WE and WL not only aids in estimating the sedimentation rate as a part of sustainable reservoir management but also provides critical insights into its environmental impacts, including greenhouse gas (GHG) emission dynamics. The sedimentation rate inversely affects reservoir capacity, as can be seen in our recent study on Maithon, which indicates a reduced

capacity rate of 7.47 MCM year⁻¹. We found GHG emissions from the reservoir vary greatly between the full reservoir (786 gCO₂e/m²/yr) and near the dead storage level (3,855 gCO₂e/m²/yr), highlighting the role of monitoring the WL of the reservoir in mitigating GHG emissions and achieving net zero emission goals.

Keywords: water level, water extent, reservoir management, GHG emission, sedimentation, Sentinel-1, Google Earth Engine

A rapid assessment of Water Hyacinth mapping in India

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Water Hyacinth (*Eichhornia Crassipes*) is a free-floating perennial aquatic plant (or hydrophyte) with broad, thick, glossy, ovate leaves. Water hyacinth (WH) may rise above the water's surface as much as 1 m (3 ft) in height. WH creates a lot of disturbances in the wetland ecosystem due to its density at the mature stage, which blocks oxygenation and sunlight, leading to an anaerobic environment in the water. This study presents a rapid Water Hyacinth (WH) mapping method using a combination of Principle component analysis, K-means and OTSU thresholding method for precise area delineation. The study was conducted on 8 major lakes/wetlands in India. High-resolution satellite imagery offered through the NICFI (Norway's International Climate and Forest Initiative) service has been used to map the distribution of Water Hyacinth across 8 Ramsar sites in India. The methodology integrates PCA for image enhancement and K-means clustering for aquatic vegetation classification, supported by OTSU thresholding for precise area delineation and removal of water pixels in the Google Earth Engine (GEE) cloud computing platform. The study aimed at mapping the weed species using the GEE environment to estimate parameters such as the area of water and WH. The study arrived at a total wet biomass estimate of the weed to be 3340609.63 tons for the selected 8 waterbodies. The findings underscore the importance of integrating remote sensing and machine learning in ecological management and offer a scalable model for similar assessments in other regions, thereby highlighting the significance of this research. The availability of high-resolution earth observation (EO) data, tailored for tropical zones and GEE cloud computing platform, provides an opportunity for the effective mapping of water hyacinths, assisting environmental monitoring through the management of invasive species in a cost and time-efficient manner.

Keywords: Water hyacinth, Remote sensing, Machine Learning, PCA, K-means

Machine Learning for Multi-Hazard Susceptibility in Kenya: Integrating Earth Observation and Reported Events

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This study presents a machine learning-based approach for mapping multi-hazard susceptibility in Kenya, focusing on flood and drought. Using a random forest classification model implemented in Google Colab, we integrated Earth Observation (EO) data and reported hazard event data to assess Kenya's vulnerability due to climate extremes. The key Variables were various geographical and environmental factors like topography, precipitation indicators (SPI), temperature, hydrology, land cover, and soil cover. Data sources used in the work were EM-DAT, FloodList, CHIRPS, HydroSheds, and WorldPop, among others. The methodology involved natural hazard susceptibility modeling using flood and drought locations with other EO-based indicators, and training of the model was done on 369 locations across Kenya. Out of the 369 locations, 48 were floods, 147 were droughts, and 174 were non-hazard sites. The dataset was split into training (70%) and testing (30%) subsets. Model performance was assessed through the Receiver Operating Characteristic (ROC) curve, resulting in an Area Under the Curve (AUC) of 0.9 for floods and 0.7 for droughts, indicating strong predictive capabilities for flood hazards. Flood susceptibility was influenced by topography (22%), soil cover (19%), and precipitation (16%), whereas Drought susceptibility was influenced by topography (18%), precipitation (18%), and minimum temperature (17%) the most. The exposure maps were derived by multiplying the drought and flood susceptibility layers with the normalized demographic data. Results show that the most susceptible areas to flood hazards are the western and central regions of Kenya, while the northern and western areas are also at risk of drought. These findings have direct implications for policymakers, enabling data-driven decision-making for disaster risk reduction. The study shows that integration of EO data into national and local planning frameworks would enhance the effectiveness of disaster preparedness, ultimately reducing the socioeconomic impacts of the disasters triggered by floods and droughts.

Keywords: Natural hazard, Kenya, geospatial machine learning, random forest, floods, drought

Insights into the Agricultural Drought Assessment: A Case Study from Odisha Using Google Earth Engine

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Agricultural droughts significantly impact food security, livelihoods, and the economy, particularly in regions heavily dependent on rainfed agriculture. Drought in Odisha occurs mostly during the Kharif season severe impacts on rice production, specifically in the rainfed regions. Google Earth Engine (GEE), a robust cloud-based platform with a large repository of historical and near real-time

data, provides an effective tool for processing Earth-observation (EO) data for rapid disaster monitoring. The 2015 drought was among the worst-affected drought years, impacting 27 out of 30 districts. This present study utilized Sentinel 2 data (10m) for extracting agricultural area using Random Forest algorithm. CHIRPS data (0.050 x 0.050) for computing Rainfall Anomaly Index (RAI) to characterize meteorological droughts and MODIS-NDVI (250 m) based Vegetation Condition Index (VCI) for agricultural drought condition considering a span of 2000-2023 to understand 2015 drought in Odisha. The analysis showed persistent agricultural drought prevailed in the southern part, with the Gajapati district being the worst affected with an affected area which worsened from (~29% to ~55%) followed by Ganjam (~33% to ~45%), Kandamal (~26% to ~41%), Khordah (~28% to ~36%) and Baudh (~12% to ~34%) showed deterioration over July and August. However, there was a positive shift in drought conditions over the months in northern districts such as Sundargarh showed improvement from 60% drought affected area to 31% affected area, followed by Jharsuguda (~55% to ~18%), Deogarh (~52% to ~26%), Balasore (~72% to ~14%) and Bhadrak (~76% to ~30%) due to a change in precipitation dynamics showed improvement over the months. Thus, this study aims to provide valuable insights for identifying agricultural drought-vulnerable zones to stakeholders for recommending tailored localized solutions to ensure agricultural sustainability and resilience for deep diving into achieving the targets of SDGs 2, 13 and 17 in addressing food security and disaster risk reduction.

Keywords: Agricultural drought, Earth Observation data, Google Earth Engine, disaster risk reduction.

Hydrogeological Controls on Land Subsidence in the Central Ganga Basin: A Case Study from Lucknow

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Land subsidence represents a critical geohazard affecting many cities around the world, primarily due to their subsurface hydrogeological conditions and the overexploitation of groundwater resources. Increasing population pressure and intensifying industrial and agricultural activities are often the principal reasons for the increasing groundwater demand and subsidence problems. This study presents the patterns of land subsidence, likely linked to groundwater dynamics in and around Lucknow, one of the largest cities in the Central Ganga Basin (CGB). The city is built on highly compressible clays, and because of over-extraction of groundwater from the aquifer, a total subsidence of more than three centimetres has been observed over the last decade, based on data from Sentinel-1 and in situ measurements collected between 2014 and 2024. In some areas, maximum subsidence velocities exceed ~36 mm/year, like in Charbagh, Indira Nagar, and nearby areas, with strong spatial gradients of the vertical displacement were identified, where a significant drop in groundwater levels is recorded, indicating that groundwater over-extraction is the principal cause of land subsidence. The estimates of mean skeletal storativity from subsidence and groundwater variations data are observed 4.73×10^{-3} over the study area, which compares well with previous studies, indicating irreversible subsidence near the Charbagh area situated on a thick clay layer. Space geodetic observations of deformations caused by hydrological changes align well with in situ observations. This suggests that a synergistic combination of methods can enhance understanding of groundwater storage changes and the associated land subsidence at higher spatial and temporal resolutions.

Keywords: Land Subsidence, Groundwater over-extraction, Sentinel-1, GNSS, Central Ganga Basin

Spatial prediction of groundwater spring potential mapping using hybrid ML and DL techniques and metaheuristic optimization in the Himalayan region

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The scarcity of groundwater spring resources and their decline pose significant challenges to sustainable development in mountainous regions globally. These pristine water resources in the tectonically active and inaccessible hilly regions require precise and accurate spatial prediction of spring resources. This research presents a comparative analysis by integrating three machine learning techniques, such as Random Forest (RF), Support Vector Machine (SVM), xgboost, and Deep learning based Multilayer Perceptron (MLP) with the metaheuristic algorithms, specifically Harris Hawk Optimization (HHO), Particle Swarm Optimization (PSO), and Differential Evolution (DE) to capture complex, non-linear relationships between geo-hydrological and spring resources. Stacking models based on ensemble learning, utilising base learners and meta learners, were also employed. The initial was digitising the ground-based field locations collected at 180 spring sites. An equivalent number of non-spring points were created randomly, and stratified sampling was conducted from both spring classes (70% for training and 30% for validation). Nineteen hydrological factors were incorporated as independent variables based on the variation inflation factor, in addition to previous literature studies and expert advice. The study hypothesizes the influence of landslides on spring potential by including this factor in spring prediction for the first time. Finally, different groundwater spring potential maps were generated using different algorithms and optimization models, and their performance was assessed using receiver operating characteristics (ROC), F1 score, and accuracy metrics. The area under the ROC curve showed that the MLP-HHO (88.1%), MLP-DE (86.6%), MLP-PSO (86.4%), and RF-DE (86.4%) outperform all models. Feature importance using RF indicates that topographical wetness index, distance from landslide, and lineament are prominent factors impacting the spring potential. This research highlights the novel impact of natural and anthropogenic landslides on the spring resources and suggests that this methodology may serve as a very effective technique for groundwater spring potential mapping with high accuracy.

Keywords: Groundwater spring potential mapping, GIS, Machine learning, Deep learning, metaheuristic optimization, Himalaya

Fields on fire: remote sensing and data-driven modelling reveal impacts of crop residue burning on soil nutrients

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Crop residue burning depletes soil nutrients, and deteriorates air quality, but studies that quantify the change in soil nutrients in burnt areas remain limited. To bridge this gap, our study introduces a novel approach that quantifies the change in soil nutrients through a combination of remote sensing and data-driven modelling. Three districts in Punjab, India, where crop residue burning is prevalent, were selected: namely Ludhiana, Patiala, and Amritsar. Burnt areas were obtained from LULC maps and MODIS datasets whereas burnt dates were obtained from literature review. For each identified burnt area, multi-temporal satellite imagery from Sentinel-2 was acquired for the pre-burning (September), active-burning (October-November), and post-burning period (December) for the years 2014-2024 and spectral indices which are sensitive to soil organic carbon and total nitrogen, such as NDVI, NBR, NDRE, and BSI, were extracted. The corresponding observed datasets on soil moisture, organic carbon, and total nitrogen were obtained from literature review. These observed datasets were then paired with the spectral indices to develop a random forest regression model for each site by using the spectral indices as predictors and the observed datasets as response variables. Model performance was evaluated using R² and RMSE as metrics. Calibration yielded R² value of 0.76 and an RMSE value of 3.2-4.8 kg ha⁻¹, and validation yielded R² value of 0.64 and an RMSE value of 2.4-4.6 kg ha⁻¹. Following validation, the models were used for quantifying soil moisture, organic carbon and total nitrogen in sites and years where observed values were not available. Results reveal that soil organic carbon in the study areas has reduced by 23% and total nitrogen has reduced by 14% from 2014 to 2024. These findings underscore the potential of remote sensing and data-driven modelling frameworks to quantify nutrient loss in agricultural burnt areas and provide insights for remedial interventions.

Keywords: MODIS, LULC, Crop Residue Burning, Soil Organic Carbon, Total Nitrogen, Soil Nutrients

Evaluation of Remote Sensing-based ET products in a Semi-arid River basin of Rajasthan, India

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Evapotranspiration (ET) is a key component for water resource management, especially in semi-arid regions for the agriculture sector as it is the most important data required for optimized irrigation scheduling. Direct ET measurement is not feasible for large-scale application due to its high cost and difficulty of instrumentation. With the advancement of remote sensing technology, it is possible to estimate ET accurately and economically over large areas. In this study, we aimed to evaluate and compare the performance of three freely available remote sensing-based ET products, namely,

GLEAM, GLDAS and MODIS with that of the SWAT model simulated ET in Banas basin, the largest river basin within Rajasthan State of India, important in the economy of western Rajasthan through agriculture. For evaluation of various ET products, we first calibrated and validated the hydrological model SWAT for rainfall runoff modeling in the basin. The simulated SWAT model provided the ET estimates through its water balance based on precipitation, temperature and discharge data along with information of soil and land use. We examined monthly and annual ET patterns of all the datasets from the three remote sensing-based ET products across all sub-basins. Statistical metrics (R^2 , NSE, PBIAS) were used to evaluate the concordance between datasets. In terms of seasonal trends, GLDAS ET was found to be the most consistent with SWAT ET out of the three satellite-based products. SWAT and GLDAS showed relatively high correlation coefficients across most of the sub-basins. Whereas, MODIS ET continuously overestimated in comparison to SWAT, especially during the monsoon months. On the other hand, GLEAM ET showed notable underestimation across all the sub-basin. The results highlight the potential of GLDAS ET products to be used for estimation of evapotranspiration values central to irrigation management in the Banas River basin of the Rajasthan State in India.

Keywords: Evapotranspiration, Remote Sensing, SWAT, Semi-arid Region

Reconstruction of Satellite Soil Moisture Series using Physical Processes

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Although remote sensing provides soil moisture (SM) information at a global scale, it is limited by coarse spatial resolution and shallow sensing depth, leading to systematic discrepancies when compared to in-situ measurements. Integrating SMAP radiometer data with land surface models have shown improvements, however, a regionalized solution is needed that harness crucial physical signatures (SM recessions) to provide further improved estimations, and address systematic bias. The present study demonstrates a procedure that splits the SMAP Level 4 SM series, mechanically segregating the recession limbs and using their initial wetness conditions and drying rates to ultimately modify the complete time series. A bivariate recursive filtering approach is introduced that models the association of these drying parameters during the recession periods (joint probability), minimizing the disparity to represent the same observed in ground assessments. Consequently, the modified drying attributes (initial wetness and recession rates) are utilized to reconstruct the complete time series. The proposed approach is validated by comparing the resulting soil moisture estimates with in-situ measurements from both dense and sparse monitoring networks during April 2015-March 2020. Validation metrics indicate improvements in the reconstructed SM time series, with significant enhancements during the recession phases of the series. Overall, the integrated method performs well, emphasizing the value of incorporating physical processes into SMAP data assimilation for regional applications.

Keywords: Bivariate recursive filter, Drydowns, Microwave remote sensing, SMAP, Soil moisture

Enhancing Field-Scale Evapotranspiration Mapping with Gap-Filled and Downscaled LST: A Machine Learning Approach over India

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Evapotranspiration (ET) is a vital component of the hydrological cycle, yet generating daily, high-resolution ET maps remains challenging due to frequent data gaps from cloud cover in remote sensing. Aggregating daily ET to weekly or monthly scales, as required for many applications, can further amplify errors when data are missing. To address this, we used a Random Forest approach with AMSR2 passive microwave data to generate gap-filled 1 km Land Surface Temperature (PMW_LST) and fill MODIS Aqua LST gaps. An Artificial Neural Network was then applied to downscale LST to 100 m resolution across India. Validation at 11 in-situ sites demonstrated robust accuracy, with an overall gap-filled 100 m LST RMSE of 2.36 K ($R^2 = 0.97$).

To evaluate the utility of these LST products for ET estimation, we used the two-source SPARSE model with MODIS Aqua LST (1 km), PMW_LST (1 km), and its downsampled version (PMW_D, 100 m) as inputs. Instantaneous ET was scaled to daily values, and temporal gaps were filled by linear interpolation before aggregation to weekly and monthly scales. ET validation was conducted at seven EC flux tower sites across India, each with at least six months of data. Results show that the weekly ET MAE was lowest for PMW_D (3.57 mm/week; RMSE: 4.48 mm/week), followed by PMW (MAE: 3.77 mm/week; RMSE: 4.59 mm/week) and MODIS (MAE: 3.80 mm/week; RMSE: 4.69 mm/week). At the monthly scale, PMW_D again showed the lowest MAE (11.81 mm/month) and RMSE (14.12 mm/month), outperforming PMW (MAE: 12.69 mm/month; RMSE: 14.97 mm/month) and MODIS (MAE: 14.40 mm/month; RMSE: 17.27 mm/month). Notably, PMW and PMW_D provided approximately 50% more ET data points than MODIS, substantially improving temporal coverage.

These findings highlight the value of gap-filled LST products for accurate, robust, and temporally complete field-scale ET monitoring and irrigation across diverse agro-ecological zones.

Keywords: Evapotranspiration, gap-filling, downscaling, Land Surface Temperature, Machine Learning

Integrating vegetation index-based evapotranspiration disaggregation and crop water balance model for farm-scale vineyard irrigation estimation

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Estimating irrigation water use at the field scale is critical for sustainable agricultural water management. However, direct monitoring of irrigation is limited, and detailed field-scale data are rarely available. Remote sensing-based evapotranspiration (ET) provides a viable alternative for estimating irrigation requirements. This study integrates vegetation index-based spatial disaggregation of ET with a crop water balance model to estimate irrigation volumes in two vineyard sites in Nashik,

India, during the 2018-2019 growing season (October-February). The study used daily MODIS Land Surface Temperature (LST), Sentinel-2A/B NDVI and LAI, and meteorological data (air temperature, humidity, wind speed, solar radiation) from the IMDAA reanalysis, interpolated to the MODIS scale. These inputs were used in the SPARSE (Soil-Plant-Atmosphere and Remote Sensing Evapotranspiration) model. The model's ET outputs were disaggregated from 960 m to 60 m using vegetation index-based methods, including the DiSoRa (Disaggregation of SOLar radiation RAtio) approach. Irrigation events were simulated using the FAO-56 crop water balance model, triggered when root zone depletion exceeded the readily available water (RAW). The irrigation amount matched the RAW level. Model results were compared with farmer practices, such as the 30% Management Allowable Deficit (MAD) approach. The seasonal irrigation volume difference was 35 mm for site 1 and 44 mm for site 2. Seasonal cumulative ET from the disaggregated SPARSE model was 473.6 mm and 424.3 mm for sites 1 and 2, respectively. These results highlight the potential of using spatially disaggregated ET to improve field-scale irrigation estimation accuracy.

Keywords: FAO-56 crop water balance model, ET disaggregation, SPARSE ET model, Irrigation volume

Assessment of the impacts of land cover change and fragmentation in Loktak wetlandscape: A remote sensing approach

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The Loktak Wetlandscape, located in the Indian state of Manipur, is an ecologically and hydrologically important ecosystem and belongs to the Indo-Burman biodiversity hotspot. The Loktak Wetland is a Ramsar site but enlisted in the Montreux Record, which highlights the need for its management and conservation. This work is focused on the assessment of land use and land cover (LULC) dynamics which seems to have played an important role in wetland degradation. We used a random forest classifier using Landsat series optical images to create land use and land cover maps from 1989 to 2024, at a frequency of 5-7 years. Google Earth Engine was used for Landsat optical image processing, classification, transition matrix computation, and landscape matrix computation. Analysis of LULC dynamics shows a significant change in the distribution of different landcover classes in the wetlandscape from 1989 to 2024. Aquaculture, the major land use cover in the wetlandscape, has been expanding at an astonishing rate. Our data shows that the area covered by aquaculture in 2024 is four times that of the area in 1989. The two main natural wetland covers-open surface water and phumdi, the floating biomass that is a distinctive feature of Loktak reduced its extent by 59% and 20% respectively as a result of the expansion of aquaculture. Landscape and class-level matrices such as PLAND, LPI, TE, ED, NP and PD were used to analyze the fragmentation of the wetland which increased significantly between 1989 and 2024 as the number of wetland cover patches increased. The ecological effects of the growth of road infrastructure were also taken into account in our study, as they cause the hydrological dis-connectivity of wetlands and channels within the wetlandscape. The remote sensing-based approach for the assessment of wetlandscape health will help to develop sustainable management strategies for wetland conservation.

Keywords: Remote sensing, LULC, wetland degradation, hydrological connectivity

Spatio-temporal dynamics of riverine islands over multi-decadal timescales of the Lower Ganga River (India): Insights from remote sensing datasets

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Riverine islands are common geomorphic features that form within the river channel, surrounded by water separating it from the floodplain. They are present in nearly all major rivers worldwide and are amongst one of the most prominent features in the Lower Ganga River. Their formation and evolution are closely linked to channel morphology, flow and sediment dynamics. Two main aims of this study are to evaluate the spatial and temporal dynamics of islands in conjunction with their interactions with the river channel, and then to understand the causal factors of their morphodynamics over multi-decadal timescales.

To examine these changes over space and time the Lower Ganga River was divided into four windows. Each window was further subdivided into reaches. We utilized Google Earth Engine (GEE) to map active channel, wetted channel and riverine islands for each reach. GIS techniques are incorporated to calculate various morphometric properties of both islands and river channels to understand their morphodynamics for ~ 30 years.

Spatial distribution of riverine islands reveals that certain reaches are more favorable locations for island formation, due to the geomorphic characteristics of different reaches. The mean island area across all reaches over a time span of 30 years is 28 Km² with a high standard deviation of 43 Km² reflecting considerable spatio-temporal heterogeneity of island sizes. During this time span, the number and area of riverine islands has shown no systematic trends in different windows, but a sympathetic relation between them is observed. The analysis of changes in spatial distribution over time reveals the persistence of islands in several reaches. We have interpreted that islands dynamics play a significant role in shaping channel planform by affecting the multiplicity of channels and width and depends on the river behavior such as lateral channel migration and channel stability.

Keywords: Riverine islands, Morphodynamics, Google Earth Engine

Statistical Hydrology (ICSH)

High-Flow Sediment Transport Alterations Due to Damming in the Godavari River Basin

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Dam construction significantly impacts river systems, particularly the movement of suspended sediment during high-flow conditions. This study explores these effects in the Godavari River Basin (GRB), one of India's largest river systems, where over 80% of suspended sediment transport occurs during high flows. Understanding these dynamics is essential for assessing changes in hydro-geomorphic behavior. Hydrological data from 13 gauging stations across the GRB, with daily records spanning the last 50 years, were analyzed. A positive correlation was identified between streamflow and sediment load. The marginal distributions of each dataset were first established, followed by the generation of joint probability distribution functions to analyze the bivariate relationships. Suspended sediment transport during high flows was examined in dammed and undammed regions of the basin using this probabilistic framework. The study underscores the importance of bivariate interactions between high flows and sediment transport in capturing changes in their temporal dependence patterns within the probability domain, contrasting with the predominantly univariate focus of previous studies. The findings reveal reduced sediment transport during extreme flood events, with dammed regions showing the most pronounced effects. Joint probability distribution functions revealed significant changes in the joint probabilities and magnitudes of sediment transport due to damming, as validated by goodness-of-fit tests using Anderson-Darling statistics and p-values. These results highlight the profound influence of dams on sediment dynamics and riverine processes, providing valuable insights for managing river systems affected by human interventions.

Keywords: Suspended Sediment, Suspended Sediment Transport, Godavari River, Dams, Joint Probability, India,

Estimating Vulnerability to Compound Dry and Hot Extremes in the Madhya Pradesh: A District-Level Perspective

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The global risk of Compound Dry and Hot Events (CDHEs) is rising due to warming levels, leading to severe impacts on water resources, agriculture, and ecosystem stability. Central India, especially Madhya Pradesh (MP), is increasingly affected by simultaneous drought and heat extremes, intensifying stress on local water resources, agriculture, and communities. This study investigates CDHEs in MP using TerraClimate data from 1958 to 2022 to analyze rainfall and temperature patterns through joint probability distribution functions, focusing on shifts before and after 1990. This historical baseline highlights trends and regional hotspots influenced by climate change. Results indicate significant post-1990 changes, with rising temperatures across seasons and a marked decline in monsoon rainfall in northern and eastern MP, heightening drought risks. CDHE frequency and severity have increased all across the seasons, particularly in the post-monsoon season, identifying northern and eastern MP as CDHE hotspots. Compound event probability, combined with LMFDH (Likelihood Multiplication Factor for Dry and Hot Events) values, further reveals a growing interdependence between drought and heat extremes in these areas. The study underscores the urgent need for adaptation strategies, including Integrated Water Resource Management (IWRM), climate-resilient agricultural practices, early warning systems, and diversified livelihoods, to mitigate CDHE risks. These strategies are essential for building resilience in MP's climate-sensitive regions, especially in high-risk districts facing compounded drought and heatwave impacts.

Keywords: Compound Extremes, CDHE, Central India, Climate Change, TerraClimate

Vine Copula based Multivariant Flood risk Assessment on Beas River Basin

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There are several variables which are the triggering factor for floods, among them precipitation, soil moisture and snowmelt is a critical factor which plays a crucial role in snow covered mountain regions. This study uses Vine Copula to determine the dependency structure of the joint variable distribution between precipitation, soil moisture and snowmelt in Beas River basin. In this study, the SWAT model is coupled with the Vine Copula model to conduct multivariate analysis for flood using the sub-basins parameters. For this purpose, the 45-year data which is generated from SWAT model were used. The Vine copula technique approach requires the marginal distributions for each variable and different copula function that combines the marginal data in a tree structure to generate a joint distribution. Considering the range of the variables eighteen univariant marginal functions were chosen. Once marginal distribution is determined, 15 list of copulas were used to analyse the correlation of variables in pairwise. Later tree sequence of R-, D- and C-vine copulas were analysed in the study. Finally, according to the structure and nature of the data, R-vine copula was selected

as the best copula and the relevant tree sequence was later used. Kendall's tau test was used to check the correlation of the variables in pairwise and showed good correlation. This study proves to be an effective approach in improvising the flood prediction and control of flood risks.

Keywords: SWAT, Copula, Flood

Deciphering Historical Rainfall Patterns in the Indian Ganga Basin: Drivers, Dynamics, and Implications

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Historically, the upper mountainous regions of the Indian Ganga Basin (IGB) have experienced short-duration, high-magnitude rain spells. At the same time, the southern parts of the IGB have witnessed a substantial reduction in rain spell volumes. Building on this understanding, the current study investigates the driving factors and behavior of rain spells over the IGB from 1901-2023. Using a daily rainfall dataset from the Indian Meteorological Department (IMD) with a resolution of $0.25^\circ \times 0.25^\circ$, rain spell attributes-such as duration, intensity, and volume-were derived for the entire study period. The joint probability distributions of these attributes were analyzed to identify breakpoints in patterns and interrelationships between the attributes. Based on the analysis, indices for Long Duration Spells (LDS) and Short Duration Spells (SDS) were developed, incorporating rain spell duration, maximum intensity, and total volume. The study further examined whether LDS are transitioning into SDS or vice versa over time. Additionally, the study explored the influence of atmospheric processes such as El Niño (NINO) and the Indian Ocean Dipole (IOD) on the frequency and intensity of LDS and SDS events. These analyses revealed significant temporal and spatial shifts in rain spell patterns. This study enhances the understanding of historical changes in rain spell patterns, their driving factors, and the underlying atmospheric interactions. The findings can inform mitigation strategies and disaster preparedness plans for highly affected areas, contributing to climate resilience and sustainable water resource management in the IGB.

Keywords: Ganga, Rain spell, Rainfall, IOD, LDS, SDS

A Comparative Study of Kalman Filters and Machine Learning Models for Predicting Groundwater Levels in Relation to Rainfall

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Prediction of Groundwater levels (GWLs) is important for water resource management, especially in areas affected by irregular rainfall and weather changes. It has been useful for planning when a reliable prediction method helps in saving water. The current study compares Kalman Filters (KFs) and machine learning methods such as Random Forest (RF), Light Gradient Boosting Machine (LightGBM), and Extreme Gradient Boosting (XGBoost) for GWL prediction using rainfall data. Despite improvements in prediction models, Rainfall-Groundwater interactions and aquifer differences make groundwater changes hard to predict. The study's results show that, for the test dataset, the Kalman Filter gives the best prediction performance (R2 and NSE of 0.964), Random Forest gave R2 and NSE of 0.889 for the machine learning models, R2 and NSE of 0.863 for XGBoost, and R2 and NSE of 0.815 for LightGBM. Kalman Filters are more accurate than machine learning models in predicting groundwater changes after rainfall. However, because they work better with larger datasets, machine learning models remain useful. This study emphasizes the importance of choosing the right groundwater monitoring methods by focusing on assessing the different models to see how well they balance prediction accuracy, computing costs, and performance strength.

Keywords: Rainfall, Groundwater Levels, Kalman filtering, Machine learning models, Light GBM, XGBOOST, Random Forest

Partitioning hydrologic uncertainty into model parameter contributions and their association with catchment attributes

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Hydrologic model uncertainties can arise from inadequate data quality, model structure, parameter estimation, and methodological choices. Parameterization plays a critical role as it directly influences the accuracy and performance of hydrologic model simulations. Despite significant development of literature on applications of hydrologic modeling, contribution of individual parameters to the total model uncertainty and the role of catchment attributes therein is still not yet fully understood. This study investigates the application of Global Sensitivity Analysis (GSA), particularly through the simple-yet-effective Analysis of Variance (ANOVA), to evaluate the contribution of different model parameters to the overall uncertainty in streamflow as simulated by the abcd monthly water balance model. One hundred and forty nine snow-free catchments in the USA were studied to explore the variability in parameter sensitivity under different environmental conditions. The results offer valuable insights into the behavior of the abcd model in arid vis-a-vis wet catchments. Parameter b, that represents thickness of the upper soil moisture zone, and a that controls how quickly surface runoff is generated from upper soil moisture zone, were identified as the primary contributors to uncertainty. Additionally, the contribution of parameter c that indicates groundwater recharge, becomes significant in wet catchments as compared to the arid ones. Interestingly, partitioning of uncertainty

to different model parameters does not vary with catchment size. Quantification of individual model parameter contributions to hydrologic uncertainty has important implications for improved model reliability and applicability and highlights the need to consider catchment attributes during calibration and validation.

Keywords: Hydrologic model, parameter uncertainty, catchment attributes, global sensitivity analysis, ANOVA

Dynamic Assessment of Delhi's Urban Heat Island Considering the Urban Sprawl Over the Past Two Decades

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Urban expansion is a major global phenomenon, particularly in emerging countries where population growth coincides with rapid city growth, driving the extension of built-up regions. The Urban Heat Island (UHI) effect, which causes localized heating in urban areas when compared to rural areas, is a critical consequence of this urban expansion. This effect is mostly caused by the removal of natural vegetation and the installation of impermeable surfaces. The UHI impact is often more noticeable at night due to the persistence of human activity and the intensity of artificial illumination. This study examines the link between urban development and the intensification of the UHI effect during the past 20 years, with a focus on the Delhi National Capital Region (NCR), one of India's fastest-growing metropolitan cities. The geographical and temporal dynamics of urban expansion and UHI intensity in the region were examined using the MODIS global land cover product (MCD12Q1.061) and the aqua MODIS daily land surface temperature (LST) data (MYD11A1.061). It was observed that Delhi NCR's built-up area increased significantly between 2001 and 2021, rising from 1375 km² to 1650 km² in 2021. The night-time LST data is used to quantify the UHI intensity, which has increased in tandem with this rapid urban expansion. The trend of the urban heat island is positive, indicating that urbanization not only increases the temperature in urban areas but also intensifies temperatures in the surrounding areas. To achieve an accurate representation of geographical patterns of UHI intensity, the Dynamic Equal Area (DEA) technique is used to establish buffer zones surrounding the NCR region. This approach avoids bias by generating a homogeneous buffer that accurately depicts the spatial patterns. The outcomes of this study highlight the critical need to address the growing UHI effect in rapidly urbanizing areas such as Delhi NCR.

Keywords: Urban expansion, Urban heat island (UHI), Dynamic equal area (DEA)

Suspended Sediment Load Estimation of the Godavari River Basin Using Tree-based Machine Learning Algorithms

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The Suspended Sediment Load (SSL) of a river serves as a critical indicator for various aspects of water resource management and hydrology. It plays a vital role in assessing ecological integrity, shaping river morphology, sustaining aquatic and riverine ecosystems, and guiding the effective management of rivers and reservoir systems. This study explores the historical changes in SSL and evaluates the predictive performance of machine learning (ML) models in the Godavari River Basin. The SSL dataset was divided into pre-1990 (1969-1990) and post-1990 (1990-2020) periods to assess temporal trends. The mean annual SSL decreased significantly from 136.85 million tonnes in the pre-1990 period to 62.38 million tonnes post-1990, driven by anthropogenic interventions such as dam construction and land-use changes. Seasonal analysis revealed that while the monsoon season contributed ~73% of the annual SSL in both periods, there was a marked decline in median and peak SSL values, with the interquartile range (IQR) narrowing substantially in both monsoon and non-monsoon seasons. Empirical cumulative distribution functions highlighted shifts in SSL distribution, with post-1990 values exceeding pre-1990 at higher cumulative probabilities, indicating altered sediment transport dynamics. To predict SSL, tree-based ML models were developed and evaluated using different metrics. Among the models, the Extra Trees Regressor (ETR) exhibited superior performance, achieving the highest R^2 (0.9666 in training, 0.8959 in testing) and lowest error metrics across various phases, including time-lagged predictions. The Random Forest Regressor (RFR) also performed well, particularly in testing phases. Gradient Boosting Regressor (GBR) showed competitive results but was slightly outperformed by ensemble models such as ETR and RFR. The study underscores the robustness of ensemble tree-based models in capturing SSL variability. These findings not only highlight the impact of anthropogenic changes on sediment transport but also demonstrate the utility of advanced ML models in predicting SSL.

Keywords: Suspended Sediment Load, Godavari River Basin, Machine Learning Models, Tree-based Models, Anthropogenic Interventions

Evaluation of different precipitation data over the Pamba River basin, Kerala

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The precipitation data from rain gauges are often found to be inconsistent, but they are essential for water resource planning. Satellite and gridded data can be considered alternatives to station data, but their suitability needs to be evaluated before application in hydrological studies. This study systematically evaluates the performance of various precipitation data sources derived from satellite and gridded products and compares them with the observed data derived from 2001-2021 for the

Pamba River basin of Kerala, India. The satellite products include Integrated Multi-Satellite Retrievals for GPM (IMERG) products, Global Satellite Mapping of Precipitation (GSMaP-MSR), Tropical Rainfall Measuring Mission (TRMM) and ERA5 Land data and the reanalysis data Modern-Era Retrospective Analysis for Research and Applications (MERRA). The gridded products include the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) and the India Meteorological Department (IMD) products. The performance is assessed using advanced statistical metrics such as normalized root means square error, Nash-Sutcliffe efficiency, coefficient of determination, and Taylor diagram. The annual and seasonal rainfall trends are also determined using the Modified Mann-Kendall and Sen's slope tests to evaluate the temporal variations. The comprehensive ranking is given to various data sources based on multi-criteria decision-making techniques.

Keywords: Statistical metrics, Multi-criteria decision-making, Satellite products, Gridded products.

Physics-based Assessment of Pluvial Flood Hazard and Exposure from Hourly Rainfall Extremes Preconditioned by Heatwaves

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Compound inland flooding resulting from sequential climate events such as extreme rainfall closely following heatwaves can cause more severe consequences compared to extreme rainfall in isolation. Several studies so far have assessed the dynamics and characteristics of extreme rainfall preconditioned by humid heatwaves across the world, but the response of such compounding events to flood hazard and exposure remains unknown, especially at the hourly temporal scale. Here, we employ a climate-informed hydrodynamic model to simulate sequential compound flooding hazards-extreme rainfall preconditioned by heatwaves from observed hourly heavy rainfall (over 90th percentile rainfall depth) events over 40 years (1982-2021), focusing on the Chennai Metropolitan Area with a population of around 9 million. We contrast these scenarios to those not preceded by heatwaves and compare the frequency, magnitude, and exposure of heatwave-compounded pluvial flood hazards compared to uncompounded pluvial flood hazards. We consider bivariate joint probability of accumulated event rainfall magnitude and peak rainfall intensity to assess the conditional role of the heatwave in flood risk zone demarcations. We found substantially higher pluvial flood inundation depths and exposure levels for heatwave-preconditioned rainfall extremes than for uncompounded rainfall extremes. Our detailed flood hazard assessment helps better understand the extremes and offers the basis for developing reliable climate adaptation measures.

Keywords: compound extreme, pluvial, floods, probability, risk

Narrowing at-site flood frequency analysis using simulations from the continental AWRA-L landscape model

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At-site flood frequency analysis (FFA) is a foundational tool used to quantify flood risk routinely around the world. The fitting of a flood frequency distribution is, however, attached with large uncertainty due to the short duration of streamflow records and the need to extrapolate flood quantiles beyond the 1% AEP threshold. Large uncertainty is difficult to communicate to stakeholders and undermines the whole process.

In this paper, a novel approach is proposed where at-site FFA is conducted both on observed streamflow records and on 110 year-long streamflow simulations at the same location obtained from the a continental landscape model developed for Australia (AWRA-L). This model runs at 5km grid scale from 1911 until yesterday, and has been used extensively across Australia for water resources assessment and climate change studies. Both fitting exercises are coupled via a copula statistical model where coupling can be tight if AWRA-L simulations are informative, or weak if they are not. In latter case, our method becomes equivalent to a standard at-site FFA method.

The method was tested at 50 sites across Australia with records longer than 60 years. The method applied to subset of the full records varying from 10 to 50 years and then compared with the fit obtained from all data (assumed to be the reference). Performance analysis suggests that our method reduces the width of uncertainty bounds by 20 to 30% without degrading the quality of the fit. These promising results highlight the potential for continental landscape models to improve at-site flood frequency analysis.

Keywords: flood frequency analysis, landscape model, bayesian statistics

Assessing Compound Dry and Hot Events in Indian Smart Cities: Historical Trends and Future Projections under +2°C and +4°C Climate Change Scenarios

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Compound Dry and Hot Events (CDHEs), characterized by the simultaneous occurrence of prolonged dry periods and high temperatures, represent one of the major challenges of the 21st century. These events have far-reaching consequences, surpassing those of individual extremes, and significantly affect water resources, agriculture, public health, and infrastructure. Globally, the frequency, duration, and intensity of climate-driven heat extremes like CDHEs are rising, particularly in climate-sensitive regions such as Europe, the United States, South America, Australia, and Asia. In India, the increasing frequency of extreme weather events intensifies vulnerabilities, especially in rapidly developing smart cities. As hubs of socio-economic activity, these cities face mounting challenges related to high population density, inadequate water resources, and susceptibility to extreme

weather. This study analyzes CDHEs across 100 Indian smart cities located in diverse meteorological zones from 1958 to 2023, using monthly precipitation and temperature data. Advanced methods, including joint probability density functions and standardized indices such as the SCEI, SPI, and STI, were employed to assess temporal patterns, frequency, and severity of CDHEs. The results reveal significant post-1990 changes, including rising temperatures across seasons and a marked decline in monsoon rainfall. These shifts have intensified CDHE occurrences, particularly in central and northern Indian cities during the pre-monsoon season, driven by regional climate changes and accelerated urbanization. Future climate projections under +2°C and +4°C global warming scenarios indicate a fivefold increase in CDHE frequency and severity, with northern, central, and southeastern peninsular cities most affected. This research connects historical trends with future projections, offering critical insights into hydroclimatic extremes across Indian smart cities. It underscores the importance of robust policies to mitigate cascading impacts, enhance urban resilience, and promote sustainable development in the face of a changing climate.

Keywords: Hydroclimatic extremes, Compound Dry and Hot Events (CDHEs), Smart cities Vulnerability, Climate change projections, Standardized indices

Beyond Historical Records: Using Counterfactual Scenarios to Improve Flood Risk Management

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Floods, triggered by heavy precipitation events (HPEs), are among the most destructive natural hazards. With climate change, HPEs are expected to become more extreme regarding spatial extent and rainfall intensity in the future. However, extreme floods do not always follow HPEs - flood severity depends on the spatial coincidence of intense rainfall with catchments that have the hydrological properties to produce extreme floods. This rare combination may not be well represented in historical records, making traditional flood risk assessments, based on stream gauge data and extreme value statistics (EVA), inherently uncertain.

To address this uncertainty, counterfactual analysis - exploring alternative event scenarios - can help remove randomness in the spatial distribution of rainfall and reduce the element of surprise. Advances in precipitation monitoring (e.g., weather radar) and computational resources now enable the systematic application of counterfactual thinking in flood risk management. Therefore, this approach is recently gaining traction in the USA and Europe to generate more robust flood scenarios, also for ungauged catchments.

Our recent studies propose a framework for counterfactual hazard assessment of (flash) floods and demonstrate that incorporating counterfactual scenarios improves flood level anticipation. After evaluating ~1 billion hydrological simulations, we found that many catchments have simply not experienced the worst-case in the recent past. A key challenge remains ensuring the plausibility of these scenarios. We present different methods for selecting counterfactuals and analyse their impact on overall hazard assessment outcomes. Furthermore we show how a counterfactual approach can be combined with traditional EVA to derive flood return levels.

By identifying potential flood hotspots and reducing uncertainty, counterfactual thinking offers a valuable tool for disaster risk management, particularly in data-scarce regions.

Keywords: flood, risk, hazard, extreme value statistics, counterfactual, statistics

A physics-informed Graph Neural Network Framework for Post-processing Ensemble streamflow simulations in a river network

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Floods are among the most disastrous events worldwide, causing extensive damage to life and property annually during the monsoon season in India. Accurate daily streamflow predictions for river systems are critical for mitigating floods, particularly in rainfall-driven river basins like those in India. However, physically based models frequently face challenges related to structural, parameter, and data errors, which can introduce biases in the outputs of hydrologic models. To address these challenges, it is necessary to develop post-processing techniques that can help minimize these errors. A practical approach to enhancing prediction accuracy without the computational burdens associated with calibration is to use deep learning techniques for post-processing streamflow predictions. This study explores the use of Graph Neural Networks (GNNs) to enhance the spatiotemporal characteristics and variability of ensemble streamflow predictions. We developed 30 ensemble streamflows daily over the Indian catchments using ILDES and 0.10-degree ensemble precipitation (IPED) dataset as the forcing input. Specifically, we employed Graph Attention Recurrent Networks (GARN) to enhance the ensemble streamflow predictions derived from the ILDES model. GARN is particularly beneficial for dynamic graph data that experiences changes in both structure and features over time. For the GARN input, we utilized features such as soil moisture, minimum and maximum temperature, relative humidity, surface pressure, soil properties, etc. The model was trained using simulated streamflow as the input variable, with observed streamflow as the target variable. GARN's ability to adapt to dynamic graph structures and assign dynamic weights enables it to focus on the most relevant neighboring nodes. We applied this post-processing technique to calibrated and uncalibrated outputs from the ILDES model. The results demonstrate that the GARN model significantly improves the KGE score across the basins over India, showcasing its potential for enhancing flood prediction accuracy.

Keywords: GNN, Streamflow prediction

High-Resolution CMIP6 Downscaled Precipitation and Temperature Dataset Over South Asia

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South Asia is highly vulnerable to climate change, which makes accurate climate risk assessments crucial for efficient planning of mitigation strategies to minimize the loss of livelihoods and resources. To improve the evaluation of climate risks, it is mandatory to have high-resolution future projections of climate data. In response to this need in South Asia, this study developed a daily precipitation and temperature dataset over South Asia at a spatial resolution of $0.1^\circ \times 0.1^\circ$, based on the three global circulation models (GCMs): ACCESS-CM2, CanESM5, FGoals-g3 from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The dataset has been downscaled, covering the historical period (1996-2014) and future projections (2015-2100) from three (Shared Socioeconomic Pathways (SSPs) 1-2.6, 2-4.5, and 5-8.5) experiments. The Generalized Analog Regression Downscaling (GARD) method has been adopted to downscale the daily GCM simulations using robust ensemble-based observational (IPED, EM-Earth) and reanalysis-based training (ERA5 Land) datasets. The downscaled outputs indicated improved performance compared to the raw GCM simulations, suggesting the reliability of the dataset to be used in South Asia for climate and hydrological studies.

Keywords: Downscaling, Shared Socioeconomic Pathways (SSPs), Global Circulation Model (GCM), Coupled Model Intercomparison Project Phase 6 (CMIP6)

Robust estimation of present and future flood quantiles, and extreme event attribution based on a non-stationary, climate-informed weather generator

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Flood risk management faces a severe challenge in robustly estimating flood quantiles in a changing climate and developing appropriate adaptation measures. The impact of anthropogenic climate change on the frequency and severity of flood-triggering rainfall extremes was pinpointed in numerous event attribution studies which stress the necessity for adaptation. However, studies that attempt to attribute flood peaks and impacts are rare. In this contribution, we address both challenges - flood quantile estimation and event attribution - by deploying a novel non-stationary climate-informed stochastic weather generator conditioned on dynamic and thermodynamic change signals from global climate models. We present a nation-wide estimation of present and future flood quantiles in Germany based on long synthetic flood series and continuous hydrologic simulations. The robustness of the weather generator-based estimates is exemplified for the flood frequency estimation in the Ahr basin which was hit by an extreme flood in July 2021. For this event, we further

demonstrate the advancement in the event attribution methodology using stochastic weather and impact model simulations going beyond precipitation event attribution. Our findings suggest that anthropogenic climate change has not only substantially increased the likelihood of precipitation events as in July 2021, but has also contributed to an increase in the likelihood of the associated peak flows, although uncertainties are amplified along the process chain. Combining a stochastic weather generator with a hydrological impact model chain opens new avenues in research towards flood event and impact attribution.

Keywords: weather generator, flood quantiles, event attribution, climate change

Climate-Informed Model for Forecasting Flood Quantiles in Indian Catchments

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Forecasting floods (peak flows/quantiles) with significant lead time is crucial for effective water resources management. Traditionally, it has been carried out by forcing meteorological drivers onto the hydrological models. However, season-ahead flood forecasting remains challenging due to the limitations of weather forecasting models and the complexities associated with multiple model-chain linkages. Thus, to circumvent this, we applied a climate-informed approach to forecast season-ahead flood quantiles. Briefly, a climate-informed model comprises 1) selection of predictands, 2) identification of climate predictors that control the predictands, and 3) derivation of a statistical link between predictands and predictors. In our study, we condition the probability distribution parameters of flood samples with large-scale climate predictors, focusing specifically on sea surface temperature (SST) patterns. The rationale behind this approach lies in the established linkage of SST in the Pacific and Indian Oceans to the Indian Monsoon system. To minimise the anthropogenic signals, we restricted our analysis to the gauging stations without significant reservoir influences by filtering the stations with reservoir indices less than 0.1. Both linear and nonlinear relations between the climate predictors and predictands have been applied in this study. Bayesian inference is used to estimate the parametric values of the Climate-Informed model. Furthermore, the selection of the suitable climate predictor and the nature of their relationship to a specific gauge is based on the widely applicable selection criterion. We assessed the prediction skill of the climate-informed model on flood quantile forecasting by performing a leave-one-out cross-validation technique. Overall, our results suggest that for the majority of the gauges, climate indices have the potential to forecast flood-quantiles season ahead. While this initial forecast can inform decision-makers regarding expected flood quantiles, it is recommended that this method be complemented with traditional approaches that account for local catchment behaviour.

Keywords: flood quantiles, climate-informed models, flood forecasting

Transforming Flash Drought Forecasting: Evaluating Custom AI and Time Series Foundation Models

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Droughts are recurring global hazards that severely affect the agricultural productivity and economic growth of the region. Compared to conventional droughts, flash droughts are characterized by their rapid onset which can have a devastating impact on socioeconomic stability. In 2012, the United States experienced the worst flash drought in history which impacted nearly 80% of its croplands and led to an estimated economic loss of \$30 billion. In 1979, India endured its most extreme summer monsoon flash drought on record which impacted 40% of the country's land area. These events highlight the complexity of predicting flash droughts and underscore the urgent need for a robust forecasting model.

In this study, we investigate the flash drought characteristics across India over the period from 1979 to 2020. We employ the Standardized Precipitation Evapotranspiration Index (SPEI) at a pentad scale to identify these events. This study analyses the key flash drought characteristics which include duration, severity, frequency, and intensity at a seasonal scale. The study aims to propose a robust flash drought forecasting model for India. While adopting a data-driven approach, we evaluated the custom deep learning models against a foundation time series model. We developed custom Transformer, Informer, Linformer, and LSTM-based models tailored for the Indian domain and evaluated their performance against TimeGPT, which is a state-of-the-art time series foundation model. This study aims to mitigate the adverse impacts of flash droughts by enhancing forecasting capabilities. It will help in effective water resource allocation, policymaking, and informed decision-making by stakeholders.

Keywords: Flash droughts, Transformers, LSTM, TimeGPT

Exceptional Flood Events: A Comparison of Spatial Counterfactuals, Perfect Storms and Stochastic Simulation Approaches

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Exceptional floods often have catastrophic impacts because people and decision-makers are unwilling to think about and prepare for events that are much larger than those observed. In many regions of the world, climate change and socio-economic changes are increasing the likelihood of such unprecedented events. It is therefore important to develop scenarios of exceptional events that are plausible and that people can understand and relate to. Here we present several methods for developing such exceptional scenarios for river flooding in Germany. These methods include spatial counterfactuals, where the flood-triggering precipitation of historical floods is shifted in space, and a perfect storm approach, where we recombine historical event precipitation with historical wet

catchment conditions. We also present the results of a stochastic simulation approach, where a large-scale weather generator drives a hydrological model. We find that with all approaches we can easily obtain flood events that are much more severe than what Germany has experienced in the last 70 years. For example, small deviations in the trajectory of the precipitation field of past floods, which were among the most expensive and catastrophic events in Germany, could have led to much higher peaks. We compare the results of these different approaches and discuss their advantages and limitations. Our results confirm the importance of stress testing current risk management approaches with exceptional flood scenarios.

Keywords: Catastrophic floods, stress test

False Nearest Neighbour: A Chaos-Based Dimensionality Analysis of Hydrometeorological Variables in the Lower Columbia River basin

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This study investigates complexity of hydrometeorological variables over the Lower Columbia River Basin using gridded data from 1980 to 2022. The complexity expressed in terms of dimensionality, a measure to represent dominant governing variables, is estimated for daily precipitation, runoff, maximum/minimum temperature, relative humidity and wind speed using the False Nearest Neighbour (FNN) algorithm. This study employs gridded datasets for 39 grid points and measured runoff at the basin outlet. FNN is a chaos-based dimensionality analysis method that relies on phase space reconstruction using lag times from the same series. Lag times can include the time step or lag where ACF is zero or where AMI is minimum. In this study, better results were achieved with a lag of 1. The results of the FNN analysis are presented as a plot of percentage of FNN versus the embedding dimension. From this graph, the embedding dimension where percentage of FNN reaches a minimum is considered optimal embedding dimension or dimensionality of the time series. The FNN results indicate that dimensionality of studied variables ranges from 5 to 9, reflecting a medium-to-high level of complexity. Minimum temperature shows the lowest complexity (5 to 7), while rainfall exhibits the highest (7 to 9). Spatiotemporal analyses of rainfall and temperature highlight significant influences of topography and climate, with a pronounced rainfall gradient across the basin. The Cascade Mountain Range receives the highest rainfall due to orographic effects, while the eastern regions experience reduced rainfall because of the rain shadow effect. The Mann-Kendall test on daily rainfall data reveals no statistically significant trends at the 95% confidence level, with near-zero slopes, indicating minimal changes over time. These findings provide critical insights into the dynamics of hydrometeorological systems and hold important implications for model development and parameterization, particularly in regions undergoing land use and climate changes.

Keywords: False Nearest Neighbour (FNN) Algorithm, Chaos Theory, Mann-Kendall test, Sen's Slope, Dimensionality

A Channel Network Morphology-based Perspective on Discharge-Basin Area Scaling

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The scaling of discharge (Q) with basin area (A) offers critical insights into the dominant hydrological processes that govern the basin's streamflow response. Previous studies primarily focused on peak discharge scaling ($Q_p = kA^{\beta_p}$) and observed that the peak scaling exponent (β_p) can be lower than 1. This is typically interpreted in terms of the basin's width function, representing the pure surface flow (PSF) condition. In the present study, we extended the scaling analysis to the entire streamflow spectrum with an aim to address a long-standing question: Are basins merely a summation of their constituent hillslopes? A channel network morphology-based streamflow routing model is employed to simulate the total flow at the basin outlet by integrating contributions from pure surface flow (PSF) and mixed surface-subsurface flow (MSSF). The model represents MSSF, the dominant flow mechanism during the recession period, by accounting for the progressive desaturation of the active drainage network (ADN) in the downstream reaches of the basin. Unlike conventional Dupuit-Boussinesq's aquifer-based low-flow models, which account solely for local subsurface flow paths, the proposed framework implicitly considers both local and regional subsurface flow contributions. The results of this study indicate that the scaling exponent approaches unity during the recession period due to the increasing dominance of MSSF, which is directly proportional to the ADN length and, consequently, to the basin area with constant drainage density. Furthermore, the analysis reveals that the scaling exponent may exceed 1 during late recession periods, as larger basins exhibit a slower rate of flow decline, attributable to contributions from regional subsurface flow paths. These findings imply that a basin cannot be viewed solely as a sum of its hillslopes, with implications for large-scale hydrological and ecological modeling.

Keywords: Discharge-Area Scaling, Recession Flow Modelling, Channel Network Morphology, Active Drainage Network

Ensemble Streamflow Data Assimilation in the Indian Subcontinent using vector-based Hydrodynamic Model and Novel Localization Techniques

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High-resolution streamflow data is crucial for effective water management, flood risk assessment, and mitigation efforts. However, accurate simulation of streamflow from a hydrologic hydrodynamic model is challenging due to multiple sources of model errors combined with the uncertainties due to initial conditions. Here we present the streamflow data assimilation framework that aims to improve the streamflow simulation and flood predictions using the streamflow data assimilation in the hydrologic hydrodynamic model. We integrated the Noah MP, a multi-parameterization land surface model with MizuRoute, a stand-alone vector-based streamflow routing model. Assimilation will be

done with the Ensemble Kalman Filter (EnKF) combined with a novel localization technique at gauge stations across the Indian subcontinent. The gauge specific along the stream covariance localization and the spatial and temporally covariance inflation will be considered in this study to simulate the improved streamflow at river reaches over South Asia. This high-resolution, river reach-based streamflow reanalysis offers significant utility for hydrologic extreme analysis and mitigation efforts in the Indian subcontinent. Moreover, it establishes a robust foundation for advancing sustainable water resource development under changing climatic conditions.

Keywords: Hydrologic-Hydrodynamic Model, Data Assimilation, Gauge Specific Localization, EnKF

Teleconnection-informed frequency analysis of rainfall extremes

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Several scientific studies show the benefits of using climate indexes (or "teleconnections") as covariates when modeling the frequency regime of annual maximum rainfall across diverse geographical regions worldwide. Typically, these analyses are based on a few, and often spatially sparse, single time series. However, the presence of regional structures in the dependency of annual maximum rainfall on teleconnections is still poorly explored. This study provides a comprehensive assessment of the effectiveness of teleconnections for representing and modeling the frequency regime of rainfall extremes at a regional scale. The study area is a large and climatically diverse region in Northern Italy. Our dataset consists of 680 annual maximum series (AMS) of rainfall depth for 1- and 24-hour durations. We select six climate indexes based on a literature review. Instead of analyzing the original AMS, we define sliding time windows to obtain time series of L-moments, which characterize the distribution of rainfall extremes. In the first phase of the study, we evaluate the correlation between teleconnections and time series of spatially gridded L-moments. To analyze the spatial patterns of the correlation with gridded L-moments, we discretize the study region into tiles with resolutions of up to 100 km. In the second phase of the study, we present a preliminary application of climate-informed regional frequency analysis of rainfall extremes, in which the L-moments are modeled as functions of the most influential teleconnections. These are selected based on (1) their significantly higher number of correlations with the L-moments of sub-daily rainfall maxima compared to other teleconnections and (2) the presence of clear spatial patterns in their correlation fields across the study area, whose robustness is confirmed by their limited sensitivity to grid resolution. Overall, our research suggests promising pathways for climate-informed local and regional frequency analysis of rainfall extremes.

Keywords: Regional frequency analysis, extreme rainfall, climate index, nonstationarity, correlation

Does River Basin Morphology Reflect Landscape Evolution?

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Understanding landscape evolution is crucial for interpreting how Earth and other planetary surfaces respond to environmental changes. In fluvial landscapes, river networks of a drainage basin serve as the primary structural element, much like skeletal structures in any biological organisms, holds valuable information about their evolutionary processes and functional dynamics. Observations reveal that some river networks form elongated, narrow basins, while others develop into more branched and compact morphologies. This variation raises a key question: Is River basin morphology intrinsically linked to landscape evolution? Using topographic data from 25 islands, we demonstrate a positive correlation between Hack's exponent (h), which quantifies basin elongation, and relative energy expenditure (E), derived from the Optimal Channel Network (OCN) algorithm. Here, E serves as a proxy for landscape age, based on the principle that river networks evolve into tree-like structures to optimize energy efficiency. Our results indicate that landscape evolution drives a gradual transition toward more compact morphologies. Further analysis of six Hawaiian Islands with well-documented geological ages confirms this pattern, supporting the hypothesis that landscapes evolve to minimize energy expenditure, leading to more compact basins over time. To validate these findings, we employ simple Stream Power Incision Model (SPIM), selected for its computational efficiency in capturing key geomorphic trends. The model further substantiates that h systematically decreases with time, reinforcing its role as an indicator of landscape evolution. Our study thus underscores the significance of h and E as key metrics in understanding landscape evolution and its connection to river basin morphology. These findings contribute to the broader field of geomorphology, with implications for landscape evolution modelling in terrestrial and planetary contexts.

Keywords: Hack's Law, Landscape Evolution, Optimal Channel Network, Basin Morphology, Stream Power Erosion Model, Geomorphology

Joint probability modelling of flood variables for the design flood estimation in South Africa

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Accurate design flood estimates associated with high return periods are essential for the design and

management of hydraulic structures such as dams. These estimates are typically derived through univariate flood frequency analyses, primarily focusing on peak flows. However, floods are inherently multivariate phenomena, making it crucial to consider representative flood characteristics, such as flood peak, hydrograph volume, and hydrograph duration, to conduct a comprehensive analysis. Multivariate flood frequency analyses have traditionally employed standard bivariate distributions to model correlated variables, such as peak and volume. Yet, these methods only study the joint probability of flood peak and volume alone, a design flood hydrograph cannot be summarised by the two scalars only. Still, these approaches have limitations, including the requirement to use the same type of marginal distribution for all variables and the assumption of a linear dependence relationship between them. Recently, the use of copulas has gained traction in hydrology due to their advantages in handling the multivariate context, as they overcome the shortcomings of the traditional approach. A copula is a function that captures the dependence structure of the studied variables and enables the determination of their multivariate frequency distribution using their marginal distributions, regardless of the types of marginal distributions considered. The estimation of multivariate return periods, and consequently multivariate quantiles, is also facilitated by the formulation of copulas. The motivation for the research resides in the need to update and improve the traditional approaches used by hydrological practitioners and create a joint distribution function between flood variables through multivariate flood frequency analysis.

Keywords: Design flood estimation, univariate flood frequency, multivariate flood frequency, copulas

Assessing the Effectiveness of Agricultural Drought Indices: A Multiplex Networks Perspective

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Agricultural drought poses a significant threat to crop growth and food security, and this threat is likely to intensify under future global warming. Proper assessment of this threat using the various existing drought indices is complicated, as such indices employ different definitions and algorithms, leading to potentially inconsistent results. This study introduces a novel complex networks-based approach, specifically employing a multiplex network, to evaluate the performance of eleven drought indices in detecting drought impacts across agro-ecological zones of India. The analysis further explores their spatial relationships with root zone soil moisture (RSM) and Solar-Induced Fluorescence (SIF) using a multiplex signed visibility graph (MSVG) approach. This technique, adapted from social network analysis, extends the concept of signed networks to visibility graphs. In the MSVG approach, edges between nodes carry both positive and negative signs, reflecting direct and inverse visibility, respectively. This dual-edge methodology allows for the comprehensive mapping and analysis of complex relationships between drought indices. Specifically, we compute the MSVG parameter, i.e., interlayer mutual information. The MSVG approach is applied to construct networks for drought index data spanning the period from 2001 to 2017. Our findings show high mutual information between precipitation-based indices (SPI, SPEI, scPDSI) and root zone soil moisture (RSM) in arid and semi-arid regions. In contrast, temperature-focused indices show weaker correlations with RSM. Indices that integrate precipitation and temperature (SCEI, SPEI) correlate well with SIF. However, in

humid regions, these indices have lower mutual information, suggesting more stable environmental conditions. Indices assessing evapotranspiration and vegetation stress (ESI, TVDI) are effective in semi-arid areas, correlating well with RSM and SIF, and underscoring vegetation health impacts on soil moisture and photosynthesis. Our study confirms that the MSVG technique is a powerful tool for analyzing complex, nonlinear relationships between time series, offering a robust framework for understanding agricultural drought dynamics.

Keywords: Multiplex Signed Visibility Graph, Interlayer Mutual Information, Soil Moisture, Solar-Induced Fluorescence.

GEV Annual Maximum Precipitation Quantile with Regional Shape Parameter

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A strategy to reduce uncertainties in annual maximum precipitation quantile estimators is to employ regional information. Regional regression models employing climatic and other physiographic characteristics can supply estimates of hydrologic statistics of interest, which can be combined with at-site estimators. This paper employs a Bayesian approach for the analysis of regional regression models of the GEV shape parameter for many sites located in the south of Brazil. Results illustrate the differences among OLS, WLS, and GLS regression models, and contrast the method-of-moments and Bayesian estimators. The resulting regression model for the region supplies regional estimates of the shape parameter and the associated variance needed to define regional prior distributions. These priors are then employed with the Generalized Maximum Likelihood (GML) method to estimate extreme precipitation quantiles. Results show that the regional prior on the GEV shape parameter reduced the uncertainty in the extreme precipitation quantiles estimators and improved the performance of ML estimators.

Keywords: Extreme precipitation, Bayesian analysis, Regional regression

Apprehending total water storage components of GRACE using temporal decomposition for the Ganga basin

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The Ganga basin is currently facing significant strain on its water resources due to burgeoning population growth and the impacts of climate change. Given the extensive area of the basin, traditional ground-based hydrological data and in situ observations are inadequate. Consequently, remote sensing data, particularly from the Gravity Recovery and Climate Experiment (GRACE) satellite and

its follow-up mission (GRACE-FO), has emerged as a vital tool for assessing terrestrial water storage anomalies (TWSA) on a broader scale since 2002. Understanding the contributions of various water storage components to TWSA is essential for detecting hydrological trends and variations. However, GRACE data lacks information on the vertical distribution of water within the Earth's profile. This study seeks to decompose GRACE TWS into distinct components-surface water, shallow and deep soil moisture, and groundwater using a wavelet decomposition technique. By employing storage components from the GLDAS-CLM model as a reference, this approach aims to enhance the utility of GRACE data for evaluating large-scale hydrological models, ultimately facilitating improved management of droughts, floods, and other hydrological phenomena.

Keywords: GRACE, Terrestrial water storage anomalies (TWSA), Wavelet decomposition technique

Towards improved flood risk management in Cote d'Ivoire: Digitization of pluviographs and incorporation of rainfall non-stationarity

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Intense short-duration rainfall events, exacerbated by climate change, are increasing the risk of urban flooding in West Africa, threatening critical infrastructure. However, the lack of reliable sub-daily rainfall data complicates the accurate design of hydraulic structures. This study proposes a solution through the digitization of these historical records and the integration of advanced statistical methods to account for rainfall non-stationarity.

The National Meteorological Directorate of Côte d'Ivoire has undertaken the digitization of pluviographs from 14 synoptic stations covering over 30 years (1940-2023) using the NUNIEAU software. These digitized data have enabled the recalculation of Intensity-Duration-Frequency (IDF) curves using established methods, such as exponential law fitting and the Montana law. Traditionally based on the assumption of stationarity, these curves have been reassessed to incorporate non-stationarity induced by climate change. To achieve this, a non-stationary Generalized Extreme Value (GEV) model was applied, allowing the distribution parameters to vary over time or with other climatic variables. This approach provides a more accurate representation of rainfall extremes in a changing climate.

Preliminary results indicate that the updated IDF curves reflect an increase in rainfall intensities over certain periods, suggesting an intensification of extreme events. These data enable better sizing of hydraulic infrastructure, particularly in critical areas such as Abidjan, where flood risks are high. While stationary methods remain useful for current risk management, they fail to capture long-term climate trends, justifying the use of non-stationary models for more robust planning.

In conclusion, this study highlights the importance of digitizing historical pluviographs and integrating advanced statistical methods to improve flood risk management in Côte d'Ivoire. These efforts, supported by IRD and UNESCO under the IRN ActNAO program, contribute to the preservation of historical data and the updating of hydrological standards in West Africa, aligning with the objectives of the WMO's DATA RESCUE program.

Keywords: pluviographs, digitization, non-stationarity, IDF curves, flooding, climate change, statistical modeling.

Detecting trends in extreme long duration rainfall data in KwaZulu-Natal, South Africa.

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Detecting trends in hydrological extremes is vital for adequate design of hydraulic structures. The current methods and models used to estimate design rainfall and flood in South Africa assume that data and hydrological processes are stationary. However, the increased reported flood events in South Africa have raised the question of whether changes in the magnitude and frequency of observed extreme rainfall events are already evident in South Africa. Therefore, there is a need to determine if there are changes in rainfall event trends and to develop a method to account for non-stationary models in extreme design rainfall and flood estimates. Several studies have shown that non-stationary design flood estimation is mainly influenced by incorporating rainfall as a covariate. Therefore, this study will investigate trends in 1-day, 3-day, 5-day, and 7-day rainfall to determine which duration is most suitable to be used as a covariate in non-stationary design flood estimation in South Africa. In this study, the peak-over threshold approach was used to extract 1-day, 3-day, 5-day, and 7-day rainfall exceeding the 90th, 95th, 99th, and 100th percentile from 46 observational stations with a 50-year record length in KwaZulu-Natal, South Africa. Temporal trends in the data were investigated using the non-parametric Man-Kendall tests. The results indicate weak evidence that the daily rainfalls have increased in magnitude and frequency over time in the different durations. The trends detected in the magnitude of the extracted daily rainfall varied across the sites, with most stations showing no trends.

Keywords: Trends, Non-stationarity, Hydrological Extremes, Rainfall

Characterizing Rainfall Thresholds for Landslide Early Warning in the Indian Himalayas

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Satellite based precipitation products provide accurate estimates for rainfall magnitude covering large spatial and temporal scale. These estimates are vital for studying climate extremes in data scarce regions. These data scarce regions include Himalayas, where assessing rainfall-induced landslide susceptibility and developing early warning systems is crucial. To build these systems, it is necessary to identify precipitation thresholds that trigger landslides. This study focuses on employing the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) precipitation product to assess the landslide thresholds in the Indian Himalayas. The study uses 491 instances of landslides in Indian Himalayas to find precipitation thresholds over different categories of slope angle values. The thresholds were calculated using exceedance probability on precipitation ranging from single day to 7-day cumulative rainfall. For relatively gentle slopes (0-10 degrees), landslide initiation is associated with rare rainfall events, with exceedance probabilities of 0.1512 for single-day precipitation and 0.18 for 7-day cumulative rainfall. On the contrary, for steeper slopes like the category 40 to 50 degrees slope the threshold for landslide initiation is not that rare with exceedance probability of 0.209 and 0.265 for single day and 7-day cumulative rainfall respectively making these regions more susceptible to landslides. The study reveals that landslides generally occur at the precipitation thresholds that have about 0.15 to 0.20 exceedance probability with slope angle being an important factor. The findings provide a foundation for improving landslide forecasting models, enabling better disaster preparedness and risk mitigation efforts in the Indian Himalayas.

Keywords: Precipitation, Landslides, Thresholds, ERA5, Slope, Susceptibility, Forecasting

Multivariate analysis of extreme space-time rainfall events based on raingauge data

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Design rainfall estimation is essential for hydrological infrastructure planning and risk management. Traditional methods primarily focus on rainfall intensity, often neglecting crucial event-scale factors such as spatial extent, duration, and total precipitation volume, which significantly influence rainfall-runoff modeling. To overcome these limitations, this study introduces a multivariate approach that integrates additional physical characteristics to improve design rainfall estimation.

A crucial first step involved constructing a comprehensive rainfall event dataset for Tuscany, Italy, using high-resolution time series data from 270 rain gauges (1999-2024). To transition from point-based intensity data to event-scale analysis, specific criteria were established to identify individual rainfall events. This process involved grouping measurements based on spatial and temporal proximity, followed by interpolation techniques to derive a unified set of event characteristics. The final

dataset encompasses key attributes such as total volume, duration, and spatial extent, providing a more complete representation of each event.

Two modeling approaches were applied to analyze event characteristics and estimate return periods for extreme rainfall. The first approach utilizes Factor Analysis to reduce data dimensionality by identifying independent latent variables that explain linear relationships among features. While this enables separate marginal distribution analysis using univariate Peak Over Threshold (POT) techniques, it limits direct physical interpretability. The second approach leverages copulas to model dependencies among original event characteristics, offering a more flexible and physically meaningful framework for joint distribution analysis.

This study advances extreme rainfall understanding by presenting a robust multivariate framework that enhances design rainfall analysis, ultimately supporting improved flood modeling and risk management strategies.

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Keywords: multivariate analysis, extreme rainfall

Surface Urban Heat Island in Indian Cities and Its Correlation with Urbanization

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The Urban Heat Island (UHI) effect, characterized by elevated temperatures in urban areas compared to their surrounding rural regions, is a critical phenomenon that significantly impacts urban planning, environmental sustainability, and human thermal comfort. As cities continue to grow and urbanize, the UHI effect exacerbates heat-related challenges, including increased energy consumption, heightened air pollution, and greater vulnerability to heatwaves. Understanding the dynamics of UHI is, therefore, essential for developing climate-resilient cities that can mitigate these adverse effects and enhance the quality of life for urban residents. This study delves into the complex nature of the Surface Urban Heat Island (SUHI) phenomenon, focusing on 30 cities across India. By analyzing temporal variations and exploring the correlation between SUHI and urbanization trends in the recent past, the research aims to provide a comprehensive understanding of how urban growth influences local climate patterns and heat distribution.

To achieve this, the study leverages satellite-derived land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, combined with an urbanization indicator obtained from remote sensing sources—namely Normalized Built-up Index (NDBI). These datasets enable a detailed assessment of SUHI intensity and its spatio-temporal heterogeneity across the selected cities.

Understanding the relationship between the NDBI and the SUHI effect is crucial for identifying how urbanization and land-use changes contribute to localized warming in cities. This relationship provides valuable insights for urban planners and policymakers to design strategies that mitigate heat intensity, promote sustainable development, and enhance climate resilience in rapidly urbanizing areas.

Keywords: Urban Heat Island (UHI), Surface Urban Heat Island (SUHI), Land Surface Temperature (LST), Normalized Built-up Index (NDBI), Urbanization, and Climate Resilience

Development of Intensity-Duration-Frequency Curves for Urban Infrastructure Design using Sub-Daily Disaggregated Rainfall Data

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Climate change is expected to increase the frequency of high-intensity, short-duration rainfall events, resulting in concentrated flooding and damage to water infrastructure. In this context, hydraulic infrastructure design often depends on the region-specific rainfall characteristics analyzed through Intensity-Duration-Frequency (IDF) curves that provide rainfall intensity values across various durations and return periods. However, the unavailability of fine-resolution data may lead to inaccuracies, particularly in capturing extremes for short durations, common in regions such as Northeast India. The objective of the study is to disaggregate coarser temporal resolution rainfall data using the Multiplicative Random Cascade model and use the disaggregated data to derive high-resolution IDF curves. The model framework uses station data from Guwahati, comprising a weighted approach and two micro-canonical models (baseline and dependent models) with Maximum Likelihood Estimation. It is observed that the dependent model outperforms the baseline model by more accurately capturing the statistical properties of observed data, though it tends to overestimate rainfall intensities for short durations and extreme events. Hence, the dependent output was used to derive IDF curves, validated against observed data. The model's applicability was further extended to future scenarios using CMIP6 climate models, with appropriate bias correction and disaggregation. This approach enhances the temporal resolution of the rainfall data, enabling the generation of more detailed IDF curves and helping to assess changes in extreme rainfall under different climate scenarios, crucial for climate resilient hydrological and engineering applications.

Keywords: Multiplicative Random Cascade Model, IDF Curves, Rainfall Disaggregation, Extreme Rainfall events, Climate Change, Bias Correction

Development of new framework on wavelet-based time-scale dependent sensitivity analysis of hydrological models

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Hydrological models are essential for understanding the dynamics of hydrological processes, which vary across different time scales from seconds to millennia. The accuracy of these models depends on appropriate calibration of parameters, which is often challenging due to issues such as scale mismatch, equifinality, and increasing dimensionality in complex models. Traditional calibration approaches do not account for the time-frequency dependency of parameter sensitivity, limiting model efficiency and interpretability. To address these challenges, we propose a novel framework for time-frequency-scale dependent sensitivity analysis using wavelet decomposition. By integrating Sobol's global sensitivity analysis with wavelet decomposition, we systematically identify the most influential parameters across different time scales and recalibrate the model based on their ranking in both time and frequency domains. We applied this approach to the GR4J and HBV hydrological models, demonstrating how parameter sensitivity varies across multiple levels of decomposition. The results reveal significant differences in parameter behaviour across time scales, some parameters which are influencing model outputs at short time scales may differ from that are dominating at longer scales, emphasizing the necessity of a multi-scale sensitivity analysis for improving model performance. Our framework enhances model calibration, provides deeper insights into parameter interactions, and supports better hydrological predictions. By bridging the gap between traditional calibration and multi-scale hydrological processes, our methodology improves model reliability and provides a more comprehensive understanding of hydrological dynamics.

Keywords: sensitivity analysis, wavelet decomposition, sobol

A Bayesian Copula-Based Integrated Drought Index (IDI) for Holistic Drought Monitoring in India

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Drought, a multifaceted and persistent hazard, disrupts agriculture, ecosystems, economies, and public health, necessitating robust assessment frameworks for effective water resource management and planning. Conventional univariate drought indices often fail to capture the interconnected nature of drought processes, limiting their predictive and comprehensive evaluations. To bridge this gap, we propose an Integrated Drought Index (IDI) that synergizes meteorological, hydrological, and agricultural drought. This study employs an Archimedean copula framework to integrate the modified Standardized Precipitation Index (SPI), Standardized Runoff Index (SRI), and Standardized Soil Moisture Index (SSMI), computed at various monthly timescales with a 0.25° spatial resolution across India from 1961 to 2024. Parameter estimation is performed using Bayesian inference via the Differential Evolution Markov Chain (DE-MC) algorithm, leveraging a hybrid approach that combines the differential evolution (DE) optimization strategy with Markov Chain Monte Carlo (MCMC)

simulations for robust and efficient inference. A suite of probability distributions, including gamma, weibull, log-normal, logistic, and generalized extreme value, is evaluated for marginal fitting, with the Kolmogorov-Smirnov (K-S) test identifying Gamma as the optimal fit for precipitation and GEV for both streamflow and soil moisture. Comparative assessments against modified univariate indices (SPI, SRI, and SSML) underscore the superior performance of the IDI in capturing the spatiotemporal evolution of drought events. The Bayesian copula-based methodology effectively encapsulates the complex dependencies between drought components, yielding a more holistic and actionable index. By integrating multiple drought indicators within a probabilistic framework, the IDI offers a significant advancement in drought characterization, facilitating improved decision-making for policymakers and resource managers. This novel approach enhances the understanding of drought dynamics, equipping stakeholders with a powerful tool for mitigating drought impacts in an era of increasing climate variability.

Keywords: Drought, Bayesian Inference, Copula, Integrated Drought Index

Unravelling the Spatiotemporal Variability of Soil Moisture and Soil Temperature Across India (1961-2023): Insights from ERA5 Reanalysis Data

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Soil moisture and soil temperature fundamentally shape terrestrial ecosystems by influencing the regional water-heat balance between land and atmosphere. These variables are essential for climate change assessments and adaptation, yet historical in situ measurements remain sparse and spatially uneven. Reanalysis products, such as the fifth-generation ECMWF Reanalysis (ERA5), offer a valuable alternative for understanding long-term variations in soil states. This study investigates the spatiotemporal evolution of soil moisture and soil temperature across India using ERA5 data from 1961 to 2023 at a $0.25^\circ \times 0.25^\circ$ resolution. The analysis considers four soil layers: 0-7 cm, 7-28 cm, 28-100 cm, and 100-289 cm. To extract non-stationary trends and intrinsic patterns, we employ the Multidimensional Ensemble Empirical Mode Decomposition (MEEMD) method. Our findings reveal an increasing trend in soil moisture in the top layer (0-7 cm) across most of India, with a persistent neutral trend along the West Coast and the northeastern states. In central India, soil moisture exhibits a consistently increasing trend across all layers, likely driven by enhanced precipitation due to climate change, while south-central India shows a decreasing trend of soil moisture over time along the bottom layers. Conversely, soil temperature trends display spatial heterogeneity, with a significant decrease over central India but a notable increase across southern India. The evaluation of soil moisture and soil temperature confirms physically consistent water-heat covariations, underscoring the intricate interactions between these variables. These findings highlight the influence of hydro-climatic changes on soil conditions and provide critical insights for land-atmosphere interactions, agricultural planning, and climate resilience strategies in India.

Keywords: Non-stationarity, Trend, MEEMD.

Exploring Spatial Drought/Flood Synchronization Across India in a Multidimensional Framework

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Tropical countries like India have been experiencing widespread extreme hydrological events occurring simultaneously across large regions. When hydrological extremes co-occur across a large region, their cascading effects amplify societal and economic disruptions. Conventional approaches to risk management have mostly focused on individual hazards, underestimating the complex nature of climate extremes that propagate spatially and temporally simultaneously. We lack an in-depth understanding of spatially connected event occurrences and which are the areas where the occurrence is coupled. This study explores the connectedness, asymmetry, and synchronization of streamflow extremes across multiple stations over India. The results show significant spatial as well as temporal connectivity in streamflow extremes over different parts of India. The outcome of research enhances the understanding of the connectivity between extreme events across India which helps to improve prediction before the events spread to a larger area and leads to effective preparedness.

Keywords: Hydrological extremes

Insurance as a tool to manage the flooding risk

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Natural Catastrophe (NatCat) risk mitigation actions can be classified in two main groups: land and event management. The first includes actions aimed at improving knowledge, reducing risk through both structural and non-structural actions and preparing for the event. In this general framework, insurance finds its specific place within non-structural actions, which do not intervene to modify the event or its probability of occurrence but limit or cancel its consequences. Insurance does not reduce the economic consequences of a flood event but rather transfers them from the insured to the insurer.

The low global diffusion of NatCat insurance products on the market can be associated with several aspects. The fundamental one derives from risk accumulation, originating both from demographic and economic development and from the globalization of markets and trade, and further intensified by the significant territorial extension of the affected areas. Furthermore, the damages caused by natural disasters are increasing due to the influence of ongoing climate change.

This paper investigates the impact of recent research results, available in the hydrological fields of flood and inundation processes, on the NatCat insurance market. Specifically, the location, size and intensity of flood and inundation events, associated with the spatial arrangement of the exposed elements, are used to evaluate significant insurance-related parameters such as the expected losses associated to given return periods and insured portfolios.

The extreme applicative importance of the results derives from the significant set of decisions taken in this area by public bodies and economic-financial sectors: development planning, civil and environmental protection. Among these, the significant role that the State is called to assume in outlining

insurance policies and in defining its possible role as insurer of last resort is underlined, together with the main implications for urban development planning and flooding risk mitigation.

Keywords: Natural Catastrophe, Flood risk mitigation, Insurance, Development planning

Resolving Data scarcity: A cluster-based rainfall regionalization of Kerala, India

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The unavailability of long-term historical data and unequal spatial distribution of rain-gauge stations are some of the major challenges encountered in the spatial and temporal analysis of rainfall datasets. In this study, a K-means cluster-based rainfall regionalization approach has been applied along with statistical characterisation of rainfall trends and patterns across the state of Kerala, India. Daily gridded rainfall data (0.25×0.25 degree) for 47 grids from 1901 to 2022 (122 years) have been taken from the India Meteorological Department (IMD), Pune. The analysis revealed that Kerala can be delineated into 3 clusters based on its rainfall similarities. The reliability of the clustered map is verified using daily rainfall data (varying data lengths) collected from 40 rain-gauge stations maintained by the Irrigation Design and Research Board (IDRB), Kerala. The rain-gauge stations can be easily clustered according to their geographic location by spatially plotting them on the clustered map. However, in order to access the rainfall homogeneity, a comparative analysis of statistical characteristics of rainfall is also performed using both gauged and clustered datasets. In terms of geographic location and rainfall statistics, it was determined that the rain-gauge stations belonged to the same cluster. This confirmed that the three homogeneous clusters of rainfall take into account not only the geographic location but also effectively capture the state's overall rainfall patterns and characteristics, providing a reliable foundation for Kerala's hydrological research. Notably, the study concluded that the IMD's gridded rainfall dataset can serve as a better substitute for conventional rain-gauge station data, offering a free and reliable long-stretch data solution for future studies, especially in locations where data scarcity is a major concern.

Keywords: rainfall, cluster, regionalization, gridded rainfall data, river-gauge station data, data scarcity

Understanding hydrodynamics of three spring clusters in Leh region of Ladakh Union Territory

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Year-round flow consistency of trans-Himalayan springs is crucial for water demands. This study focuses on the Leh Watershed of Ladakh, India, which covers 136.28 km². Leh, the capital, relies on natural springs for drinking water, especially in winter. The springs in Leh are fed by melting snow and glaciers. Seven spring outlets, three from Skara, three from Changspa, and one from Chubi, were studied. These springs are all 3300 meters above sea level. The springs were selected based on accessibility, local drinking water usage, and expert consultation. Daily monitoring of spring discharges began in May 2024. All springs are perennial, and their mean discharges varied from 0.82 lpm to 27.61 lpm from May to December 2024. Chubi Spring had the highest mean discharge (104.67 lpm), while Changspa-II had the lowest (5.14 lpm). The average spring discharges at Chubi, Skara-II, Skara-III, Skara-I, Changspa-I, Changspa-III, and Changspa-II were recorded to be 104.67, 34.08, 32.14, 27.61, 20.84, 10.37, and 5.14 lpm, respectively. Classifying them according to the Meinzer (1927) system, Chubi was the fifth-order spring, Skara-I, Skara-III, Skara-IV, Changspa-I, and Changspa-III were the sixth-order springs, and Changspa-II was the seventh-order spring. The FDCs were analyzed for slope characteristics and overall variability. Skara-I, Skara-II, Changspa-I, and Changspa-II had moderately flat slopes, while Skara-III and Chubi had steep slopes. The springs were classified as "extraordinarily balanced" and "unbalanced" based on the FDCs. Continuous monitoring and analysis are essential for ensuring the reliability of Leh's drinking water sources, and further efforts are being made to understand the hydrodynamical characteristics of these springs for sustainable water availability.

Keywords: Spring, FDCs (Flow Duration Curve), Daily monitoring, Aquifer, Leh, Ladakh

Change in probable maximum precipitation in a changing climate over the Upper Indus Basin.

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A precise evaluation of probable maximum precipitation (PMP) is essential for determining the resilience of high-risk water infrastructure, optimising water resource management, and mitigating hydrological hazards. Generally, PMPs are estimated assuming static climatic conditions with a high spatial resolution that neglects the variation in complex geography. Climate change (CC) induced global warming to accelerate the hydrological cycle and increase the extreme events, indicating the account for climate change in estimating PMPs. Neglecting CC PMP estimation will lead to an increased underestimation of flash flood disasters in the Upper Indus Basin, which frequently experiences such extreme events. Understanding these changes is crucial for effective flood risk

management and developing resilient infrastructure in the region. This study uses daily ERA-5 precipitation data from 1941 to 2020 as the historical data and CMIP6 data for the two Concentration Pathways (RCPs) to generate a map of the 1-day PMP. The Historical time series is divided into two parts (1941-1980) and (1981-2020). The future period is divided into three parts: near future (2021-2050), Mid-future (2051-2080) and far future (2081-2100). The modified Hershfield method is used to estimate PMP with an updated method for the enveloping technique. The expected outcomes are a rise in the percentage of PMP after 1980 (1981-2020) compared to 1940-1980. Similarly, the estimation of changes in the PMP of near, mid, and far future in comparison to the recent past (1981-2020). These results are helpful for policymakers in creating early warning plans, developing disaster mitigation strategies, and ensuring resilience against future hydrological extremes.

Keywords: Probable Maximum Precipitation, Climate Change, Upper Indus Basin, Hershfield method

Evaluating the Performance of Uni- and Multivariate Bias Correction Techniques: Challenges in Preserving Temporal and Dependence Structures

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Global Climate Models (GCMs) are the most reliable tools for simulating past and future climate scenarios, despite inherent knowledge gaps and variability. However, their systematic errors and coarse spatial resolutions limit their direct application in scientific analyses and impact assessments. To address these issues, bias correction (BC) and downscaling techniques, including dynamical and statistical approaches, are employed. Among statistical downscaling methods, quantile mapping (QM)-based bias correction is widely used in climate change impact studies. However, QM operates on a univariate basis, potentially distorting inter-variable and temporal dependencies, which can propagate biases in subsequent analyses. This limitation has driven research toward multivariate bias correction (MBC) methods that aim to restore multidimensional dependencies. Despite recent advancements, the applicability and assumptions of MBC methods remain poorly understood, leading to inconsistencies in their results. This study systematically compares the performance of three MBC methods-Dynamical Optimal Transport Correction (dOTC), Rank Resampling and Distribution Dependences (R2D2), and N-dimensional multivariate bias correction (MBCn)-alongside the univariate QM method in reproducing various statistical features of precipitation and temperature across the Indian subcontinent. Additionally, it evaluates the effectiveness of these methods in preserving dependence structures crucial for capturing complex climate signals, particularly in the context of the Pacific Walker circulation. The findings provide practical guidance for end users in selecting appropriate bias correction methods for climate applications.

Keywords: Bias Correction, Univariate and Multivariate methods, Precipitation and temperature, Pacific Walker circulation, Climate change, India

Application of Polynomial Chaos Expansion method for hydrological model uncertainty

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Hydrological models are effective and efficient tools in the quantification of hydrological processes such as runoff, evapotranspiration and groundwater contributions over a region, which plays a vital role in the preparation of water management strategies. However, associated uncertainties are unavoidable in the modelling process due to a variety of reasons, including insufficient understanding and representation of natural processes, and other associated errors and approximations in the modelling process. Thus, this study aims to efficiently measure parameter uncertainty using surrogate modelling techniques. Model complexity and parameter uncertainty are inherently trade-offs; that is when a sophisticated hydrological model with high model accuracy is used, parameter uncertainty typically rises while the necessary computational effort also rises dramatically. To account for this trade-off, the present study considered the Soil Water Assessment Tool (SWAT). Computationally intensive simulations often hinder hydrological modelling processes; therefore, the modellers can opt for surrogate models, which mimic the simulation model and also reduce the computational burden. Therefore, the present study utilized both Polynomial Chaos Expansion (PCE) and Least Angle Regression (LAR) to build an effective surrogate model in the quantification of uncertainty in model predictions, especially when a large number of model runs are needed or the model takes a long time. It is found that LAR-PCE outperforms Ordinary Least Squares (OLS)-PCE with the same or better accuracy in estimating its coefficients with a smaller number of runs. Also, this study emphasized the application of PCE in improving the model performance and its advantage especially for complex models.

Keywords: Hydrological model, Polynomial Chaos Expansion, Uncertainty assessment, SWAT model

Streamflow drought indices in the Morava River basin - an update

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It has already been over five years since a comprehensive study was conducted analyzing selected mean daily discharge series from the Czech territory of the Morava River basin. Therefore, the current contribution is meant as an update, taking into account the data from the identical water-gauging stations until the end of 2023. The same streamflow drought indices were derived, including 7-, 15- and 30-day low flows for each possible water-management year (starting on 1 April), and for summer (April-November) and winter seasons (December-March). The time series were accompanied by the information on low-flow timing (i.e. Julian days; first occurrence). Other derived streamflow drought indices were the deficit volume and the drought duration considering seasonal (monthly)

thresholds defined as 90th and 95th percentiles of flow duration curves. Using the time series of all the indices with the longest ones allowed by the length of the discharge series and the two other types representing hydrological reference periods 1981-2010 and newly 1991-2020, trend analyses were performed allowing for the presence of short-term persistence as well as long-term persistence. In the case of deficit volumes and drought durations, only the summer seasons were investigated, because they provided a reasonable amount of data for studying trends (i.e. series of sums and maxima). A different approach was applied to estimate the missing data in a few time series of discharge. Linear models were constructed for individual Julian days for all individual stations, based on which estimates of missing values better reflecting the seasonal course were obtained. This way, the results coming from much longer time series could be compared (e.g. through plots or maps).

Keywords: climate change, stochastic processes, statistical hydrology, missing value imputation, Moravia, Czech Republic

A rainfall runoff database for improving the flood forecasting: The Case Study of the Crati River Basin - the Tech4You Project

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Exposure to major natural hazards has increased worldwide, due to the growth and spread of urbanisation phenomena. It is of paramount importance to identify the most effective measures to adequately mitigate the impact of extreme events, taking the ongoing global climate change into account. Among natural hazards, there is evidence that floods and flash floods are increasing on a global scale, resulting in increased human and economic losses. Moreover, from a sociological perspective, robust institutional frameworks and effective governance are essential to ensure that scientific findings and technological solutions are translated into concrete, community-centered policies and practices. By building trust, enhancing capacity, and fostering collaboration, institutions play a crucial role in bridging the gap between research-driven innovation and real-world applications, ultimately increasing societal resilience and sustainability in the face of increasing flood risks. In Italy, a country particularly prone to extreme natural events, a number of different initiatives have been launched to monitor, predict and mitigate the effects of extreme floods. Among them, research projects such as the TECH4you PNRR project, funded by the Italian Ministry of Universities and Research, have been initiated. TECH4you is the Calabria and Basilicata innovation ecosystem, whose main purpose is technology transfer of research products to the territory for the development of innovation. The establishment of an effective early warning system for flood forecasting several days in advance would be beneficial.

The objective of this work is to present a comprehensive rainfall-runoff database, which will be used as an integrated tool for flood forecasting in the Crati river basin, in Calabria. The database will contain a substantial number of rainfall-runoff scenarios, accounting for the inherent uncertainties in rainfall forecasts and soil moisture conditions. Consequently, this work will demonstrate how decision-makers can readily ascertain the potential stream flow values resulting from defined rainfall amounts, and viceversa.

Keywords: stochastic modelling, Flood forecasting

Incorporating Non-Stationarity in Design Flood Estimation Guidance

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The relevance of stationarity, which assumes that the future is informed by past knowledge, is being challenged with climate change. With unprecedented changes in both the intensity and frequency of extreme hydro- meteorological events, the past can no longer aptly predict the future. This begs us to question the reliability of the traditional methods that assume stationarity, to estimate the design flood of our hydraulic structures. Several approaches that incorporate non-stationarity have been proposed to make our hydraulic structures future proof. However, they have not found footing in the real-world application due to numerous uncertainties involved in them such as the uncertainty in the future climatic data. This study aims to shed light on these non-stationary approaches and understand their limitations. The study starts with a review of the traditional methods used for determining the design flood, then the drawbacks and alternatives to the hydrologic design approach of return period are covered. The equivalent reliability method has been deemed the most suitable alternative to the return period till now. Different non-stationary approaches for estimating design floods are analysed followed by how uncertainty is managed within decision-making framework. The existing flood estimation guidelines in India and the world are also covered in brief. Our results provide a comprehensive understanding of current advancements and limitations in non-stationary design flood estimation to support more adaptable and robust flood infrastructure planning.

Keywords: non-stationarity, design flood, return period

Comparative Analysis of the compounding effects of zero and extreme rainfall events with extreme temperatures in the southern peninsula of India

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The Southern peninsula of India is notably influenced by fluctuations in post-monsoon climate. The cumulative impact of extreme hydrometeorological occurrences may inflict significant harm on agriculture, human health, and infrastructure. This study seeks to analyze the simultaneous occurrences of exceptionally high temperatures alongside both zero-rainfall and extreme rainfall on the southern peninsula of India during the post-monsoon season. We used gridded data for daily precipitation and maximum temperature from the Indian Meteorological Department (IMD) during 1951-2023 to examine the frequency of these compound events by joint frequency analysis. We also examine the alteration in the spatial extent of influence of these compound occurrences during the given period. Extreme temperature (precipitation) is characterized by daily maximum temperature (rainfall)

beyond the 90th percentile. A co-occurrence lasting three consecutive days is regarded as a single occurrence. The research enables us to recognize regions characterized by zero rainfall and excessive temperatures, as well as those where extreme rainfall and temperatures frequently coincide. A decline in return periods and a steep trend of occurrences indicate that the south peninsular region is especially vulnerable to compound climatic extremes. This study's findings highlight the regional diversity of compound climatic extremes, underscoring the need for targeted adaptation techniques to mitigate their impacts on water resources, agricultural systems, and overall catastrophe resilience. This research combines statistical hydrological methods with climate risk evaluation, providing significant insights for policymakers.

Keywords: compound events, post-monsoon, southern peninsula, trend analysis

Recurrence Analysis of Streamflows of Krishna River Basin

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Analysing the non-linear characteristics of streamflow is crucial for understanding river dynamics and assessing the influence of hydraulic structures. This study investigates the non-linear behaviour of streamflow in the Krishna basin using recurrence plots and recurrence quantification analysis (RQA). Daily streamflow data from 14 gauging stations in the basin, spanning 17 years (1985-2001), were analysed. Recurrence plots and RQA metrics such as determinism, diagonal length, and recurrence rate were used to assess patterns of predictability and uncertainty. The mean determinism for the basin was found to be 0.82, indicating overall high predictability. However, significant spatial variability in streamflow dynamics was observed. Notably, stations influenced by hydraulic structures, such as the Koyna Dam and Rajoli Banda, exhibited the lowest determinism and average diagonal length, indicating reduced predictability due to anthropogenic influence. Conversely, the Arjunwad station, located away from major hydraulic structures, showed the highest determinism. However, its high percentage of zero values (approximately 65%) adds complexity to its predictability. Downstream stations of major dams, including Nagarjuna Sagar and Tungabhadra, showed relatively higher predictability, reflecting the regulated nature of their streamflows. The station downstream of the Jurala Project exhibited very low recurrence rates, indicating reduced streamflow consistency. These findings highlight the significant influence of hydraulic structures on streamflow dynamics, emphasising their implications for effective water resource management and planning in the Krishna basin.

Keywords: Recurrence Analysis, Streamflow, Krishna Basin

A Copula-Based Approach for Estimating Temporal Probability of Landslides using Hydrometeorological factors

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Rainfall is often the triggering factor for landslides in regions that experience heavy precipitation, such as the Western Ghats in Kerala, India. The increase in landslides in the mountainous regions emphasizes the importance of considering the trigger-cause factors when assessing landslide hazards. This study presents a new framework for integrating hydrometeorological parameters, such as rainfall and soil moisture, using a joint probability technique using copula functions. The work demonstrated an application of the above approach for the landslide occurrences in the Kottayam district of Kerala, India. Initially, the rainfall and soil moisture thresholds causing landslides in the multisite of the study area were obtained. The hydrometeorological components were fitted with their marginal distributions and then the best fitted Archimedean copula was identified. The temporal probability of landslides over a period of 1 to 50 years was then determined by computing the conditional exceedance probability of the rainfall and soil moisture thresholds. The results indicated that incorporating a joint probability approach can significantly enhance the accuracy of temporal probability estimation compared to those based on rainfall threshold alone. This study showed the potential of joint probability approaches to improve landslide hazard mapping reliability. Furthermore, it provides valuable insights to aid in effective landslide risk management and mitigation strategies in areas susceptible to landslides.

Keywords: Landslide, Temporal Probability, Copula, Rainfall, Soil Moisture

Evaluating the Water Availability Status in Jammu and Kashmir using Statistical Hydrological Approach

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Water is essential for socio-economic development in Jammu and Kashmir, supporting agriculture, hydropower, tourism, and domestic use. However, the region's unique geographical and climatic conditions pose challenges to sustainable management. This study uses ILDA, integrating land surface and hydrodynamic modeling with ground station data to assess water supply and balance. The water budget quantifies the balance between water availability and demand across different sectors, establishing a robust foundation for water management strategies. The study for the year 2022 delineated that the Total Storage (TWS) estimated exhibits the highest water availability of 9.595 BCM and 6.332 BCM in the Kishtwar and Doda districts, respectively. On the other side

Shopian records the least availability at 1.302 BCM, closely followed by Kulgam and Ganderbal with 1.926 BCM and 1.970 BCM, respectively. Amongst the various districts of the UT of Jammu and Kashmir, Badgam exhibited the highest demand at 2.669 BCM, followed by Jammu with 2.333 BCM, and Baramulla with 2.090 BCM. On the lower end of the spectrum, districts like Ramban, Reasi, and Shopian reported much lower water demands, at 0.372 BCM, 0.351 BCM, and 0.385 BCM, respectively, due to limited agricultural activities and less industrial development compared to other regions, etc. Considering some scenarios, we estimated the water balance for 2032 and 2052. The district of Kishtwar exhibits the highest water balance across all years, with values of 9.011 BCM in 2032, 8.958 BCM in 2042, and a slight decrease to 8.905 BCM in 2052. On the other hand, Ganderbal has one of the lowest projected water balances, starting at decreasing to 0.215 BCM in 2032, decreasing to 0.051 BCM by 2042 and decreasing to 0.113 BCM by 2052. The study emphasizes the usage of assimilated data over conventional hydrological models that provide administrative-level water resource management capabilities.

Keywords: Hydrological Cycle, ILDas, Water Supply, Water Demand, Water budget, Indian Land Data Assimilation System (ILDAS)

Assessing the Transition from Meteorological to Hydrological Extremes: A Circular Statistics Analysis of Drought and Flood Dynamics in the Mahanadi Basin

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Climate variability is increasingly driving extreme wet and dry events, profoundly impacting water availability, ecosystem stability, and disaster risk management. Understanding the complex interplay between meteorological and hydrological extremes is crucial, particularly in assessing the transition from meteorological drought to hydrological drought and the influence of prolonged wet periods on streamflow patterns. This study investigates these relationships using the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Streamflow Index (SSI). To ensure a robust analysis, rainfall and temperature data from the India Meteorological Department (IMD) and discharge data from the GloFAS-ERA5 reanalysis dataset are utilized. Additionally, circular statistics are employed to examine the seasonal timing and patterns of extreme precipitation and streamflow events. A detailed trend analysis explores variations in drought and flood patterns on both monthly and seasonal scales, offering deeper insights into shifting hydrological extremes. The results identify critical periods when meteorological anomalies strongly influence streamflow responses, providing a clearer understanding of the temporal evolution, severity, and persistence of droughts and floods. The integration of circular statistical methods further uncovers key seasonal alignments between rainfall and discharge, enhancing our knowledge of drought-to-flood transitions. By distinguishing climate-driven and hydrological variability, this research strengthens early warning systems and supports data-driven water resource management strategies. The findings offer valuable insights for policymakers and disaster risk managers, aiding in the development of adaptive strategies to mitigate the growing threats of droughts and floods in the Mahanadi Basin.

Keywords: Circular statistics, Climate variability, Drought, Flood, Mahanadi Basin

Integrated Flood Characterization and Index Development in the Narmada Basin

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Floods are among the most devastating natural disasters, with their characteristics and impacts varying due to climatic and anthropogenic influences. Understanding flood dynamics is crucial for effective management and mitigation. This study investigates flood characteristics in the Narmada basin by analyzing volume, peak, and duration across 13 hydrological stations. These attributes were systematically derived to establish a comprehensive understanding of flood behavior in the basin. To integrate and quantify flood characteristics, an empirical joint distribution method was employed, leading to the development of a composite Flood Index. This index provides a holistic assessment of flood events by incorporating multiple flood parameters. Additionally, to capture the temporal variability of floods, two specialized indices were developed. The Long-Duration Flood Index (LDFI) was introduced to evaluate the persistence and severity of prolonged flood events, offering insights into sustained inundation risks. Meanwhile, the Short-Duration Flood Index (SDFI) was formulated to assess the intensity and frequency of short-duration floods, which are often associated with flash flooding and abrupt hydrological changes. The integration of these indices enhances the understanding of both long-lasting and short-lived flood events, providing a structured framework for assessing flood risks in the Narmada basin. By applying advanced statistical methodologies, this study contributes to improved flood prediction, management, and resilience-building strategies. The findings are valuable for policymakers, hydrologists, and water resource managers, enabling them to develop adaptive strategies to mitigate flood impacts and enhance regional flood preparedness. Overall, this research provides a data-driven approach to flood risk assessment, offering insights that can inform sustainable water resource planning and disaster management in the Narmada basin.

Keywords: Flood, Peak, Volume, Duration, Short Duration Flood, Long Duration Flood

Risk of Extreme Precipitation on Dam Infrastructure under changing climate over India

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India's aging dam infrastructure is at a critical juncture due to climate change and rapid urbanization. According to the National Large Register of Dams (NLRD) report (2019), the country has more than 5700 dams, which were designed based on the estimation of extreme events [such as design storm, 100-year return period precipitation, and Probable Maximum Precipitation (PMP)]. These extreme events were evaluated based on historical meteorological data and do not consider the effect of future climate change, which poses significant challenges to the safety of dam infrastructure. Here, we analyzed the risk of extreme precipitation events on dam infrastructure due to changing climate considering the observed and Global Climate Models (GCMs) datasets. Using observed

meteorological datasets, we evaluated the changes in the frequency and intensity of high precipitation (precipitation more than the 99th percentile) during the period 1951-2022 and found that the frequency and intensity of high precipitation have increased over the majority of dams except dams located in Brahmaputra River. The increase in frequency and intensity of high precipitation occurred during the period 1987-2022. Furthermore, we estimated 100-year return period precipitation using Generalized Extreme Value (GEV) distribution and PMP using the modified Hershfield method during the period 1951-1986 and 1987-2022. Our results showed that the risk of extreme precipitation has increased in the last few decades. In addition to the observed analysis, we evaluated the changes in the 100-year return period precipitation and PMP during the future climate using the CMIP6-GCMs. We found that the majority of dams observed frequent extreme precipitation in the future, which exceeds the historical 100-year return period and PMP (1-day) values under warming conditions. Overall, our findings highlight the escalating hydrological risks to dam infrastructure due to climate change. To minimize risk, regular dam safety assessments and inspections are essential for enhancing flood capacity.

Keywords: Probable Maximum Precipitation (PMP), Generalized Extreme Value (GEV)

Advancing Flood Forecasting and Early Warning Systems Through Multivariate Frequency Analysis

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Flood frequency analysis is essential for assessing and mitigating the risks associated with extreme flood events. However, conventional approaches often assume stationarity, overlooking the complex physical mechanisms driving changes in flood behaviour. This study tackles the challenge of nonstationary multivariate flood frequency analysis by incorporating multiple covariates that capture key physical processes influencing flood characteristics such as peak discharge, volume, and duration. Utilizing advanced statistical techniques, including copula-based modelling and covariate selection methods, we establish a robust framework for analyzing the dependencies and dynamics of flood variables under evolving climatic and hydrological conditions. Applying this framework to the Barakar River Basin, we identify significant nonstationary trends driven by covariates such as precipitation intensity, land-use changes, and soil moisture. Our findings indicate that the 100-year joint return period for extreme flood events has notably decreased from (219,247 8264.58) in the stationary case to (175,881 7,241.52) in the nonstationary case for the volume-peak pair. Similarly, for the duration-volume pair, the stationary 100-year return period has declined from (21.41 149,776) to (21.44 159,189) under nonstationary conditions. Additionally, the 100-year return level under stationary assumptions (8150.44 30.23) is significantly higher than its nonstationary counterpart (6995.5 25.09). By accounting for the temporal evolution of key flood variables, the proposed methodology enhances the reliability of flood risk assessments. While not directly aimed at early warning systems, the insights gained from this study can inform probabilistic flood forecasting models and improve disaster preparedness strategies. By integrating physical drivers into multivariate flood frequency analysis, this research advances the understanding of nonstationarity in flood regimes. The findings offer valuable implications for designing more adaptive and region-specific flood forecasting and warning systems, ultimately supporting global efforts to mitigate the impacts of extreme hydrometeorological events.

Keywords: Nonstationarity, Multivariate analysis, Climate change, Flood risk assessment, Flood extremes

Interpolation and simulation of precipitation in space and time using a combination of traditional observations and crowdsourced data

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Precipitation is the most important input for flood forecasting and hydrological modelling. The traditional rain gauge networks (primary networks) operated by national weather services are not able to capture the high temporal and spatial variability of precipitation, even in countries with dense networks such as in Germany. Precipitation uncertainty is the major cause of hydrological model errors and unfortunately it leads to a systematic underestimation of flood peaks. In order to improve precipitation estimates other sources of information have to be taken into account. In this contribution, the use of precipitation measurements from personal weather stations (PWS) for the improvement of estimation is investigated. Such PWS are typically operated by different agencies and private persons. The use of these PWS data requires a thorough quality control as these rain gauges are typically not installed and maintained according to professional standards and therefore prone to various errors and uncertainties. Therefore, a set of statistical filters which serve to filter out erroneous data is required. For this purpose, spatial indicator correlations and time power spectra are used. In space indicator correlations, in time power spectra are used for this purpose. The possible bias of the measurements is assessed by comparing precipitation distributions of nearby primary and secondary stations. The random error is assessed by a cross validation approach. The observations of the primary and the corrected secondary networks are interpolated using a modified Kriging and a Copula based interpolation approach. Additional influencing factors such as topography are included in a co-Copula approach. In order to assess the uncertainty a simulation model is developed which can be used to provide ensembles of precipitation realizations. Observations of the primary (1,000 locations) and the secondary network (up to 35,000 stations) for Germany are used to demonstrate the methodology. The examples show a significant improvements.

Keywords: Precipitation, interpolation, simulation, crowdsource data, statistics

Identifying threats to protection goals in intermittent rivers

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Understanding how climate change caused hydrological alterations affect risks to species and biodiversity preservation is of great societal relevance. In the ongoing research project carried out by Warsaw University of Technology, University of Life Sciences (SGGW) and University of Silesia we aim to: (i) obtain data on flow intermittence for the selection of representative protected areas and to use this data in hydrological models to identify the effects of climate change on flow intermittence; (ii) to test the suitability of environmental DNA for assessing the biodiversity of intermittent streams, and (iii) implement novel tools that can be used to set targets for species-based protection and preservation of biodiversity and to identify priority conservation areas. The project will also assess benthic invertebrate fauna communities and EU-protected species through standard (multi-habitat sampling) and molecular (targeted/metabarcoding eDNA approach) biodiversity assessments. A hydrological model will be used to determine the impacts of climate change on the frequency and duration of flow intermittence for the selected study sites. Finally, the project will detect and quantify flow intermittence effects on selected biodiversity indicators and translate the results to policy statements, stakeholder recommendations, risk assessments, and management and monitoring plans for protected areas.

Keywords: intermittent rivers, Central Europe, habitat, eDNA

Towards achieving reliable probabilistic hydrological predictions at the hourly scale

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Floods are among Earth's most widespread, frequent, and destructive natural hazards. In highly responsive catchments, daily streamflow predictions will underestimate flood hazards. For example, peak flows occurring on sub-daily timescales caused hundreds of fatalities and billions of Euros in damages in the devastating floods in Germany in 2021 and Spain in 2024. Particularly in small and mesoscale catchments: 1) peak flows may last only a few hours, so forecasts of daily flows can greatly underestimate flood peaks; 2) A landscape's responsiveness to precipitation depends critically on how wet it is; thus, it is essential to accurately model the wetting and drying of the catchment, and hourly streamflow is needed to capture and understand the hydrological processes in the rising limb of the hydrograph; and 3) the dominant processes affecting short-term predictions are not necessarily the same as those affecting streamflow at longer time scales. For example, over longer time scales, predictions become more a question of mass balance, rather than dynamics and routing, while the opposite is true for short-term predictions.

Thus, reliably assessing flood hazards requires understanding hydrologic responses at hourly time scales. But paradoxically, hourly predictions have received relatively less focus. In this work we use a conceptual hydrological model to obtain deterministic hourly predictions and estimate its uncertainty using a residual error model. Case study catchments include hydrologically diverse catchments in Europe and the USA. We consider bias, heteroscedasticity and autocorrelation by employing the Box-Cox transformation, autoregressive (AR) and moving average models (ARMA) models. Our findings generally favour the log transformation in combination with an AR3 model.

This work advances streamflow prediction by developing statistically rigorous methods for postprocessing the residuals of conceptual models at the hourly time scale.

Keywords: Statistical hydrology, probabilistic hourly model predictions, hydrological design, uncertainty, conceptual models, probabilistic models

Improving Hershfield method-based Probable Maximum Precipitation estimates with the use of Peaks over threshold series

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Probable Maximum Precipitation (PMP) is one of the key inputs to arrive at design flood estimates for risk assessment of critical infrastructure (e.g., spillways of large dams, flood protection measures of nuclear power plants) whose failure could result in catastrophic consequences for ecology, environment, and economy. The Hershfield method is a widely used statistical method recommended by the World Meteorological Organization for estimating PMP in areas with sparse information on various hydrometeorological variables. The effectiveness of PMP estimates derived using the Hershfield method primarily depends on the length of the precipitation records available for sites in a region. Hence, there is a need to explore options to augment/supplement the records to improve the accuracy of the PMP estimates. Against this backdrop, this study proposes using peaks over threshold (POT) series instead of the conventional annual maximum series (AMS) in implementing the Hershfield method. Its potential is demonstrated through a case study on India using 121-year-long 0.25° gridded precipitation data corresponding to three durations (1, 2, and 3 days). The results indicate that analysis with the POT series reduces the overestimation of PMP, which is evident in analysis with the AMS, especially for higher durations. Furthermore, uncertainty in PMP estimates was lower in analysis with the POT series than with the AMS. These insights suggest there is scope for improving Hershfield method-based PMP estimates by opting for analysis with POT series instead of conventional AMS. The results are significant, as the Hershfield method could become a potential option for PMP estimation at locations with even short/sparse precipitation records.

Keywords: Probable maximum precipitation, Statistical method, Peaks over threshold, Hershfield method

Assessing Future Dam Breach Risks and Safer Hydropower Solutions in the Himalayan River Basins: A Case Study of Tamakoshi Basin

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The future is becoming increasingly uncertain due to climate change and erratic precipitation patterns, particularly for countries like Nepal, where numerous Himalayan rivers flow through fragile terrains, hosting multiple hydropower projects in high-seismic zones. Dam failures in these regions could trigger devastating transboundary floods, severely impacting both Nepal and India. Hence, in the present study, a hypothetical dam breach is simulated at the Tamakoshi Hydropower Project, a transboundary river system originating in the Himalayas. This study assesses the potential impacts of such an event on downstream land cover and population in Nepal and the Indian floodplain under present and future climate conditions. Using discharge data from 2020 as a baseline, a breach scenario for July 2020 is simulated using HEC-RAS. To account for climate change-driven hydrological shifts, precipitation projections from CMIP6 under SSP 2.6 and SSP 8.5 for two future time periods-Near Future (2020-2040) and Mid-Century (2041-2060)-are incorporated. The precipitation data is statistically downscaled using quantile mapping to enhance regional accuracy. Four simulations are conducted to compare breach-induced flooding under different climate scenarios, evaluating variations in flood extent, peak discharge, and inundation depth. The results highlight the increasing role of precipitation variability in exacerbating flood hazards and quantify potential risks to settlements, livelihoods, and infrastructure in both Nepal and India. The findings emphasize the urgent need for adaptive flood management strategies, transboundary cooperation, and early warning systems to mitigate the socio-economic consequences of dam failures. Additionally, this study explores the feasibility of smaller, distributed dams as a less destructive alternative to large hydropower projects. By integrating hydrodynamic modelling with climate and social vulnerability assessments, this study provides

Keywords: Himalayan, Tamakoshi, Risks, Hydrodynamic, Simulation, Climate Scenarios

Regional Calibration of a Lumped Hourly Hydrological Model Using a Decision-Tree Approach

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Hydrological simulation in ungauged basins is essential for analysing extreme events and reconstructing historical data. A major challenge is deriving consistent model parameters that reflect basin characteristics. Regionalization methods address this by transferring information from gauged to ungauged basins, linking catchment attributes to model parameters.

An innovative approach - PArAmeter Set Shuffling (PASS) - uses a machine learning decision tree algorithm to establish relationships between locally calibrated parameters and basin descriptors, enabling spatially distributed and lumped parameter predictions. PASS has yielded valid results with

semi-distributed hydrological models in flat terrains such as Germany and in more complex regions like the Alpine areas, but its application to lumped models remains largely unexplored.

This study investigates the performance of PASS for regionalizing an hourly lumped rainfall-runoff model, GR5H, in the eastern mountainous region of Emilia-Romagna, Italy. Specifically, the method was applied to a pool of 23 medium-small mountainous basins, using hourly discharge data covering up to 20 years for many of the catchments considered. The selection of the study region is motivated by the devastating 2023-2024 floods, causing casualties, significant losses and widespread displacement. Extensive levee breaches and damaged river gauges hindered accurate flood flow measurements.

KGE and NSE were adopted as efficiency measures in the calibration process and two independent analyses were conducted, providing additional insight into the potential, strengths, and weaknesses of these two metrics. The results demonstrate that the PASS procedure enables the attainment of good regional model efficiencies without significant loss of performance when transitioning from calibration to leave-one-out cross-validation, confirming the robustness of the methodology in handling complex terrains and diverse hydrological conditions with a simpler hydrological model. These findings highlight the potential of PASS to streamline parameter estimation for ungauged basins and provide a reliable tool for hydrological modelling with reduced computational complexity.

Keywords: PArAmeter Set Shuffling (PASS), Machine learning, KGE and NSE efficiency metrics, Extreme hydrological events, 2023-2024 Emilia-Romagna floods

Index based approach for the assessment of spatiotemporal variability of extreme climatic conditions using GCMS for the Mahanadi river basin

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Climate change has intensified the frequency and magnitude of extreme weather events, significantly impacting hydrological systems and water resource management. This study employs a statistical hydrology approach for Mahanadi River basin (MRB) to analyse historical and projected trends in extreme climate conditions using data from five selected CMIP6 General Circulation Models (GCMs). This study examines variations in the frequency and intensity of climate extremes using four temperature-based indices (Tx10p, Tx90p, Tn10p, Tn90p) and four precipitation-based indices (PRCPTOT, SDII, R95, R95-TOT) recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI). The analysis spans historical (1951-2014) and projected future period (2015-2100) under two Shared Socioeconomic Pathway (SSP) scenarios: SSP2-4.5 and SSP5-8.5. The SSP2-4.5 represents a medium stabilization scenario, reflecting a policy-driven moderate emissions trajectory, while SSP5-8.5 projects a high-emissions pathway, capturing an extreme warming scenario. Statistical trend detection method, the Sen's slope estimator, is applied to identify significant trends in extreme temperature and precipitation patterns. The study outcomes include an increase in Tx90p and Tn90p, indicating a rise in extreme heat events, while a decrease in Tx10p and Tn10p may suggest a reduction in cold extremes. The precipitation indices, particularly PRCPTOT and R95-TOT, are projected to exhibit spatial heterogeneity, indicating shifts in seasonal rainfall intensity and distribution. Additionally, SDII (Simple daily intensity index) and R95 (Heavy rainfall days) are analysed to assess changes in extreme precipitation and potential flood risks. The findings enhance

statistical hydrology-climate modelling integration, aiding adaptive water management and climate resilience. Study results can be useful and supportive to the policymakers in developing sustainable strategies to mitigate climate extremes. Future research may incorporate hydrological modelling for improved flood and drought risk assessment.

Keywords: Extreme Climatic Events, Extreme climate indices, General Circulation models, SSP, Trend analysis

Correcting Biases in the Wind Simulations of Climate Models: Improving Drought, Extremes, and Spatial Coherence

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Bias assessment of wind simulations of global climate models (GCMs) remains relatively underexplored from a hydrological perspective compared to temperature and precipitation. However, the increasing frequency and severity of wind-related natural disasters, as well as the growing recognition of wind as a potential clean energy resource, highlight the urgent need to have unbiased modelled wind simulations. Inaccurate wind simulations not only hinder disaster risk assessments but also affect climate-driven energy forecasting, making it essential to enhance the reliability of GCM wind projections. This study evaluates biases in wind variability across three raw GCMs in the 6th Climate Model Intercomparison Project (CMIP6), despite their identical spatial resolution. Using reanalysis datasets and historical climate model outputs, we analyze biases in magnitude and frequency of wind speed, focusing on extreme values. Lower tail biases affect low-wind conditions, impacting drought-related patterns and energy availability, while upper tail biases distort extreme wind events, influencing storm assessments and disaster preparedness. To address these biases, we apply a well-established time-frequency bias correction approach, Wavelet Bias Correction (WBC), which allows us to effectively rectify errors in historical wind simulations while improving the accuracy of future projections. The wavelet transformation captures biases between model and observation, through the decomposition procedure and ensures that wind characteristics are properly represented across temporal and frequency domains. Beyond correcting wind speed magnitudes, WBC also preserves spatial correlations between grid cells, maintaining the cross-correlation structure of wind fields in GCM simulations. This is particularly crucial for regional-scale applications, where spatial coherence in wind patterns influences hydrological processes, extreme event modeling, and energy sector planning. Our findings emphasize the importance of integrating advanced time-frequency bias correction techniques into climate models to enhance the reliability of wind-related projections, ultimately supporting better adaptation and mitigation strategies in a changing climate.

Keywords: drought in wind, extreme, global climate models, time-frequency bias correction, wind simulations

From Uncertainty to Reliability: Validating and Merging Soil Moisture Data in India

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Soil moisture is a key component in hydrology, influencing water availability, flood dynamics, and agricultural productivity. However, obtaining accurate soil moisture data in India remains challenging due to the limited availability of in-situ observations. While satellite and model-based datasets provide large-scale estimates, their accuracy remains uncertain without proper validation. To address this, the Triple Collocation (TC) method is applied to estimate the error variance of three independent soil moisture datasets. The Soil Moisture Active Passive (SMAP) mission, a satellite-based product, provides high-resolution soil moisture estimates using active and passive microwave remote sensing. The Global Land Data Assimilation System (GLDAS) integrates satellite and ground-based observations with land surface models to produce global soil moisture simulations. The ERA-Interim/Land reanalysis dataset, generated by the European Centre for Medium-Range Weather Forecasts (ECMWF), offers long-term soil moisture estimates derived from numerical weather prediction models. Through TC-based validation, the error characteristics of these datasets over India are assessed, revealing regional variations in their reliability. A merged soil moisture product is then developed, leveraging the strengths of each dataset to minimize uncertainties. The merged product exhibits lower error variance compared to individual datasets, making it a more robust alternative for hydrological modeling and water resource applications. This study underscores the necessity of statistical validation techniques in regions lacking ground truth data and demonstrates how merging complementary datasets can enhance soil moisture accuracy. By reducing uncertainties in soil moisture dataset, the findings contribute to improving hydrological predictions and climate studies in India.

Keywords: Soil moisture, Triple Collocation, Unbiased validation, Data merging.

Morphometric Analysis and Hydrological Modeling of the Meenachil River Basin Using Digital Elevation Models (DEMs)

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This study provides a comprehensive morphometric analysis of the Meenachil River Basin using Digital Elevation Models (DEMs) from the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Key morphometric parameters, including linear, shape, relief, and hypsometric attributes, are analyzed to understand the basin's geomorphology and hydrology. A comparative assessment of SRTM and ASTER DEMs examines differences in elevation precision and data consistency, emphasizing their implications for morphometric and hydrological analyses. ArcGIS software is utilized to integrate morphometric parameters

with spatial analysis, facilitating the assessment of flood susceptibility through hydrological modeling and floodplain mapping. The study also investigates the statistical relationship between rainfall and runoff, employing the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) to simulate the basin's hydrological response to precipitation. Findings from the DEM comparison, flood assessment, and hydrological modeling provide crucial insights into the river basin's topographic characteristics, hydrodynamics, and flood hazards. The study underscores the importance of accurate DEM selection in watershed management and contributes to sustainable land-use planning, enhanced flood mitigation strategies, and improved environmental management and disaster preparedness efforts.

Keywords: Morphometric analysis, Meenachil River Basin, Digital Elevation Models (DEMs), ArcGIS Software, Linear Metrics, Shape Metrics, Relief Metrics, Hypsometric Attributes, Flood Susceptibility, Flood Mitigation Strategies, Disaster Preparedness, Statistical Relationship, Hydrological Modeling.

Have heat and cold waves intensified over Central India in the recent period?

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Climate change has alleviated the warming levels, altering global weather patterns. Temperature-related extremes, viz., heat-and-cold waves, have become frequent in many parts of the globe in the twentieth-century. Heat and cold waves significantly impact human health, infrastructure, and the environment. Heat-and-cold waves are anomalous episodes characterized by prolonged periods of extremely high and low surface air temperatures. Characterizing and assessing the severity of heat-and-cold waves is essential for formulating disaster mitigation measures. The present study aims to determine whether the heat-and-cold waves have intensified recently (i.e., 2001-2023) vis-à-vis the past (i.e., 1951-2000) across the Madhya Pradesh state in Central India. This study uses the daily gridded temperature data to analyze the frequency, magnitude, timing, and duration changes of temperature extremes. Several statistical tests, such as the Mann-Whitney, Ansari-Bradley, Kolmogorov-Smirnov, Modified Mann-Kendall, and Sen's Slope estimator are adopted to evaluate the changes in temperature extremes. Data analysis reveals that northern Madhya Pradesh exhibits higher temperature variability. In addition, the regions of southern Madhya Pradesh, like Khargone, often experience temperatures shooting above 45°C, while plateau areas like Pachmarhi experience the coldest temperatures in the state. On average, a few regions in the state exhibit prolonged heating (i.e., maximum temperature $\geq 40^\circ\text{C}$) for around 40 to 45 days annually. The study indicates a significantly increasing trend in heatwave occurrences across 15 districts in northwestern Madhya Pradesh, which are frequently affected. The results indicate a consistent warming, in terms of rising maximum and minimum temperatures, in the recent period versus the past. The region has noted a significant increase in the frequency and duration of heat waves recently, while some areas are prone to both heat-and-cold wave severity. Thus, understanding the space-time evolution of heat-and-cold wave patterns would help us assess their region-specific impacts and formulate adaptive measures to mitigate their adverse effects.

Keywords: Climate change, heat waves, cold waves, statistical tests, Central India

Multi-Model Evaluation of Sub-Seasonal Rainfall and Temperature Forecasts in India: Implications for Drought Prediction

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Droughts pose significant challenges to water resources and agriculture in India, often resulting in severe socio-economic impacts. This study evaluates the forecasting skill of two key drought-influencing variables, 2m temperature and precipitation using three Global Climate Models (CCSM4, GEOS2S, and CFSv2) from the North American Multi-Model Ensemble across six homogeneous rainfall regions of India. Based on 42 years of data, we assess two-month lead forecasts, which are essential for drought early warning systems. IMD rainfall and ERA5 2m air temperature are considered as reference datasets for evaluation. All model forecasts are downscaled to $0.25^\circ \times 0.25^\circ$ resolution using bilinear interpolation method. The ensemble mean of all available ensemble members for each model is considered for analysis. Skill metrics such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Anomaly Correlation Coefficient (ACC) are used to compare predictions with observations. Additionally, ensemble forecasts and observations are categorized into terciles, with a focus on the lower tercile related to drought events. The terciles were defined separately based on the individual distributions of the observations and the forecasts. The forecasts are further assessed using Brier Skill Score (BSS), Heidke Skill Score (HSS), Probability of Detection (POD), False Alarm Ratio (FAR), and Equitable Threat Score (ETS). Results show that CFSv2 excels in rainfall prediction, while CCSM4 performs best for 2m temperature. Overall, CFSv2 is the most reliable model, especially for rainfall forecasting. Similar assessments are carried out in the context of droughts. For this purpose, the reference drought events are identified using Standardized Precipitation Index (SPI) at 3-months timescale computed with IMD precipitation data. Our findings provide a systematic evaluation of model strengths and limitations, offering insights for enhancing sub-seasonal drought forecasting and supporting early warning systems, agricultural planning, and water resource management in India.

Keywords: Sub-seasonal forecasting, North American Multi-Model Ensemble (NMME), CFSv2, GEOS2S, CCSM4, Skill assessment

Exploring the Linkages between Heatwaves and Droughts in the Upper Chambal Basin

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Drought and heatwave events have profound socio-economic, environmental, and health impacts. The Upper Chambal Basin (UCB), a critical region in central India, is increasingly experiencing droughts and heat waves. Understanding the linkages between temperature extremes and droughts will help us in water resource management and agricultural planning. This study analyzes meteorological droughts using the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI) for the period 1971-2023. The droughts are assessed at multiple time scales ranging from one to twenty-four months to estimate the drought characteristics, viz., frequency, duration, intensity, and severity. Further, the frequency and duration of heatwaves are estimated using absolute and percentile-based temperature indices. Further, the correlational analysis is performed to establish the linkages between heat waves and droughts across the basin. The results indicate that the southern (northern) part of UCB exhibits a rise (decline) in the heatwave duration. Further, an increasing trend in the frequency of days surpassing the 90th percentile of historical maximum temperature is also noted. In addition, the long-term droughts are more profound than the short-term droughts across most parts of the UCB. The frequent droughts, combined with rising heatwaves, underscore the urgent need for adaptive strategies in agriculture, water management, and community health to effectively address the escalating challenges posed by these extremes.

Keywords: Drought, heatwave, temperature extremes, correlation, Upper Chambal basin

Exploring Coincidental Compound Extremes in Pan-Himalayan River Basins under Changing Climate

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Rising global temperatures are intensifying extreme events, with more frequent compound extremes posing unprecedented risks to natural and human systems. This study examines trends and changes in the frequency per decade of annual-scale compound extremes across four key Himalayan River basins: Beas and Teesta (in India), Marshyangdi (in Nepal), and Puntsangchhu (in Bhutan), which are crucial for regional water security and highly sensitive to climate variability. Using the Indian Monsoon Data Assimilation and Analysis (IMDAA) and CMIP6 GCMs dataset, the study analyzes historical data (1979-2014) and projects future scenarios under SSP 2-4.5 and SSP 5-8.5 for the near future (2015-2040), mid future (2041-2070), and far future (2071-2100). Compound extremes are categorized into four types: Compound Dry and Hot Events (CDHE), Compound Wet and Cold Events (CWCE), Compound Dry and Cold Events (CDCE), and Compound Wet and Hot Events (CWHE). Annual correlations between precipitation and mean temperature are analyzed to understand their temporal dependence. Different patterns of changing compound extremes are observed

across these basins. The frequency of CDCE and CDHE events in the Beas basin is projected to increase more significantly under SSP 5-8.5 than SSP 2-4.5 across all future scenarios. In the Marshyangdi basin, similar trends are observed, with a slight rise in CWCE events under SSP 5-8.5. The Teesta and Puntsangchhu basins display no occurrences of CWCE and CDHE, with only CDCE and CWHE events observed. These trends persist across all future scenarios. In the Teesta basin, CWHE events are expected to increase, especially under the far-future SSP 5-8.5 scenario, with higher CDCE in the south and greater CWHE in the north. The Punatsangchhu basin shows a similar rise in CWHE events. These spatial variations underscore the complex impacts of climate change on compound extremes, posing serious threats to freshwater ecosystems and necessitating basin-specific adaptation strategies.

Keywords: Compound Extremes, Climate Change, Pan-Himalayan Region, Hydroclimatic Patterns.

Enhancing Hyperlocal Extreme Rainfall forecasts for Mumbai

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The increasing frequency and intensity of extreme weather events, such as heavy rainfall-induced flooding, underscore the critical need for advanced early warning systems. This study introduces a machine-learning model that leverages spatial convolution to capture intricate rainfall patterns during extreme conditions. By integrating Convolutional Neural Networks (CNN) with Transfer Learning (TL), the model effectively downscales gridded daily accumulated rainfall data to station-level observations for Mumbai, a flood-prone coastal city in India. This approach enhances the resolution and accuracy of rainfall forecasts, providing crucial insights for disaster preparedness and mitigation. The model utilizes gridded Global Forecast System (GFS) rainfall data at a $0.25^\circ \times 0.25^\circ$ resolution as predictors, with station-level observed rainfall as the predictand. It was trained on JJAS rainfall data from 2015 to 2020, validated using 2021-2022 data, and tested on 2023. On the unseen 2023 dataset, the proposed model achieved a 15% reduction in Root Mean Square Error (RMSE), a 15.6% increase in Correlation Coefficient (CC), and a 66.7-400% improvement in the Critical Success Index (CSI) at the 95th percentile for Lead Day 1. For Lead Day 2, RMSE decreased by 10.3%, CC improved by 16%, and CSI values increased across rainfall percentiles from the 80th to the 95th for Lead Days 2 and 3. These results highlight the model's superior performance in forecasting hyperlocal extreme rainfall events compared to existing GFS models, making it a valuable tool for flood risk management and early warning systems.

Keywords: Global Forecast System (GFS), Extreme events, Machine Learning, Daily Rainfall Forecasts, Mumbai

Filling Intermittent and Continuous Discharge Data Gaps: A Comparative Evaluation of Imputation Methods

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Intermittent and continuous missing discharge data gaps pose significant challenges in calibrating and validating hydrologic simulation models, which require chronologically continuous (gap-free) data. These gaps in data also lead to inaccurate inferences about the characteristics of time series data and missed extremes, ultimately affecting climate variability and change assessments based on statistical parametric or nonparametric hypothesis tests. To address the issue of filling missing discharge data to ensure a complete time series, in this study, multiple spatial and temporal interpolation models are developed using traditional regression-based approaches and emerging machine learning(ML)-based approaches. Simple persistence-dependent methods and regression-based methods, including their linear and nonlinear variants that facilitate the selection of temporally lagged values in case of temporal interpolation, are developed and evaluated. Other methods developed in this study include Gaussian Kernel Regression (GKR), K-nearest neighbor (KNN) supported interpolation, and model-tree(MT) approaches. A universal functional approximation-based method, such as an artificial neural network (ANN), is also evaluated. A caste study region consisting of multiple contiguous watersheds in the Narmada River basin, India, with missing discharge data issues, is used as a test bed to comprehensively assess different interpolation methods. Sites with observations without gaps within a basin and outside are selected through an objective selection process. Several error and performance measures are used to assess the developed methods and evaluate their applicability for filling intermittent and continuous gaps. Recommendations for selecting the best methods are expected to be based on the length of the missing data and the characteristics of the time series of the discharge. The efficiency of spatial and temporal interpolation approaches and comparative assessments of these two approaches for specific cases of missing data will also be conducted. The best methods selected and used for imputation will generate chronologically continuous discharge data that benefits hydrological modeling.

Keywords: Imputation, Discharge, Missing data, Machine Learning, Narmada River basin

Efficacy of Change Point Tests in Identifying Non-stationarity Conditions in Hydrological Time Series

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Change point tests and trend assessments are carried out as a first step to identify non-stationarity

conditions in hydro-climatological variable time series. The suitability of change point tests to identify potential temporal break points in the time series with differing statistical properties requires an exhaustive assessment, considering the limitations of these tests. Such assessment should include evaluating the Pettitt test and its variants as a suite of tests for drawing inferences about non-stationarity evaluated for time series of different hydro-climatological variables at different temporal scales. A comprehensive assessment of nonstationary requires confirmation of changes in statistical moments of different orders and characteristics of any time series. A recently developed methodology based on a nonoverlapping block stratified random sampling technique is used as an alternative method in the current study to evaluate the efficacy of the change point test for the assessment of nonstationary. Comparative assessments of random sampling and change point methods using multiple streamflow, temperature, and precipitation time series at different temporal scales, including extremes, are carried out in this work. Results from the study are expected to identify the advantages and limitations of both methodologies and their abilities to distinguish a nonstationary series from a stationary one based on natural and synthetically generated time series.

Keywords: Change point, Stationarity, Statistical tests, Hydrological variables

Statistical Characterization of Upstream Flooding Patterns Induced by Culvert Capacity Exceedance

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Culverts are critical infrastructure at stream-road crossings, playing a vital role in maintaining hydraulic connectivity, mitigating flood risks, and preventing transportation disruptions. However, the increasing frequency and intensity of extreme weather events, coupled with aging infrastructure and land use changes, necessitate a reassessment of their hydraulic capacity and resilience. Culvert failures can lead to significant upstream flooding, threatening communities, property, and transportation networks. To address these challenges, an uncertainty-aware framework is developed to identify the extent of the upstream flooding caused by the culvert failures across New York State. The proposed framework estimates the maximum tolerable discharge for each culvert based on key structural attributes including culvert shape, size, and material. By incorporating a range of storm return periods-both historical and projected-the analysis captures variations in cumulative flooded areas when culvert capacities are exceeded. A fast, topography-based inundation mapping approach is then employed to efficiently estimate the resulting flood extent using high-resolution DEM data. By understanding the spatial and temporal patterns of inundation risk, this study provides a scalable methodology for assessing rainfall-driven flooding during culvert failures. The findings offer valuable insights for decision-makers, supporting disaster management efforts, enhancing infrastructure resilience, and informing replacement strategies.

Keywords: Culvert Failure, Failure Probability, Flood Inundation Mapping

Prediction of Temperature and Precipitation in Narmada River Basin Using GUI Matlab Tools

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This study presents a comprehensive analysis of climate change impacts on the Narmada River Basin using Artificial Neural Networks (ANN). Historical temperature and rainfall data spanning 20 years (2001-2020) are utilized to develop predictive models for future climate scenarios. The research gives a multilayer perceptron architecture with Levenberg-Marquardt backpropagation algorithm, optimized through cross-validation to prevent overfitting. The ANN model demonstrated robust performance with a satisfactory correlation for temperature predictions and rainfall patterns. Results indicate a projected increase in mean annual temperature of 3-5°C and a 15% variation in seasonal rainfall distribution by 2030. The model successfully captured the non-linear relationships between climate variables and their temporal evolution, providing valuable insights for water resource management and climate adaptation strategies in the region.

Keywords: Neural Networks, Climate Projection, Narmada Basin, Hydroclimatic Modelling, Temperature-Precipitation Analysis

Spatio-temporal Analysis of Monsoon Rainfall patterns in the Pennaiyar Basin using a Bayesian Hidden Markov Model

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Understanding the spatio-temporal variability of monsoon rainfall over a basin is vital for sustainable water resource planning and management. This study employs a Bayesian Hidden Markov model (HMM) to analyse daily rainfall occurrence and intensity at IMD grids ($0.25^\circ \times 0.25^\circ$) over the Pennaiyar Basin during the monsoon season (June - Sept) from 1980-2024. The HMM captures both spatial distribution and temporal variation in rainfall patterns, classifying weather conditions into distinct states ranging from very rainy to dry. The optimal model is selected based on the Bayesian Information Criterion (BIC), and State transition probabilities provide insights into dynamics of rainfall, including the shifts between wet and dry periods. The study highlights significant seasonal and inter-annual variability in rainfall patterns across the Pennaiyar Basin, offering valuable insights for predictive modelling, adaptive water resource management, and mitigate the challenges posed by climate variability.

Keywords: Hidden Markov Model, Rainfall state, Pennaiyar Basin, Rainfall variability

Regularized calibration of conceptual hydrological models

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This paper applies recent results of risk bounds for time series forecasting to identify optimal complexity of conceptual models and complexity regularised streamflow predictions based on Vapnik-Chervonenkis generalization theory. Earlier reported similar study with SAC-SMA and SIXPAR conceptual models but on two large regions from CAMELS data set is extended to more basins in CONUS to demonstrate the effect of regularizing hydrological model calibration on streamflow prediction over unseen data. SAC-SMA and SIXPAR (conceptual simplification of SAC-SMA) are used as model examples. Results show that the effect of complexity regularization more visible on SIXPAR than SAC-SMA. Results further suggest that when basins itself are complex, regularizing complexity of models does not help and depends on hydrological characteristics of the basins. The benefits of complexity regularization are more evident when assessed based on variance based performance metrics such as correlation coefficient and the slope of observed vs predicted fit than bias and mean absolute error metrics. The paper therefore offers a novel, though computationally intense, method to calibrate conceptual models while controlling for their model complexity.

Keywords: conceptual models, calibration, regularization, statistical learning theory

Rainfall Forecasting using Deep-Learning based LSTM Model

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Rainfall has always been a critical factor shaping both past and present global conditions. Accurate rainfall forecasting remains a critical yet complex challenge due to the highly spatio-temporal variability of precipitation. This study explores advanced deep learning techniques, specifically Long Short-Term Memory (LSTM) networks, to improve rainfall prediction accuracy. This research based on the western ghat study area with IMD gridded daily rainfall as the only input (2000-2020). This study aims to develop a single forecast model for a large area with varying climatic properties which produces an improved prediction. The research compares 1D and 2D LSTM models, incorporating methodologies such as Principal Component Analysis (PCA) and pixel to pixel correlation for dimensionality reduction and performance optimization. Correlation Coefficient (CC) and Nash-Sutcliffe Efficiency (NSE) are used as the evaluation metric. Findings indicate that the 2D LSTM model outperform 1D LSTM models by better capturing the spatial and temporal variability of rainfall. For the Western Ghat region, overall range for CC in 1D LSTM is 0.22-0.83, while in 2DLSTM it is 0.37-0.85. In case of NSE median value improved from 0.44 to 0.49 when forecasting next-day rainfall.

Keywords: Rainfall forecasting, Deep learning, LSTM, Principal Component Analysis (PCA), Spatio-temporal modelling

Statistical Flood Frequency Analysis of the Beas River: Evaluating Extreme Flood Events in a Himalayan Basin

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Flood frequency analysis plays a crucial role in hydrological studies, particularly in mountainous river basins where extreme flood events pose significant risks to infrastructure and communities. The Beas River, a major Himalayan River, frequently experiences flooding due to intense precipitation, glacial melt, and steep terrain. This study aims to assess the flood frequency of the Beas River using various probability distribution functions to estimate peak discharges for different return periods. A discharge dataset from 1988 to 2024 was analysed using Log-Normal, Gumbel, and Log-Pearson Type III distributions to predict flood magnitudes for 5, 10, 50, 100, and 150-year return periods. The suitability of each distribution was evaluated based on the coefficient of determination (R^2) to determine the most accurate model. The results revealed that different probability distributions yielded varying flood quantile estimates. Among them, Log-Pearson Type III exhibited the best statistical fit, achieving an R^2 value of 0.91, indicating its superior reliability in predicting extreme flood discharges. The flood magnitudes increased significantly with longer return periods, underscoring the growing flood risk in the Beas River basin. This study provides crucial insights for flood risk assessment, hydraulic structure design, and disaster management strategies. In addition, the study highlights the importance of selecting an appropriate probability distribution function to improve flood prediction accuracy, particularly in climate-sensitive mountainous regions like the Himalayas.

Keywords: Flood Frequency Analysis, Probability Distributions, Beas River, Hydraulic Structure Design, Himalayan Rivers, Climate Change

Quantifying Multivariate Streamflow Drought Hazards in Large River Basins Accounting Onset Seasonality and Event Magnitude

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Streamflow droughts are recurring events expected to intensify in a warming climate. Previous studies have primarily focused on understanding streamflow drought seasonality at a regional or point scale or, at most, analyzing multivariate frequency considering the severity and duration of droughts. Yet, the interdependence between onset seasonality and event magnitude across different climates remains unexplored. This study analyzes the influence of onset seasonality on drought severity using global daily streamflow observations available from 1901-2024 across 1,148 catchments in tropical, subtropical, and temperate zones between 60° N to 60° S. Our results reveal that 80% of sites show a significant dependency ($\alpha = 10\%$) between drought onset seasonality and severity, influencing drought dynamics and catchment-scale propagation. Analysis of six representative catchments from three distinct climate regions in the northern (NH) and southern (SH) hemispheres revealed severity and onset seasonality shows interdependence that ranges from 0.04 (indicating independence) to 0.78 (strong dependence). We evaluate deficit volume of droughts conditional

on drought seasonality and compare severity of droughts during primary seasons summers and winters across both hemispheres. SH catchments exhibit an 85% higher exceedance probability for severe droughts (≥ 90 th percentile) conditional on mean onset time compared to NH, indicating a higher likelihood of severe droughts in those representative catchments. We find no significant influence of onset seasonality on drought severity in the catchment with the lowest dependence strength, which is located in temperate climate and showing little seasonal variations. In contrast, a tropical SH catchment with a significant modest dependence strength shows substantial changes in exceedance probability during austral summer compared to the austral winter season, which varies across catchment and climate types. The specific insights highlight the need for implementing onset seasonality in developing near-real-time hydrological low flow forecasting system, useful for reservoir planning and operations during extreme drought years.

Keywords: Streamflow drought, Onset, Severity, Conditional probability, Multivariate risk

Assessing Rainfall Seasonality Regimes in India's East Coastal Region during 1953-2022

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This study aims to examine the rainfall variability of the East Coastal Region of India using three indices, i.e., the individual seasonality index (Sli), the overall seasonality index (SI), and the replicability index (RI). While SI represents the climatic characteristic of a region, RI indicates the degree of noise in the continuous time series, i.e., representing interannual variations. These indices were derived from monthly rainfall data from 1953 to 2022, obtained from the India Meteorological Department's high-resolution gridded observation dataset. To assess trends in the Sli series, the modified Mann-Kendall test and Sen's slope estimator were employed. Further, a regression analysis of these indices against geographical longitude revealed a statistically significant linear correlation. The findings indicate that the coastal region experiences a highly seasonal rainfall regime. Furthermore, an assessment of two 35-year sub-periods highlights notable shifts in mean values, suggesting a transition toward more extreme seasonality, characterized by an extended dry season. The findings of the study shall be crucial for water resources planning and management over the east coastal region of India.

Keywords: Climate Change, East Coast, Replicability Index, Seasonality Indices, Trend Analysis

Enhancing smallholder sociohydrological predictions at plot scale by novel data assimilation of high-resolution soil moisture and biomass data

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Increasing competition for water resources and rainfall variability driven by climate change have led to irrigation water scarcity, particularly in drought-prone regions such as Vidarbha, Maharashtra (India). Enhancing irrigation water efficiency is essential for sustainable agricultural intensification; however, adopting new technologies poses a risk for farmers, as it requires significant investment of time and financial resources to modify their practices. In this context, we have developed a mobile application that implements a hybrid model combining a sociohydrological approach with a KPCA-based structural error model, providing farmers with timely information to support decision-making in the adoption of new irrigation technologies and the implementation of Good Agricultural Practices (GAPs), such as irrigation and fertilization. Although the model explains 20% of the observed variance in yields at the plot scale, its main purpose is to provide farm-scale predictions to encourage the adoption of GAPs. In this work, we venture into providing more precise forecasting to the users for direct applicability for forward-looking field advisories. By integrating higher-resolution data (e.g., Sentinel-2A) and exploring Bayesian methods along with machine learning techniques, the accuracy of the state variables, such as biomass and water storage, was enhanced. This advancement is incorporated into the mobile application to provide opportunistic and precise forecasting to farmers in their decision-making process when implementing GAPs.

Keywords: Bayesian methods, Kernel Principal Component Analysis, Machine learning, Remote sensing

A framework for the safe-fail design of urban stormwater management infrastructure for flood mitigation under changing climate.

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Urban flooding is one of the global challenges that has frequently caused significant damage to infrastructure, socio-economic stability, and livelihoods. Unplanned settlement and poor maintenance of existing urban stormwater management infrastructure combined with climate change drive intensified climate extremes have led to aggravated urban flood disasters. Existing engineering design solutions to tackle these problems are simplistic in nature and do not account for flood consequences in the design procedures, warranting innovative solutions. We propose a novel safe-fail framework for the design of urban stormwater conduits, which incorporates failure consequences such as flood severity into the design procedure under changing climate. An event-based simulation framework that extends to a wide range of extreme occurrences under changing climate conditions,

driven through detailed hydrodynamic modeling, was formulated. The framework was demonstrated for a small urban catchment in Chennai. We observe that the consequences of failure for the initial risk-based design would be unsafe for at least 50% of the conduits in the study area, and a revision of the design would need to be done through a safe-fail approach. The results reiterate the inefficiencies of the conventional design storm approach and recommend location-specific conduits design failure return periods for minimal flood severity. This design framework can be expanded to any location and would be valuable for a sustainable urban environment.

Keywords: urban flood, climate change, stormwater management

Climate change Impacts North Indian Region using CMIP6 Model outputs

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This study presents a comprehensive analysis of future rainfall projections for Northern India using data from five CMIP6 General Circulation Models (GCMs), including MIROC6, MPI, CanESM5, and CNRM-ESM2. The raw GCM outputs were first regridded to the Indian domain using the Climate Data Operators (CDO) tool to ensure spatial consistency with observed data. Bias correction was applied to reduce discrepancies between the modelled and observed rainfall data from the India Meteorological Department (IMD), improving the reliability of future projections. Principal Component Analysis (PCA) was performed to extract dominant rainfall variability patterns across the Indian subcontinent and highlight key regions experiencing significant changes. The projected rainfall for Northern India data were then compared with IMD historical records, and absolute and percentage difference maps were generated to compare and visualize spatial and temporal deviations across historical and future periods under various Shared Socioeconomic Pathways (SSP) scenarios. The multi-model mean of the five GCMs indicates, better matching with observed IMD data. the future rainfall projections projects heterogeneous distribution rainfall across North India, and offering valuable information for water resource management, flood mitigation, and climate resilience planning under future climate change scenarios.

Keywords: North Indian Region, Down Scaling, CMIP6

Performance Evaluation of TIGGE Precipitation Datasets and Post-Processing Techniques for Enhanced Flood Forecasting Accuracy

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Accurate flood forecasting is essential for disaster preparedness and risk mitigation, particularly in semi-arid river basins like the Sabarmati River Basin. However, raw ensemble precipitation forecasts often contain biases that impact their reliability. This study evaluates the performance of TIGGE (THORPEX Interactive Grand Global Ensemble) precipitation datasets from ECMWF, NCEP, IMD, and NCMRWF, alongside various bias correction and post-processing techniques, to enhance flood prediction accuracy. A hydrological modeling framework was developed to assess the predictive performance of different ensemble datasets and their effectiveness at various lead times. To improve forecast reliability, multiple post-processing techniques-including Censored Non-Homogeneous Logistic Regression (cNLR), Bayesian Model Averaging (BMA), Logistic Regression (logreg), Heteroscedastic Logistic Regression (hlogreg), Heteroscedastic Extended Logistic Regression (HXLRL), and Ordered Logistic Regression (OLR)-were applied. The results indicate that ECMWF and NCMRWF precipitation datasets perform best, particularly at a three-day lead time, yielding a high correlation coefficient of 0.86 using the cNLR method. Additional verification metrics such as the Brier Score and ROC-AUC confirm the effectiveness of post-processing techniques in reducing forecast uncertainty and improving event detection. Despite advancements in hydrological forecasting, India still lacks a comprehensive ensemble-based post-processing approach for flood prediction. This research fills that gap by integrating ensemble forecasting with machine learning-driven bias correction to refine precipitation predictions and optimize lead times. The findings provide valuable insights for disaster management agencies, policymakers, and water resource planners, enabling more effective early warning systems and flood mitigation strategies. By leveraging multi-model ensemble forecasts and advanced bias correction techniques, this study presents a scalable and adaptable framework for flood risk assessment in semi-arid river basins. The approach can be extended to other regions facing hydroclimatic variability, offering a robust tool for climate resilience and sustainable water management.

Keywords: TIGGE ensemble forecasts, bias correction, post-processing, flood forecasting, Reservoir Forecasting

A novel approach to detect changes in the variability of the hydro-climatic record in the wettest state Meghalaya, India.

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Trend analysis in the hydro-climatological variable can be important for identifying the climate change

signal. In the current scenario, trend analysis is solely implemented to detect trends only in the magnitude of the climatic variables. However, there could be a trend in the higher moments of the data. A non-parametric systematic approach is proposed where the data are transformed to another scale to capture the information of variability in the data. We propose a systematic approach (PSA) to detect trends in the variability of the data. The effectiveness of the approach is first demonstrated by considering a simulation experiment that applies PSA to the simulated records which are generated considering normal and generalized extreme value GEV distribution to mimic the annual average and annual maximum series. Later, PSA is applied to the annual average and annual maximum series of precipitation and temperature of the IMD data. The analysis reveals that the application of PSA to the annual average series shows significant trends in the variability at many locations displayed in the spatial maps.

Keywords: Trend, Variability, Precipitation, Temperature, Annual Maximum, Annual Mean

Evaluation of the performance of satellite-based rainfall products in the South-East of the Congo Basin in Lubumbashi region

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Rainfall is recognized as the central component that controls the overall land surface hydrological system in the hydrologic cycle. Despite its fundamental role, its spatio-temporal information is critical within the Congo Basin (CB) due to the small number of operational rainfall stations. To overcome this problem, efforts have been evaluating the performance of satellite-based rainfall products (SRP) in the CB as a whole. Considering the spatial heterogeneity in the CB, regional assessment of SRP is needed. Therefore, the purpose of this study is to evaluate over 2018 - 2021 period SRP including TAMSAT v3.0, TRMM_3B43, ARC2 and RFE2 against in-situ rainfall data from four rainfall stations in Lubumbashi region and its surrounding using the following performance statistical methods: correlation coefficient (r), Root Mean Square Error (RMSE), percent bias (%Bias), and Mean Absolute Error (MAE). The results of the comparison at interannual and annual average scale showed that RFE2 and TRMM_3B43 products performed better ($r \geq 0.90$, RMSE ≤ 70 mm month⁻¹) than TAMSAT v3.0 and ARC2 ($r \leq 0.85$, RMSE ≥ 70 mm month⁻¹). At the annual average time scale, RFE2 (average $r = 0.97$) is the one depicting well the seasonal dynamics in the region. RFE2 and TRMM_3B43 are recommended for different applications in the region.

Keywords: Satellite-based rainfall products, Congo Basin, Lubumbashi rainfall, Spatial hydrology, Remote sensing

Optimal satellite based precipitation datasets for extreme precipitation analysis in Meghalaya: a comprehensive study on dataset selection and spatio-temporal trends

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This study focuses on identifying the best-suited satellite and gridded precipitation dataset out of the 7 freely available datasets in open domain and assess the extreme precipitation indices to better understand the intensity and frequency of extreme precipitation events in the State of Meghalaya. After identification of the best precipitation dataset, we assessed the Standard Precipitation Extreme Indices (SPEIs), such as consecutive wet spells, dry spells, wet days, dry days and maximum 1-day precipitation depth. For a better understanding of the precipitation pattern, we identified the precipitation trends at the annual and seasonal scales using Innovative Trend Analysis (ITA) and the Mann-Kendall (MK) method. Results revealed APHRODITE performed better than the CHRPS, IMD and other datasets. However, APHRODITE data is no longer available, so we have opted for CHIRPS dataset for further analysis. We assessed the efficacy of CHIRPS in capturing the behavior of intense precipitation occurrences over Meghalaya. Based on this, we discovered that the number of 5-day wet spells increased, but the maximum 1-day precipitation depth showed a decreasing pattern in most of the area. Based on ITA and MK, we found ITA is more sensitive than the MK test to identify hidden trends. At all grids, the MK test and the ITA test exhibit a nearly identical pattern; however, the ITA test over predicts the slope (S) values in contrast to the MK test's Z value. For recognizing trends, the ITA is more effective than the MK test. Both approaches (ITA and MK tests) exhibit a decreasing trend in the winter. The remaining seasons have displayed a contradictory pattern. Overall, this research contributes to a more comprehensive understanding of precipitation dynamics, which is vital for water resource management, disaster preparedness, and climate change studies.

Keywords: Satellite precipitation datasets, Trend analysis, Statistical analysis, Precipitation extreme indices

Accounting for the Harmattan in Seasonal Precipitation Forecasting: A Statistical Analysis of Climatic Variability in Northern Benin

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Seasonal precipitation forecasting does not account for the influence of the Harmattan, a period characterized by dry, dust-laden winds emanating from the Sahara towards West Africa. To address this shortcoming, the present study investigated the statistical relationships between the Harmattan and precipitation in northern Benin. Based on climatic data spanning from 1970 to 2022,

the study first characterized the monthly variability of precipitation using rainfall and the number of rainy days as variables. Concurrently, the Harmattan was described through three variables, the number of Harmattan days, temperature range, and relative humidity. Using these variables, the study examined the possible correlations between the Harmattan and precipitation. The findings indicate that when the number of Harmattan days is below 17, there exists a negative correlation with both rainfall (ranging from 46% to 61%) and the number of rainy days (ranging from 48% to 70%); beyond this threshold, the trend reverses. Furthermore, an increase in temperature range is strongly associated with a decrease in both rainfall (ranging from 87% to 95%) and the number of rainy days (ranging from 90% to 94%) across all the stations studied, whereas relative humidity is positively correlated with rainfall (ranging from 81% to 85%) and the number of rainy days (ranging from 86% to 89%). These trends, particularly pronounced in the western (Natitingou) and southern (Parakou) areas of the study region, underscore the importance of incorporating the Harmattan into seasonal precipitation forecasting models and advocate for similar research in other regions.

Keywords: Harmattan, Seasonal Precipitation Forecasting, Temperature range, Relative humidity, Northern Benin

Spatio-temporal Assessment of Meteorological Droughts in Central India: Historical Trends and Emerging Patterns

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Central India, particularly the agrarian state of Madhya Pradesh, experiences significant rainfall variability, with nearly 70% of its agriculture relying on rainfed systems. When this variability results in lower-than-average rainfall, it can severely impact crop yields. This study assesses historical (1951-2022) and near-future (2025-2055) meteorological droughts using the Standardized Precipitation Evapotranspiration Index (SPEI) at seasonal (SPEI-4) and annual (SPEI-12) scales. The analysis reveals significant spatiotemporal changes in drought characteristics across the region. During the baseline period (1951-1990), approximately 35-40% of Madhya Pradesh experienced drought conditions (SPEI ≤ -1) during typical monsoon deficit years. However, in the recent period (1991-2022), this spatial extent increased to 50-55%, with particularly severe intensification observed in the semi-arid regions of Malwa and Bundelkhand. The frequency of short-term monsoon droughts (SPEI-4) increased by 30-40% in these regions, while long-term annual droughts (SPEI-12) became more frequent compared to the baseline. Future projections under SSP2-4.5 and SSP5-8.5 scenarios (using CMIP6 multi-model ensemble) indicate further worsening of drought conditions. Notably, the study identifies emerging patterns of drought, with most seasonal monsoon droughts evolving into annual hydrological droughts in the recent period, compared to during 1951-1990. The northern and central districts of the state show the most pronounced increases in drought intensity. These findings underscore the urgent need for climate-resilient water management and adaptation planning in India's agricultural heartland.

Keywords: Meteorological drought, SPEI, Central India, Drought frequency, Rainfed agriculture

Downscaling of Satellite Soil Moisture for field scale predictions

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Efficient water resource management is critical for addressing the growing challenges of water scarcity and agricultural sustainability, particularly in regions with significant climatic and anthropogenic pressures. This study focuses on downscaling satellite-derived soil moisture (SM) data to farm-scale root zone soil moisture (RZSM) to support precision agriculture and optimise irrigation practices. Current satellite datasets, such as SMAP, provide coarse-resolution soil moisture data that fail to capture farm-scale spatial variability influenced by factors like soil heterogeneity, topography, and human activities. To address this gap, we aim to employ machine learning techniques and physics-based modelling to develop high-resolution soil moisture prediction models. Validation of the satellite data indicated its inability to capture farm-scale variability. Our preliminary efforts utilised an LSTM-based approach to downscale RZSM using site-level sensor data from June 2023 to January 2025. The model achieved good results, including an RMSE of 0.01 and R^2 of 0.88. To enhance model robustness, we aim to incorporate multiple predictors, such as precipitation, vegetation indices, and land surface temperature, and use robust machine learning architectures to capture spatiotemporal heterogeneity effectively.

Keywords: Downscaling, Soil Moisture Prediction, Physics Based Machine Learning

Enhancing Large-Scale Flood Modeling through Satellite Data Integration: The RESCUE_SAT Project

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Over the past two decades, floods have been recognized globally as the most frequent and impactful natural disasters in terms of population affected (UNDRR, United Nations Office for Disaster Risk Reduction). Consequently, developing innovative methods for flood forecasting and modelling has become a priority, with the aim of enabling the proactive planning of risk mitigation measures (e.g. hydraulic structures and insurance policies). Current models typically require a large volume of input data and involve significant computational costs to produce detailed results. Geomorphological models, such as RESCUE, which primarily rely on digital terrain models (DTMs), offer a valuable compromise, providing a rapid and efficient solution for large-scale flood mapping. However, the quality of the results is limited by the resolution of the DTMs, particularly in critical areas such as riverbeds, coastal zones and urban areas. Against this backdrop, the RESCUE_SAT project has been launched as part of the 'Innovation for Downstream Preparation for Science' (I4DP_SCIENCE) program (Agreement no. 2025-2-HB.0 between the Italian Space Agency - ASI - and the University of Roma Tre), with the aim of improving the performance of the RESCUE flood model by integrating variable resolution DEMs derived from high-resolution satellite imagery. Satellite data also offer numerous advantages for detailed land use classification and enable more accurate flood estimation at the intersections of watercourses with typical structures and infrastructure. The key challenge for

the RESCUE_SAT project is therefore to deliver a flood modelling tool that offers a more reliable and detailed representation of flood phenomena through the integration of satellite data and physically based hydrological-hydraulic modelling, thereby effectively supporting risk management efforts.

Keywords: Flood, Risk, Geomorphological-hydrological-hydraulic model, Satellite data

A High Resolution Daily Precipitation Dataset of Statistically Downscaled CMIP6 models over South Asia

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Accurate precipitation data at local scales is critical for climate impact assessments, water resource management, and disaster preparedness. However, precipitation outputs from Global Climate Models (GCMs) are typically available at coarse spatial resolutions and exhibit systematic biases, limiting their applicability for regional-scale studies, particularly over complex and diverse regions like South Asia. To address this, we apply the Double Bias Corrected Constructed Analogue (DBCCA) method to statistically downscale daily precipitation data from 10 CMIP6 GCMs across South Asia. Using the MSWEP dataset as a reference, we generate a high-resolution (0.1°) product spanning the historical period (1950-2014) and future projections (2015-2100) under four Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). The DBCCA method significantly reduces mean bias in daily precipitation, effectively correcting systematic errors in raw GCM outputs. Raw GCMs also demonstrate a strong ability to capture the frequency of extreme heavy precipitation events ($>100\text{ mm/day}$), as indicated by minimal deviation from the reference dataset. Evaluation metrics such as Mean Absolute Error (MAE) show substantial improvement in the downscaled outputs, while Taylor plots reveal enhanced correlation, reduced deviations and root mean-square errors (RMSE) relative to the raw GCMs. The resulting dataset offers a valuable resource for localized climate change analysis and hydrological modeling across South Asia.

Keywords: Bias Correction, Statistical Downscaling, DBCCA, South Asia, CMIP6, GCMs

Giant aufeis in the northeast of Russia according to the historical data of 1958 and satellite images of 1973–2021

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Data on the actual maximum area of 71 largest (≥ 10 km²) aufeis in the northeast of Russia have been obtained from Landsat images for the period of 2013–2018 (661 km²) and Sentinel-2 images for the period of 2020–2021 (838 km²). The total area of aufeis glades is at least twice as small as their area indicated in the Aufeis Cadaster of 1958 (1680 km²). The aufeis area for 1973–1975 has also been estimated for 42 objects according to Landsat/MSS data. Their total area reaches 555 km², which is close to the modern estimate for 2020–2021 (581 km²), and, on average is 1.9 times smaller than their total area according to the Cadaster (1083 km²). Individual giant aufeis demonstrate very high interannual variability: their area can change up to two times from year to year (100%); for most aufeis glades, interannual variability is about 20%. Numerous examples point to discrepancy between the boundaries of aufeis glades and the boundaries of ice massifs. The total area of aufeis glades, including those indicated in the Cadaster of 1958 and identified on the modern satellite images, significantly exceeds the actual area of aufeis. Estimating the area of aufeis on the basis of data on the size of aufeis glades can lead to significant errors in the calculation of dynamic reserves of aufeis-forming groundwater and other characteristics. In the period after 1973–1975, no significant changes in the total aufeis area in the northeast have been identified. Further field studies of the giant aufeis, including the establishment of long-term monitoring sites, are important to for understanding the factors of their high temporal variability. The study is supported by St. Petersburg State University (Project "Comprehensive assessment of natural and anthropogenic factors of intensification of water exchange processes in the permafrost zone under conditions of climate change").

Keywords: giant aufeis, Landsat images, Aufeis Cadaster (1958), aufeis glade, northeast of Russia, climate change

Development of a New Model Platform to Represent Forest Snow Interactions Using Relative Canopy Structure Metrics

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Forest structure modulates snow accumulation, retention, and ablation. However, snow and watershed models that can function over large spatial scales typically do not account for forest structure and shading, and therefore display substantial uncertainty when attempting to account for forest change or when comparing hydrological response between forests with varying characteristics. This study collected snow water equivalent (SWE) measurements in a snow-dominated forest, comprised of varying sized forest gaps, forest edges, and canopy densities. The measurements were integrated with 1m lidar derived canopy structure metrics and incoming solar radiation to create empirical SWE offset equations for four canopy structure groupings that varied in size compared to an open area. The structure groupings were defined relative to local mean tree height (forest gaps, south-facing forest edges, north-facing edges, and the interior forest). These simple equations indirectly integrate terrain shading and canopy shading by incorporating relative canopy structure and radiation data and resolved up to 70% of SWE variation in a heterogeneous forest. The equations were then applied to output from a snow model with a 100 m grid size by applying the area-weighted average of SWE offsets from the four canopy groupings in each model cell. This tiled configuration allowed for the model to better represent the subgrid heterogeneity of a forest environment that can be seen through an ensemble of potential outputs rather than a singular estimate.

Applying the offsets after model runs can reduce computational time and negates the need for multiple models runs to represent forest change. A web platform is in development where this new framework is integrated. The user can define an area and a canopy change scenario to understand and visualize how general changes in forest structure impacts snow water in the headwaters of the Colorado and Rio Grande Rivers in the Southwestern United States.

Keywords: forest snow modeling, forest–snow interaction, subgrid model heterogeneity, forest change, snow models, forest structure

Impact of Spring Sea Ice Variability in the Barents-Kara Region on the Indian Summer Monsoon Rainfall

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The rapidly evolving Arctic climate plays a crucial role in shaping global weather systems, primarily through teleconnections that originate from high latitudes. While the association of Arctic with the mid-latitudes is well-established, its linkages to the tropical systems, particularly the Indian Summer Monsoon Rainfall (ISMR) remains limited. This study unravels the impact of spring (March-May) sea ice anomalies in the Barents-Kara (B-K) region on the ISMR patterns from 1959 to 2021. By identifying low- and high-sea-ice years, the study reveals contrasting atmospheric circulation patterns that drive monsoonal variability over India. During low-sea-ice years, weakened ice cover over

the B-K region induces negative sea level pressure anomalies in summer over the region. This triggers cyclonic activity, which initiates southward-propagating Rossby wave trains. The wave train exhibits a distinct ridge-trough-ridge-trough pattern as it propagates from Europe to the Far East and towards the North Pacific. This atmospheric configuration shifts the subtropical westerly jet southward, enhancing subsidence and suppressing monsoonal convection over the Indo-Gangetic Plain, ultimately reducing the monsoon rainfall over this region. Conversely, high-sea-ice years exhibit a reversed pattern, with negative geopotential height anomalies over the B-K region and a ridge over central Asia. This promotes upper-level divergence, enhancing convection and strengthening monsoonal rainfall over the Indo-Gangetic Plain. These findings reveal the critical role of springtime B-K sea ice in shaping summer atmospheric circulation and monsoonal rainfall patterns over India, highlighting the far-reaching impact of Arctic Sea Ice variability on tropical weather systems.

Keywords: Arctic, Barents-Kara Sea, Indian Summer Monsoon Rainfall, Composite Analysis

Assessing the Impact of Forest Disturbances on Snowpack Dynamics: A Multi-Model Intercomparison

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In response to climate warming and declining snowpack, there is an increase in the frequency of large forest disturbances, such as fires, insects, or wind damage around the world. In turn, these forest disturbances impact the snowpack dynamics by altering the canopy cover, surface albedo, and the surface energy budget. The impact of forest disturbances on snowpack is persistent and widespread and in-turn have a significant impact on snow accumulation and snowmelt. Depending on climate conditions, the occurrence of forest disturbance and associated canopy removal could accelerate or delay snowmelt, and often snowmelt models do not properly represent those processes. Since snow is an important part of mountain hydrology, such changes will have a significant impact on water supply for agriculture, domestic use, and hydropower generation.

In this study, we aim to investigate the impact of forest disturbances on key snowpack processes such as accumulation, ablation, and runoff. We aim to employ a range of models, from simple lumped (e.g., GEOframe modelling system) to physically-based and spatially-distributed models (e.g., GEOtop and SnowModel). The analysis will be conducted at two distinct study sites: one in the Western United States (Santiam River Basin, Oregon), where recent forest fires are extensive and another in the European Alps (upper Adige catchment) where in 2018 forests have been affected by widespread wind damage.

This intercomparison will highlight the importance of model selection and parameterization complexity in analyzing the impacts of forest disturbance on snowpack dynamics. Additionally, this will improve our understanding of the impacts on downstream runoff in snow-dominated forested watersheds.

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Keywords: Snow Modelling, Forest Fire, Disturbances, Models, Climate Change

Diminishing glacier melt contribution for summer droughts in an alpine catchment

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Glacier meltwater is crucial for sustaining summer streamflow in mountainous regions, but rapid glacier retreat is weakening this buffering effect. This study examines glacier melt contributions to summer flows and drought mitigation in the upper Adige River basin, Italian Alps (6900 km²), from 1997 to 2023.

A dynamic glacier module was integrated into the ICHYMOD hydrological model to improve meltwater estimates under retreat conditions. The model accurately captured glacier area reduction (from 98 km² in 2005 to 79 km² in 2017) and glacier mass balance, with a validation error of 4.66% against ASTER-derived data (1997–2022). Runoff simulations showed strong performance, with a mean Kling-Gupta Efficiency (KGE) of 0.81.

On average, glacier melt contributed 4.76% to summer flows at the basin scale, reaching 50–63% in highly glacierized subbasins during droughts. The study highlights the critical role of snowpack duration and temperature in regulating glacier melt contributions. While higher temperatures accelerate melting, shorter snow cover duration further increases glacier melt, significantly affecting streamflow during droughts.

Analysis of three extreme summers (2003, 2005, and 2022) revealed variable melt contributions. In 2003, elevated temperatures led to a 12% contribution at the basin scale, while in 2005, cooler temperatures reduced it to 5%. In 2022, despite high temperatures, reduced glacier areas limited contributions to 8%; if 1997 glacier extents had persisted, contributions could have reached 15%. These findings underscore the declining role of glacier melt in mitigating droughts. As glaciers continue to shrink, future summer streamflow in the Adige River basin will increasingly rely on precipitation and earlier snowmelt, heightening the vulnerability of water resources to climate variability.

Keywords: Glaciernelt, Droughts, Alps, Runoff, Climate Change

Seasonal Shifts in Snowpack Dynamics and Their Response to Climate Change in the Swiss Alps

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In response to global climate change, the Swiss Alps are undergoing significant transformations in snowpack dynamics, crucial for ecological, economic, and human activities. This study focuses on the Snow Water Equivalent (SWE) as a critical indicator of climate impacts, analyzing its seasonal variability over several decades.

Using three climate projection models, we forecast changes for the years 2035 and 2060 under two climate scenarios, RCP4.5 and RCP8.5. First, the high-resolution SWE (HR-SWE) images are predicted using a machine learning method (Zakeri et al., 2024), which is based on the relationship between meteorological estimators and historical HR-SWE data. Using the predicted HR-SWE data, we identify and analyze melting seasons by noting peak and minimal SWE values, which mark the shift from accumulation to melting phases. Our comparative analysis with historical melting patterns from 2000 to 2022 indicates a substantial decline in snow-covered days, forecasting shorter snow seasons and decreased SWE in the future. Specifically, under RCP4.5, the reduction in SWE by 2060 is expected to be similar to that of 2035, whereas, under RCP8.5, a sharper decline is expected.

(Reference) Zakeri, F., Mariethoz, G., and Giroto, M.: High-Resolution Snow Water Equivalent Estimation: A Data-Driven Method for Localized Downscaling of Climate Data, EGUsphere [preprint], <https://doi.org/10.5194/egusphere-2024-1943>, 2024

Keywords: Climate Change, Swiss Alps, Climate Projection Models, Time Series, High-Resolution Snow Water Equivalent, Machine Learning, Forecasting Climate Impacts

Geocryological Conditions of Small Mountain Catchment in the Upper Kolyma Highland (Northeastern Asia)

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The research presents a comprehensive environmental assessment of a small mountain permafrost catchment of the Anmangynda River in the Upper Kolyma Highland (Northeastern Asia) over the period of 2021–2024. The study reveals significant diversity in climatic, geocryological, and hydrogeological conditions within this confined area, emphasizing the need for extensive field data

collection and monitoring in vast permafrost regions with limited data availability. Key findings include variations in ground temperature, maximum seasonal thaw depth, and depths of zero annual amplitudes of ground temperature at different elevations and landscape types. Groundwater and surface flow dynamics within spring aufeis basins exhibit complex geocryological regimes influenced by icing processes. The presence of aufeis and its impact on local hydrology highlight the ecological significance of this phenomenon. Future research should focus on long-term trends in permafrost dynamics and their relationship with climate change, as well as the ecological effects of aufeis. The study underscores the importance of a multi-faceted approach to environmental assessment, incorporating various environmental parameters and processes, to gain a comprehensive understanding of the intricate interactions within the cryosphere and their responses to changing climate conditions. Such knowledge is essential for addressing broader questions related to climate change, ecosystem resilience, and sustainable resource management in Northeastern Siberia.

The study is supported by Russian Scientific Fund and the Government of the Magadan region, the project (23-17-20011) "Assessing the risks of hazardous phenomena for the infrastructure of the Magadan region caused by climate- and anthropogenic-induced transformation of permafrost".

Keywords: permafrost, ground temperature, active layer thickness, groundwater, aufeis, the Kolyma basin

Physics-based simulation of long-term hydrological changes at high-elevation alpine catchments with varying glaciations in central Europe since 1850

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The European Alps are highly sensitive to climate change, with accelerating glacier retreat, reduced snow cover, and altered precipitation patterns. Glacier and snowmelt play a crucial role in the streamflow changes in such environments. However, quantifying historic streamflow variations due to changes in glaciers and snowmelt is rare due to limited long-term hydroclimatic observations, complex topography, and intricate interactions and feedback between water, landscape, and climate systems in these regions. Here, we develop a cascading hydroclimatic coupling framework (Reanalysis-WRF-WaSiM) to simulate streamflow changes in three high-elevation alpine catchments with varying glaciation rates (3% to 31%) in central Europe from 1850 to 2015. We first calibrate a fully distributed, physics-based hydrological model, WaSiM, for each catchment to the observed river discharge, glacier coverage and mass balance, snow water equivalent, and snow cover duration. The model is then forced with the hourly and daily meteorological data from the Weather Research and Forecasting Model (WRF), which are dynamically downscaled from a global reanalysis and temporally and spatially bias-corrected for the local topography. There are a few unavoidable constraints in this cascading framework. For example, the hydrological results are sensitive to the simulation lengths, different glacier initializations, and the bias-correction approaches of the climate

model outputs to the highly heterogeneous local scales. This cascading workflow is innovative and at the forefront of understanding the long-term hydrologic trends, extreme events development, and the switching dominant roles of glacier melt and snowmelt on discharge changes of glaciated catchments in the past 165 years, given rare long-term hourly observations available. Overall, this study contributes to understanding the evolving hydrological patterns in the high-elevation glaciated catchments with accelerating diminishing trends under climate change.

Keywords: climate-change, European Alps, WaSiM

Arctic Climate Variability and Its Influence on Seasonal Snow Dynamics in the Hindu Kush Himalayas

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The Hindu Kush Himalayas (HKH), often called the "Third Pole," are critical in sustaining South Asia's hydrological systems. However, recent Arctic climate changes, particularly Arctic Sea Ice Extent (SIE) loss and Arctic Oscillation (AO) shifts, may alter seasonal snow and runoff dynamics in the HKH. This study investigates Arctic-HKH teleconnections, focusing on snow accumulation, runoff, and precipitation variability. We employ the Global Land Data Assimilation System (GLDAS), a land surface model that integrates observation-based meteorological forcing alongside NOAA's AO index and NSIDC's SIE records (1980–2014). Seasonal snow depth, snow water equivalent (SWE), total runoff, snowmelt, and precipitation are analyzed through correlation and composite analysis, stratified by AO phases. Statistical significance tests assess robustness, while pre- and post-2000 comparisons identify possible regime shifts. Our findings reveal a significant positive correlation between winter SIE and snow depth ($r = 0.5$ to 0.8 , $p < 0.05$), particularly in the Indian and Nepal Himalayas, suggesting enhanced poleward moisture transport during years of extensive sea ice. AO phases exhibit contrasting impacts: positive AO winters are linked to reduced snow depth ($r = -0.2$ to -0.6), most pronounced in the Western Himalayas, Karakoram, and Qinghai-Tibetan Plateau. Conversely, negative AO winters correspond to increased snow accumulation ($r = 0.2$ to 0.5) and sustained late-season runoff ($r = -0.4$ to -0.6), particularly in the Northern Indus Basin. Post-2000, a decline in snow accumulation and earlier melt onset are observed, likely driven by intensified Arctic warming and evolving moisture transport pathways. These findings enhance our understanding of Arctic-HKH climate linkages, offering a framework for seasonal hydrological forecasting and climate adaptation strategies in high-altitude regions. Future work will integrate atmospheric reanalysis datasets to quantify moisture transport mechanisms further.

Keywords: Arctic Oscillation, Arctic Sea Ice Extent, Snow Hydrology, Teleconnections, Hindu Kush Himalayas

Spatial and temporal variability of snow in Himalayan Mountains Catchment

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Understanding the rate of snow accumulation and snowmelt is crucial for assessing how water stored as snow and contribute to streamflow. This study analyses the spatio-temporal variability of snow across the five major river basins of Himachal Pradesh, India, a significant part of the Himalayas. Data from multiple 22 snow monitoring stations under National Hydrology Project (NHP) and Hydrological Department Mandi, across the region were utilized to estimate variations in snow depth and accumulation. Initially, temporal variations were found to explain most of the variance in the analysis. To account for the spatial variability, a residual linear correlation model was used. Further analysis revealed that factors such as elevation of instrument (from 1571 m to 4181 m), longitude, slope, temperature, and land cover type contributed significantly to the observed variations. Some of the snow stations are getting monsoon precipitation in the form of snow for the period June to September and getting maximum average snow accumulated on the ground of more than 1000 millimetres. For evergreen forests, canopy density played a major role in enhancing melt rates, whereas for all other land cover types classified as non-evergreen, snowmelt were found to be lower at north-facing slopes, higher latitudes, and on higher elevations. For the Beas and Satluj basins, the snow depth and snow accumulation varies differently for the both catchment because of major changes in land cover. Nash-Sutcliffe Efficiency and R^2 (coefficient of determination) are used to evaluate the performance of regression models. These findings indicate that in colder environments, snowmelt is less efficient compared to milder climatic conditions. This study provides valuable insights into the snowmelt dynamics of the Himalayan region, which is essential for hydrological modeling, water resource management, and predicting seasonal streamflow variations.

Keywords: Snow, Spatio-temporal variability, Residual linear correlation.

Glacier meltwater has limited contributions to the annual runoff in the major rivers draining the Tibetan Plateau

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The Tibetan Plateau is the headwaters of several major river basins, but uncertainties exist in the estimated contributions of glacial melt and groundwater to runoff. We present a new tracer-aided glacio-hydrological model constrained by multiple datasets for five major river basins of the Tibetan Plateau. The model is able to simulate the hydrological, cryospheric and tracer processes simultaneously and can be validated using multiple datasets. We show that the contribution of glacier melt to the annual runoff is less than 5% in all the five basins at the outlets—much less than previous estimates. Rainfall dominated the source water in all five rivers, contributing 74-87% to the total water input. Our secondary finding is that the partitioning between surface runoff and groundwater flow varied greatly across the watersheds, with groundwater runoff contributing 35%-75% of the annual runoff. The contribution of glacier melt has a strong spatial variability and scale dependency, but the

population heavily dependent on it is limited, so a potential significant decrease in water resource due to glacier shrinkage is not a problem that should raise public worries in the Tibetan Plateau. Our work shows the value of tracer data on improving model performance and runoff component estimation.

Keywords: Tibetan Plateau, Runoff component, Tracer-aided hydrological model, Meltwater, Groundwater

Advancing Non-Contact River Flow Measurements: Winter Flow Assessment Using LSPIV and Ice-Covered Channel Analysis

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Accurate river flow measurements remain crucial for hydrological studies; however, in-situ methods can be impractical, particularly in extreme conditions such as flood events or ice-covered channels. Large Scale Particle Image Velocimetry (LSPIV) offers a promising non-contact alternative, capable of capturing surface velocity dynamics through video imaging techniques. While previous studies have demonstrated the effectiveness of LSPIV in urban river systems during open-water conditions, its application to winter flows under partial or complete ice coverage remains underexplored. This study extends prior LSPIV assessments on Black Creek, a small urban stream in Toronto, by incorporating video analysis of winter river flow in ice-covered conditions. Using an iPhone 14 Pro Max, we recorded both seeded and unseeded flow scenarios and segments where ice coverage left only portions of the channel exposed. Velocity estimations were obtained using FUDAA-LSPIV, and the results were compared with previous open-water observations. We aim to evaluate the feasibility of LSPIV in mixed ice-water conditions, examining the influence of surface tracers, ice roughness, and optical limitations on velocity estimations. Our preliminary findings suggest that ice-covered sections present unique challenges, such as reduced tracer movement and complex flow interactions. However, areas of exposed flow yield measurable velocities, reinforcing LSPIV's potential for winter hydrological monitoring. Future work will explore methodologies for estimating depth-averaged velocities under ice, thereby improving flow characterization in cold-region environments. This study contributes to broadening the applicability of LSPIV beyond open-channel conditions, offering insights into river flow measurement techniques under seasonal constraints.

Keywords: LSPIV, FUDAA, Ice, Non-Contact, Toronto, Black Creek

Assimilation of multichannel passive microwave data for improved estimates of snow microstructure

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Snow is a vital water resource yet is difficult to monitor with satellites due to the sensitivity of the signal to both mass and microstructure at microwave frequencies. Inversion of forward radiative transfer models to obtain snow water equivalent requires a priori estimates of snow structure. On large scales, this is derived from land surface models. Although these models may capture important structural evolution processes such as melt and snow crystal metamorphism, the size and shape of snow crystals may not be represented with sufficient accuracy required for snow water equivalent retrieval. Penetration of the microwave radiation depends on the frequency, with higher frequencies more sensitive to surface properties and lower frequencies responsive to properties lower in the snowpack. Assimilation of multifrequency remote sensing observations may help to constrain layered snow microstructure in the model. Here, we use the Multiple Snow Data Assimilation system to quantify the change in snowpack properties from assimilation of passive microwave data in the frequency range 1-36 GHz. A range of assimilation techniques and frequency combinations are presented. Implications for use of data from the planned Copernicus Imaging Microwave Radiometer mission are discussed.

Keywords: snow, data assimilation, microwave remote sensing, MuSA, CIMR

Reconstruction of the South Lhonak Lake Glacial Lake Outburst Flood (GLOF) in Sikkim Himalaya India

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In the Sikkim Indian Himalaya, numerous glacial lakes have been identified as highly vulnerable, including the South Lhonak Lake (SLL), which catastrophically breached on October 4, 2023. This event caused extensive devastation across the Teesta Valley, impacting four districts of Sikkim, India. According to the Sikkim state government, the disaster destroyed 33 bridges, numerous highways, and 100 villages, including 2002 houses and approximately 70 lives were lost. Key infrastructure such as Chungthang and the Teesta-3 Dam, a 1200 MW hydropower project, suffered severe damage due to the flash flood in the Teesta River. The breach of SLL was primarily attributed to the collapse of a massive lateral moraine (approximately $3.2 \times 10^7 \text{ m}^3$) and glacier ice calving, which significantly amplified the outflow wave. The breach, spanning a length of 91 meters, released an estimated peak flow of around 18,000 m^3/s within just 30 minutes of the Glacial Lake Outburst Flood (GLOF). This flood resulted in downstream water depths reaching 13.79 meters and velocities of

up to 26.51 m/s. Satellite imagery analysis (Landsat and Sentinel) revealed that the area of the lake expanded by 127% between 2000 and 2023, primarily driven by the accelerated melting of its parent glacier. Contributing factors such as rapid glacier retreat, high precipitation events, and substantial diurnal temperature variations collectively increased the lake's susceptibility to breaching. This study reconstructs the SLL breach conditions using coupled hydrologic (e.g., SPHY model) and hydrodynamic (2D HEC-RAS) modeling, providing detailed insights into both pre- and post-GLOF scenarios. The findings underscore the critical need for continuous monitoring of similarly vulnerable glacial lakes and the implementation of proactive risk mitigation strategies. By analyzing glacier dynamics, hydrological processes, and associated triggering factors, this research highlights pathways to reduce future hazards and enhance disaster preparedness in fragile high-altitude environments.

Keywords: Glacial Lake Outburst Flood (GLOF), Glacier Retreat, Hydrologic-hydrodynamic modeling, South Lhonak Lake, Sikkim Himalaya

Evolving snow drought impacts on the hydrological behavior of headwater catchments in the Andes Cordillera.

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Snow accumulation is the main driver of hydrological variability in many high mountain regions of the world, including in the Extratropical Andes Cordillera. Snow accumulation deficits in these regions are therefore of special concern; unfettered global heating is perturbing snow dynamics and drought properties pertaining the seasonal snowpack may differ from the historical record in such way that downstream impacts can be much harder to predict. Global snow drought analyses rely on coarse scale reanalysis or land-surface models that often fail to capture local processes which in turn determine strongly the dynamics of snow accumulation and melt. On the other hand, data-driven analysis may fail to capture the interplay between precipitation, temperature and runoff generation processes. For the snow-dominated domain in the extratropical Andes Cordillera, understanding of the temporal evolution of snow droughts at scales relevant for water resource planning is of key importance for municipal, agricultural and socio-ecological adaptation. In this paper, we present a model-based analysis of snow droughts in high mountain basins in central Chile, with the objective of understanding the features of snow drought over a time period spanning several decades. Specifically, we show how the type of snow-drought in this domain has evolved, present spatial patterns of changes in key snow and hydrological indices and link them to trends and tipping points in hydrological processes. Also, we discuss how recent droughts could provide valuable lessons as a climate analogue for adaptation to future scenarios in snow-dominated high mountain areas.

Keywords: Snow hydrology, drought, hydrological impacts, Andes Cordillera

Impact of snow land data assimilation on hydrological processes in Community Land Model version 5 with SWEML

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Snow plays a key role in the global water cycle and energy balance. Snow Water Equivalent (SWE) represents the water volume released during snowpack melt and thus indicates the volume of water that will flow into rivers and streams as the snow melts. SWE can be estimated using different methods, including in-situ measurements, remote sensing, and physical models. Each method has certain limitations, such as high costs, low spatiotemporal resolution, and model representation and parameter calibration. This study presents the introduction and application of a new machine learning-based daily global gridded SWE product (SWEML) at 0.25° from 1980 to 2020. We generated SWEML using the random forest algorithm, incorporating 11,653 in-situ measurements from eight sources and 11 meteorological and orography variables. SWEML provides high-accuracy spatiotemporal data in high-elevation mountainous regions. Then, we assimilated the SWEML into Community Land Model version 5 (CLM5) to improve the hydrological processes via snowpack simulation improvement. CLM5 was simulated hourly at a 0.25° spatial resolution for the Northern Hemisphere from September 2009 to June 2010, a period of rapid snowpack decrease. We employed the Ensemble Adjustment Kalman Filter for data assimilation (DA) and used 40 ensemble members from the Community Earth System Model 2 Large Ensemble Community Project. DA was performed daily, and analyzed the changes in evapotranspiration, runoff, soil moisture, and aquifer water storage. Our SWE DA results indicate that enhanced snow simulation has resulted in significant changes to the water balance. We particularly observed significant variations in grid runoff.

(Acknowledgement) This work was supported by the National Research Foundation of Korea, which was funded by the Ministry of Science, ICT and Future Planning (RS-2024-00457308), and the Korea Environment Industry & Technology Institute through the R&D Program for Innovative Flood Protection Technologies against Climate Crisis, funded by the Korean Ministry of Environment (RS-2023-00218873).

Keywords: Snow water equivalent, Machine learning, Snow land data assimilation, Community land model version 5

Analysing the hydrological response of the glaciated Gangotri Basin under dry, wet and normal precipitation years

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The Himalayan river basins are characterized by cryosphere components and are crucial in sustaining downstream water availability. The Gangotri Basin, a major headwater and source of the Ganges, is primarily fed by glacier melt, snowmelt, and precipitation, making it highly sensitive to climatic variability. Understanding the hydrological responses of glacierized watersheds to the shifts in meteorological parameters is crucial for effective water resource management, flood and drought

forecasting, disaster risk reduction, ecosystem sustainability and policy making. The research analyses the hydrological response of the glaciated Gangotri basin in the Standardised Precipitation Index (SPI) derived wet and dry years with normal years serving as a baseline using glacio-hydrological modeling from 2010 to 2022. Wet years recorded higher precipitation and discharge together with a lower range of air temperatures (max., min. and average) with respect to normal years whereas dry years exhibit opposite trends. Wet years experience an increase in snowmelt runoff by 104.14% owing to the increase in precipitation by 5.2% whereas dry years experience an increase in snowmelt by 80.89% with an increase in average temperature by 67.57 %. However, the relative contribution to discharge by each runoff component in wet years is similar to that in normal years while the dry years were found to have increased runoff contribution from glacial melt (+3%) and baseflow (+1%) to compensate for the decreased contribution from snow melt and rain-induced runoff (-2% each). Deviations in key parameters such as snowmelt, glacial melt and rain-induced runoff components, demonstrate intricate seasonal hydrological responses to climatic anomalies, especially during post-monsoon season. The research provides valuable insights into the resilience and vulnerability of the Gangotri basin's hydrological system by quantifying the impact of precipitation variability on runoff dynamics.

Keywords: Glacio-Hydrological Modeling, SPI, Gangotri Basin, Climate Variability, Glacier Hydrology

Decadal Changes in Glacier Facies and ELA in the Himalayas: Implications for Regional Hydrology

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Seasonal snow and glaciers are vital components of regional hydrology, supplying freshwater to downstream river systems. This study analyses the spatiotemporal variability in glacier facies and equilibrium line altitude (ELA) across six major glaciers: Siachen (Ladakh), Samudratapu, Chota Shigri, Badashigri (Himachal Pradesh), and Gangotri (Uttarakhand) of India and Fedchenko glacier of Tajikistan. Fedchenko Glacier (~77 km) and Siachen Glacier (~75 km), the longest non-polar glaciers on the planet, were included to provide a comprehensive perspective on glacier facies evolution and ELA trends across different climatic regimes. The study has been performed over a period of 10 years (2015–2024). Sentinel 1A & 1B Ground Range Detected (GRD) SAR imagery were used to generate time series composites (winter, early summer, and late summer) for the glacier facies mapping from 2015 to 2024. A Support Vector Machine (SVM) algorithm, trained using previous facies classifications and validated against optical imagery, was applied to delineate percolation zones, wet snow, superimposed ice, bare ice, and debris facies. Based on the literature, the ELA lies between the wet snow and bare ice facies (in absence of superimposed ice) or between the superimposed ice and bare ice facies. ELA variations were estimated by identifying these facies transitions in SAR imagery, using the SRTM DEM (30m) as a reference elevation dataset. The results reveal a consistent upward ELA trend, with temporary downward shifts in 2019 and 2023 due to increased snowfall during these years. These changes in glacier facies and ELA influence seasonal runoff patterns by advancing peak meltwater discharge and early summer flows, and potentially reducing late-summer water availability. Such shifts have significant implications

for downstream water resources, particularly for agriculture, hydropower, and freshwater supply in glacier-fed river basins. This study highlights the importance of continuous glacier monitoring to assess climate driven hydrological changes in the Himalaya.

Keywords: Glacier Facies, Equilibrium Line Altitude, Support Vector Machine, Sentinel1, Hydrology, Remote Sensing, Cryosphere

Long-term Snow Cover Dynamics in the Indian North-Western Himalayas using Multi-Sensor Satellite Data

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Snow cover is a vital component of the Earth's climate system, playing a crucial role in water resource management, regional hydrology, and ecosystem stability. This study analyzes long-term trends in the snow-covered area (SCA) of the Indian North-Western Himalayas (NWH) from 2000 to January 2025 using snow products from Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Wide Field Sensor (AWiFS), and Interactive Multisensory Snow and Ice Mapping System (IMS). The Mann-Kendall (MK) statistical test indicates no significant trend in mean annual SCA over this period. The highest annual mean SCA was recorded in 2019, exceeding the long-term average by 28%, whereas the lowest occurred in 2016, measuring 44% below the long-term mean. The maximum daily SCA was observed on February 8, 2019, covering 62.46% of the NWH, while the minimum was recorded on August 5, 2016, covering just 6.02%. Seasonal analysis reveals shift in peak SCA timing over the years. Between 2000 and 2010, peak SCA was typically observed in January or February, whereas from 2011 to 2025, its occurrence became more variable. Notably, in 2020, peak SCA was recorded as late as April 20, suggesting changes in snowfall patterns and accumulation dynamics. Additionally, this study examines SCA variations at different elevation levels above 1500 m, segmented at 1000 m intervals, offering insights into elevation-dependent snow distribution trends. A state and Union Territory (UT)-wise assessment was also conducted across Uttarakhand, Himachal Pradesh, Ladakh, and Jammu & Kashmir, highlighting regional disparities in snow cover dynamics. The findings underscore the value of multi-sensor remote sensing approaches and continuous satellite observations in monitoring long-term snow cover trends. These insights are essential for hydrological resource management, climate change assessments, and policy-making for the Himalayan cryosphere.

Keywords: Snow-Covered Area, Indian North-Western Himalayas, MODIS, AWiFS, IMS, Remote Sensing, Himalayan Cryosphere.

Aerosol-Driven Changes in Glacial and Polar Ice Melt: A Multi-Scale Analysis Using Remote Sensing and Transport Modeling

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While temperature anomalies are the primary drivers of glacial and polar ice melt, aerosols play a crucial yet underexplored role in accelerating this process. Black carbon (BC) and secondary organic aerosols (SOAs), transported over long distances, deposit onto ice surfaces, reducing albedo and enhancing radiative forcing. This leads to increased absorption of solar radiation, triggering feedback mechanisms that further amplify regional warming. Understanding the role of aerosols in glacial melt is essential for improving climate projections and mitigation strategies. This study aims to quantify aerosol deposition and its impact on ice melt using a combination of satellite remote sensing, reanalysis datasets, and atmospheric transport modeling. MODIS Aerosol Optical Depth (AOD) data, along with MERRA-2 and ERA5 reanalysis, will provide spatial and temporal trends of aerosol presence over glaciated regions. HYSPLIT backward trajectory analysis will identify potential source regions contributing to aerosol deposition in polar and high-altitude glacier environments. To assess radiative effects, the SNICAR model (Snow, Ice, and Aerosol Radiation model) will simulate surface albedo changes due to BC and SOA accumulation, improving our understanding of aerosol-induced cryospheric feedbacks. By integrating observational datasets with transport modeling, this research aims to establish a framework for assessing the role of anthropogenic and natural aerosol sources in glacial melt. The findings will help refine climate models and contribute to targeted policy recommendations for emission controls, particularly in the areas where aerosol impacts on the cryosphere remain insufficiently constrained.

Keywords: Glacial Melt, Polar Ice Sheets, Aerosols, Black Carbon, SNICAR, HYSPLIT, MODIS AOD, Climate Feedbacks.

Co-Creating Water Knowledge for Climate Resilience: Understanding Precipitation Shifts and Their Impacts in South Asia and China

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Climate change is driving significant shifts in precipitation patterns across South Asia and China, affecting water availability, disaster risk, and ecosystem stability. A key transformation is the transition of precipitation phases from snow to rain, which disrupts hydrological regimes and accelerates

glacial melt, altering river flow and water storage. These changes amplify flood and drought risks, impacting water, food, and energy security in the region.

This study, part of the APN Project CRRP2024-06MY-Pradhananga Enhancing Climate Resilience in South Asia and China, employs an interdisciplinary and participatory approach to analyze precipitation shifts and their implications. By integrating high-resolution climate data analysis, remote sensing, modeling, and stakeholder engagement, we assess spatiotemporal precipitation trends and phase transitions across river basins in Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The co-creation framework ensures that scientific insights translate into actionable strategies for policymakers, disaster managers, and local communities.

Preliminary findings reveal increasing monsoon variability, heightened extreme precipitation in previously arid zones, and a concerning shift from snowfall to rainfall in mountain regions, threatening water storage and seasonal flow regulation. These insights underscore the urgency of adaptive water management strategies and enhanced early warning systems. The project fosters regional collaboration, builds scientific capacity through training programs, and co-develops community-driven solutions to mitigate climate risks.

This presentation contributes to the IAHS Snow and Ice Hydrology (ICSIH) and Co-Creating Water Knowledge sessions by demonstrating how participatory science strengthens climate resilience. We emphasize the role of collaborative research in addressing hydrological challenges and provide recommendations for integrating scientific knowledge with community adaptation efforts.

Keywords: Climate resilience, precipitation phase shift, snow-to-rain transition, monsoon, hydrology, co-creation, South Asia and China, disaster risk reduction, water security

Strengthening GLOF Risk Mitigation in India: Challenges and Strategies

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The Indian Himalayan Region (IHR) is increasingly vulnerable to Glacial Lake Outburst Floods (GLOFs) due to climate change-driven glacial retreat. Furthermore, GLOFs pose significantly increasing threat to communities and infrastructure in the Indian Himalayan Region (IHR). This study investigates strategies for reducing GLOF risks in India, particularly in the context of the National GLOF Risk Mitigation Project (NGRMP). The NGRMP, an initiative across four hill states of India viz., Arunachal Pradesh, Himachal Pradesh, Sikkim, and Uttarakhand, addresses GLOF risks through comprehensive hazard and risk assessment, enhanced early warning systems, targeted mitigation interventions, and capacity building.

This study aims to identify the gaps in GLOF risk management and explores opportunities for strengthening mitigation strategies. Key challenges include the lack of standardized hazard mapping, limited last-mile connectivity in early warning dissemination, and insufficient integration of community knowledge with scientific interventions.

Additionally, the study analyzes temporal and spatial characteristics of GLOF disasters, conditions and mechanisms of GLOF disaster formation, and proposes risk management strategies. By evaluating the challenges and opportunities in GLOF mitigation, this research aims to strengthen and enhance risk management capabilities, safeguard infrastructure, inform land use planning, and improve disaster preparedness in vulnerable Himalayan regions, by integrating scientific advancements, community engagement, and traditional knowledge. A more holistic, adaptive, and inclusive

approach to GLOF risk management in India will not only mitigate immediate threats but also contribute to sustainable disaster preparedness in the Himalayan region.

Keywords: Glacial Lake Outburst Floods (GLOFs), Indian Himalayan Region (IHR), GLOF risk mitigation, Early Warning Systems, capacity building, sustainable disaster preparedness

Modelling Snow Avalanche Flow Dynamics Using RAMMS: A Case Study of Solang Valley and Alaknanda Basin

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Snow avalanches are common and fatal catastrophic events in high-altitude regions, generally caused by a combination of terrain, weather, and snowpack conditions and often triggered by natural factors or human interventions. It is necessary to understand the flow dynamic of snow avalanches, which is crucial for avalanche-prone regions for hazard assessment to develop strategies for mitigation planning. The present study focuses on the simulation of snow avalanche flow dynamics using the Rapid Mass Movement Simulation (RAMMS) model at the sites that were marked during field visits in the Solang Valley and Alaknanda Basin. The study utilizes the Cartosat-10 m Digital Elevation Model (DEM) to run simulations in Solang Valley and Alaknanda Basin (above and before Badrinath temple). A total of eight simulations were done, where six simulations were run for Alaknanda and two for Solang Valley, respectively. In the Alaknanda basin, the first three simulations were carried out above Badrinath, where One was at Mana village, where in 2015 a massive avalanche was reported by Indo-Tibetan Border Police (ITBP), second was done for a location near Musa Band, and the third was done for a location near Ghastoli. The three other simulations were done before Badrinath, one near Badrinath, the second across the road where avalanche debris was visible during the field, and the third carried out in the middle of Badrinath and Hanuman Chatti. It was observed that the location before the Badrinath had the least volume but maximum velocity. It was also observed that at one of the locations above, the Badrinath has the largest volume with the least velocity. The study simulated the medium-intensity avalanche for the 30-year return period. The study concludes that additional locations can utilize the RAMMS model to calculate the runout zone of avalanche sites for risk management.

Keywords: Snow avalanche, flow dynamics, Mana village, Solang valley, and Alaknanda basin.

Study on Soil Moisture Redistribution during Freezing Processes under Pressure

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Soil water redistribution induced by freezing has a significant impact on the mechanical behavior of artificial frozen walls. Understanding the effects of pressure on soil moisture redistribution is critically important for frozen soils in deep underground environments, where they are often subjected to substantial geostatic stress. This study investigates moisture redistribution in fine-grained soil under confining pressure during the freezing process. A custom-designed freeze–thaw apparatus was used to monitor the thermal conditions and the propagation of the freezing front in a soil column. Moisture content profiles were measured at the end of the freezing process, to identify the stable position of the freezing front and to characterize the water redistribution pattern. The results indicate that, under applied pressure, the freezing front stabilizes after approximately 14.5 hours once a specific temperature gradient is imposed. Notably, the stable position of the freezing front shifts toward the warm end as the temperature gradient increases. The frozen zone generally retains higher moisture content than the unfrozen zone. The minimum moisture content near the freezing front (within the frozen fringe) is influenced primarily by the applied pressure rather than the temperature gradient. Conversely, the maximum moisture content in the ice lens region increases with a steeper temperature gradient. These findings confirm that, under pressure and one-dimensional closed-system freezing conditions, water from the unfrozen zone migrates through the frozen fringe into the ice lens region without accumulating within the fringe itself.

Keywords: water redistribution, ground pressure, freezing

Cryospheric melt and streamflow dynamics in High Mountain Asia (HMA): Insights from stable water isotopes

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High Mountain Asia (HMA) serves as a critical water tower of Asia, supplying freshwater to major river systems that support the livelihoods of nearly 1.9 billion people. However, due to ongoing climate change reduced snowfall, and accelerated glacier mass loss is profoundly altering the cryosphere and associated hydrological processes. This study investigates the spatio-temporal dynamics of meltwater contributions and routing within glacierized catchments of the UIB, India, using stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$). Isotopic characterization of precipitation (fresh snow), surface snow, glacier meltwater, and streamflow revealed significant spatio-temporal heterogeneity driven by physiographic controls, seasonal hydrometeorological variations, and altitude-dependent climatic regimes. Freshly deposited snow exhibited a distinct altitude effect. Conversely, surface snow showed an inverse altitude effect, particularly in arid, high-elevation zones, due to enhanced post-depositional sublimation and kinetic fractionation. Evidence of isotopic homogenization was observed in firn layers, resulting from melt-refreeze cycles and isotopic exchange between meltwater and snowpack. Seasonal variations in streamflow isotopic composition were indicative of

mixed source contributions, with snowmelt dominating early-season discharge, followed by increasing glacier melt inputs during peak ablation periods. Quantitative source apportionment using a Bayesian isotope mixing model (SIMMR) estimated that cryospheric meltwater accounts for approximately 40% to 70% of total streamflow, varying by sub-basin and season. Slope and intercept deviations of the local meteoric water line (LMWL) from the global meteoric water line (GMWL) reflected seasonal influences of convective versus stratiform precipitation and revealed the integrated isotopic imprint of meltwater contributions to river flow. These deviations also suggested variable moisture source regions and enhanced evaporation signals during dry months. The study emphasizes the pivotal role of snow and glacier melt in sustaining hydrological regimes in the UIB. Projected changes in the timing, magnitude, and phase of precipitation, coupled with continued glacier mass loss, could lead to significant hydrological regime shifts.

Keywords: Cryosphere, Himalaya, Meltwater, Modeling

Surface Water (ICSW)

Processes and water balance over the last 60 years in the Chari-Logone sub-basins, Lake Chad basin

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This study aims to improve understanding of the hydrological functioning of the Chari-Logone basin (Lake Chad basin) under the influence of pronounced rainfall variability that has affected the Sahel over the past six decades. The analysis is based on hydro-climatic data spanning the period 1960-2015, sourced from national and international institutions. The methodological framework comprises three main steps: (1) Estimation of mean hydrological balances across distinct geographic zones to identify the most productive subregions of the basin; (2) Comparative assessment of rainfall-runoff relationships during the wettest and driest decades of the study period, to determine which areas most strongly amplify hydrological responses to precipitation variability; and (3) Evaluation of long-term stability in the rainfall-runoff relationship under near-average climatic conditions, to detect potential evidence of anthropogenic influence.

Over the 1960-2015 period, the mean runoff depth of the Chari-Logone basin (42 mm/year) accounted for only 5% of total precipitation. Between the two most contrasting climatic periods-wet (1960-1971) and dry (1982-1997)-mean runoff varied by 75%, while precipitation declined by only 15%. The hydro-climatic dataset does not reveal any clearly detectable anthropogenic impact that could explain a reduction in runoff or a shift in the hydrological regime of the Chari-Logone basin. (English translation autogenerated from the original French using Microsoft Copilot)

Keywords: Lake Chad, Chari-Logone, hydrological, climate and variability

Projected Hydrological Drought Characteristics and trends over the Pra River Basin, Ghana

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This study assesses projected hydrological drought characteristics and trends over the Pra River Basin in Ghana to inform integrated water resource management. Using the VIC hydrological model, streamflow was simulated, and the Standardized Streamflow Index (SSI) was employed as a hydrological drought indicator. The analysis utilized simulations from thirteen regional climate models

under CORDEX Africa for RCP4.5 and RCP8.5 scenarios, spanning the near (2021-2040), mid (2041-2070), and far (2071-2100) future periods. Key drought metrics, including duration, severity, and intensity, were analyzed using run theory, while trends were examined through Mann-Kendall analysis. The projected SSI trends suggest increases in streamflow during the near and mid-future periods under both RCP4.5 and RCP8.5 scenarios, with a decline in the far future. For the near future under RCP4.5, show most models project reductions in drought duration by up to 20%. Similarly, under RCP8.5, drought duration is expected to decline by as much as 100%, although some models suggest increases of up to 80%. Across both scenarios, drought severity is projected to decrease by up to 50%, while drought intensity shows modest increases of less than 20% for most models. In the mid-future, RCP4.5 projections indicate drought duration reductions of up to 60%, though some models predict increases of up to 50%. RCP8.5 similarly suggests general reductions, with occasional moderate increases. Drought severity aligns with these trends, showing overall declines with sporadic marginal increases. Drought intensity is projected to rise modestly, ranging from 15% to 40%, though some models indicate slight decreases. By the far future, most models under both scenarios project significant reductions in drought duration and severity, often exceeding 50%. However, drought intensity is expected to increase, signaling the possibility of more intense but less frequent drought events. Justifying the need for comprehensive adaptive water resource management strategies to mitigate the impact of intense drought over the basin.

Keywords: Hydrological drought, Pra River Basin, Climate Scenarios, CORDEX Africa, trends

Enhancing River Discharge Observations: A Comparative Study of Current Meter and ADCP Methods using Rating Curves in Himalayan Rivers

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Recent advancements in river discharge measurement are being focused on reducing the efforts and period of gauging required for reliable river discharge measurements. To achieve this, various non-contact techniques, such as Doppler radars and camera-based sensors, are being developed globally. However, reliably capturing flow dynamics in stations with highly fluctuating flow conditions with various discharge observation methods is a significant challenge. Therefore, an investigation was performed on two Himalayan River sections situated in Devprayag, i.e. the Bhagirathi River, characterized by highly fluctuating flow behaviour, and the Ganga River, which exhibited relatively stable flow conditions. The study employs least-squares and entropy-based rating curves to compare observed discharge obtained using two widely used methods, namely current meter and ADCP (Acoustic Doppler Current Profiler). The comparison evaluates the effectiveness of the two discharge observation methods in representing estimated discharge using an entropy-based method that employed a non-contact telemetry radar. The findings reveal that both least square and entropy-based rating curves performed exceptionally well with the ADCP discharge observations at the Bhagirathi River, achieving an R^2 more than 0.9. In contrast, the current meter method yielded poor results, with an R^2 value below 0.6, underscoring the superiority of the ADCP method in highly fluctuating flow conditions. Conversely, both methods demonstrated comparable accuracy at the Ganga River station, where flow fluctuations are minimal. Notably, the entropy-based rating curve method showed minor deviations in regions with sparse data, particularly during low or high flow

conditions. Nevertheless, it provided reliable discharge estimates with fewer data points, making it a promising tool for poorly gauged sites.

Keywords: ADCP, Current meter, Least square rating curve, Entropy

Climate Change impacts on freshwater quantity and quality in Canada

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Canada's climate is warming faster than the global average, with the Arctic region warming even faster—about three times the global rate. Due to the varying responses to increasing greenhouse gases, different regions experience different warming rates. In Canada, loss of snow and sea ice increases solar radiation absorption, leading to more warming than in southern regions. Snow cover has decreased by 5-10% per decade since 1981, and sea ice has declined by 5-20% per decade since 1968.

This presentation will provide recent assessments of ongoing changes and future freshwater vulnerabilities under climate change scenarios. This includes water supply, demand, and quality. Climate change and human development are threatening freshwater ecosystems due to increased precipitation, longer ice-free seasons, and changing runoff patterns. Ongoing changes in freshwater quantity and quality and future scenarios show mixed trends. For example, freshwater supplies have shifted, resulting in higher winter stream flows and lower summer stream flows. In regions with sufficient data, there are no significant changes in lake and wetland levels, but future levels may change rapidly in many northern lakes. Periodic droughts have occurred across much of Canada, but no long-term changes are currently evident. Future droughts and soil moisture deficits are projected to be more frequent and intense during summer, especially at the end of the century under a high emission scenario. Projected changes in temperature and precipitation will influence future groundwater levels, though the magnitude and direction are unclear. Spring recharge of groundwater aquifers is expected to occur earlier due to the earlier snowmelt.

These anticipated changes from anthropogenic climate warming will directly affect the timing and amount of future freshwater supplies, and they may be exacerbated by human management alterations to freshwater systems.

Keywords: Climate change, rivers, lakes, wetlands

Analysis of asymmetric behavior of storm runoff components in a tropical experimental catchment

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The concentration-discharge (C-Q) relationship provides complimentary avenues for a better understanding of catchment water sources and the dominance of hydrological processes across temporal (storm event to annual) and spatial (slope to basin) scales. Due to the advent of high-resolution sensors, the measurement of Concentration and discharge at storm scale has become relatively more straightforward. C-Q analysis provides more insights into the dominant runoff generation mechanism during storm events than derived through traditional hydrograph separation approaches using environmental tracers. It would be interesting to study C-Q hysteresis analysis, especially in the humid tropical forested VAManapuram Experimental Catchment (VAMEC) of southern western ghats, which have a steep topographic gradient, receives enormous rain (>3000 mm annually) in the South-West and North-East monsoons.

The VAMEC is instrumented with a rain gauge, AWS, river gauge, groundwater level loggers, electrical conductivity loggers, etc., and collects data at 30-minute intervals for understanding of catchment hydrological processes. Electrical Conductivity (C) - Discharge (Q) hysteresis behaviour has been studied at the upstream Kallar River Gauging Station (KRGs) and downstream Chettachal River Gauging Station (CRGS) in several storm events between 2022 and 2023. The hysteresis index and slope were calculated to classify individual storm events into different loop categories. The majority of storm events occurring during the monsoon and non-monsoon seasons are categorized as C- and C+ Loop types. This indicates that even water dilution and pre-event water mobilization are dominant runoff generation mechanisms in the monsoon and non-monsoon periods. The salient results from the C-Q relationship and their spatial and temporal variability in the Vamanapuram experimental catchment will be presented at the conference.

Keywords: Runoff generation, Concentration-Discharge relationship, Experimental catchment, storm event

Using Ensemble Machine Learning to Analyze Climate Change Impacts on Hydropower Inflows in West Africa

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This study introduces a comprehensive five-step modeling framework to assess the impacts of climate change on reservoir inflow patterns across four dam basins in West Africa: Buyo, Manantali,

Nangbeto, and Taabo. The research addresses the vulnerability of hydropower resources to changing and variable climatic conditions, with the goal of enhancing predictive accuracy through advanced ensemble machine learning techniques. Observation data from CHIRPS precipitation and CHIRTS mean temperature were utilized for the period 1983 to 2016 using a multi-lag approach. Projections were based on bias-corrected precipitation and mean temperature data derived from twelve CMIP6 models and the multi-model ensemble mean, analyzed under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. These projections were examined for the near-term (2036-2067) and long-term (2068-2099) periods. Model performance validation, employing metrics such as R^2 , NSE, MAPE, and RMSE, demonstrated significant improvements in predictive accuracy across multiple layers. Key findings revealed projected temperature increases of up to 6°C under SSP5-8.5 in the far future. In terms of reservoir inflows, while the Manantali dam is projected to experience a maximum inflow increase of 15.2%, other dams face potential inflow decreases of up to 24%. These results underscore the vulnerability of hydropower systems to climate change and the increasing likelihood of greater reliance on thermal energy sources. To address these challenges, the study recommends that dam managers and policymakers adopt adaptive management strategies aimed at enhancing hydropower system resilience. Strategies should include diversifying energy portfolios, integrating mixed-renewable energy sources, and promoting sustainable resource management to ensure energy security in the face of climate change.

Keywords: Machine Learning, Algorithm, West Africa, Climate change, Inflow

Climate change impact assessment on the hydrological response of the Tawa basin for sustainable water management

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Sustainable water resources planning and management are essential for meeting the needs of both current and future generations while mitigating environmental impacts. River basins, integral components of ecosystems, are pivotal in implementing well-balanced and responsible management strategies. River basins serve as crucial sources for freshwater supply, irrigation, hydropower generation, and industrial activities. In the face of climate change, it becomes imperative to prioritize the hydrological impact assessment of river basins. This prioritization aims to ensure the resilience of water systems, recognizing the heightened challenges posed by changing climatic conditions. The present study examines the projected changes in the mean and high flow of Tawa River, an important Narmada River tributary that is critical for agriculture and hydropower generation using two conceptual lumped hydrological models, MIKE 11 NAM and GRJ4 respectively, and thirteen CMIP6 global climate models (GCMs) for two shared socioeconomic pathways (SSPs), SSP2-4.5 and SSP5-8.5, in the near (2030-2060) and far (2070-2100) futures. Our findings reveal a significant rise in both mean monthly and extreme discharge levels for two scenarios: SSP2-4.5 and SSP5-8.5. Notably, the projections indicate that the mean annual discharge, extreme discharge levels, and their frequency are anticipated to rise considerably more dramatically in the period of far future (2070-2100), particularly under the SSP5-8.5 scenario. This study underlines the importance of establishing a mitigation strategy for sustainable water resources and increased community resilience to climate change in the Tawa River Basin.

Keywords: Climate change, Hydrological models, MIKE11 NAM, GR4J, CMIP6, Tawa river basin

Streamflow Estimation in the Upper Narmada Watershed: Evaluating the Efficacy of Transformer Models

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Accurate streamflow estimation is crucial for effective water resource management, particularly in regions prone to hydrological extremes such as floods and droughts. Reliable predictions enable better planning and preparedness, reducing the impacts of these events on livelihoods, infrastructure, and ecosystems. In this study, we explore the potential of Transformer-based deep learning models for rainfall-runoff modelling in the Upper Narmada Basin, a hydrologically diverse and complex region in central India. Transformer models, known for their ability to capture long-range dependencies within time series data, are compared with traditional approaches, including the Long Short-Term Memory (LSTM) network and the GR4J conceptual hydrological model. The Upper Narmada Basin presents significant modelling challenges due to its diverse climatic and topographic conditions. To evaluate the performance of Transformer models, we designed two distinct experiments. In the first experiment, we trained deep learning models, including Transformers and LSTMs, for each watershed individually. In the second experiment, we trained a basin-level model by combining the input datasets from all sub-basins within the Upper Narmada Basin. As per our results demonstrate that Transformer models consistently outperformed both LSTM and GR4J models. For the individual watershed models, the Transformer achieved a median NSE of 0.84, while the basin-level model yielded an improved median NSE of 0.88. In comparison, the LSTM models achieved median NSE values of 0.61 for individual basins and 0.71 for the basin-level model. The GR4J model, which was evaluated for individual basins only, achieved a median NSE of 0.69. Additionally, Transformer models exhibited lower RMSE values across both experimental setups, further highlighting their superior accuracy. The basin-level Transformer model effectively captured hydrological dynamics at a regional scale, demonstrating its potential for large-scale applications in data-scarce regions.

Keywords: Rainfall-runoff modeling, Transformer models, Streamflow estimation

Development of a pre-computed surface water flood scenario catalogue using CARTINO 2D

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The development of efficient urban surface water flood forecasting systems is challenging especially with respect to rapidly evaluating flood probabilities and issuing timely alerts. This study presents an alternative to conventional threshold-based approaches and computationally intensive real-time hydraulic simulations through developing a pre-computed scenario catalogue using the Jarret River basin in Marseille, France as a case study. The methodology employs Telemac 2D hydrodynamic modeling via the CARTINO 2D approach, utilizing a nine-year (2014-2023) radar rainfall dataset with 15-minute temporal and 1-kilometer spatial resolution for two-hour convective events. Two approaches were developed: (1) a temporal pattern analysis examining three hyetograph shapes (short triangle, long triangle, rectangular), and (2) a monofrequency method using triangular hyetographs with consistent return periods across 15-minute intervals, where each duration determines a concentration time and corresponding inundated area. Both approaches were simulated for five return periods (5, 10, 20, 50, and 100 years) under three antecedent moisture conditions, generating 45 and 15 scenarios respectively. The resulting catalogue demonstrates the significant influence of temporal rainfall variability over small catchment areas. This work will also aid in evaluating both approaches through reanalysis of past events and integrating the catalogue into an operational forecasting chain, offering a practical framework for rapid flood response in urban areas exposed to high-intensity, short-duration rainfall events.

Keywords: surface water floods, hydrodynamic modelling, urban flood forecasting

Runoff and water regime of Russian rivers under climate change conditions

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Russia is the largest country with river runoff accounting for about 10% of the world runoff and two thirds of the inflow to the Arctic Ocean. With a huge variety of physiographic conditions, the response of river runoff to climate change is very diverse and has not been comprehensively studied to date.

Main objectives of the research are study and mapping of hydrological systems response to climate change for adaptation of water management and ensuring economically efficient and environmentally safe water use.

The analysis of historical changes in runoff at almost 700 hydrological stations throughout the country, located on rivers with a long period of observation and insignificant anthropogenic impact, is presented. Complex statistical criteria were applied to identify changes in the series of annual, seasonal, maximum and minimum runoff.

The report outlines a number of new fundamental and scientific-practical results, including new and modernized methodological approaches to the joint analysis of hydrometeorological and hydrogeological indicators, regional assessments of changes in the water regime of plain and mountain rivers,

their intra-annual distribution and dangerous manifestations at the turn of the XX-XXI centuries under the current climatic trends.

Multidirectional trends in river flow fluctuations in different climatic zones are identified and examples are given to link the detected flow changes with regional climate change. The physical mechanisms of the sharp decrease in spring runoff and increase in winter runoff were analyzed, including decrease in solid precipitation, snow water equivalent, soil freezing depth and increase in the frequency of winter thaws.

For the general assessment of water regime transformation, a number of possible parameters were analyzed. As a result, the selected set allows, by means of mathematical processing and cartographic analysis, to typify the water regime and assess the degree of its transformation.

Keywords: climate changes, annual and maximal runoff, statistical criteria, mapping

Evaluating the spatiotemporal variations in the streamflow drought characteristics in the Godavari River Basin

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Water availability in arid and semi-arid regions has experienced significant fluctuations in recent decades, largely due to the increasing frequency and intensity of hydrometeorological extremes driven by global climate change. Recurrent streamflow droughts are a critical concern, making it essential to understand their spatiotemporal patterns and driving factors to effectively manage future water resources. This study investigates streamflow drought conditions in the Godavari River Basin, India's second-largest river basin, which features diverse climatic conditions ranging from humid regions in the Western Ghats to semi-arid areas in the central and western parts. These variations make the basin particularly vulnerable to hydrological droughts. Despite the susceptibility of the region, the combined impact of human activities and climate variability on streamflow drought characteristics has not been thoroughly explored in the Godavari basin. This research analyses the spatial and temporal patterns of streamflow droughts and the regional factors influencing these characteristics across the basin. The findings reveal that the central and eastern regions of the basin are most affected by intense streamflow droughts. Significant differences were also observed between dammed and undammed areas: dam-affected regions exhibit prolonged drought durations, while undammed areas experience more severe streamflow deficits and drought conditions. These results underscore the need for region-specific, sustainable water management strategies in the Godavari Basin. They also highlight the critical role of both natural processes and anthropogenic interventions in shaping the vulnerability of river basins to streamflow droughts under future climate scenarios.

Keywords: Streamflow, Drought, Dam, Climate Change, Godavari, India

Impact of human activities on altering flood characteristics in the Godavari River Basin

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Recent geospatial analysis reveals that over 20% of the population in Low- and Middle-Income Countries faces 100-year flood risks annually. Understanding spatiotemporal flood patterns is critical for addressing these escalating threats and devising effective disaster prevention and resilience policies. While dams and reservoirs are traditionally designed to mitigate floods, their effectiveness in real-world scenarios varies significantly, often creating unpredictable risks for vulnerable regions. Geographic factors, such as terrain and dam functionality, play a crucial role in influencing flood outcomes, leaving some communities exposed to residual hazards. This study examines the combined impacts of climate patterns and dam operations on flood risks in India's Godavari River Basin from 1965 to 2020. Advanced statistical methods, including Peak Over Threshold and CUSUM trend analysis, were employed to investigate the complex interplay of human interventions and climatic shifts. The findings reveal significant differences in flood dynamics before and after 1990, a period marked by rapid dam construction. The Wainganga, Indravati, and Sabari sub-basins were identified as major contributors to severe floods, influencing downstream flood characteristics in the Godavari Basin. Moreover, the analysis highlights notable differences in flood attributes between dammed and undammed regions, underscoring the nuanced effects of human interventions on flood patterns. These insights provide a deeper understanding of regional flood dynamics and their driving factors, offering valuable guidance for implementing efficient flood management strategies and enhancing resilience in the Godavari Basin.

Keywords: Flood volume, flood peak, flood duration, dams, climate

Does MC-LSTM model improve the reliability of streamflow prediction in human-influenced watersheds in India?

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Long Short-Term Memory (LSTM) model has a unique structure that captures long-term dependencies and stores information over longer sequences. However, they often lack physical interpretability, particularly regarding the principle of hydrological balance. To address this limitation, the Mass-Conserving LSTM (MC-LSTM) has recently been developed by integrating mass-balance constraints into its architecture, ensuring physically consistent predictions. Despite these advancements, the performance of MC-LSTM in human-influenced watersheds remains underexplored. In the present study, we compare the performance of MC-LSTM with the traditional LSTM model to identify its advantages and limitations in simulating streamflow across 51 human-influenced watersheds in India. The results indicate that MC-LSTM achieves a median Nash-Sutcliffe Efficiency (NSE) of 0.72, slightly outperforming LSTM (median NSE of 0.70). However, MC-LSTM exhibits less bias and captures high flows more accurately. Additionally, while the LSTM is more sensitive to the

length of the training data, MC-LSTM provides consistent and stable results even with limited data. The study also highlights that regionally trained models significantly improve predictions across all watersheds except for semi-arid and non-perennial river watersheds. Although MC-LSTM demonstrates slightly better performance in capturing variability in semi-arid regions, its performance in these contexts remains limited. The results also indicate that the LSTM model struggles to provide reliable predictions in large, human-influenced watersheds, whereas MC-LSTM offers relatively improved performance in such cases. Overall, the findings highlight the advantages of MC-LSTM in providing more reliable streamflow predictions for human-influenced watersheds compared to traditional LSTM models.

Keywords: Streamflow, LSTM, MC-LSTM, Indian watersheds, Mass balance, human-influenced watershed

Assessment of Wildfire Impacts on Water Balance Using the SWAT Model

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Wildfires are a global phenomenon that profoundly impact watershed hydrology, resulting in increased surface runoff, reduced infiltration, and altered groundwater recharge. These effects are closely tied to wildfire severity, which is influenced by factors such as fire intensity and vegetation type. In Chile, an average of 65,000 hectares burned annually over the last six decades; however, this figure has surged to approximately 155,000 hectares per year in recent years.

This study evaluates the impacts of wildfires on the water balance using the SWAT model, focusing on the southern hillside Andes Mountains of Chile, specifically within the Quepe River watershed, which spans approximately 1,648 km² between latitudes 38°37'S and 38°50'S. Pre- and post-fire flow rates were analyzed to identify the water balance components most affected by wildfire events. The model was calibrated for the period 1981-1999 and validated using data from 2000-2011. Subsequent simulations modeled pre- and post-fire conditions by incorporating burned areas, with the 2017 wildfire serving as the primary case study. The year 2015 was selected as the pre-fire reference due to its annual precipitation being nearly identical to that of 2017, differing by only about 4%. The integration of wildfire impacts into the SWAT model involved the development of post-fire land cover raster files. Burned areas were categorized into high-burn land use classes based on the vegetation type affected and were updated accordingly in the model. Results showed increased surface runoff across all sub-basins. These findings emphasize the critical need for targeted post-fire management strategies aimed at reducing surface runoff and enhancing infiltration to restore the hydrological balance in mountainous regions like the Andes.

Keywords: Wildfire, water balance, SWAT

Unveiling hydrological dynamics in data-scarce regions: experiences from the Ethiopian Rift Valley Lakes Basin

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The hydrological system of the Rift Valley Lakes in Ethiopia has experienced significant changes over the past two decades due to anthropogenic, hydro-climatic, and geological factors. This study employed an integrated approach, combining a hydrologic model (SWAT+), change point analysis, indicators of hydrological alteration (IHA), and bathymetry surveys, to investigate these dynamics in a data-scarce region. The SWAT+ model was calibrated for gauged watersheds and extended to ungauged watersheds using multisite regionalization techniques, achieving satisfactory performance for daily streamflow based on Kling-Gupta efficiency (KGE), Nash-Sutcliffe efficiency (NSE), and Percent Bias (PBIAS). Results indicate notable changes in lake inflows and levels. Chamo Lake expanded by 30.1 km² (9.5%), deepened by 4.4 m (30.9%), and increased in volume by 7.8 × 10⁸ m³ (27.2%). Conversely, Lake Abijata experienced a dramatic 68% reduction in area and a depth decrease of 1.6 m (37.2%). During this period, mean annual rainfall declined by 6.5% for Lake Abijata and 2.7% for Lake Chamo. Actual evapotranspiration dropped by 2.9% for Lake Abijata but rose by 4.5% for Lake Chamo. Surface inflow decreased by 12.5% for Lake Abijata, whereas Lake Chamo saw an 80.5% increase. Sediment depth in Chamo Lake also rose by 0.6 m (4.2%). The study highlights that increased surface runoff and sediment intrusion, driven by anthropogenic activities, altered the hydrology of Chamo Lake. Meanwhile, water abstraction for industrial and irrigation purposes significantly impacted Lake Abijata. This integrated methodology provides a comprehensive understanding of the hydrological systems and their drivers in data-scarce regions like the Rift Valley Lakes, offering potential global applicability.

Keywords: Hydrological change, IHA, Bathymetry, Lake Chamo, Lake Abijata, SWAT+, Rift Valley, Lake level

A Study on Flooding Characteristics of Pallikaranai Marshland, Chennai

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The December 2015 floods that battered Chennai city is one such event that resulted from indiscriminate urbanization, expansion of the city at the cost of waterbodies and wetlands, coupled with

insufficient capacity of the drains to handle flood waters. In this context, the current study is an attempt to address the issue of flooding and drainage characteristics that involves hydrologic modelling of the region to assess the hydrologic response of the watershed. The current study employed HEC-HMS hydrologic model to quantify the flood inflows into the Pallikaranai Marshland (PML). The connectivity (or the lack of it) among the cascading lakes were mapped from high resolution satellite imagery, field visits as well as from 10m resolution digital elevation Model (DEM) data. Automatic weather stations, raingages and water level staff gauges were installed to understand the watershed response for rainfall and water level. Rating curves were developed for four locations along major storm water drains to convert water levels into discharges. Several large lakes were modelled as reservoirs within HEC-HMS to simulate their storage and discharge behaviour in a realistic manner and to understand the cumulative impact of them on the flood inflows into the PML. Discharge measurement campaigns were undertaken for December 2016 to help parameterize the model. HEC-HMS model was calibrated and verified for 4 different rainfall events during December 2016 at different inlets to PML. The simulations indicate that the peak inflow into the PML could be as much as 1350m³/s during both December 2015 flood event as well as during the Vardah cyclone in December 2016. Due to the limitation of discharge capacity of Okkiyum Maduvu, the water levels within PML could swell as much as 3.5m above the normal levels such as those happened during Decembers of 2015 and 2016 resulting in flooding of the adjacent regions.

Keywords: Flood, HEC-HMS, Parameterization, Calibration

Changes in runoff response to rainfall along forest degradation gradients in the Lesser Himalaya of NW India

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Introduction

Forest cover affects rainfall partitioning into infiltration and overland flow (OF), influencing storm runoff. Undisturbed forests promote infiltration and subsurface flow (SSF), while degraded forests increase OF, causing stormflow dominance.

Aim and Objectives

This study examines how forest degradation impacts storm runoff in Himalayan catchments by:

- (1) Comparing runoff in dense versus degraded forests.
- (2) Assessing overland flow generation.
- (3) Evaluating infiltration capacity and soil moisture retention.

Methods

Runoff data were collected from Arnigad (dense oak forest) and Bansigad (degraded oak forest) in NW India. Rainfall and infiltration were also studied in the Jijli catchment with varying forest conditions. Soil moisture, hydraulic conductivity, and runoff plots (1-3 m²) were analyzed.

Results

Rainfall was highly seasonal, with up to 92% occurring in the monsoon. Arnigad had stable base-flows (90%) with minimal stormflow (8-11%), dominated by SSF. Bansigad had higher stormflows (49%) and ceased flowing in the pre-monsoon season, indicating significant OF contributions. Jijli data confirmed saturation-excess overland flow (SOF) during prolonged rains, while infiltration-excess overland flow (IOF) was limited.

Soil moisture patterns mirrored baseflow contrasts. Arnigad's permeable soils prevented OF. MCA analysis showed stormflow-associated values at Bansigad ranging from 23-30%. Further examination in Jijli revealed high infiltration rates, yet frequent OF in prolonged monsoon rains. Threshold analysis indicated decreasing rainfall + antecedent soil water (ASW) values for OF from dense forest (~400 mm) to shrubland (~250 mm).

Conclusion

Forest degradation alters runoff generation, reducing soil moisture retention and groundwater recharge. Protecting topsoil and organic matter is vital for sustaining water resources. Further research is needed to confirm storm runoff mechanisms in degraded landscapes.

Keywords: Overland Flow, Subsurface Flow, Hydraulic Conductivity, Soil Moisture

Improving Evapotranspiration Resolution with Attention U-Net Downscaling

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Evapotranspiration (ET) is an essential part of the water and energy cycles on Earth. It has a major impact on climate regulation, agricultural productivity, and hydrological processes. Terra Net Evapotranspiration Gap-Filled 8-Day Global 500m dataset, which is widely used for regional and global ET studies and offers high-resolution information on terrestrial energy exchange and water use. However, the coarse spatial resolution limits its application in areas requiring finer-scale analysis. This study employs a deep learning-based U-Net model for a diverse region in India, covering latitudes 28° to 32°N and longitudes 74° to 78°E. This study also includes MODIS Land Cover Type data as auxiliary information. By which we are leveraging land cover characteristics to improve the downscaling process. A synthetic design of experiments was used to generate and evaluate training data systematically, ensuring robust model performance and reliable downscaling results across the diverse terrain of the study area. This study investigates the relationship between ET and land cover dynamics, incorporating deep learning component: the Attention module to capture interactions between ET and land cover features, along with the U-Net module to downscale and enhance the spatial resolution of ET data. The network's downscaling accuracy was assessed using both simulated and real data experiments, and results were compared to the SRCNN model. The findings demonstrate that the Attention U-Net (AU-Net) model surpasses the SRCNN model. It achieves a 17.6% increase in PSNR and a 22.7% increase in SSIM. The improvement demonstrates the proposed method's effectiveness in enhancing the spatial resolution and structural details of Terra MODIS ET data, providing valuable insights for ET downscaling research advancement.

Keywords: Evapotranspiration, Downscaling, Deep Learning, Remote Sensing

Blending Subseasonal-to-Seasonal Hydrological Predictions from Multiple Forecasting Systems

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The development of accurate and reliable hydrological prediction systems at subseasonal-to-seasonal (S2S) timescales is critical, given the escalating vulnerability associated with the increased frequency and severity of hydrological hazards driven by climate variability and change. However, regional operational forecasts remain limited due to insufficient local observations and the absence of regional hydrological models. Meanwhile, global models often lack calibration for local conditions, making it difficult to capture region-specific dynamics. Additionally, decision-makers face challenges in interpreting complex ensemble forecasts from multiple models, which lack the simplicity of single-model approaches. Addressing these limitations requires integrating global, regional, and local forecasting systems to deliver skilful, standardized, and comprehensible predictions.

Here, we are exploring approaches to: (i) validate and enhance the skill of probabilistic S2S hydrological forecasts, and (ii) blend multi-model ensemble simulations to produce reliable operational forecasts. This involves developing a framework for bias-correcting and integrating global multi-model forecasts, adapting them to the specific skill of each model for individual catchments. Our research, based on global hindcasts from various prediction systems, demonstrates that this framework can reliably post-process raw model outputs to generate accurate S2S forecasts across diverse hydrological regimes. This approach holds the potential for improving water resource management and mitigating hydrological risks, particularly in data-scarce regions.

Keywords: multi-model blending, hydrological forecasts, subseasonal-to-seasonal

Hydrological validation of Satellite Precipitation Products in Upper Beas basin

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The mountainous regions such as Himalayas are still under-represented due to the lack of ground observations of precipitation, which makes the hydrological modelling difficult. Recently, satellite precipitation products (SPPs) and model-based re-analysis products (RAPs) have emerged as viable substitutes for ground-based observations. However, they often suffer from low prediction accuracy and are unreliable for hydrological assessments. In this study, several SPPs and RAPs, including APHRODITE, CHIRPS, ERA5, ERA5-LAND, IMDAA, GPM-IMERG, and PERSIANN, were evaluated for their prediction accuracy and hydrological applications in the Upper Beas Basin. These products were assessed based on their ability to capture rainfall events, daily and monthly totals,

and extreme precipitation events (=95th, and =99th percentile) using statistical and categorical metrics. Further, all products were hydrologically validated using observed streamflow data and hydrological modelling. Our findings revealed that SPPs estimated the daily and monthly precipitation magnitudes better in comparison to RAPs. Among all the products, APHRODITE offered a superior agreement with gauged and IMD data in all the aspects considered. Hydrological validation also confirmed the superiority of SPPs over RAPs in simulating the streamflow. APHRODITE, PERSIANN and GPM-IMERG produced streamflow with NSE in the range 0.61-0.88 and PBIAS in the range -2.18% to -18.98% while RAPs underperformed in producing reliable streamflow with NSE ranging from 0.06 to 0.61 and PBIAS ranging from -34.59% to -55.57%. In conclusion, SPPs delivered an overall better performance in estimating the precipitation as well as hydrological modelling with an exception that RAPs better estimated the extreme events and high flows. This study provides a comprehensive understanding of the suitability of the precipitation products for various hydrological applications.

Keywords: Hydrological Validation, Beas basin, Precipitation products, performance evaluation, Streamflow

Multy-year spatio-temporal changes of water temperatures and river heat flux in rivers of Russian permafrost zone: patterns and drivers.

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River water temperature serves as a critical indicator of numerous biological and chemical processes essential for ecosystem support and water quality maintenance. River heat flux which is related to river water temperature plays an important role in the formation of water temperature in rivers crossing various natural zones, in the formation of ice phenomena, including ice cover of Arctic Ocean, as well as the microclimate of river valleys, especially on big rivers. The long-term variability of both river water temperature and river heat flux is studied relatively poorly in the permafrost zone. We have tried to close some gaps in our knowledge about the long-term variability and conditions of formation of water temperature and heat flux in the permafrost zone of the Russian Arctic (north of 60 N), as well as in the basin of Lake Baikal. For the analysis, we collected data on monthly water temperature (counted from 2 times a day observations) from the beginning of observations (1930-1950) to 2022 and for 10-day periods from 1985 to 2022 (also counted from twice a day observations). We used data from both meteorological stations and reanalysis for estimations of the role of different factors in formation of studied rivers characteristics. It has been revealed that the air temperature in the permafrost zone is an important, however, not always a determining factor in the formation of water temperature and heat flux. Long-term changes in water temperature on rivers have been estimated, and it has been shown that all rivers experience an increase in water temperature, which is quite significant during the transition seasons. The intensity of the increase in river water temperature is not as significant as previously assumed.

Keywords: River water temperature, river heat flux, climate changes, permafrost zone

Wasted Years: Evaluating the time-effectiveness of top-down versus bottom-up approaches during development of an operational flood forecast model for Denmark

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The increasing performance of continental/global hydrological models presents an interesting question for modelers seeking to develop new model setups for regions within these large-scale modeling domains: is it more time-effective to develop new models using a top-down approach or a bottom-up approach? A top-down approach uses an existing large-scale model to inform the development of a new model by e.g. extracting the desired domain from the large-scale model and then refining the model structures, process descriptions, and calibration. In a bottom-up approach, however, a new model is constructed entirely from scratch without guidance from another model.

The time-effectiveness of both modeling approaches was evaluated during the development of an operational flood forecasting system for Denmark. In order to implement an operational warning system as quickly as possible, a "top-down" model for Denmark was first extracted from the pan-European E-HYPE model developed using European and global data sources. This provided nearly immediate access to model forecasts that could be used to issue warnings. Meanwhile, a separate model, DK-HYPE, was gradually developed for Denmark from the "bottom-up" using national data sources combined with high-resolution catchment delineations and more detailed model process representations.

Evaluation of the two modeling approaches showed a trade-off between time invested and societal benefit. Overall, the top-down approach provided the greatest benefit early in the project phase by expediting model development and providing rapid access to the model results required to implement an operational warning system. In contrast, the bottom-up approach provided the greatest benefit later during the project as it provided the best model performance but required a significantly longer development period than that of the top-down model. So, don't feel that you've wasted your time always searching for those wasted years on developing a perfect model, and realize you're living in the golden years of model application.

Keywords: hydrology, modeling, flood, warning, large-scale, national

Development and Evaluation of Impact-Based Flood Forecasting in India

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Flooding is a significant and increasing hazard in India, exacerbated by climate change and a growing population. To address this critical issue, India is adopting Impact-based Forecasting (IbF) and warning approaches in line with World Meteorological Organisation guidelines. Such approaches forecast both the flood hazard and its potential impacts on people, property, transport and agriculture. Supporting this initiative, the WCSSP India programme has developed the Flood Hazard Impact Model for India (FHIM-India), an advanced, real-time, automated IbF framework.

FHIM-India integrates state-of-the-art tools: high-resolution ensemble weather forecasts from NCM-RWF (4km), regional-scale flood modelling using the Grid-to-Grid model (1km), city-scale flood inundation modelling via SynxFlow (~30m), and impact/risk quantification methods developed by Britain's Health and Safety Executive. While FHIM-India is operationally-ready in the state of Kerala, further evaluation of model performance, uncertainty and reliability is needed.

This study focuses on calibrating and evaluating FHIM-India using data from past flood events to assess its ability to simulate fluvial and pluvial flooding impacts. Model forecasts are compared against historical data, ensuring the calculations of risk and impact for key elements, such as infrastructure and population within defined geographical boundaries, are robust and reliable. Through this evaluation, the ability of the FHIM-India framework to quantify flood magnitude and impact has been rigorously tested.

Preliminary results from 2023, spanning dry to monsoon seasons, provide an overview of FHIM-India's IbF performance. These insights have informed adjustments to the modelling framework, enhancing reliability and robustness. Ongoing work is examining how risk magnitude and probability translate into actionable impact assessments, ensuring the framework's effectiveness in real-world applications.

By refining FHIM-India, this work advances real-time flood forecasting and supports risk-informed decision-making in India.

Keywords: Impact-based Forecasting, Flood Forecasting

PASSing the Test: Improving Hydrological Modelling for Brazil's Ungauged Catchments

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Conceptual bucket-type hydrological models are widely used tools in large-scale hydrology. While these models, when calibrated, often reproduce observed streamflow well, their predictive performance significantly decreases when applied to ungauged catchments (PUC) or ungauged regions

(PUR). This study investigates the predictive capabilities of a fully distributed model, SALTO, applied to Brazilian catchments using a recently developed parameter regionalization method called PArAmeter Set Shuffling (PASS). The PASS method derives regionalized functional relationships between distributed model parameters and catchment descriptors by leveraging locally calibrated lumped behavioral parameter sets through a random forest approach.

The study employs 300 catchments from the CAMELS-BR dataset to develop the parameter regionalization schemes, testing their performance in predicting streamflow in approximately 500 additional ungauged catchments. Modelling 10 years of daily streamflow with regionalized model parameters achieved a median Kling-Gupta Efficiency (KGE) of 0.5 for ungauged catchments, compared to a median KGE of 0.67 for the 300 training catchments.

Further analysis using hydrological signatures, climate indicators, and landscape descriptors reveals the regions and conditions where the model successfully reproduces streamflow, as well as those where it fails. The study also examines how reservoirs and anthropogenic water use influence model performance and alter the hydrological signatures of specific regions. This research highlights the predictive potential and limitations of bucket-style models with regionalized parameter sets in ungauged catchments, particularly within Brazil's diverse climate and landscape gradients, providing valuable insights for large-scale hydrological modelling in similar environments.

Keywords: hydrological modeling, regional parameterization, PUB

Time of Concentration: A Key Parameter for Urban Drainage System Modeling and Flood Management

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Time of Concentration (ToC) is a vital parameter in urban hydrology, playing a crucial role in rainfall-runoff modeling and the design of urban drainage systems (UDS). However, varying estimation methods often produce significantly different ToC values, leading to discrepancies in UDS design and performance analysis. This study investigates eight lumped methods and two distributed methods for ToC estimation, comparing their results for an urban catchment in Gurugram, India. The NRCS velocity method, described in the TR-55 manual, was adopted as the reference to evaluate the accuracy of other methods.

The findings indicate that ToC values estimated using these methods range from 0.19 to 6.14 hours. Among the lumped approaches, the Carter method exhibited the closest agreement with the reference method, while the SWDM method showed the least deviation among the distributed approaches. To assess the implications of these variations, a hydrological model was developed in the Storm Water Management Model (SWMM) to simulate UDS response. The results revealed that flood volume increases by 4.25 times, flood duration extends by 7.25 times, and time-to-peak discharge rises significantly when ToC increases across this range.

The study underscores the importance of carefully selecting ToC estimation methods to improve the

accuracy of hydrological analyses and minimize errors in UDS design. Distributed methods, particularly NRCS and SWDM, demonstrated greater reliability for urban catchments. Additionally, the sensitivity of flood hydrograph parameters to ToC highlights the need for site-specific assessments to mitigate urban flooding risks effectively. This research provides valuable insights into the practical implications of ToC estimation and offers a framework for selecting appropriate methods for urban hydrological applications.

Keywords: Time of concentration, Urban drainage, SWMM, NRCS, SWDM

The inflow of river waters into the seas of the Russian Arctic, and its long-term and intra-annual, natural and anthropogenic changes

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On the basis of improved series of annual and monthly water runoff at 73 gauges on rivers flowing into the seas of the Russian Arctic, long-term series (for 1936-2022) of annual inflow of river waters into the Arctic seas were obtained and the total annual runoff was estimated at 2,775 km³, the water runoff from individual sections of the sea coasts, at the closing hydrometric cross-sections and in the estuaries of the main northern rivers. It was found that the average annual runoff to the seas increased by 238 km³ per year, or 8.9%, compared with 1936-1988, and 1989 should be considered the general turning point. The proven increase is provided by the same trends in annual runoff fluctuations in almost all rivers in the catchments of the Arctic seas, with the exception of rivers in the northeast of the country, and mainly positive trends in seasonal runoff fluctuations. The statistical structure of long-term fluctuations in annual runoff has been studied. It is shown that water management activities practically do not affect the long-term dynamics of annual runoff (with the exception of the Yenisei River), but changed the water regime of many rivers regulated by reservoirs, including the largest ones. The research has been performed at the expense of RSF grant No. 24-17-00084

Keywords: Arctic, river, annual and seasonal runoff, long-term changes, water management

Cascading Hazards of a Wildfire in the Tropical Rwenzori Mountains

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Tropical mountain regions face an emerging risk of wildfires due to climate change, land-use changes and increased human activities. Their unique ecological, geological and hydrological characteristics make these regions highly vulnerable to hydrogeological hazard cascades, putting the estimated 336 million people living in them globally at risk of severe consequences. We investigated the impacts of an unprecedented 2012 wildfire in 30 km² of pristine tropical forest in the Rwenzori Mountains National Park, Western Uganda, combining mixed methods of key informant interviews, remote sensing, humanitarian data analysis and field data collection. The effects of the wildfire resulting in increased discharge, channel switching and sediment generation have substantially contributed to increased flood risk, with 10 flood events in the catchment exceeding the impacts of any documented flood prior to 2012. The mobilisation of glacial sediment is enabling previously undocumented debris floods, with an erosive power responsible for pervasive undercutting, landsliding and erosion of riverbanks and adjacent hillslopes. The river's width has increased by a factor of 7 since 2012, and current trends suggest a multi-decadal increase in erosion rates due to a positive feedback processes between erosion, hillslope undercutting and new sediment-generation. Erosion has had extreme impacts, with channel switching events causing casualties and losses in property and agricultural land in Kasese town. Erosion has also breached copper-cobalt tailings of Kilembe Mines, with 1 million tonnes of solid tailings slumping into the River Nyamwamba, causing major environmental and health concerns for downstream settlements and Queen Elizabeth National Park. We conceptualize these hazards as a multi-decadal cascade initiated by a tropical high-mountain wildfire. Our findings reveal that the interactions between these hazards enable their propagation through space and time within the landscape. This study exemplifies the potential widespread and long-term consequences driven by hydrological changes caused by wildfire in a tropical mountain landscape.

Keywords: Hazard cascade, hydrogeological hazards, tropical mountain, wildfire, flood, debris-flood, erosion

Improving peak flow estimation using an iterative channel routing approach

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Accurate peak flow estimation is essential for effective disaster management and flood risk mitigation. While many factors affect peak flow characteristics, flow velocity is particularly crucial as it determines the magnitude and timing of peaks. Existing conceptual routing models often simplify calculations by assuming constant flow velocity across space and time. However, this study presents an improved approach through an iterative channel routing framework that dynamically updates flow velocity using a non-linear velocity-discharge relationship. The model was tested in the Godavari River Basin, with results demonstrating significant improvements in peak flow estimations and timing of peaks compared to a hydrodynamic routing model as well as a conceptual routing model.

Keywords: Conceptual channel routing, Manning's Equation, Iterative Routing

Water security indicators on a climate change scenario and implications for sustainable surface water management

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Water security is an increasing challenge in many regions worldwide, particularly in areas with resource scarcity and complex management needs. Reservoirs play a critical role in mitigating water crises, yet their operations can be influenced by climate change and human pressures. Understanding the evolution of water security indicators in basins with existing reservoirs is essential for developing long-term sustainable management strategies. This research investigates water security indicators (WSI) in river basins with existing water reservoirs, focusing on implications for sustainable water management. The study employs a comprehensive approach combining temporal analysis of time series data, spatial analysis using Geographic Information Systems (GIS), and statistical modeling to explore water security trends across different time horizons (2011-2040, 2041-2070, and 2071-2100). Data are sourced from Brazilian national databases, encompassing climatological, hydrological, ecological, and socio-economic variables, which are correlated to uncover causal relationships within the human, economic, ecosystemic, and resilience dimensions of water security. Future scenarios are modeled using climate projections from CMIP6 under varying Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), allowing for the assessment of potential changes in water security. Preliminary analysis reveals spatial and temporal variability in water security, suggesting key hotspots and vulnerabilities, particularly in semiarid regions. These initial insights highlight aspects that should be considered, indicating potential interactions between environmental and human factors that may shape sustainable water management strategies adapted to regional challenges.

Keywords: Water Security Indicators, Reservoir Management, Sustainable Water Management, Climate Change, Spatial and Temporal Analysis.

Urban hydrology challenges and solutions: insights from the Birmingham Urban River Observatory

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Urbanisation and climate change increase impervious surfaces and extreme events that in turn cause water scarcity, flooding, pollution and threaten river health in cities and watersheds downstream. Stormwater management and blue-green infrastructure yield further human impact on urban hydrology, and offer potential mitigation and adaptation strategies to improve ecosystem and

societal resilience in a changing world. Hydrological research on the space-time dynamics of urban water quantity and quality is essential to quantify multi-scale patterns, to understand controls and process, and to provide the evidence-base for targeted, scalable, sustainable and effective management interventions.

In this context, the NERC-NSFGEO SMARTWATER project aims to diagnose and manage watershed-wide pollution 'hotspots' (locations) and 'hot moments' (times). This interdisciplinary initiative integrates environmental sensing, data science and numerical modelling to unravel the dynamic drivers of multi-contaminant pollution. Here, we focus specifically on results from the Birmingham Urban River Observatory - designated a UNESCO Intergovernmental Hydrology Programme Ecohydrology Demonstration Site (part of a global network of case studies that apply ecohydrology principles for sustainable watershed management). The Birmingham Urban River Observatory deploys high-frequency, in-situ water quality monitoring technologies to span low- to mid-order streams along a highly urbanised to peri-urban gradient.

For this overview, our objectives are to reflect on: (1) identifying and characterising pollution dynamics using scalable field diagnostic technologies; (2) developing smart water quality monitoring networks; (3) applying data science innovations (e.g. AI) for pollution tracking; and (4) using high-frequency, distributed observations to improve pollution models and predictions ; and (5) collaborating with stakeholders (e.g. citizen science with Birmingham River Champions) to implement practical steps for water quality management and enhancing planetary health. It is intended that sharing our experiences helps transform how we diagnose, understand, predict and manage urban water challenges.

Keywords: urban hydrology, water quality, river pollution, sensors, monitoring networks, models, stakeholders, sustainable water management, ecohydrology

Quantifying water balance dynamics and associated uncertainties in an irrigated catchment using open-source gridded datasets and hydrological modelling with improved process representation: case of Hindon River Basin, India

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Irrigation can significantly influence the hydrological system of agriculturally productive catchments thus understanding the dynamics of the water balance is indispensable for sustainable (agricultural) water management. Accurate estimation of catchment water balance, using distributed hydrological modelling and earth observation data, requires thorough consideration of the associated uncertainties from different sources such as uncertainties in the model representation of system processes and the errors and uncertainties embedded in the remotely sensed data.

In this study, we estimate the spatial distribution and temporal dynamics of the water balance of the Hindon River Basin, a sub-basin of the Ganga River Basin in India, where intense irrigation has

driven overexploitation of water resources, highly influencing the hydrological regime. For this estimation the open-source distributed hydrological model `wflow_sbm` is used and evaluated with open global datasets, demonstrating the applicability of this method in data scarce regions. We emphasize on representing relevant hydrological features of the Hindon Basin that are often neglected in hydrological model applications: irrigation, domestic and industrial water use, and (infiltrating) river-aquifer interaction. Our analysis includes the quantification and assessment of the uncertainties associated with the global datasets used and model representation of important processes. First, prior uncertainties of the input variables were analyzed by comparing the errors and correlations of the products from different sources. Second, the impact of different schematizations of irrigation application and subsurface flow (including river infiltration to aquifer) on the modelled water balance is assessed. Finally, model output is evaluated by comparing the estimates and uncertainties of modelled water balance components with estimates from various global datasets.

Our analysis reveals the impact of different model choices, highlighting the necessity of proper model representation of hydrological processes and uncertainty assessment to achieve a more reliable estimation of catchment water balance.

Keywords: hydrological model, irrigation, water balance, Hindon River

Complexity and Connectivity in Hydrology

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Hydrologic processes are complex and nonlinear in nature. They are often driven by many variables that are also interconnected among themselves and change over space and time. Various theories have been proposed and applied for hydrologic modeling and prediction. In recent decades, chaos theory and complex network theory have found widespread applications in hydrology. Either of these theories offers unique perspectives regarding the complexity and connectivity of hydrologic systems and processes. The purpose of the present study is to discuss the coupling of these two theories to provide a more reliable representation of hydrologic data and improve their modeling. In particular, the study focuses on the use of embedding theorem for the reconstruction of a multi-dimensional phase space from a scalar time series to capture the underlying system dynamics and then use the reconstructed vectors (rather than the original time series) to form networks for studying their complexities and connections. The effectiveness of this coupled framework is tested through its application for addressing some key problems in hydrology, including temporal dynamics of hydrologic data (e.g., rainfall, streamflow, groundwater level, water quality parameters) and performance assessment of General Circulation Models (GCMs) for climate change impact studies. The results indicate that this coupled framework, by combining the strengths of both theories, is effective in capturing the complexities and connections in hydrologic data. The results also highlight the potential of the coupled chaos theory-complex network theory framework in addressing the global challenges related to climate change, water resources, and environment.

Keywords: Hydrologic modeling, Complexity, Nonlinearity, Chaos theory, Complex networks

Hydrological Modeling of Extreme Floods in Mountain Permafrost Regions: A Case Study of Magadan Oblast, Russia

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Climate change is significantly altering hydrological processes in mountain permafrost regions, increasing the frequency and intensity of catastrophic floods. This study focuses on Magadan Oblast, a remote region in the Russian Far East that is important to the Russian economy due to its mining industry. The region is highly susceptible to extreme hydrological events. However, flood forecasting methods have not been developed for this area. Such methods could be based on hydrological modeling.

The aim of this study was to assess the possibility of flood modeling using pluviograph data. Using pluviograph data and the deterministic hydrological model Hydrograph, we simulated maximum water discharge for three small rivers-Krivulya, Ambardakh, and Susuman. Model verification, based on historical data from 1966-1994 for Krivulya and 1966-1987 for Ambardakh and Susuman, demonstrated a satisfactory result with median Nash-Sutcliffe efficiency coefficients ranging from 0.52 to 0.62.

Modeling was carried out for historical floods on an hourly interval: August 16, 1986, for the Susuman and Ambardakh rivers (maximum observed discharges were 393 m³/s and 74.7 m³/s, calculated-420 m³/s and 78.5 m³/s, respectively) and July 26, 1984, for the Krivulya stream (observed discharge-14.2 m³/s, calculated-16.5 m³/s). The relative error of simulated and observed maximum discharges did not exceed 20%. The study highlights the feasibility of intraday hydrological modeling using pluviograph data while emphasizing the critical limitation posed by insufficient precipitation data in mountain permafrost regions. A promising solution may be the integration of climate model data with hydrological models, which opens up new opportunities for assessing and predicting maximum runoff characteristics.

Keywords: floods, hydrological modeling, Hydrograph model, maximum runoff, the Magadan Oblast, cryosphere, mountainous territories, pluviograph

Improving Hydrological Simulation Using Satellite-Based Rainfall Data

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Satellite-based precipitation products play a crucial role in addressing data scarcity challenges, which could be used to improve the accuracy of hydrological modelling. However, assessing the suitability of satellite products is essential to calibrating hydrological models to improve prediction. This study evaluates the suitability of satellite-based precipitation products for process-based hydrological modelling over the Mahanadi River Basin (MRB), India. The methodology includes implementing the Variable Infiltration Capacity (VIC) model forced with ERA-5 precipitation data and evaluating

their performance with the observed streamflow data. The results suggested that streamflow simulation using ERA-5 precipitation products is comparable with those employed using station-based precipitation data from the India Meteorological Department (IMD). The findings not only yielded improved simulations but also provided valuable insights for characterizing the model parameters based on the selection of satellite-based earth observation data for hydrological applications, mainly flood forecasting, water resources management and climate change adaptation.

Keywords: ERA-5, Hydrological modelling, Satellite precipitation products, VIC

Statistical Analysis for Detecting the Impact of River Regulation in the Godavari basin, India

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Reservoir regulation is an anthropogenic action that alters the hydrological systems by adjusting the natural spatial-temporal distribution of water resources. However, the adverse effects such as relocation of upstream population, disturbance of ecosystems, and the life threats posed by a potential dam failure makes the necessity of reservoirs debatable, requiring a thorough understanding of the impacts of reservoirs on a catchment. This study presents a statistical analysis to investigate the impacts of reservoir regulation on the streamflow characteristics of the Godavari River basin, India. Long-term observed streamflow data of selected gauge stations distributed across the basin are collected and their naturalized flows are simulated by the macroscale VIC hydrological model for the same time period. Statistical tools are leveraged to unveil trends and detect significant temporal shifts in streamflow characteristics. Furthermore, the spatial variations of these changes are also analysed across the basin. The findings of the study provide insights into how the anthropogenic actions – reservoir operation in specific – affects the surface water availability of a highly regulated catchment.

Keywords: reservoir, river regulation, streamflow characteristics

Impact of Prescribed Burn on Suspended Sediment Concentration and Discharge: Learning from California's Oak Woodland

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Forest fires pose significant ecological threats by causing extensive damage to vegetation, soil properties, and infrastructure, leading to severe degradation of ecosystem services and biodiversity loss.

This results in accelerated soil erosion due to loss of vegetative cover and soil structure modification, which subsequently increases surface runoff and flash flood susceptibility, creating a cascading impact on watershed hydrology and downstream ecosystem stability. Vegetation removal techniques such as forest thinning, mastication, and prescribed burning are commonly used to reduce fuel load and improve ecosystem resilience to forest fires. However, there is a tradeoff between these forest management practices and their impact on catchment-scale processes. This study analyzed the impact of prescribed burn on suspended sediment and discharge in four experimental catchments (8-23 ha) located in northern California, USA. These experimental catchments are dominated by native grass and oak trees. The study was conducted during 1999-2006, and a prescribed burn was performed in two of the catchments on June 6, 2003. The mean annual suspended sediment yield ranged between 92 ± 113 and 667 ± 445 Mg/km²/yr across these experimental catchments. We observed a 212% to 257% increase in annual suspended sediment yield in the post-prescribed burn period. The effects of prescribed burns were most significant in the first year compared to subsequent years. Similarly, for discharge, we observed a 9-30% increase in slope in burned catchments compared to unburned catchments. Overall, we observed an increase in discharge and suspended sediment yield in the post-prescribed burn period; however, this increase was significantly lower than previously reported values for forest fires. After comparing the effects of both forest fires and prescribed burns, our study highlighted the benefits of using prescribed burns as a mitigation strategy for forest fires.

Keywords: Forest fire, solution, prescribed fire, sediment

River basin trajectories under global change: earth observations and participatory hydrological modelling in the Senegal river basin

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In West Africa, surface water dynamics of large rivers are subject to strong climatic variability and under the growing influence of large dams built to meet the growing demands for hydropower and irrigation. Understanding river basin trajectories and their impacts in alluvial floodplains are essential to evaluate the trade-offs for the Water-energy-food-ecosystems (WEFE) nexus and guide water allocation strategies. Combining the continuous advances in earth observations with participatory hydrological modelling and extensive in situ fieldwork, this research seeks to improve our understanding of surface water dynamics under global change in the Senegal River. Landsat, MODIS and Sentinel-2 earth observations were extracted to monitor surface water variations, using a site specific MNDWI classification adapted to complex, wetland environments. Validated against extensive ground truth data, the approach is upscaled using cloud computing over 2813 mosaics from 1999-2022 covering the 2250 km² floodplain. Statistical regression models are developed to estimate flooded areas based on upstream flow values and incorporated in a combined GR4J rainfall-runoff

and WEAP allocation model. Seven river basin development scenarios co-constructed with the river basin agency and projections from Cordex regional circulation models (RCMs) are simulated to assess their impact on surface water dynamics and water-energy-food-environment NEXUS indicators. Results identify large historical variations in peak flooded areas between 150,000 ha and 450,000 ha (mean 227,000 ha). Scenarios of river basin development to support navigation and hydropower objectives reveal inundated areas could decline drastically by 59% to reach around 100,000 ha. Trade-off scenarios which optimize water allocation between growing, competing demands and allow translucent releases from the future dams are shown to reduce this decline to 32% with minimal impact on hydropower production. Outputs were discussed in participatory workshops with regional stakeholders to help define optimal and equitable river basin development strategies in the Senegal river basin.

Keywords: Large rivers, NEXUS, Remote sensing, Hydrological modelling, West Africa

Reconstruction of historical flow duration curves using reanalysis data

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Historical time-series of discharge data is essential for deriving flow duration curves (FDC) and regional flood frequency analysis, subsequently used for water resources management, reservoir operation, and flood protection. Further, with growing water demand, many water resource projects are planned across small streams, necessitating historical discharge data. However, many river-reaches worldwide lack a discharge time-series of sufficient duration. Hence, this study aims to reconstruct the historical time-series of daily discharge of the Baitarani River basin in eastern India during 1940-1990. The study basin experiences a tropical monsoon climate, with 80% of rainfall occurring during the monsoon. Concurrent gauge-discharge data has been available in the river basin at two gauging sites since 1990. We used the rainfall and temperature reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) for modelling. The reanalysis data was first compared with the corresponding gridded data from the India Meteorological Department for accuracy assessment. Thereafter, the semi-distributed Soil and Water Assessment Tool (SWAT) was forced with the ERA5 datasets to simulate the basin-scale rainfall-runoff response. The entire basin was delineated into 23 sub-basins and 107 hydrological response units based on the land use land cover, soil, and topographic slope. SWAT model was calibrated (1990-1999) and validated (2000-2006) to reproduce the historical discharge at Champua (in head-water) and Anandpur (in delta) gauging stations. Model performance was evaluated using statistical indicators of Nash Sutcliffe Coefficient (NSC), Kling-Gupta efficiency, root mean square error, and percentage bias. SWAT performed with $NSC \geq 0.60$ during calibration and validation. Subsequently, with historical ERA5 forcings, daily discharge time-series were obtained for each sub-basin and gauging station to reconstruct FDC. The simulated event-scale flood hydrographs of 1999 and 2003 were compared with observed ones. The water managers could adopt the methodology proposed to reconstruct the historical streamflow of ungauged basins.

Keywords: Flow duration curve, reanalysis data, SWAT, modelling, runoff

Impact of Climate Change on Hydrology and Extreme Events in the Mahanadi River Basin: A SWAT+ Approach

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The Mahanadi River's hydrological regimes are being profoundly impacted by climate change, which has a major impact on ecosystem dynamics, water quality, and flow patterns. In this study, we pioneer the application of the Soil and Water Assessment Tool Plus (SWAT+), a cutting-edge hydrological modeling framework, to thoroughly examine the hydrological dynamics of this complex and vulnerable catchment. The model was calibrated and validated using the SPE algorithm, and the results for calibration (NSE=0.81) and validation (NSE=0.79) indicate the model's robustness and reliability in simulating the observed data, ensuring its suitability for future projections. The model integrates future climate projections derived from the Climate Change for East Asia with Bias corrected UNet Dataset (CLIMEA-BCUD) dataset, which is based on advanced downscaling and bias correction techniques applied to the CMIP6 models. The CLIMEA datasets were evaluated against IMD observations using various performance metrics, including the correlation coefficient (CC), Nash-Sutcliffe efficiency (NSE), and Kling-Gupta efficiency (KGE), to assess the dataset's accuracy and reliability. The results demonstrated that the CLIMEA datasets provided satisfactory performance across all metrics. The dataset was further utilized to study precipitation patterns and extreme climatic events in the Mahanadi Basin. Analysis revealed an increasing trend in annual precipitation under SSP2-4.5 and SSP5-8.5, with more pronounced changes in the far future (2076-2100). Extreme rainfall events ($>10\text{mm}$ and $>20\text{mm}$) also showed significant increases, particularly in the far future. The model results project a substantial increase in streamflow under future climate scenarios, indicating an increased risk of flooding in the near future (2024-2050), mid-future (2051-2075), and far future (2076-2100). The findings of this study will be valuable for stakeholders, planners, and policymakers associated with water resource management in formulating adaptation strategies to mitigate the adverse effects of climate change in the Mahanadi River Basin.

Keywords: SWAT+, SPE Algorithm, CLIMEA BCUD, Climate Change, Extreme Climatic Events, Mahanadi Basin

Prediction of Monthly Rainfall Using Classification and Regression Tree (Cart) Model for Semi-Arid Region, Chhattisgarh, India

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Predicting monthly rainfall accurately is essential for disaster relief, agricultural planning, and allocating water resources, especially in semi-arid areas where rainfall varies greatly. A machine learning method that can handle intricate, nonlinear interactions in meteorological data, the Classification

and Regression Tree (CART) model is used in this study to predict monthly rainfall in Chhattisgarh, India. The study makes use of the India Meteorological Department's (IMD) historical rainfall data from 1981 to 2021 in addition to other meteorological factors to improve prediction accuracy. The CART model finds important meteorological factors affecting rainfall variability by analysing data patterns. The decision tree-based approach increases prediction accuracy by categorising rainfall patterns according to several meteorological variables. With a high coefficient of determination (R^2) of 0.96, the model demonstrated a high degree of agreement between the predicted and observed values. Additionally, its 0.96 Nash-Sutcliffe Efficiency (NSE) rating attested to its ability to accurately reproduce observed rainfall patterns. A low Root Mean Square Error (RMSE) of 23 mm indicated the model's accuracy in reducing prediction errors, while the Correlation Coefficient (CC) of 0.98 showed a strong linear link between observed and actual values. The potential of machine learning techniques to enhance rainfall prediction in areas with little data is highlighted by this study. The study advances the creation of more accurate and flexible climate forecast systems by offering an alternative to conventional statistical models. In order to improve climate resilience and lessen the effects of unpredictable rainfall, policymakers, farmers, and managers of water resources can use the data to inform their decisions. The Seonath River Basin application of the CART model shows how effective it is in resolving hydrological issues, promoting sustainable development, and maximising the management of water resources.

Keywords: Machine Learning, CART Model, Rainfall Prediction & Seonath River Basin.

Integration of non-linear conceptual reservoirs without tears using the QuaSoARe method

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Most hydrological models use conceptual reservoirs to simulate fluxes like runoff and evapotranspiration. However, since the flux functions are often highly non-linear, the resulting differential equations must be solved numerically. Yet, using inappropriate numerical schemes can have disastrous consequences leading to large errors, poor simulations, and fragile calibration.

This work presents a novel approach to solve a generic reservoir equation and compute all associated fluxes with a simple algorithm that can be easily integrated in a modelling workflow. The algorithm referred to as "Quadratic Solution of the Approximate Reservoir Equation" (QuaSoARe) is based on the approximation of flux functions by piecewise quadratic polynomials. A comparison of our algorithm against a high accuracy implicit Runge-Kutta scheme applied to a set of highly non-linear hydrological models shows that our algorithm can speed up integration by a factor of 10 to 50 while maintaining comparable accuracy.

Beyond reservoir simulation, our algorithm enables exploration of flexible model structures where the form of reservoir equations, hence the model structure, can be parameterised. As an example, the structure of a well-known rainfall-runoff model (GR4J) is first integrated into the QuaSoARe framework, and then modified to better match observed runoff in a large dataset of catchments.

Keywords: reservoir equation, differential equation, analytical solution, flexible models

Performance Evaluation of the Lumped Hydrological Model for Streamflow Simulation Across Indian Subcontinent (ISC)

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Streamflow modelling is of fundamental importance for water resources management, particularly in hydrologically diverse country like India. This study assesses the capabilities of MILC- a lumped hydrological model by simulating streamflow over 112 river basins that differ climatically, geologically and land use. The model uses simplified mathematical representation of watershed, treating the entire catchments area as a single unit, without considering the spatial variation within the basins. To evaluate the predictions, median NSE, median RMSE, and % bias range have been used. The model was calibrated on 70% data and validated on the rest 30%. The median NSE for calibration period is 0.6129, while for validation, it is 0.4421. For calibration, the best performance is observed in 31.25% of cases where $NSE = 0.7$, indicating strong predictability. 30.36% of the cases lie in the range of $0.5 = NSE \leq 0.7$, demonstrating moderate performance. However, 33.93% of cases have $0 = NSE \leq 0.5$, reflecting weaker predictive ability, while 3.57% of cases show $NSE \leq 0$, indicating poor performance. The RMSE has a median value of 155.71 m³/s, and the bias ranges from 0.06 to 1.39, highlighting variability in model accuracy across different basins. For validation the best performance is observed in 16.07% of cases where $NSE = 0.7$ which signify good predictability. About 24.11% fall into the range of $0.5 = NSE \leq 0.7$, showing moderate behaviour. 35.71% cases lie between $0 = NSE \leq 0.5$, and 24.11% falls under the category of $NSE \leq 0$, which depicts poor performance in those cases. The RMSE has a median value of 186.27 m³/s and bias varies between 0.04 and 15.96; thus, model predictability varies among basins. The study reveals the strength of lumped hydrological model in Indian subcontinent.

Keywords: MILC, hydrological modelling, Nash-Sutcliffe Efficiency, Indian Subcontinent (ISC)

A simple calibration-free Dynamic Budyko model for streamflow prediction in data scarce regions

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Accurate streamflow prediction in data-scarce regions remains a critical challenge for sustainable water resource management, as traditional rainfall-runoff models often rely on observed streamflow time series for complex calibration processes. The fundamental assumption in calibration is that each basin has a unique hydrological (streamflow) response to given rainfall inputs. Consequently, most hydrological models focus on dissimilarities between catchments, assuming that model parameters estimated during calibration represent the static catchment characteristics of a basin. However, establishing a direct relationship between model parameters and static catchment

characteristics has been largely unsuccessful, as different sets of model parameters can yield similar performance—an issue known as the problem of equifinality. This raises questions about the physical significance of model parameters. In this study, we assume that all catchments are hydrologically similar, meaning that climate plays a major role in determining the hydrological response of basins, while static catchment characteristics are secondary. We tested this hypothesis by selecting two hydrological models, the Dynamic Budyko (DB) model and the HBV model, to predict daily streamflow for 96 Indian basins. The DB model is calibration-free and requires only meteorological inputs (daily rainfall and temperature) to predict daily streamflow, whereas the HBV model requires observed streamflow data for calibration in addition to meteorological inputs. Both models showed very similar performance in predicting daily streamflow, with median R² and NSE values of 0.54 and 0.45, respectively. Thus, the proposed DB model can serve as a valuable tool for water resource management in data-scarce regions.

Keywords: Rainfall-runoff modeling, Dynamic Budyko model, Calibration-free

Satellite-based Surface water mapping using combined Optical and SAR

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Surface water bodies are vital to the Earth's hydrological cycle and indicators of climate change impacts, supporting ecosystem services and human needs. In tropical regions with volatile water availability, accurate monitoring is crucial for effective water resource management. While satellite-based Earth observation offers monitoring capabilities, complex environmental conditions limit effectiveness in tropical regions. Optical satellites are hindered by persistent cloud cover during wet seasons, while SAR systems, despite their cloud-penetrating capabilities, struggle to distinguish water from features with similar backscatter characteristics like flooded vegetation and bare surfaces, limiting their standalone application in tropical contexts.

To address these challenges, we present an improved surface water monitoring system for tropical regions by integrating multiple satellite sensor data. Our research focuses on (1) developing a multi-sensor integration framework combining optical and radar data, (2) evaluating classification approaches for water body mapping, and (3) assessing the temporal improvement in monitoring frequency.

The study proposes a multi-sensor integration framework combining Sentinel-1 SAR (VV/VH polarization) with Landsat-8/9 and Sentinel-2 optical data. The methodology addresses the geometric reconciliation between SAR's side-looking geometry and optical sensors' near-nadir observations. We evaluated pixel-based and object-based (OBIA) classification approaches, and validated them across three tropical regions, with water bodies ranging from 0.5 to 500 hectares, using high-resolution Planet imagery (3m) as a reference. Object-based classification achieves higher accuracy (85-90%) than pixel-based approaches (75-80%) in complex water-land boundaries. The integrated approach allows sub-weekly monitoring, with average temporal gaps reduced from 1-2 months (optical-only) to 12-16 days (combined sensors).

Integrating multiple sensors with improved methods allows more frequent and accurate measurements, crucial for understanding surface water dynamics and their response to climate variability in tropical regions. Improved surface water mapping aids flood prediction, drought assessment, and overall water resource management in these environments.

Keywords: Surface water, Sentinel, Random Forest, SAR, Optical

Representation of Hydrological Processes in an Agricultural Watershed Using the SWAT+ Model. A case study in Central Côte d'Ivoire, West Africa

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Effective water resource management in West African agricultural watersheds is crucial for ensuring sustainable food production and environmental security. This study applies the Soil and Water Assessment Tool+ (SWAT+) to simulate hydrological processes in the dammed Lake Taabo Watershed (LTW), located in central Côte d'Ivoire within the Bandama River basin. The primary objectives were to evaluate the ability of this enhanced SWAT version to simulate streamflow and represent the spatially distributed components of the water balance.

Model calibration and validation were performed using monthly flow data from the Bouaflé station within the LTW. The water balance components were simulated over the period 1986-2020 (35 years). The calibrated and validated LTW/SWAT+ model demonstrated satisfactory performance, with NSE efficiency values of 0.78 (calibration) and 0.69 (validation), R^2 values of 0.81 and 0.70, PBIAS of -18.58% and -23.9%, and RSR values of 0.47 and 0.56.

The analysis revealed significant spatial heterogeneity in the water balance components across the LTW. Over the study period, rainfall, surface runoff, percolation, lateral flow, and evapotranspiration ranged from 950 to 1,270 mm, 120 to 690 mm, 30 to 480 mm, 70 to 680 mm, and 30 to 790 mm, respectively. The LTW water balance indicates a surplus of water, with percolation being the dominant component. Additionally, baseflow contributes more to total streamflow than surface runoff.

This study demonstrates the applicability of the SWAT+ model to simulate flow and represent the spatially distributed components of the water balance in the basin on the reservoir watershed and provides valuable insights for water resource managers. Understanding the hydrological dynamics of this basin is essential for developing sustainable water management strategies, especially in the face of increasing anthropogenic and climatic pressures.

Keywords: water balance, Taabo Lake, water management, SWAT+ model

Insights into the relations among natural flow, water abstractions and e-flow from a distributed hydrologic modeling approach.

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The European Water Framework Directive (WFD, 60/2000/EC) aims to achieve or maintain at least a good ecological status of surface water bodies, partly by defining appropriate environmental flows (e-flows). Hydrographic District Authorities develop Water Management Plans based on available water resources, establishing e-flows and permitted water abstractions to support human activities such as domestic and agricultural use. This study evaluates whether restoring natural river flows in catchments would ensure a good ecological status. The method relies on a 20-year water balance simulation using a distributed hydrological model that integrates both vector and raster data, capturing anthropogenic influences like water abstractions, reservoir regulations, and discharges. A new dimensionless eco-hydrological distance index is introduced to assess how far river flows deviate from ecological targets, considering actual flow regimes and catchment pressures such as land use and climate. The methodology is applied to a central Italian region with approximately 11,000 river reaches in a Mediterranean climate, where nearly 50% of water bodies currently fail to meet WFD standards. Findings indicate that during summer, the driest season, many rivers approach the threshold of poor ecological status. Notably, in 48% of rivers, even if natural summer flows were restored, they would still not meet good ecological status due to the significant eco-hydrological distance from target e-flows. These results highlight the need for integrated water management strategies beyond flow restoration to achieve WFD objectives.

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Keywords: e-flow, distributed hydrologic modelling

Comparison of Flash Droughts and Conventional Droughts in Madhya Pradesh Using the SPEI Index

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Droughts are major challenges for agriculture and water resources, especially in the state of Madhya Pradesh, India, where agriculture depends on rainfall and the region is prone to recurring droughts. Existing literature shows that much of the state has seen a significant drop in monsoon season precipitation, and the frequency of heat waves has increased over recent years and droughts have been more widespread and intense. This makes studying both flash and conventional droughts essential for better managing their impact. Flash droughts are characterized by a sudden onset and rapid intensification due to precipitation deficit, high evaporative demand, leading to rapid soil moisture depletion. In contrast, conventional droughts develop gradually over an extended period due

to prolonged precipitation deficits, resulting in sustained soil moisture decline and long-term water stress. In this study, we focus on identifying both types of droughts - Flash Drought and Conventional Drought particularly meteorological drought, using both satellite data and meteorological variables. In this study, Standardized Precipitation Evapotranspiration Index (SPEI) was used to differentiate both drought types, a widely recognized index for drought monitoring. SPEI index was calculated using Precipitation (P) and Evapotranspiration (ET). Flash drought events were identified by a decline of $SPEI = -2$ in the 1-month, which signals an onset of drought conditions. Conventional drought events were identified if it took more than 1 month for the SPEI value to drop below -2. Our findings show that the SPEI index can effectively distinguish between flash and conventional droughts in Madhya Pradesh. By studying the occurrence of both types of drought, we can determine which is more dominant in the study region, providing crucial insights for drought preparedness which can aid for better water resource management and agricultural planning in the region.

Keywords: Flash Drought, Conventional Drought, SPEI, Onset

Surface hydrology based hydro-meteorological thresholds for early warning of rainfall-induced landslides

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Hydro-geomorphological hazards, such as rainfall-induced landslides and debris flows, have escalated in frequency and magnitude in recent years due to the impacts of climate change posing significant risks to infrastructure, ecosystems, and human settlements in vulnerable areas. The interplay between land and the atmosphere is crucial, as rainfall infiltrates the surface, leading to significant changes in pore water pressure. This process reduces slope stability and increases the risk of hazardous events. Many existing early warning systems for landslides and debris flow primarily rely on statistical methods, such as rainfall intensity-duration (I-D) thresholds, which do not adequately capture the complex interactions among rainfall, surface, and subsurface hydrology. Therefore, it is essential to integrate surface and subsurface hydrology along with antecedent rainfall data for improved accuracy of early warning. The present study employs the three-tank model, a conceptual rainfall-runoff model, to estimate water content in terms of the Soil Water Index (SWI) and develop hydro-meteorological thresholds for early warning systems. Our approach was validated in the Periyar River Basin, Kerala, India, which experienced catastrophic landslides during the extreme rainfall event of 2018. In this basin, landslides typically occur when values exceed 30% and 40% of the hydro-meteorological threshold. Our findings highlight the need for a more integrated approach to landslide prediction, incorporating hydrological parameters to enhance early warning capabilities. Thus, surface hydrology-based thresholds present a promising alternative to existing methods for regional-scale landslide forecasting.

Keywords: Surface Hydrology, Soil Water Index, Rainfall induced landslides, Early Warning Systems.

Can Blended Models Offer a Better Approach to Streamflow Prediction? A large sample study

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Numerous process-based (PB) models have been developed for streamflow estimation; however, uncertainties in model outputs persist due to the incomplete representation of physical processes. With advancements in machine learning (ML), various efforts have been made to enhance streamflow predictions. However, ML-based approaches often lack physical consistency, making them potentially unreliable for future hydroclimate projections when climate and land-use conditions extend beyond the range of training data.

This study develops blended hydrological models by integrating state variables from PB models, specifically soil moisture and discharge outputs, with the most effective ML algorithms to simulate streamflow across 671 catchments representing diverse hydroclimatic conditions in the conterminous United States. Eight distinct PB models were evaluated using different optimization techniques, with the best-performing model identified based on the number of catchments exceeding a Nash-Sutcliffe Efficiency (NSE) threshold of 0.7. Similarly, the best ML model was determined by the number of catchments surpassing the same performance criterion.

Catchments where the best PB model achieved NSE $\geq$ 0.7 while the best ML model had NSE $<$ 0.7 were identified, and blended hydrological models were developed by pairing PB model outputs with ML methods. The results demonstrate that the blended models substantially improve streamflow simulation performance, particularly in catchments where standalone ML models exhibit deficiencies. These findings underscore the potential of hybrid modeling approaches that leverage PB model outputs to enhance the predictive reliability of ML-based streamflow simulations.

Keywords: Process-based, Machine learning, Blended models

Sustainable Solutions for Stormwater Management in Urban Environments

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Worldwide, in recent years, both the magnitude and frequency of short but destructive urban floods have grown, resulting in greater economic losses and higher mortality. Climate change and urbanization are the major driving forces of this trend, particularly in highly populated developing cities where the management responses lag behind the rate of population increase. Therefore, it is essential to perform an accurate assessment of urban food systems and improve pre-disaster mitigation strategies in at-risk areas. Traditional urban stormwater management emphasizes swift runoff transport via lined systems; yet, in some cases, poor management raises the risk of floods downstream. It is essential to implement sustainable methods that emulate natural processes to mitigate peak flow and extend the time of concentration through the retention of floodwater. Implementing Low Impact Development (LID) practices is often considered a more environmentally sustainable approach for managing stormwater in urban settings. This research evaluates the efficacy of LIDs at

different levels in reducing the likelihood of flooding of different return periods in a basin of Delhi. The study finds that rain gardens have significantly reduced the average flow rate, total flood volume. Moreover, the analysis indicates that the area with the greatest flood hazard does not necessarily align with the highest urban flood risk area, which is a function of both flood hazard and vulnerability. This crucial information will assist urban developers in prioritizing places and mitigating urban floods more effectively.

Keywords: Urban Floods, Flood Mitigation, Sustainability, LID

Assessing the Role of Wetlands as Nature-Based Solution in Flood Mitigation in Delhi-NCR

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Urban flooding, often caused by unplanned settlement and climate change-driven intensified extremes, poses significant risks to communities, infrastructure, and ecosystems. Wetlands, which have been generally overlooked in flood management strategies, however, have the potential to offer nature-based solutions to mitigate flood peaks by storing excess runoff. Evaluating their potential to alleviate floods requires integrated modeling exercises with catchment hydrological processes. Existing hydrologic models often fail to accurately represent the dynamics of wetlands due to limited representation of real wetland features and oversimplified parameterization methods. Current approaches, such as lumped sub-basin-scale models, do not adequately capture the spatial variability and hydrologic connectivity of wetlands, leading to underutilized insights into their flood mitigation capabilities. We have developed a methodology to enhance the ability of Soil and Water Assessment Tool Plus (SWAT+) to model wetlands by improving the accuracy of their spatial representation and the dynamics of inflow and outflow processes for realistic simulation of wetland hydrology. Additionally, we are currently evaluating the efficiency of wetlands in mitigating flood peaks in the Delhi NCR through ongoing testing. The results will underscore the importance of wetlands as a sustainable solution for flood management. This study will provide a modeling framework that can guide policymakers in wetland restoration by demonstrating the hydrologic benefits of wetlands in mitigating flood risks, making it highly relevant for planning under a changing climate.

Keywords: Wetland, Nature Based Solution, Flood, Resilience.

Assessment of Climatic and Anthropogenic Activities Impact on Streamflow Response of the Anandapur Subbasin using SWAT Model

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Both climatic factors and human activities alter the streamflow in river basins, causing the need of assessing the impact. This study focuses on the Anandapur subbasin situated at the southern bank of the Baitarani River (Orissa), using the Soil and Water Assessment Tool (SWAT) model to assess how climate change and human interventions have impacted its hydrology. The main objectives are to create a hydrological model of the area and quantify the effects of both of the factors. The study examines historical data from 1972 to 2018, including soil maps, digital elevation models (DEM), runoff, temperature, precipitation, and land use/land cover (LULC). A change point analysis was done using the double mass curve and the Mann-Kendall test. It identified 2011 as the transition year separating the baseline period from 1972 to 2010 and the change period from 2011 to 2018. The SWAT model was generated for the study area.

Preliminary findings reveal a significant reduction in runoff during the change period-dropping by 50.41% compared to the baseline-despite a 5.12% increase in precipitation. The watershed's average curve number (80.03) indicates a moderate runoff potential.

Remaining work will involve finalizing model calibration and validation, simulating streamflow for the change period, and performing sensitivity analyses on key parameters. The final results will offer valuable insights into how climate change and human activities have altered the subbasin's streamflow. This will be ultimately helpful for water resource management, flood control, and sustainable development planning in the region.

Keywords: Hydrology, surface hydrology, SWAT, climate change, streamflow, surface runoff,

Regionalising high-mountain wetland hydrological behaviour in the Tropical Andes

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High-mountain wetlands have the potential to store large quantities of water and slowly release it, regulating flow and prolonging catchment residence times. This is particularly important in seasonally dry climates because it ensures a regular supply of water for highland communities and receiving

lowlands. Despite their significance to catchment hydrology and water resources, few attempts have been made to quantify high-mountain wetland outflow and residence times and no attempts have been made to regionalise high-mountain wetland behaviour. To address this gap, this study aims to build a regional model to determine the controls on high-mountain wetland hydrological behaviour and advance predictions in ungauged basins, allowing us to understand their influence on larger scales. We are implementing a standardised wetland monitoring protocol across six representative study catchments (0.38 km² - 12.58 km²) with varying wetland coverage from Northern Ecuador to Southern Peru. Monitoring includes rainfall-runoff and wetland water levels at the 5-minute interval over the course of at least one year. Additionally, twice per catchment (dry and wet season), 2lbs of fluorescein dye is injected into the wetlands and monitored downstream using passive carbon samplers to trace the movement and timing of flow through the wetlands. These data will be used to build simple bucket hydrological models for each catchment and parameters will be regionalised using multiple linear regression with topographic, vegetative and meteorological indices as descriptor variables. We expect to see a positive correlation between wetland coverage and catchment residence times, demonstrating the seasonal buffering role of high-mountain wetlands in providing higher flows during the dry season.

Keywords: high-altitude wetlands, bofedales, paramo, residence time, seasonal buffering, water security, regionalisation

A review on instrumentations for hydrological measurements: Current status and way forward

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The observed river discharge data having a higher spatial and temporal resolution is crucial for effective planning, management, and operational activities of water resources projects pertaining to irrigation, hydropower, drinking water supply, navigation and recreation. Continuous measurement with high spatial density would help develop more accurate models varying from simple statistical analyses for estimating dependability, occurrence, frequency, and trend to more sophisticated deep learning-based machine learning models to forecast floods accurately. While several conventional methods exist, continuously observing on a shorter interval is expensive in terms of cost and time involved. Furthermore, it might be potentially dangerous to observers during high flooding periods. Moreover, in India, like countries, only larger rivers at very limited locations are equipped with automatic monitoring of streamflow measurements. Therefore, it is very important to design and develop alternative instruments that are reliable and affordable for continuously monitoring the streamflow dynamics on a real-time basis. This paper addresses the need to develop low-cost instruments to measure the streamflow data accurately. The limitations in the functioning of conventional methods are identified using several factors such as cost, installation procedure and accuracy. The paper

also highlights the way forward in terms of quality checks, policy-level changes, public participation and data management locally and centrally.

Keywords: River Discharge, automatic monitoring, floods, real-time, low-cost instruments

Development of A Novel Approach for Studying Landslides Under Current and Future Rainfall Conditions

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Landslides are among the most destructive natural disasters, causing significant damage to infrastructure and loss of life, often with minimal warning. They result from a combination of factors, including intense rainfall, steep slopes, geological instability, deforestation, seismic activity, and human interventions such as unplanned construction and excavation. In the Himalayan region, landslides are primarily triggered by heavy monsoon rainfall, making susceptibility mapping crucial for risk assessment and infrastructure planning. However, future changes in precipitation patterns due to climate change could further intensify landslide risks. Understanding how projected rainfall variations influence landslide susceptibility is essential for proactive planning and disaster preparedness. This study uses a machine learning-based Random Forest model to assess landslide susceptibility in some selected regions in Uttarakhand and Himachal Pradesh states. The analysis incorporates multiple conditioning factors, including topography, land use, and rainfall patterns. Model performance is evaluated using the Area Under the Curve (AUC) method and validated through field visits. The results indicate that major highways in Uttarakhand and the central and southern regions of Himachal Pradesh are highly susceptible to landslides. The obtained AUC values are 80.86% for Uttarakhand and 88.06% for Himachal Pradesh, both considered acceptable in terms of accuracy. Field validation at 158 locations reveals that 68% of sites have a landslide probability exceeding 90%, classifying them as very high-risk zones. Additionally, 23% of sites fall within the high-risk category (75-90% probability), while the remaining locations have a moderate probability of 40-75%. Potential landslide hotspots are identified for future scenarios based on projected precipitation changes. These findings emphasize the need for continuous monitoring and improved risk mitigation strategies. This study provides valuable insights for policymakers and planners, supporting long-term infrastructure resilience and disaster risk reduction in landslide-prone areas.

Keywords: Land slides, Susceptibility Mapping, Rainfall Patterns

Analytical Derivation of Richards' Equation and its Coupling with SCS-CN Concept for Efficacious Irrigation Scheduling

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The accurate determination of soil profile depth is crucial for effective irrigation scheduling, yet it is often estimated based on conventional assumptions of root zone depth (typically 1-1.5 m below ground level), leading to subjective and potentially inefficient water management practices. This study presents an analytical derivation of Richard's equation and integrates it with the Soil Conservation Service Curve Number (SCS-CN) concept to develop a novel approach for determining soil profile depth. By incorporating the three-phase soil column model commonly used in geotechnical engineering, an analytical expression is derived to estimate the maximum storage capacity of soil based on its hydraulic and retention properties. Furthermore, this relationship is mapped onto the SCS-CN parameter, specifically the potential maximum retention (Curve Number, CN), to enhance its applicability in practical irrigation management. Results demonstrate that for row crops under optimal hydrologic conditions, applying the proposed methodology can lead to significant water savings of up to 83% and 75% in sandy soils (HSG-A) compared to the traditional fixed-depth assumptions of 1.5 m and 1 m, respectively. In clayey soils (HSG-D), water savings can reach 94% and 92%, respectively. Additionally, the proposed approach offers valuable insights into the volumetric assessment of field capacity, soil moisture content, and maximum water storage capacity across various agricultural soils and land management practices, facilitating more judicious and efficient irrigation scheduling.

Keywords: SCS-CN technique, potential maximum retention, soil profile depth, Richard's equation, rainfall intensity.

Understanding the impact of urban heat island effect on precipitation patterns in an urban microclimate

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The Urban Heat Island (UHI) effect significantly alters local meteorological conditions, including precipitation dynamics, within urban microclimates. This study examines UHI's influence on precipitation patterns in Dehradun, a sub-tropical capital city located in the foothills of the Himalayan state of Uttarakhand in India. The high-resolution observed hourly meteorological data is obtained from seven weather stations in the city between 2021 and 2023. The spatial and temporal analysis of rainfall anomalies uses data from urban and rural stations. The UHI intensity or temperature difference between urban and rural regions (ΔT) showed a connection with precipitation events, which affected diurnal rainfall patterns. The study also analyzed how humidity and wind patterns influence changes in convective rainfall patterns. Preliminary results indicate that UHI intensity positively correlates with enhanced precipitation downwind of urban areas, with a mean increase of 15% in rainfall volume compared to peri-urban regions. The findings indicate that cities in core urban areas experienced 10% less rainfall. The diurnal analysis indicates an increase in nocturnal rainfall events of the

order of 20% within urban areas due to increased convective activity due to UHI-induced thermal gradients. Research indicates that urban cores receive 10% less rainfall, while urban centers located in the core experience augmented rainfall, the effect of UHI on precipitation is enhanced. The findings highlight the complex interaction between UHI and local precipitation patterns, highlighting the role of urban planning and mitigation strategies.

Keywords: Urban microclimate, Urban Heat Island, Precipitation, Hydrometeorology, Climate Change

Enhancing streamflow simulation of the SWAT model using parameter regionalization and high-resolution remote sensing data

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Surface water is one of the key components in the hydrological cycle. It significantly contributes to ecosystem health, food production, and energy generation. The streamflow measured at the outlet of a watershed is commonly used to calibrate the parameters of hydrological models and simulate various fluxes, which are essential for effective planning and management of water resources. For this endeavor, the Soil and Water Assessment Tool (SWAT), a widely accepted, semi-distributed, physics-based hydrological model is utilized to simulate key hydrological processes under various anthropogenic activities (i.e., irrigation, crop and land management, reservoir operation, source pollution, etc.). SWAT considers numerous numbers of parameters to simulate hydrological processes, which primarily depend upon climate, land use, and topography. As standard parameters, especially the width and depth of river channels, are often estimated based on the data pertaining to USA river basins, adopting the similar sets of parameters for other regions might increase model uncertainties and leading to poor simulation of streamflow. To overcome this limitation, we focused on improving the streamflow simulation using parameter regionalization and finer resolution land use and soil maps. This was achieved using various open-source remote sensing (RS) data, field observation, and machine learning models. The methods developed was verified using the data from Peninsular River basins of India. The results suggested an improvement in the model accuracy and also achieved characterizing the parameters of less uncertainty. The paper concluded that the model simulations when used for decision making would be beneficial to derive optimal policies ensuring the long-term sustainability.

Keywords: surface water, hydrological modeling, remote sensing, field observation, machine learning

Trends in Urban Flooding with Rapidly Expanding Impervious Area

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Peak discharge and flood volume are significantly impacted by land use and land cover (LULC) changes in urban watersheds. It is essential to comprehend these changes in order to mitigate flooding and manage urban water resources effectively. This study aims to investigate the decadal effects of urbanization from the past to the present on urban floods in the Barapullah sub-basin of NCT Delhi between 2000 and 2020. Random forest method was used to classify LULC for 2000, 2010, and 2020. The impact of urbanization on flood volume and peak discharge was then evaluated by integrating the hydrodynamic model SWMM 5.1 with the classified LULC data. The trend analysis shows a prominent expansion in impervious surface area, which raised the volume of floods for rainfall events of 2, 5, and 10-year return periods. LULC modifications have also affected peak discharge magnitude and duration. The study shows that an increase in rapidly impervious areas impacts urban hydrology and increases flood hazards. This research helps urban planners and policymakers adopt sustainable drainage and flood management measures in this rapidly urbanizing city.

Keywords: Urbanization, LULC Change, Flood

Investigation of Open-Source LULC Datasets for Watershed Hydrology Simulation

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Land Use Land Cover (LULC) datasets serve as fundamental spatial inputs for various hydrological applications. However, the availability of these datasets from multiple sources, each employing distinct classification algorithms and techniques, introduces variability that can significantly impact hydrological modeling accuracy. Such discrepancies affect the representation of hydrological features and, consequently, the reliability of model simulations. This study investigates the openly available LULC products such as ESRI LULC, ESA World Cover LULC, and ISRO-Bhuvan for watershed hydrology simulation using the Soil and Water Assessment Tool (SWAT). The evaluation focuses on the Ong River watershed, a forest- and cropland-dominated region within the Mahanadi River basin, India, covering an area of 4,650 km². The performance of each LULC dataset in hydrological simulations is analyzed using multiple statistical metrics, including Willmott's Index of Agreement, Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R²), Percent Bias (PBIAS), and the RMSE-observations standard deviation ratio (RSR). The findings of this study provide valuable insights into the suitability of different open-source LULC datasets for hydrological modeling, highlighting the importance of dataset selection based on catchment characteristics and accuracy requirements.

Keywords: Hydrological Modeling, LULC, open-source, SWAT

How does a higher density of small water reservoirs affect catchment hydrology?

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Small water reservoirs play a crucial role in the hydrographic network, significantly affecting catchment runoff. Their impact is primarily associated with key hydrological processes such as flood attenuation, evaporation losses, changes in groundwater levels, and overall water balance modifications. While the influence of a single reservoir on the hydrological regime can be estimated with relative ease when sufficient data is available, the challenge arises when attempting to assess their cumulative effect at the catchment scale. This complexity increases when multiple reservoirs are present, especially when employing lumped or semi-distributed hydrological models. Understanding the collective behavior of these reservoirs is essential for accurate hydrological modeling, water resource management, and flood risk assessment.

To address this challenge, our study investigates the hydrological response of catchments with a significant presence of small water reservoirs. We adopt a comparative approach, analyzing long-term time series data from two neighboring catchments with similar climatic and geological conditions but differing in reservoir density. The selected study areas are the Skalice River and Lomnice River catchments, both situated southwest of Prague in the Czech Republic. By comparing their hydrological responses, we aim to quantify the extent to which small reservoirs influence runoff patterns, storage dynamics, and water availability. The findings of this study provide valuable insights into the role of small reservoirs in shaping catchment hydrology and contribute to improving modeling strategies for regions with similar hydrological settings.

Keywords: small water reservoir, catchment hydrology, time series analysis

Complexity of Historical and Future Rainfall Dynamics in India under Climate Change: A Nonlinear Dynamic Dimensionality Approach

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Global climate change has emerged as a major environmental issue today. Climate change affects rainfall (and other hydroclimatic processes) in various ways, including its temporal and spatial variability and extremes. Therefore, understanding the variability of rainfall under climate change is crucial for better planning and management of our water resources and environment. This study

examines the temporal dynamic complexity of historical and future rainfall in India. Monthly rainfall data at a spatial resolution of $0.25^\circ \times 0.25^\circ$ are analyzed. The historical rainfall comprises observed (interpolated) data obtained from the India Meteorological Department (IMD) and from the CMIP6 (Coupled Model Intercomparison Project Phase 6) GCMs for the period 1961-2014, and the future rainfall constitutes rainfall simulated by the GCMs under shared socio-economic pathway scenarios (SSPs). For the future, four scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and three different timeframes (near future: 2020-2039, mid future: 2040-2069, and far future: 2070-2099) are considered to examine how rainfall complexity varies across scenarios and timeframes. The false nearest neighbor (FNN) algorithm is employed to determine the dimensionality and, hence, the complexity of rainfall dynamics. The algorithm involves two major steps: (i) reconstruction of the single-variable rainfall time series in a multi-dimensional phase space; and (ii) identification of "false" neighbors in the reconstructed phase space and estimation of the dimension of the rainfall time series. The FNN dimensions show that the future rainfall projections from the GCMs generally exhibit greater rainfall complexity when compared to that of historical rainfall, across all SSP scenarios and for all three timeframes. However, the complexity of the rainfall in the far future is greater when compared to that in the near- and mid-future periods. Furthermore, during the mid- and far-future periods, the complexity of the rainfall is greater under the SSP5-8.5 scenario when compared to that under the other scenarios.

Keywords: Rainfall, Climate change, Complexity, Chaos theory, False nearest neighbor

Assessing the Temporal-Spatial Stability of Cross-Section Mean Flow Velocity in Small and Large Rivers

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Streamflow monitoring is a crucial aspect of understanding the hydrological characteristics of natural waterways. Accurate streamflow estimates are essential for designing hydraulic structures, predicting flood events, and managing water resources. Reliable discharge evaluation depends on the measurement of water levels and flow velocities. However, velocity measurements are often limited to low-flow conditions due to the challenges of sampling during high-flow events. For wide rivers, additional challenges arise when cableways cannot be employed, necessitating the use of boats to maintain proper alignment across the cross-section. This complexity, especially during floods, highlights the need for systematic seasonal measurement campaigns to indirectly estimate discharge using water levels. Such methods rely on stage-discharge relationships, which require periodic updates due to morphological and hydraulic changes in the measurement site. Deep sections of the channel can become inaccessible, and measurement operations can pose significant risks to field personnel. The current research aims to develop a method based on identifying representative points within the cross-section where localized velocity measurements closely approximate the sectional average. It requires spatial knowledge of the variable and a sufficient number of measurements for statistical reliability. To this end, the data from Italian Tiber River as well as the Amazon

River, as small and large rivers, consequently, were selected. The findings could significantly improve monitoring efficiency by reducing the number of verticals required for velocity measurements and minimizing risks to field operators, particularly during high-flow events.

Keywords: Temporal stability, Mean velocity, Large rivers, Tiber River, Amazon River

Declining Water Storage in Small and Medium Inland Waterbodies of Chennai: Implications for Mitigating Flood Risks

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Small (≤ 10 ha) and medium (10-100 ha) inland waterbodies are essential for understanding hydrological, biogeochemical, and flood risk mitigation processes, yet their size and complex bathymetry make water storage estimation challenging using conventional models and satellite altimetry. This study introduces a novel machine-learning (ML) model to estimate the monthly water storage of 914 waterbodies (98% small and medium) in India's highly flood-prone Adyar-Chennai basin. The ML model was trained using 86 in-situ bathymetric measurements and dynamic water spread area extracted from 857 LANDSAT images (1988-2023). The ML model showed superior performance ($R^2 = 0.94$) in estimating the water storage compared to previous global ($R^2 = 0.57$) and regional models ($R^2 = 0.24$). Our findings indicate a significant decline in the water storage of small and medium waterbodies from ~ 100 (92.57- 109.17) Million m^3 (MCM) in January 1988 to ~ 40 (30.83-48.31) MCM in December 2023. Notably, 76% of small and 61% of medium waterbodies demonstrated significant storage decline ($p \leq 0.001$), primarily due to urban expansion. Besides this, declining rainfall and vegetation loss reduced storage in small waterbodies, while increased vapor pressure and cropland expansion led to storage decline in medium waterbodies. Given the flood-prone nature of the Adyar-Chennai basin, the study also assessed the flood mitigation potential of small and medium waterbodies. During this assessment, their absence led to a 50% increase in peak flood rates, emphasizing their crucial role in flood mitigation. Hence, the study proposed (i) creating 90 new waterbodies and (ii) deepening existing waterbodies by 1 meter to completely mitigate the basin's floods. A novel tankshed overflow index, integrating hydrological and land-use variables, was developed to identify locations for 90 new waterbodies. This research provides a robust framework for water storage estimation and flood mitigation, offering actionable insights for water resources management.

Keywords: Small and Medium Inland Waterbodies, Water storage, Machine Learning, Tankshed Overflow Index, LANDSAT

Performance Evaluation of the Variable Parameter McCarthy-Muskingum Method and the Kinematic Wave Method for Overland Flow Simulation

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The Variable Parameter McCarthy-Muskingum (VPMM) method directly derived from the Saint-Venant equations (SVE) considering uniform lateral flow is presented for overland flow runoff simulation. The operational performance of the method is extensively evaluated using the observed rainfall-runoff data available in the literature based on standard metrics. Besides, the simulation results are also evaluated by comparing with the analytical solutions of the kinematic wave equation and with the various numerical method solutions of the Saint-Venant, diffusive and kinematic wave equations. In this context, the kinematic wave number (k) given by Woolhiser and Liggett (1967) and the parameter $k(Frp)^2$ is used to assess the flow regime. Accordingly, the recommended values of k , $k(Frp)^2$ are ≥ 20 and ≥ 5 , respectively, when the overland flow process is governed by the kinematic wave equation. However, this study shows that the VPMM method can closely reproduce the outflow discharge in a manner similar to the diffusion wave and Saint-Venant solutions when $k(Frp)^2$ is greater than equal to 1 and, thereby demonstrating the wider applicability of the VPMM method for overland flow simulation than the KW method. The study details will be given in the presentation.

Keywords: Overland flow, variable parameter McCarthy-Muskingum Method, Kinematic wave method, Saint-Venant equations

Interannual Rainfall Variability of Indian River Basins: Long-term Stability and Emerging Climate Teleconnections

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The Indian River basins exhibit significant interannual rainfall variability driven by a complex interplay of multi-scale atmospheric and oceanic influences. This study examines a reconstructed rainfall dataset spanning over two centuries (1813-2020) across 20 major river basins in India to assess long-term trends, regional disparities, and evolving climatic influences on monsoonal precipitation. The analysis reveals substantial decline of 6.6% and 19.7% in rainfall over key river basins like Ganga, Brahmaputra, Cauvery, Brahmani, Pallar, and Ponniyar over the past two decades compared to last century, while the Surma basin exhibits a notable 7.9% increase. Despite these shorter period regional fluctuations, ISMR has shown a modest 1.3% increase over the past 101 years, indicating long-term stability. Spectral analysis highlights the dominance of short-term fluctuations, accounting for over 75% of total rainfall variability across river basins. The study further explores the evolving teleconnections between ISMR and ten global climatic indices, including the Southern Oscillation Index (SOI), Arctic Oscillation (AO), Niño3.4, and the Pacific Decadal Oscillation (PDO). The influence of these indices varies across monsoon months, with stronger correlations

observed in June and September than in peak monsoon months of July and August due to overlapping climatic influences. While SOI and AO have historically maintained positive correlations with ISMR, and Niño3.4 an inverse relationship, a notable weakening of the AO-ISMR link is observed post-1980s, likely due to Arctic warming. This shift is particularly pronounced in the Indus, Ganga, Krishna, Cauvery, and WCDS basins, whereas correlations with the Godavari and Narmada basins have strengthened. Regionally, northern and eastern basins correlate strongly with warming over the eastern and central Afro-Asian highlands, while southern basins are influenced by equatorial climate dynamics. These findings emphasize the increasing complexity of monsoonal variability and critical need for localized and adaptive water management strategies to enhance climate resilience across river basins.

Keywords: Interannual rainfall variability, harmonic analysis, global teleconnections, tropospheric warming.

Assessing Extreme Flood Inundations in Brahmani-Baitarani Delta under Future Climate Change Scenarios with BiLSTM and HEC-RAS 2D Models

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The increase in human activities and greenhouse gas emissions has significantly altered climate patterns, leading to rising global temperatures and shifts in precipitation regimes. These changes escalate extreme weather events, resulting in increased coastal flood vulnerability. The Brahmani-Baitarani River delta, located near the Indian Bay of Bengal, is susceptible to climate-induced flooding due to its low-lying topography, tropical cyclones and high population density. As extreme rainfall events during the near future period (2030-2050) are projected to intensify as assessed in the high-emission Shared Socioeconomic Pathway (SSP) 8.5 scenario of the Coupled Model Intercomparison Project Phase (CMIP) 6, it becomes imperative to conduct flood inundation studies to identify high flood risk zones under this scenario. For this, the most suitable General Circulation Model (GCM) has been identified for the selected study area during the historical period. Subsequently, a Bidirectional Long Short-Term Memory (BiLSTM) model, trained and validated with historical meteorological data, is used to project inflow to the Rengali reservoir using the best GCM meteorological forcings. This projected inflow is routed through the reservoir by the HEC-ResSim model to project the reservoir outflow, which are then forced to the HEC-RAS 2D hydrodynamic model as the upstream boundary condition to generate high-resolution flood inundation maps and the vulnerable zones. The results in this study indicate a significant alteration in the projected rainfall and inundation patterns in the SSP 8.5 scenario when compared to the historical records. Detecting vulnerable coastal zones would aid in disaster preparedness, facilitate effective risk mitigation strategies, and support adaptive flood risk management.

Keywords: BiLSTM, Climate change, Coastal flooding, HECRAS 2D, Streamflow, Vulnerability

Enhancing weather radar estimates of heavy rainfall for near real time landslide and flash flood EWS in Thailand

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Flash floods and landslides are among the most widespread hydrometeorological hazards and often coincide and cause widespread economic damage and casualties. Intense rainfall events result in immediate discharge generation leading to flash floods and/or result in pore pressure buildup in the soil leading to destabilization of slopes. Accurate precipitation input data is key in predicting these hydrometeorological events. This research aims to develop a near real-time, joint early warning system for flash floods and landslides in Thailand using near real time ground-based weather radar data.

The research consists of two tiers: deriving high-resolution gridded radar composite precipitation data and spatially distributed physical-based modelling of flash floods and landslides. The spatially distributed precipitation has a temporal resolution of 6 min and a spatial resolution of 600-600 m² and combines two overlapping weather radars. Unfortunately, in mountainous regions the radar products often show some low quality sections in radar reflectivities. Here we developed a novel technique to transform reflectivities into rainfall intensities based on quality indexes of two radar stations improving the accuracy of spatial rainfall estimates. Additionally, we develop an improved mean field bias adjustment technique by including the spatial variability of the bias adjustment factors associated with the quality of radar observations.

For landslide predictions, we established a landslide inventory based on field observations and remotely sensed spectral information. The landslide susceptibility map gives spatial insight in landslide occurrence. The temporal probability was assessed using a physical-based multi hazard model. The hydrological model includes the driving hydrological process for each grid cell and the slope stability was assessed using the infinite slope approach. The results show good performance in predicting flash floods and landslide occurrence.

This research contributes to disaster risk management by demonstrating the effectiveness of integrating hydrological modeling with high-resolution and high quality rainfall data.

Keywords: Early Warning Systems, weather radar, landslides, flash floods

Comparative Study of Shallow Water Model (SWM) and Zero-Inertia Model (ZIM) for Flood Simulation in a Simplified Urban Catchment

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Urban flood (UF) is a critical challenge that requires accurate hydrodynamic modeling for its prediction and risk assessment. UF modeling has been widely performed utilising the Shallow Water Models (SWMs). Such models yield very accurate results but are computationally expensive. The Zero-Inertia Model (ZIM) is an approximated form of the SWM, where the inertial terms in the governing equation are neglected to enhance the computational efficiency of surface overland flow simulations. ZIMs exhibit satisfactory accuracy under subcritical flow conditions, particularly for Froude numbers less than 0.5. However, the applicability of the ZIM for urban flood simulations is yet to be ascertained as the buildings and other impermeable structures in an urban catchment channelize the flow along directional pathways and induce flow resistance due to wave reflections and wake formations. This study presents a comparative analysis of SWM and ZIM for a simplified theoretical urban catchment to evaluate the effectiveness of ZIM in simulating the urban flood dynamics. A Finite Volume (FV) method-based SWM has been developed to simulate the flood flow dynamics. The results of SWM and ZIM are in good comparison with each other for low rainfall intensities and mild bed-slopes. However, with the increase in rainfall intensity and bed-slope, the accuracy of the ZIM decreases. Moreover, the ZIM is computationally efficient than the SWM for all the simulations. Although computationally efficient, the ZIM cannot be considered as a suitable tool as it compromises the solution accuracy. This study highlights the trade-off between computational efficiency and accuracy in urban flood modeling. It highlights that the full-scale SW Equations should be preferred for urban flood modeling, with a need to develop mathematically improved approaches to reduce the associated computational cost without compromising the accuracy which will make it a more effective tool for real-time flood forecasting.

Keywords: Urban flooding, Building footprints, Shallow Water Model (SWM), Zero-Inertia Model (ZIM), Computational efficiency, Finite Volume (FV) method

Spatiotemporal Characterization of Hydro-Meteorological Disasters in Indian Himalaya: An MCDM based Prioritization Approach for Disaster Resilience

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To optimize the management and mitigation of Hydrometeorological disasters, this study sought to cluster spatiotemporal risk zones based on the distribution of previous hydrometeorological disasters (HMDs) that occurred in Uttarakhand Himalaya, India along with the prioritization of Tehsils of Uttarakhand for disaster proneness based on MCDM tools. The k-means spatial clustering approach has been employed to identify disaster-prone regions based on historical events. Spatial clustering, in conjunction with the multi-criteria decision-making (MCDM) technique, facilitated the identification of the state's disaster-vulnerable areas. Using clustering techniques, more than 60

documented HMDs that happened in the state between 1857 and 2024 were examined. The state can be divided into zones that face different levels of threat after clusters have been identified. The state's subdivisions, such as Districts and Tehsils, serve as the foundation for this clustering technique. Because of higher vulnerability and fewer resources for socioeconomic recovery, the designated cluster regions should be thoroughly examined before, during, and after disasters. This HMD zonation of Uttarakhand by clustering at the Tehsil level yielded six tehsils, namely: Bhatwari, Okhimath, Joshimath, Karnaprayag, Dharachula, and Didihat have been identified as the clusters based on the locations of the historical disaster locations. Further prioritizing Tehsils on disaster proneness was done using MCDM approaches such as AHP, VIKOR and TOPSIS physiographical factors and demography as inputs. This approach shows that VIKOR can be successfully applied for the prioritization of the Tehsils prone to disaster with an appropriate consistency ratio. To effectively protect the populace, policymakers and stakeholders need to become aware of the regions that are most vulnerable to natural disasters as well as the kinds of disasters that occur most frequently. Using this knowledge, preparedness actions can be taken in advance of, during, and after disasters, potentially reducing their severity.

Keywords: Hydrometeorological disasters (HMDs), Uttarakhand Himalaya, Multi-criteria decision-making (MCDM), Prioritization

Development of Urban Flood Inundation and Hazards Maps using Hydrodynamic Modelling and Geospatial Techniques

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This study aimed to simulate urban flood flow analysis of urban catchment. The focus is to study the existing storm water network system and identify the most vulnerable zone among sixteen hydraulic zones of Greater Hyderabad Municipal Corporation. The flood simulation was carried out using the coupled 1D - 2D Personal Computer Storm Water Management Model (PCSWMM), with the Hydraulic zone-XII watershed covered the areas of Begumpet and Kukatpally catchments. The hydrodynamic model of PCSWMM has been used to simulate rainfall-runoff data and developed the flood inundation maps of the catchment. The model is first calibrated with the extreme rainfall events that occurred in the Hyderabad urban scenarios during October 13-15, 2020 flood events and compared with the observed flow data measured through Ultrasonic flow measurement sensors. The rainfall events 2020 are used for calibration and previous year rainfall events such as 2016, 2018 and year 2022 events are used for model validation. The outcomes of the simulation results are found to be reasonably well satisfactory and in good agreement with the observed data. Then, the hazardous maps are generated for the past rainfall events for the years 2014, 2016, 2018 and the year 2022. After simulating past extreme flood events, the model identified flood-prone locations and generated flood inundation and hazardous maps. These maps are essential resources for disaster response planning and infrastructure enhancement projects. Finally, hazard maps help to find the most vulnerable areas in Hyderabad. Flood Hazard maps in particular, identify low lying areas that are vulnerable to flooding during periods of heavy rain, allowing improvements to be prioritized.

Keywords: Urban floods, Hydrodynamic modelling, Flood hazard maps, Geospatial Techniques

The identification of critical zones in Southern Kerala river basins employing combined clustering and prioritization strategies.

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Effective watershed management is crucial for water resource conservation and mitigating environmental threats. Identifying critical clusters within a large watersheds or river basins, such as areas vulnerable to erosion, pollution, or flooding, is vital for targeted interventions. The present study develops a novel methodology to pinpoint the critical clusters within a river basin using combined prioritization and clustering techniques.

This integrated approach offers a robust and comprehensive framework for identifying critical zones within the diverse watersheds of southern Kerala. Clustering, specifically Fuzzy C-Means, enables the delineation of distinct, homogeneous zones based on topography and climatic factors. Prioritization, utilizing morphometric and topo-hydrological parameters through a combined method of Principal Component Analysis (PCA) and the GIS-based Sub Watershed Prioritization Tool (SWPT), facilitates the ranking of these zones according to their determined level of importance. PCA was used for dimensionality reduction of a large dataset of morphometric and hydrological parameters, highlighting the most influential variables. The user-friendly SWPT, a GIS extension, enables the prioritization of sub-watersheds and the identification of critical regions. SRTM DEM of 30m resolution was used to delineate sub watersheds and calculate morphometric parameters in terms of linear, areal and relief aspects.

The methodology's suitability for identifying critical conservation and restoration areas is demonstrated through its application to a specific watershed. This holistic approach strengthens resource management and conservation practices, enhancing their efficiency and effectiveness within river basin contexts.

Keywords: Watershed, Prioritization, Cluster, Fuzzy C-Means, Sub Watershed Prioritization Tool, GIS, Principal Component Analysis, Critical zone

Research on Ensemble Probabilistic Flood Forecasting Based on Runoff and Rainfall Knowledge-Guided Deep Learning

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Traditional deep learning point forecasting models face issues such as unclear flood forecasting mechanisms, limited accuracy, and the inability to reflect interval risk information, making it difficult to meet the needs of flood prevention, disaster reduction, and efficient water resource utilization in the new era. To address the issues of poor interpretability and heavy reliance on large datasets in deep learning models, a hybrid deep learning model for flood process forecasting, GRGM-RPV-LSTM, was developed based on the "physical information combination + physical information fusion" guidance mode. Application results in three river basins in the middle and upper reaches of the Yellow River and the controlled basin of the Zhongmu Station show that, under the same lead time

conditions, the GRGM-RPV-LSTM model exhibits better predictive performance than the GRGM-LSTM and RPV-LSTM models in the three basins, with higher Nash-Sutcliffe efficiency coefficient (NSEQ) and coefficient of determination (R^2), as well as lower relative error of flood peak (REQ) and root mean square error (RMSEQ). The forecasting accuracy of all three models gradually decreases as the lead time increases. However, when the lead time is extended to 4-6 hours, the GRGM-RPV-LSTM model still maintains a good level of accuracy, with relatively small flood peak errors, demonstrating better robustness. Ablation experiment results indicate that coupling the vector feature values calculated by the RPV model to the LSTM input layer contributes the most to improving flood forecasting accuracy. Modifying the LSTM loss function based on water balance has the second-highest impact, while coupling the grid-based net rainfall data simulated by the GRGM model to the LSTM input layer has the least effect. The research findings can provide scientific basis for coordinated management of flood control and disaster reduction in watersheds.

Keywords: Flood forecasting, Deep learning, Runoff and rainfall calculation, Hybrid model, Probabilistic forecasting, Small and medium-sized watersheds

Assessing Ensemble Medium-Range Weather Forecasts for Streamflow Prediction in a Southern Asian River Basin

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Numerical Weather Predictions (NWP) play a crucial role in hydrological modelling, particularly in river flow forecasting and flood warning systems. Integrating NWP ensembles with multiple hydrological models can enhance flood predictability and significantly impact the accuracy of streamflow forecasts. Evaluating the accuracy of NWPs is, therefore, essential for improving the reliability of streamflow predictions. This study aims to assess the rainfall prediction capabilities of NWP models, specifically the NCMRWF (National Centre for Medium-Range Weather Forecasting) forecasts obtained from the TIGGE (THORPEX Interactive Grand Global Ensemble) dataset. These forecasts are used as input for a hydrological model to generate Ensemble Flood Forecasts (EFFs) for flood management. Both raw and perturbed NCMRWF precipitation forecasts are utilized to estimate the range of possible streamflow volumes over lead times of one to five days for the middle Tapi River basin in India. Findings indicate that hydrological model uncertainty has a more significant influence on capturing flood peaks than input model uncertainty. The quality of the simulated flood forecasts is assessed by computing the probability of 'Hits,' revealing that NCMRWF ensemble forecasts perform best for one-day lead-time predictions. This research provides valuable insights into the application of NWP data for hydrological modelling, particularly in improving flood forecasting capabilities.

Keywords: Numerical Weather Prediction, Streamflow forecasting, Ensemble Forecasts

An integrated framework for quantifying flood risk at Ramsar wetlands

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Wetlands, which commonly occur in depressions and around water bodies like rivers, lakes, and coastal seas, are subject to periodic flooding. This research introduces an innovative techno-societal framework to evaluate how heavy rainfall events (HREs) affect both wetland ecosystems and nearby communities in India. Our framework combines cutting-edge technological tools, including Bayesian analysis, fuzzy logic, and remote sensing, with social factors to deliver a thorough assessment of wetlands' vulnerability to climate change. The research examines several key aspects: the changing patterns of HREs, wetland flooding characteristics, impact assessment, and future rainfall projections using CMIP6 data. Analysis of extreme precipitation patterns revealed that Thane Creek experienced the longest return periods, with Bhoj Wetland following closely behind. Using fuzzy logic, we developed a risk index incorporating hazards, vulnerabilities, and exposure parameters for each wetland. This analysis identified six wetlands at "very high" risk: Bhoj Wetland, Thane Creek, Point Calimere, Deepor Beel, Sasthamkotta Lake, and Vembannur Wetland. The study further investigated flooding patterns in these high-risk wetlands, with particular attention to Bhoj Wetland, where we evaluated how HREs impact local infrastructure, residential areas, and ecosystems. Additionally, several wetlands-Point Calimere, Vembannur Wetland, Karikili Bird Sanctuary, Vendanthangal, and Vaduvur Bird Sanctuary-showed marked increases in precipitation in both historical data and future projections under the ssp245 scenario. These insights provide valuable guidance for policymakers in implementing effective wetland management strategies at the local level.

Keywords: Flood Risk Analysis, Non-stationary Assessment, Ramsar Sites, Rainfall Projections, Wetland Conservation

A hydro-signature integrated physics-informed machine learning (HS-PIML) framework for enhancing streamflow predictions across diverse catchments

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Accurate streamflow prediction is vital for sustainable water resource management, especially in catchments significantly impacted by human activities. These disruptions alter natural flow patterns, making streamflow prediction more challenging. Traditional process-based hydrological models (e.g., HBV) and data-driven approaches (e.g., Long Short-Term Memory (LSTM) networks) often struggle to consistently and accurately predict extreme peak flows across diverse catchments. This study evaluates the performance of the HBV model, LSTM model, and our proposed Hydro-Signature integrated Physics-Informed Machine Learning (PIML) approach across 341 UK catchments selected from the CAMELS-GB database. Preliminary results show that incorporating hydrological signatures, such as the baseflow index and rainfall-runoff ratio, into the PIML framework enhances model performance, particularly in capturing peak flows for non-natural catchments. These

signatures enable the model to better represent catchment-specific processes, including those in reservoir-influenced, urban, and groundwater-influenced systems. For instance, in reservoir-influenced catchments, the signatures can capture features like reservoir release timing, storage fluctuations, and the influence of regulation on downstream flow. Combining the physical realism of HBV with the flexibility of machine learning improves both low and high flow predictions, offering a more robust solution for streamflow forecasting in modified catchments. This study demonstrates the substantial potential of the HS-PIML framework to improve streamflow predictions across a diverse range of catchments.

Keywords: Deep Learning, PIML, Hybrid modelling, streamflow prediction

Remote Sensing based Systematic Wetland Improvement and Management (SWIM) Protocol: A Nature-Based Solution for Disaster Risk Reduction in Bihar, India

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Wetlands, a vital part of the hydrological system, are generally considered surface water bodies that support biodiversity, maintain ecological balance, enhance carbon sequestration, etc. However, as the wetlands modulate peak flows, storing runoff, and releasing gradually, improving soil moisture retention, they can be used for managing multiple hazards viz. Flood and Drought, especially in the states like Bihar.

Bihar has a huge network of rivers and streams as well as numerous surface water bodies. The Northeastern flood-prone districts have the highest number of wetlands, while the drought-prone southern part has fewer. However, the number and extent of these wetlands are diminishing faster, about 50 % in the last 15 years.

Thus, to monitor, protect, and harvest the multi-pronged potential of these wetlands, a science and technology-based process "Systematic Wetland Improvement and Management (SWIM)" is being developed in Bihar. SWIM identifies and gauges the potential of wetlands, classifies them based on the potential, monitors them through meteorological, hydrological, geomorphological, and biological factors and guides customised and targeted intervention. High-resolution Remote Sensing data coupled with ground-based sensors network is the engine of SWIM.

SWIM-supported wetlands are to act as a nature-based solution for managing and mitigating multiple hazards. This integrated approach not only supports DRR activity but also aligns with government initiatives for strengthening sustainable livelihood for local communities through the cultivation of Makhana (*Euryale ferox*), Singhara (*Trapa Natans*), and Mushroom (*Agaricus Bisporus*), fisheries etc. Further, properly managed wetlands can also be used for recreational water parks and other activities like water sports.

Another major advantage is that the authorities can make use of SWIM to minimise the incidences of drowning in these wetlands, which has been a major hazard in Bihar, causing the loss of thousands of human lives every year.

Keywords: Wetland, Remote-Sensing, Disaster Management, Drowning, Sustainable Development, Nature-based Solution

Hydrologic drought-to-flood transitions in India

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The transition from drought to flood poses severe challenges related to risk management and water management. In this study, for the first time in India, the hydrologic transition of droughts to floods is investigated using the hydrometeorological and landscape dataset from catchments in India. The study will highlight the evolution of spatio-temporal patterns of transition duration - the period between the end of a drought event and the start of a flood event - from the perspective of seasonality and spatial connectivity. The study will check if strong seasonal patterns in monsoon seasons also impact the seasonal patterns of transition durations. Furthermore, special attention will be given to two types of transition - fast and slow transitions. In addition, the dam operations have a strong potential to alter or modulate the transition from droughts to floods. This study will focus on the impact of such operations on both fast and slow transitions. The findings of the study will be useful in both risk and water management, as floods after droughts are becoming more frequent and have been shown to have disastrous impacts.

Keywords: Hydrologic droughts, floods, water management, human activities

Rainwater Harvesting Potential Zone Mapping in Urban Areas Using GIS, Remote Sensing, and AHP: A Case Study of Hyderabad City

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Rapid urbanization and population growth have intensified the challenges of urban water management, particularly regarding surface runoff in metropolitan areas. The expansion of impervious surfaces significantly reduces natural infiltration, increasing surface runoff and placing substantial pressure on stormwater systems, thereby exacerbating urban flooding and water scarcity issues. Rainwater Harvesting (RWH) presents a promising sustainable solution, offering potential to capture and utilize rainwater, decrease runoff volumes, mitigate flooding, and enhance stormwater management. This study aims to identify and map potential RWH zones by using an integrated approach that combines Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytical Hierarchy Process (AHP). Various topographic datasets, including Digital Elevation Model (DEM), Land Use Land Cover (LULC), soil characteristics, along with the hydrogeological attributes, socio-economic and urban landscape data were incorporated to perform a comprehensive analysis of the study area. The AHP methodology was employed to assign relative weights to critical factors influencing RWH suitability, followed by a Weighted Overlay Analysis (WOA) to generate a Rainwater

Harvesting Potential Map. The developed framework was implemented on a stormwater management area covering 173.68 km² (Zone 12) of the Greater Hyderabad Municipal Corporation (GHMC), Telangana, India. The findings classified the study area into four categories of RWH potential: 'Very Low,' 'Low,' 'Moderate,' and 'High.' The results indicated that the majority of the area (80.20%) fell into the 'Low' category, with 17.52% classified as 'Moderate.' While, 2% of the study area, primarily concentrated in the highly urbanized central region, showed 'Very Low' potential, further a small portion (0.254%) near the southeastern region, close to Hussain Sagar Lake, was identified as having 'High' potential. This study underscores the importance of RWH in mitigating surface runoff and offers critical insights for urban planners and policymakers to implement effective, sustainable stormwater management strategies in rapidly urbanizing regions.

Keywords: Urban Rainwater harvesting, Sustainable Stormwater management, Potential zone mapping, Urban Planning

A non-Newtonian approach to model 2023 Sikkim Glacial Lake Outburst Flood

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Glacial Lake Outburst Floods (GLOFs) often occur at high elevations, resulting in catastrophic flash floods while leaving little or no time for effectively managing them. They are characterized by destructive velocities of several m/s, enabling the transport of a large amount of debris and sediments. Due to a combination of the solid and liquid forces, these flows are characterized by greater momentum and they continue to recruit debris and sediments along the path. As a result, they achieve farther run out distances compared to clear water flows. Hence, they deviate largely from pure water mechanics or Newtonian hydraulics. Modelling them using non-Newtonian physics and sediment transport may pave the way for an accurate simulation of these floods. Therefore, in this study, we use various non-Newtonian schemes in a freely available hydraulic model to simulate the recent 2023 Sikkim GLOF flood. We perform Monte Carlo uncertainty-based calibration to estimate the behavioural parametric values for different non-Newtonian approaches in the model. As an outcome of this study, we identify the best-performing non-Newtonian approach and its calibrated parametric ranges. Thus, the study serves as a guideline towards accurate modelling of GLOFs. The framework adopted in this study can be used elsewhere to simulate GLOFs realistically. As they are expected to become more frequent due to climate change, a pre-assessment modelling strategy for gauging the potential damage can be established for the existing glacial lakes.

Keywords: Glacial Lake Outburst Floods, Debris flows, non-Newtonian approach

A Coupled Hydrological-Hydraulic Model for Urban Flood Simulation for the City of Hyderabad, India

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Floods are among the most frequent and devastating disasters, affecting millions worldwide. Urban flooding, in particular, has intensified in recent years due to rapid urbanization and climate change, leading to increased damage to infrastructure, transportation networks, and human lives. As a result, even short-duration, high-intensity rainfall events now lead to substantial peak runoff in urbanized areas, causing disturbances to the population. Hyderabad, a Tier-1 city in India, is highly vulnerable to such flooding, necessitating the development of a model with finer resolution data. To this end, this study aims to develop a coupled hydrological-hydraulic model utilizing finer resolution rainfall data, Digital Elevation Model (DEM) and Land Use Land Cover (LULC), for a part of the Hyderabad city (Zone I) to simulate flood inundation and water depth. A rainfall-runoff model is developed using HEC-HMS (Hydrologic Engineering Center -Hydrologic Modeling System) with the SCS-UH (Soil Conservation Service-Unit Hydrograph) as the transform method. This hydrological model is then coupled with a hydraulic model HEC-RAS (Hydrologic Engineering Center -River Analysis System) which simulates 2D unsteady flow to generate flood inundation maps. Defining the boundary conditions is a key challenge in 2D modelling. This is addressed by specifying the flow generated by the hydrologic model at each catchment outlet as boundary conditions. The coupled model ran for a rainfall event that lasted for 6 hours on 20th August 2024. The results show a peak discharge of 53 m³/s for a rainfall of 116 mm, with a maximum water depth of 0.7 m and a hydrograph duration of 10 hours. The coupled model, utilizing finer resolution rainfall data, enhances flood simulation capabilities, contributing to floodplain mapping and vulnerability assessment and, consequently improving urban flood risk management and resilience planning.

Keywords: HEC-HMS, HEC-RAS, urban flood, flood inundation mapping, Hyderabad

Integrating Drought Monitoring and Crop Modelling for Enhanced Resilience in India

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Drought is a natural disaster that significantly impacts rainfed agriculture in India, with its frequency and severity escalating due to climate change and monsoon variability. It exacerbates crop losses and poses a serious threat to food security, particularly in regions heavily reliant on rainfed farming. Effective drought monitoring systems provide critical early warning insights that support timely interventions. This study explores the integration of drought monitoring, hydrological modelling (Variable Infiltration Capacity), and crop modelling (DSSAT) to enhance resilience and support informed

decision-making. The VIC model tracks real-time meteorological and hydrological droughts and soil moisture conditions, whereas the DSSAT model is used to forecast the impact of drought on rain-fed agriculture. The VIC model was calibrated and validated using hydrometeorological data and satellite-based soil moisture observations for ten years (2001-2020). The DSSAT model was calibrated and validated using historical yield data (1998-2020) and weather information to simulate spatial crop yield losses for rainfed rice, cotton, soybean and sorghum during the Kharif season. By combining real-time drought monitoring with predictive crop modelling, this integrated approach made available in the South Asia Drought Management System (SADMS) facilitates early warning, adaptive irrigation strategies, and climate-smart agriculture (CSA) interventions, including the selection of drought-tolerant crops and optimized resource management.

Keywords: Drought Monitoring, Variable Infiltration Capacity (VIC) Model, DSSAT Crop Model, Rain-fed Agriculture

Performance Evaluation of Seven Combination Techniques Applied on Nine Rainfall-Runoff Models for Water-Availability Assessment

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Combination of outputs of a number of individual models, i.e. a committee approach, is often found as being useful in Rainfall-Runoff modelling for flow-simulation and water-availability assessment of river-valley projects. The improvement of performance achieved by Model Output Combination Techniques (MOCTs) is attributed to their formulations aimed at pooling the strengths and deemphasizing the shortcomings of the individual models. Several MOCTs have been developed under distinct categories, such as those based on linear-weighting, statistical theories, and Machine Learning (ML). Depending on the computational frameworks, the characteristics of the timeseries of data being modelled and the quality of outputs simulated by the individual models, the performances of these techniques vary. In this study, seven MOCTs were applied to the outputs of nine individual models comprising five Linear-Relation-Based (LRB) and four ML-Based (MLB) models to simulate ten-daily runoff of the Kamala River for assessing the water-availability of an upcoming 1800 MW Kamala Hydro Electric Project in the state of Arunachal Pradesh in northeast India. It was found from analysis that, generally, the combinations of the outputs of the five LRB models produced the best results, and that the MOCTs applied on the outputs of the four MLB models were the least performing ones. When applied to the group of LRB models, the variance-based Bates-Granger averaging technique was found as being the best followed according to the achieved level of performance by the Mallows model averaging technique employing a scheme of penalized sum of squared residuals. As expected, the equal-weight averaging technique performed the worst, and the averaging by a Neural Network based technique was marginally better in combining the outputs of the LRB models. The study highlights the importance of employing simpler and parsimonious LRB individual models and MOCTs over their relatively complex and non-parsimonious counterparts for flow simulation by rainfall-runoff modelling.

Keywords: Model Output Combination, River Flow Simulation, Machine Learning Models, Linear Models

Enhanced Streamflow Simulation Using a Hybrid HEC-HMS and LSTM Framework: Integrating Physics-Based Modeling with Deep Learning

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Accurate streamflow simulation is vital for effective water resources management and flood risk mitigation, especially in data-scarce and hydrologically complex regions. Physically based models such as HEC-HMS provide a structured representation of watershed hydrology but may not fully capture nonlinear temporal patterns. On the other hand, deep learning models like Long Short-Term Memory (LSTM) networks can learn such patterns but lack physical interpretability. This study proposes a hybrid streamflow modeling framework that combines the strengths of both HEC-HMS and LSTM models. The objectives are: (i) to simulate streamflow using a calibrated HEC-HMS model, (ii) to train an LSTM model using HEC-HMS outputs and meteorological data, and (iii) to assess and compare the performance of standalone and hybrid models. The methodology includes HEC-HMS setup using rainfall, temperature, land use, soil, and terrain data for a selected watershed. The HEC-HMS simulated discharge and meteorological inputs serve as training features for the LSTM model. Model performance is evaluated using standard indices: Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Percent Bias (PBIAS). Results show that the hybrid HEC-HMS-LSTM model outperforms both individual models, offering improved accuracy in streamflow prediction. It better captures peak flows and adapts to hydrological variability, yielding lower errors and more reliable simulations during both calibration and validation phases. In conclusion, the integration of process-based and machine learning models enhances the robustness of hydrologic simulation. The proposed hybrid approach is a promising tool for improved flood forecasting and climate-resilient water management in complex watersheds.

Keywords: Streamflow Simulation, Hybrid Modeling, Long Short-Term Memory (LSTM), Hydrologic Modeling, Flood Risk Mitigation, Machine Learning, Physics-Based Model

A River's Burden: Interplay Between Microplastics and Heavy Metals, and Their Ecotoxicological Consequences

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Microplastics (MPs) and heavy metals (HMs) are common environmental pollutants, and their presence raises serious concerns about environmental health and safety. This insight looks into the complex interactions between MPs and HMs, specifically the implications for pollutant transport, bioavailability, toxicity, environmental health, and safety. MPs, with their vast surface area and hydrophobic character, can act as vectors for HMs, thereby changing their environmental fate. This work investigates the adsorption kinetics and processes of several HMs on distinct MP types under changing environmental conditions. Furthermore, the abstract highlights the altered toxicity of MPs and HMs when present in combination, considering potential synergistic effects. We evaluate the

implications for human health, particularly through ingestion and inhalation pathways. This review synthesizes current research on the combined ecotoxicological and environmental health impacts of microplastics (MPs) and heavy metal (HM) contamination in a riverine environment. The synergistic effects resulting from the co-occurrence of these pollutants pose significant risks to both aquatic and terrestrial ecosystems, as well as human health. This also emphasizes the need for comprehensive risk assessment strategies for the combined effects of MP and HM co-exposure. Finally, we discuss the safety implications for water resources and food chains, underscoring the urgency for developing effective mitigation strategies to minimize the risks associated with these co-contaminants.

Keywords: Microplastic, heavy metals, toxicity, environmental health, and safety.

Flood Risk Mapping for The Isipingo River Catchment, Kwazulu-Natal: Enhancing Resilience Through Hydraulic Modelling

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Floods rank among the most destructive natural hazards, presenting substantial risks to infrastructure, ecosystems, public health, and socioeconomic stability. In South Africa, regions such as KwaZulu-Natal, the Eastern Cape, North-West, and Limpopo face increasing exposure and vulnerability to flood hazards due to climatic variability, insufficient infrastructure, and rapid urban expansion. The Isipingo River catchment within eThekweni Municipality, KwaZulu-Natal, serves as a critical case study, having experienced recurrent and severe flooding, particularly during the extreme flood events of February and March 2025. These disasters underscored the pressing need for accurate flood risk assessment and enhanced disaster preparedness in urban and peri-urban areas.

This study employs a comparative approach, utilizing HEC-RAS 2D Rain-On-Grid (ROG) flood simulation alongside a coupled HEC-HMS and HEC-RAS model framework to reconstruct the March 2025 flood event. The methodology involved simulating key hydraulic parameters, including flood depth, water surface elevation, and flow velocity, followed by generating and validating a 3D inundation boundary in Google Earth Pro to delineate high-risk zones. The analysis provides critical insights for risk-informed urban planning and infrastructure development by mapping potential flood extents.

Results indicate that densely populated areas in Isipingo and Umlazi face significant flood exposure. While the 2D model effectively simulated flash flood dynamics, computational demands were notably high. Key recommendations include enhancing drainage infrastructure, deploying early warning systems, enforcing land-use regulations in flood-prone areas, and promoting community-based disaster risk awareness initiatives. This study advances research on urban flood resilience in South Africa, demonstrating that 2D hydraulic modeling offers a viable alternative to coupled hydrological-hydraulic approaches due to its reduced parameterization requirements, thereby supporting data-driven adaptation strategies.

Keywords: Floods, Flash Floods, HEC-RAS,

Heavy Metal Pollution in Surface Water Bodies of Uttarakhand

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Heavy metal contamination in surface water sources is an emerging environmental issue in Uttarakhand, posing serious ecological and human health risks. This research work provides an overview of studies conducted within the state to assess the extent, sources, and implications of heavy metal pollution in rivers and freshwater systems. Key contaminants identified include cadmium, chromium, copper, lead, mercury, and zinc introduced primarily through industrial effluents, agricultural runoff, and the discharge of untreated or partially treated sewage.

Uttarakhand's unique topographical features, comprising mountainous terrain, glacier-fed rivers, and densely populated pilgrimage towns, make its water resources highly susceptible to both point and non-point pollution sources. Several investigations have reported elevated levels of heavy metals in major surface water bodies such as the Ganga River, its tributaries, and local streams, particularly in urban and industrial hubs like Haridwar, Dehradun, SIDCUL (Integrated Industrial Estate), and parts of the Garhwal Himalayas. These contaminants persist in aquatic ecosystems, threaten aquatic biodiversity, and pose potential health risks through drinking water and bioaccumulation in the food chain.

The reviewed studies underline an urgent need for improved monitoring frameworks, stricter regulatory enforcement, and sustainable pollution control strategies. With the ecological sensitivity and socio-cultural significance of its water bodies, Uttarakhand must prioritize heavy metal mitigation to safeguard public health and environmental sustainability.

Keywords: Heavy Metals, Water Pollution, Surface Water Pollution, Emerging Pollutants, Trace Metals, River, Pollution

Assessment of impact of Land use/Land cover changes on temporal dynamics of wetland watershed using remote sensing technique: A case study of Sonbeel wetland watershed

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Wetlands provide essential ecological services, support biodiversity, regulate floods, and control temperatures. But they are facing severe threats from both natural and human activities, and the Sonbeel wetland in Assam, India, is no exception. It is experiencing significant challenges, including a shrinking water cover area and major land use changes. Focusing on the entire watershed from 1990 to 2020, this study analyzes how land use and land cover (LULC) changes affected Sonbeel wetland's dynamic, mainly swampy areas and water bodies. Using multi-temporal Landsat imagery and DEM data, LULC maps were generated through maximum likelihood classification, and future changes for 2030 were projected using the CA-ANN model. Findings reveal an increase in forest and built-up areas, while agricultural land, swampy area, and water bodies declined across seasons. Water bodies decreased from 2.86% to 2.44%, and swampy area from 1.64% to 1.56% during post-monsoon, linked to rainfall changes and encroachment. By 2030, further declines are expected,

with agricultural land expanding. Water bodies may drop from 2.44% to 2.41% pre-monsoon, and swampy area from 1.62% to 1.54%. During post-monsoon, water bodies and swampy area may shrink by 133 and 78 hectares, respectively. The study highlights strong negative (positive) correlations of water body and swampy area changes with population growth and potential evapotranspiration (rainfall), indicating the indirect impact of climatic fluctuation and anthropogenic encroachments. Additionally, low threshold values of water presence frequency (WPF) analysis depict the risk of a declining trend in swampy area and water bodies more distinctly. This study thus emphasizes the need for wetland restoration, conservation, and sustainable land use planning to mitigate further degradation and ensure ecological balance.

Keywords: Wetlands, LULC, CA-ANN, Agricultural land, Swampy Area, Water body.

Dry-to-wet abrupt transitions and the changes in these with global warming

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It is not uncommon for drought spells to be broken by heavy precipitation events. When heavy precipitation follows a drought or a prolonged dry spell in close succession, we call this a dry-to-wet abrupt transition. These events can have severe potential consequences, including having detrimental impacts on food security, life and property. This study answers the question: Are droughts and floods mutually exclusive events, i.e., can drought events affect flood risk? To this end, the study investigates the occurrences of these events across Australia and central Europe. Furthermore, the frequency of these events, as well as the magnitude of the precipitation associated with such events, is also studied to identify the regions more prone to risk from these events. Future projections of these events obtained from downscaled global climate models suggest that these events are likely to increase in some regions, while for some regions their frequency would remain more or less the same. There is thus a need to support adaptation initiatives to better protect human society from the losses caused by these events, as well as the need to move towards more climate-resilient designing.

Keywords: droughts, floods, catchment response, precipitation, global climate models, projections, risk

A SWMM-Based Framework for Evaluating Functional and Structural Failures in Urban Drainage Systems

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Urban areas are increasingly vulnerable to flooding due to rapid urbanization and intensifying rainfall patterns driven by climate change. This study presents a resilience-based evaluation of an urban drainage system (UDS) in a part of Gurugram, India, using the Storm Water Management Model (SWMM). Both functional and structural resilience are assessed under various future scenarios, including increased imperviousness and extreme rainfall events. Design storms were estimated using frequency analysis of satellite-based rainfall data, and subcatchment widths were compared using three alternative methods to optimize model performance. A sensitivity analysis was conducted to overcome the lack of calibration data and to identify key model parameters influencing flood volume, flood depth and duration. The results show that urbanization has a more significant impact on system resilience than climate-induced rainfall increases. Functional analysis revealed a potential 21% reduction in resilience under combined stressors, while structural analysis identified 22 vulnerable nodes where system performance is highly sensitive to conduit failures. The study demonstrates a practical resilience evaluation framework for stormwater infrastructure, particularly valuable for rapidly growing urban areas with limited hydrological data.

Keywords: Urban flooding, Resilience, Urban drainage system, Urbanization, Climate change

Process-based Classification of River Floods Using Explainable Machine Learning in Monsoon-Dominated Catchments of India

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River floods arise from complex interactions between hydroclimatic triggers and catchment-specific processes, often exhibiting nonlinearity and regional heterogeneity. Understanding these drivers is critical for attributing flood types and anticipating how flood risks might evolve under changing climatic and land-use conditions. In this study, we analyzed over 15,000 flood events across 242 Indian catchments using the CAMELS-IND dataset to classify floods into three dominant process-based types: excess rainfall floods, short-duration rainfall floods, and long-duration rainfall floods - reflecting the dynamics of the Indian monsoon.

Flood events were identified using a Peaks-Over-Threshold (POT) approach and subsequently classified using CatBoost, a gradient-boosted machine learning algorithm. We applied SHAP (SHapley Additive Explanations) to quantify the influence of key hydroclimatic and physiographic variables, including antecedent soil moisture, rainfall intensity and duration, slope, land use, and soil type. This explainable AI framework allows for process-level attribution, offering insights into the relative

importance of climatic vs. catchment controls across diverse physiographic regions.

Our results reveal distinct spatial patterns in flood-generating mechanisms and indicate a strong regional dependence that is likely to intensify under future climate scenarios. Moreover, the framework exposes limitations in both traditional and data-driven flood models by identifying contexts where key drivers are underrepresented. This has significant implications for flood forecasting, early warning systems, and adaptation planning in ungauged or human-modified basins.

By integrating physical reasoning with interpretable machine learning, this study contributes to the ongoing effort to develop catchment-specific, transparent, and adaptive strategies for flood risk reduction - a key objective of the HELPING decade. Our findings support the case for embedding explainable models in flood risk governance, especially in data-scarce regions facing increasing uncertainty.

Keywords: Flood Generation, CatBoost, SHAP

Enhancing flood forecasting system in India to support healthcare and strengthen community resilience

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India is highly vulnerable to flood hazards due to its geographic location and seasonal monsoons. Floods are among the most devastating natural disasters in the country, often affecting millions of people and causing widespread disruption. For example, the 2018 Kerala flood, which was triggered by 164% above-normal rainfall, resulted in severe inundation across approximately 338 km² lasting for 78 days. Under climate change, the magnitude and frequency of floods are projected to increase across many regions of India. Flooding emergencies pose critical challenges to healthcare services, particularly for patients with non-communicable diseases such as cardiovascular diseases, chronic respiratory conditions, and diabetes. Interruptions in access to medications, prescriptions, and health services during floods significantly impact their health conditions. Current flood forecasting approaches in India are constrained by short lead times (often less than 3-5 days), limited spatial resolution, and a lack of integration between weather forecasts, flood inundation models, and healthcare planning.

To enhance community resilience and preparedness for flooding emergencies, our project focuses on selected flood-vulnerable clusters in Kerala and Bihar, aiming to: 1) identify impact-based rainfall and flood thresholds for different clusters using flood impact data collected from surveys and questionnaires; 2) develop an integrated meteorological-hydrological forecasting system to substantially improve flood predictions in both lead time and accuracy; 3) quantify future changes in flood risk under climate change to support long-term disaster and healthcare planning. It is expected that improved flood forecasting and a better understanding of flood thresholds and future risks will greatly improve health outcomes and lead to more resilient communities.

Keywords: Flood forecasting, flood risk, community resilience, impact-based flood thresholds, health-care service

Developing a national scale drought modelling and forecasting framework for Scotland

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Climate change is resulting in many countries including Scotland being increasingly vulnerable to periods of dry weather, impacting water users and the natural environment. As of mid-May 2025, Scotland Environmental Protection Act (SEPA) reports that all of Scotland remains at some level of water scarcity, with notable impacts in some region with ongoing abstraction restrictions and an increasing risk of bans as dry conditions persist. Managing water scarcity events requires developing a national-scale short- to medium- term drought forecasting capability. We are developing a national-scale drought forecasting framework that integrates hydrological model structural and parametric uncertainties. Two hydrological models of differing complexity were used: GR6J (lumped conceptual model) and HYPE (semi-distributed model based on hydrological response units). Both were calibrated across 81 catchments monitored by SEPA using robust multi-objective techniques. Both models performed well, particularly in small to medium-sized, natural or near-natural catchments (e.g., Eden, Ugie, Almond). While KGE scores suggest comparable performance, logNSE scores indicate that GR6J better captures low flows. We are utilizing these calibrated set of models in conjunction with ensemble 15day rainfall and temperature forecasts from European Centre for Medium-Range Weather Forecasts (ECMWF) within a hindcasting framework developed for year 2023 to forecast streamflow at 81 catchments. This setup allows us to evaluate questions such as: How well does the forecasting system perform in real-time? How does forecast skill degrade across lead times from 0 to 15 days? Which hydrological model is more robust at longer leads? ECMWF forecasts are being compared against meteorological observations from HadUK-Grid dataset. Post-processing techniques such as bias correction shall improve both meteorological and hydrological forecast accuracy. This framework enables producing probabilistic streamflow forecasts along with total forecast uncertainty. Ultimately, this research aims to support SEPA in improving early warning systems, enhancing resilience to drought through reliable, uncertainty informed streamflow forecasts.

Keywords: drought, water scarcity, modelling, ECMWF, HYPE, GR6J, forecasting

Performance Evaluation of ANN for Rainfall Runoff modelling in the Sher Basin Using CAMELS-INDIA data

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This study develops and evaluates a data-driven rainfall–runoff model for the Sher Basin, a sub-basin of the Upper Narmada River in Madhya Pradesh, India, using Artificial Neural Networks (ANN) trained on the CAMELS-INDIA dataset. The Sher Basin, covering approximately 1,479 km² between 22°15′–23°05′ N and 79°00′–79°45′ E, with an outlet at Belkhedi, exhibits pronounced seasonal variability, making it an ideal region for machine learning applications in hydrology. Daily time series data from 2000 to 2020 were preprocessed into multiple input configurations to capture hydrological dynamics, including rainfall, one-day and two-day antecedent rainfall, soil moisture, evapotranspiration (ET), potential evapotranspiration (PET), and river stage. An 80:20 train–test split was applied, with reproducibility ensured via a fixed random state of 42. Results demonstrate that model performance improved progressively as hydrologically informative variables were added: models using only rainfall showed limited predictive accuracy, while the inclusion of antecedent rainfall, soil moisture, ET, PET, and stage substantially enhanced performance. The optimal configuration, combining present-day rainfall, one-day and two-day antecedent rainfall, soil moisture, ET, PET, and river stage, achieved an R^2 of 0.92 on the test dataset, indicating the strong capability of ANNs to capture complex rainfall–runoff relationships. These findings highlight the potential of data-driven approaches for effective hydrological modeling in Indian river basins, demonstrate the value of the CAMELS-INDIA dataset for machine learning applications, and provide a framework for improving flood forecasting and water resources management in similarly variable catchments.

Keywords: Neural Networks (ANN), CAMELS-INDIA, Evapotranspiration data, Potential Evapotranspiration data, Rainfall Runoff modelling, Soil Moisture data

Tracers (ICT)

Seasonal Variations in Nitrogen Loading Processes in Tropical Land Use at the Langat River Basin, Malaysia

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Nitrate pollution in water resources causes eutrophication and deterioration of drinking water quality, negatively impacting ecosystems and human health. This study aimed to identify the sources of nitrogen pollution and seasonal variation of nitrate ions in river water in the Langat River basin, Malaysia, which includes tropical rainforest upstream, urban areas midstream, and oil palm plantation areas downstream. Water samples including the river water, irrigation water, groundwater (dry season only), and precipitation were collected in April (inter-monsoon season), July (dry season), and December (wet season) 2024 and analyzed for major dissolved ion concentrations, water isotope ratios ($\delta^2\text{H}$ and $\delta^{18}\text{O}$ of H_2O), and nitrate nitrogen and oxygen isotope ratios ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ of NO_3^-). Seasonal variations were observed in the spatial distribution of nitrate concentrations in river water. Upstream areas consistently exhibited low nitrate levels (1.4 mg/L) throughout the year, while midstream areas showed elevated nitrate levels (19.1 mg/L) during the dry season. Water isotopic values of river water during the inter-monsoon season showed altitude effects, while dry season isotopic ratios were close to groundwater isotopic ratios. Nitrate nitrogen isotope ratios (0.73‰ to 12.8‰) in several river water samples were similar to groundwater, suggesting that the nitrate sources included ammonium fertilizer and sewage. These findings indicate that river waters during the inter-monsoon seasons are affected by the dilution effect of precipitation, while nitrate concentrations increase during the dry season due to groundwater discharge containing nitrate. This study provides valuable understandings of the interactions among seasonal variations, groundwater discharge, and nitrate loading, providing essential information for the nitrogen cycle and promoting sustainable water resource management in tropical river basins.

Keywords: isotope tracer, nitrate nitrogen, oil palm plantation, tropical land use

Role of strike-slip faults in regional groundwater flow systems revealed by a multi-tracer approach

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Faults can function as hydraulic barriers or conduits, shaping groundwater flow systems. While strike-slip faults often act as barriers, their role in regional groundwater flow fields remains poorly understood. This study aims to make clear the role of a strike-slip fault in the regional groundwater flow process within a watershed containing a pull-apart basin. Groundwater table observations, sampling of spring water, groundwater, river water, and precipitation, alongside analyses of water quality, isotope ratios, and SF6 concentrations, revealed the following findings.

Regional groundwater generally flows from higher elevations toward the lake. However, in the pull-apart basin, surface water-groundwater exchange is limited by a thick silt layer. Groundwater in the basin differs largely in water quality from outside the basin, with isotope ratios indicating precipitation as the primary water source. Interestingly, the main recharge area is not the watershed's upper reaches but the mountainous region adjacent to the basin. Groundwater in the basin has a long residence time, suggesting recharge from surrounding mountains via the fault line, influenced by volcanic activity. Conversely, water flow from the upstream watershed into the basin appears to be impeded by strike-slip faults.

These findings would reveal that in geologically active watersheds with pull-apart basins, hydrological cycles cannot be fully explained by topography alone. This highlights the critical role of geological structures, particularly strike-slip faults, in shaping regional groundwater flow systems.

Keywords: Faults, Tracers, SW-GW interaction, Regional groundwater flow

Rainfall-runoff Processes in a Vegetated Alpine Headwater Catchment in Northern Alps, Japan

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We conducted field surveys and daily water sampling from July through October 2023 in an alpine headwater catchment of Mt. Norikura, Japan to clarify the role of subsurface water in rainfall-runoff processes in a vegetated alpine zone. We performed the observation in two neighboring watersheds, namely NR1 and NR2 watersheds with vegetation coverage of 20.7% and 51.2%. In addition to daily sampling, an intensive sampling was conducted at a three-hour resolution during a rainfall event in NR2 from August 29 through September 2, 2024.

The stream runoff occurred only during the snowmelt season and after rainfall in NR1, whereas it occurred perennially throughout the observation period in NR2. In addition, runoff in NR1 was not

observed even in several rainfall events, indicating that rainwater could infiltrate into the subsurface zone in NR1. Hydrograph separation was conducted during snowmelt season and post snowmelt season. The runoff of groundwater component was 12.8 mm in NR1 and 458.7 mm in NR2, which accounts for 13.3% and 73.5% of total stream runoff, respectively. Additionally, the runoff of precipitation component was higher in NR1 than that in NR2 after the late September, when rainfall was high, suggesting that rainwater could discharge to stream quickly in NR1 under the wet condition. However, the runoff height of precipitation component increased, whereas groundwater runoff did not decrease, when the API (Antecedent Precipitation Index) value exceeded 10 mm as a threshold in NR2. In addition, the ion concentrations and stable isotopic compositions in the stream water during a rainstorm varied quickly affected by those of rainwater in NR2. These results indicate that rainwater could mix with subsurface water and discharge to the stream quickly, and the moisture condition of watershed could influence the rainfall-runoff processes in a vegetated alpine headwater catchment with thin soil layers.

Keywords: Alpine, Rainfall-runoff, Hydrograph separation, Subsurface flow

Groundwater and Surface Water Cycle System in the Klang and Langat River Watersheds, Malaysia

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We applied multi-tracer approach using stable isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and dissolved inorganic constituents to clarify the groundwater flow system and its discharge processes in two adjacent humid tropical watersheds, the Klang River and the Langat River in Malaysia. Both watersheds are underlain by granite and meta-sedimentary rocks with annual average rainfall of 2,300 mm, an area of 2,423 km² in Langat River watershed and 1,288 km² in Klang River watershed.

In Klang River watershed, $\delta^{18}\text{O}$ shows -8.3‰ upstream and increase with flow and reach the highest value (-7.2‰) at 26 m a.s.l., however, decrease to -7.7‰ in downstream area. Whereas, in Langat River watershed, $\delta^{18}\text{O}$ shows -8.4‰ in upstream and increase with flow and the highest value (-5.7‰) was observed at the coast. Average gradient of $\delta^{18}\text{O}$ with elevation is -0.16‰/100 m. We applied this trend to evaluate the approximate recharge elevation of groundwater. The groundwater in the downstream area is estimated to be recharged by the rainfall on the elevation from 140 to 630 m a.s.l. (n=12). Therefore, in Klang River watershed, groundwater with low $\delta^{18}\text{O}$ recharged at high elevation discharges to the stream, and as a result, $\delta^{18}\text{O}$ of river water shows reverse trend in the downstream area. However in Langat River watershed, groundwater discharge is not dominant so that $\delta^{18}\text{O}$ in the river water shows increasing trend in downstream.

Keywords: Groundwater discharge, Tropical hydrology

Groundwater flow system in Tokyo Metropolitan City area, Japan

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Groundwater is an important water resource in the urban areas of Japan, however, there are few existed studies on recent situation of the groundwater flow in Tokyo Metropolitan area.

We applied multi tracer method from upland to lowland in Tokyo area. We performed an intensive monitoring and sampling of groundwater, river water, spring water in the area and stable isotopic composition of oxygen 18 and deuterium, inorganic solute concentrations were determined on all water samples. Also, SF₆ concentration were analyzed on some groundwater samples.

The SF₆ age of groundwater in the upland area ranges from a few years to 40 years, whereas that in the lowland area ranges from 40 years to more than 80 years. The solute concentrations are characterized by Ca-HCO₃ type in the upland, whereas that is categorized in Na-HCO₃ or Na-Cl type. In addition, d18O of the groundwater in the upland ranges from -10.4 per mil to -8.8 per mil, whereas that in the lowland ranges from -9 per mil to -8 per mil.

The shallow groundwater shows a similar chemical characteristics at the boundary between upland and lowland, suggesting that the shallow groundwater connects hydraulically between upland and lowland.

These results show that the groundwater flows from west toward east directions across the border of the upland and the lowland, and it flows across the boundary of the aquifers, meaning the unconfined groundwater recharges the confined groundwater in an area where a certain amount of unconfined groundwater is pumped up.

Keywords: groundwater flow system, Tokyo, upland, lowland

Sulfur and oxygen isotopes in rivers of Northeastern India: Source partitioning in coal mining areas

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Stable isotopes of sulfur and oxygen in water can provide valuable information about sources, geochemical and biogeochemical processes, and conditions influencing source to sink movement of sulfur in hydrological systems. Although research on stable isotopes of sulfur and oxygen in water has gained momentum worldwide, there are limited study from water bodies in the States of north-east India. The present study was conducted in the States of northeast India, in rivers flowing near Namchik-Namphuk Coalfields in Arunachal Pradesh, Makum Coalfields in Assam, and coal mining areas near Changki village in Mokokchung district of Nagaland. Water samples were collected from sixteen (16) stations and analyzed for major ions, sulfur and oxygen stable isotopes ($\delta^{34}\text{SSO}_4$ & $\delta^{18}\text{OSO}_4$) in sulfate and hydrogen and oxygen stable isotopes in water ($\delta\text{DH}_2\text{O}$ & $\delta^{18}\text{OH}_2\text{O}$).

$\delta^{18}\text{OH}_2\text{O}$ and $\delta^{18}\text{OSO}_4$, combined with $\delta^{34}\text{SSO}_4$, are used to partition riverine sulfate sources in water. pH of water samples in the study area ranged between 2.90 and 7.95 and ionic abundance was in order $\text{SO}_4^{2-} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{HCO}_3^- > \text{Na}^+ > \text{K}^+ > \text{Cl}^- > \text{NO}_3^- > \text{NH}_4^+ > \text{F}^-$. Sulfate ion ranged between 9.29 and 5051.57 mg/L. $\delta^{34}\text{SSO}_4$ ranged between -0.97 and 11.26 ‰ (V-CDT) and $\delta^{18}\text{OSO}_4$ ranged between -1.72 and 4.62 ‰ (V-SMOW). $\delta^{18}\text{OH}_2\text{O}$ ranged between -6.60 and -3.94 ‰ (V-SMOW) and $\delta\text{DH}_2\text{O}$ ranged between -41.04 and -29.98 ‰ (V-SMOW). The difference between oxygen isotope compositions in SO_4^{2-} and H_2O ($\delta^{18}\text{OSO}_4\text{-H}_2\text{O}$) ranged from 4.26 to 10.56 ‰. Oxidation of sulfides contributed sulfur largely in rivers impacted by acid mine drainage (AMD) followed by evaporites weathering and dissolution in the study area. Evaporation and mineral dissolution play dominant roles in AMD-impacted water. The results from the study will help in defining measures for remediation of polluted rivers in the region.

Keywords: sulfur stable isotopes, stable isotopes, hydrogeochemistry, acid mine drainage (AMD), northeast India, mining pollution, hydrochemistry

Characterization of groundwater in high bedrock mountains: insights from isotopic and chemical tracers

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Groundwater systems in fractured bedrock mountainous areas play critical roles in geotechnical engineering, catchment-scale hydrological cycling, and ecological maintenance. The structural heterogeneity inherent to fracture-dominated aquifers, governed by complex fracture networks and weathering-induced fissures, poses significant challenges in resolving spatially discrete recharge mechanisms and preferential flow dynamics at high resolution. This investigation implements an integrated multi-tracer analytical framework, synthesizing isotopic tracers ($\delta^2\text{H}$, $\delta^{18}\text{O}$, $87\text{Sr}/86\text{Sr}$, ^3H , and ^{14}C) with hydrogeochemical parameters (e.g., pH, TDS, ionic speciation), to elucidate the provenance, migration pathways, and residence time distribution of a fracture-zone groundwater in alpine bedrock system. Systematic analysis of hydraulic connectivity between tunnel discharge points, surface water bodies, and meteoric inputs was conducted through coupled environmental tracer interpretation. Key findings demonstrate: (1) Diagnostic hydrochemical and isotopic fingerprints distinguishing fracture-controlled groundwater from surficial hydrological compartments; (2) Fracture network architecture exerting first-order control on groundwater storage distribution and transit velocities; (3) Tritium (~ 5 TU) and radiocarbon (0.5-85 pMC) evidence revealing multi-generational mixing processes with residence times spanning contemporary recharge (^3H -detected) to paleowater contributions (> 10 ka BP). The developed methodology establishes a transferable analytical framework for resolving groundwater dynamics in structurally complex mountain belts, with particular relevance to climate-resilient water resource management in analogous lithotectonic settings.

Keywords: Isotopes, groundwater, bedrock mountainous area

Tracing hydrological processes using d18O-d mixing approach: Estimating snowmelt contribution in river water of Kameng catchment, Northeastern Himalaya

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High-altitude Himalayan river systems are significantly influenced by snow and glacier melt, ground-water, and rainfall, which regulate the hydrological processes within the catchment. Understanding the contribution of these sources is vital for effective water resource management, especially in the context of climate change. Quantifying different water source contributions in river system can be achieved using reliable methods of stable isotope tracers such as $\delta^{18}\text{O}$, δD and d-excess. This study aims to estimate the snowmelt contribution to the Kameng river and distinguish the snowmelt from other hydrological components, assessing the seasonal variation using stable isotopes. Water samples of all potential sources were collected in air-tight vials with no headspace to prevent isotopic fractionation due to evaporation during pre-monsoon, monsoon, and post-monsoon. Stable isotope analysis was performed using laser-based, off-axis integrated cavity output spectroscopy. A two-component stable isotope mixing was performed using $\delta^{18}\text{O}$ and d-excess to estimate snowmelt contribution. The mixing model results suggest that the early summer (pre-monsoon) indicates a higher snowmelt contribution, around 46-50%. As the monsoon rainfall dominates, it gradually decreases. The result shows a glacier melt contribution of 34-42% in the river discharge of the Kameng catchment. This study emphasizes the importance of snowmelt in maintaining the early summer river flow in the Kameng catchment. These findings provide essential insight into the hydrological processes in the river catchments of the northeastern Himalayas, emphasizing the necessity for climate-adaptive water resource management planning. Future studies should focus on long-term isotopic monitoring for a more comprehensive understanding.

Keywords: Stable isotope, d18O-d mixing model, Hydrological processes, Kameng catchment, Snowmelt contribution

Nano-enhanced bioremediation: a new sustainable solution for emerging contaminants

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Phthalates a synthetic chemical used as plasticizers in polyvinyl chloride that enhance flexibility and durability of plastic material but can leach into the environment due to their weak binding to polymers. These persistent organic pollutants (POPs) exhibit carcinogenic, hepatotoxic, mutagenic, teratogenic, and endocrine-disrupting properties, and degrade via physical, chemical, and biological mechanisms. Biodegradation is a promising approach, as microbes utilize phthalates as a carbon source. However, bioremediation require extensive nutrient supply for bacterial growth which can lead to algal bloom and secondary contamination limiting real-field applicability. This study explores

multi-nutrient nano phosphate as a bacterial nutrient supplier to accelerate bacterial growth and phthalates degradation. Experiments with varying nano phosphate concentrations were conducted in MQ (Milli-Q) water and MSM (mineral salt media) and across different water matrices—distilled, tap, river, and synthetic wastewater.

Results showed that at 100 mg/L phthalate, W+P200 (MQ Water + 200 mg/L nano-phosphate) achieved 92.84 mg/L biomass growth, comparable to MSM. W+P100 and W+P150 exhibited biomass growth of 74.27 mg/L and 82.91 mg/L, respectively with nano-phosphate had higher biomass than MSM alone, with MSM+P200 reaching 111.08 mg/L. Experiments with MQ water and MSM achieved complete phthalate degradation within 3 hours, regardless of initial nano-phosphate concentration. Similar degradation patterns were observed in all water matrices. Scanning electron microscopy revealed enhanced biofilm formation and bacterial aggregation in nano phosphate-treated samples. These findings suggest nano phosphate as a promising material for bacterial growth and phthalate remediation, offering an efficient strategy for environmental cleanup.

Keywords: Nano enabled bioremediation, multi nutrient nano phosphate, phthalates degradation

Water Vapour Isotopes and controlling factors at Roorkee, Uttarakhand India

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The variations in the isotopic compositions of air moisture are useful in studying the various components of hydrological cycles by understanding the processes resulting in alteration of their sources. This research paper evaluates the stable isotopes Oxygen-18 and Deuterium in atmospheric water vapour and precipitation during the year 2024 at Roorkee, Uttarakhand, India, from January to November. The aim is to assess the isotopic signatures of different sources of atmospheric air moisture and precipitation. The main objectives are to determine the sources of moisture and air masses and to evaluate the influence of atmospheric conditions on isotope compositions. The Iso-tope Water Vapour Line (Iso Val) was drawn together with the Global Meteoric Water Line (GMWL) and the best fit line was $\delta D = 5.66 * \delta^{18}O + 32.31$. The precipitation samples were also collected during the study period and were best fitted with $\delta D = 8.00 * \delta^{18}O + 9.14$ in the Local Meteoric Water Line (LMWL). The Monsoon Water vapours of Oceanic origin are most depleted isotopically ($\delta^{18}O < -21$, $\delta D < -92$), while the enriched vapours are of local origin. The d-excess of ground level vapours (GLV) reveals the continental recycled moisture and evapo-transpiration effect adding additional moisture to the study area. The application of the work is useful in understanding the monsoon arrival and departure signatures observed in advance through the changes in air moisture isotope values, their depletion and enrichment by sub-cloud evaporation effects.

Keywords: Air moisture, stable isotope composition, isotope water vapour line, climatic controls, source signatures

Groundwater Age Distribution and Isotopic Characteristics in the Arid Kachchh Region, Western India

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Groundwater is a critical resource in arid regions, particularly in Kachchh, western India, which receives an average annual rainfall of only about 376 mm. The region lacks perennial surface water bodies, making groundwater the primary source for meeting the growing water demands. However, extensive groundwater mining, with extraction rates reported to be ten times higher than the annual recharge, has raised concerns about overexploitation and contamination of deeper aquifers. To address these issues, it is essential to understand the groundwater age distribution and recharge characteristics in this region. To understand groundwater age distribution, groundwater samples were collected from 16 locations across Kachchh during May 2023, for stable isotope ($\delta^{18}\text{O}$, δD , $\delta^{13}\text{C}$) and radiocarbon (^{14}C) analyses. The isotopic and radiocarbon data provide significant insights into groundwater dynamics in the region. The isotopic composition of deeper groundwater was found to be more depleted (Average $\delta^{18}\text{O} = -4.5\text{‰}$) compared to shallow groundwater (Average $\delta^{18}\text{O} = -3.1\text{‰}$) in this region. This suggests different recharge sources for shallow and deep aquifers. Groundwater ages ranged from ~500 years BP in easternmost part of Bhuj Formation to as old as 6000 years BP in central part of Bhuj Formation. Older groundwater, primarily found in the Bhuj Formation, exhibited $\delta^{18}\text{O}$ values around -5.4‰ . Such depleted isotopic signatures of groundwater recharged ~6000 years BP suggest significantly different recharge conditions from the present, and are unlikely to result from modern rainfall. Isotopically depleted groundwater indicates paleo-recharge from isotopically depleted source in the past. The isotopically depleted sources water could be the local rainfall during different climatic regime, or the surface water transported from different climatic regime. These findings provide valuable clue about the paleoclimate and also underscore the critical need for sustainable groundwater management in socio-economically, culturally and strategically sensitive Kachchh region of India.

Keywords: Stable isotopes, deeper aquifer, radiocarbon, arid region

Water Quality (ICWQ)

Understanding the roles of climate change, land use and land cover change and water diversion project in modulating water- and carbon-use efficiency in Han River Basin

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Water-use efficiency (WUE) and carbon-use efficiency (CUE) are critical indicators of ecosystem function and hydrologic processes, reflecting the water-carbon flux exchange rate. Climatic variables, land use and land cover change (LUCC) and water diversion project (WDP) have altered water-carbon cycle; however, their roles in modulating WUE and CUE remain uncertain. To explore these effects, a framework is proposed and Han River basin (HRB) in China is selected as a case study including the data sets from both remote sensing and in situ observations during 2000-2020. The process-based Regional Hydro-Ecological Simulation System model and a supervised machine learning model are applied to simulate the impacts of climatic variables, LUCC and WDP on WUE and CUE, which are conducted by designing four experiments. We find that no significant WUE and CUE trends attributed to contrasting trends in the dry (October to March) and wet (April to September) seasons. Temperature variations greatly affect WUE and CUE, with WUE decreasing in the wet season and increasing in the dry season due to minimum temperature changes. LUCC has litter impacts on WUE and CUE changes. From 2014-2020, the middle route of the South-to-North WDP decreased WUE by 0.22 gCkg⁻¹H₂O in the middle-low HRB's wet season, slightly affecting CUE. Seasonal CUE was stable, with the largest decrease of 0.04 in the upper HRB during the wet season. The WDP also increased WUE sensitivities to minimum and maximum temperatures, while CUE sensitivities remained constant. Our case study has proven that the proposed framework is an effective way to understand the roles of climate change and WDP in modulating WUE and CUE.

Keywords: water use efficiency, carbon use efficiency, evapotranspiration, RHESSys, Random Forest, water diversion project.

The Impact of Abattoir Effluent on the Quality of Ogun River in Kara Market, Southwest Nigeria.

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The impact of abattoir effluent on the water quality of the Ogun River in Kara Market, Southwest Nigeria, was investigated to evaluate pollution levels and potential health risks. Five sampling points were selected at 100-meter intervals around peak pollution hours (6:00 - 9:00 am). Various physical, chemical, and microbiological parameters were analysed, including pH, turbidity, total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metals (e.g., manganese, lead, cadmium), and microbial contaminants like total coliforms and E. coli. The

Water Quality Index (WQI) was calculated, yielding a score of 334.74, categorising the river as "unsuitable for drinking." The results showed that key pollutants, such as nitrates, manganese, hydrogen sulphide, and TDS, exceeded National Industrial Standards (NIS 554:2015) permissible limits, underscoring severe contamination from both organic and industrial effluents. The findings highlight critical pollution from abattoir waste, threatening the surrounding communities' ecological balance and public health. This study underscores the urgent need for enhanced waste management practices, stringent regulatory enforcement, and public awareness to prevent further degradation of the Ogun River.

Keywords: Abattoir Effluent, Water Quality, Ogun River, Pollution, Environmental Management

Adverse Impacts of Climate Induced Global Changes on Water Quality, Security and Availability in India: Necessary Mitigation Measures and Appropriate Adaptation Strategies Needed

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Water is the life line for the people of India. Water quality, security and availability are getting disturbed because of climate induced global changes, pollution, environmental degradation and various other human induced activities due to which the economic and social development of India is getting significantly affected. The Indian sub-continent with abundant water resources is experiencing problems such as huge wastage of fresh water, lack of integrated water management systems, inappropriate cropping patterns, inadequate and poor irrigation systems, population growth, poor economic development, lack of infrastructure and other factors.

The water situation in the Indian subcontinent is going to be further affected by climate induced global changes as climate change is a major driver of water quality and is surely creating grounds for newer and more severe risks for water security and availability in India. Though the Government introduced several measures to ensure water sustainability, the water supply systems in India are being compelled to practice intermittent supply due to water scarcity, water shortage, economic factors, unexpected demands, inefficient operational strategies and infrastructure failures. Hence, in India, there is an urgent and imminent need to combat climate change and protect environment, bio diversity, eco systems and fresh water resources by undertaking various climate change mitigation measures and appropriate adaptation strategies. India needs to adopt climate resilient water resources management system and strengthen its water supply planning, storage, distribution and monitoring mechanisms and take strict measures to prevent pollution of water. This paper briefly discusses the adverse impacts of climate induced global changes on water quality, security and availability in India and deliberate on strategies including water security planning, treatment, flood/drought management etc.to ensure resilience to water related climate change issues and the necessary mitigation measures and appropriate adaptation strategies needed to be taken for ensuring sustainable development.

Keywords: Water Quality, Water Security, Global Warming, Integrated Water Management, Climate Change Adaptation, Mitigation and Sustainable Development

Increasing wastewater pressure on rivers in New Moscow area

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The rapid urbanization of the New Moscow area, transferred to Moscow in year 2012, is placing increasing pressure on its river systems (e.g. Pakhra, Desna, Setun) due to rising wastewater discharge. This study aims to assess the extent of this pressure and its potential ecological consequences. The objectives were to: (1) quantify wastewater discharge volumes from key sources, (2) evaluate water quality parameters in selected rivers, and (3) analyze potential impacts on riverine ecosystems. Methods included the compilation of wastewater discharge data from municipal and industrial sources, combined with field hydrological measurements at various locations along the river systems. Satellite imagery and data from previous research were used to understand long-term trends. Results indicated an increase in wastewater discharge over the past decade, particularly from newly developed residential areas. While direct ecological impacts are yet to be thoroughly investigated, the observed changes point to potential risks to aquatic biodiversity and human health. The study concludes that wastewater discharge is a growing stressor on rivers in the New Moscow region during last 13 years. Effective implementation of sustainable wastewater management practices, including improved treatment technologies and enhanced monitoring efforts, is essential to mitigate these negative impacts and maintain the ecological integrity of the area's river systems. Further investigations are needed to precisely link the detected changes in water quality to the ecological state.

Keywords: wastewater discharge, small rivers pollution, urban runoff, water quality, New Moscow area, wastewater management, nutrients

Revealing climate-induced patterns in crop yields and the water-energy-food-carbon nexus: insights from the Pearl River Basin

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In the context of growing concerns over food security and climate change, research on sustainable agricultural development increasingly emphasizes the interconnections within agricultural systems. This study developed a regionally integrated optimization and prediction agricultural model to systematically analyze the impacts of climate change on agricultural systems and their feedback mechanisms from a water-energy-food-carbon (WEFC) nexus perspective. Applied to the Pearl River Basin, the model evaluates future trends in grain yield, water use, energy consumption, and carbon emissions under various climate scenarios throughout this century. The results indicate that rising temperatures significantly reduce crop yields, particularly in the western basin, increasing the environmental footprint per unit of grain produced. However, the CO₂ fertilization effect substantially offsets these negative impacts. Under the SSP585 scenario, CO₂ concentrations rising from 599.77 ppm to 1135.21 ppm by the century's end led to a shift in crop yield trends from negative ($Z = -7.03$) to positive ($Z = 11.01$). This also reduces water, energy, and carbon footprints by 12.82%, 10.62%, and 10.59%, respectively. These findings highlight the critical importance of adaptive management

strategies, including precision irrigation, optimized fertilizer use, and climate resilient practices, to ensure sustainable agricultural production. Despite these insights, the model has limitations. Future research should incorporate uncertainty analysis, diverse adaptation pathways, and advanced technologies such as machine learning and remote sensing to improve predictive accuracy and applicability. This study offers valuable guidance for mitigating the adverse impacts of climate change on the WEFC nexus, supporting sustainable agricultural practices and science-based policy development.

Keywords: AquaCrop model, NSGA-II method, Sobol sensitivity analysis, machine learning, climate change

Understanding the hydrological drivers of global human health risks - a call to the international hydrological community to co-create solutions at the Water and Health Nexus

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While the role of water in environmental and ecosystem health is increasingly well recognised, our understanding and recognition of the linkages between hydrological variability and processes with human health remain inadequate. Substantial growth of interdisciplinary research, including dynamic hydrological system understanding at the Water and Health Nexus, is urgently required to help address increasing pressures of infectious and non-communicable diseases that are exacerbated by hydrometeorological change.

For instance, proliferation, evolution, and increased exposure to water borne infectious pathogens coupled with the global rise in hydrometeorological extremes can lead to critical health impacts through heatwaves, floods and drought and polluted water resources. These stresses in water quantity and quality require the hydrological community to come forward to provide understanding of the underlying mechanisms that link pathogens to exposure and risk, and to define the scale, magnitude, and duration of extreme hydrometeorological events. This knowledge is essential to build resilience of health services and infrastructure as well as changing demands on necessary resources (including water) in the event of crisis including the potential displacement of people.

We advocate for targeted efforts in leveraging hydrological advances (e.g., process-based understanding, increased modelling capabilities) and integrate this alongside health care intervention strategies. Here, we present selected examples from interdisciplinary research initiatives demonstrating the vital role hydrological process knowledge can play in (i) improving the efficiency of water, sanitation and hygiene practice, (ii) reducing the risk of flood induced disruption of health care services and (iii) using knowledge of the dynamic evolution of hydrological connectivity to predict pathogen dispersal and resulting human exposure risks. We call the international hydrological community to engage around this most critical quest, contributing to the discussion and co-creation of integrated water and health solutions."

Keywords: Water, Health, Nexus, Pollution, Heat, Disease

Sand-Gravel Mining Impacts on Water Quality in an Alluvial River with Tributary Intervention: A case study of Thoubal-Itok River system, Manipur, India

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Sand-Gravel mining in Thoubal river in Manipur, India, has inflicted environmental and hydrologic degradation to the natural fluvial regime. While sand mining supports local livelihood, it raises concerns about river degradation and environmental flows. The study objective is to assess the impacts on water quality in Thoubal river due to unregulated sand-gravel mining, along with the tributary sediment laden inflows from Itok stream, which confluences with Thoubal river at Leirongthel. The physiochemical water quality parameters used in this study included pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), temperature, salinity and other parameters. For this study we have selected five reach stations in the mid-reaches of Thoubal River upstream (U/S) to downstream (D/S) viz., Nongpok Keithelmanbi, Nungbrang, Leirongthel, Nungaipokpi and Changamdabi sampling sites, where rampant sand-gravel mining takes place. The results indicated that at Nongpok Keithelmanbi (most U/S reach), the pH of river water is slightly acidic with pH ranging from 6.35-6.86 likely due to repeated translation of sand and sediment deposits following flood discharge from the Thoubal multipurpose barrage, that accumulated minerals are mixed in water while that of other 4 sites are in pH range of 7.01-7.08. EC at Nongpok Keithelmanbi ranging from 143-164 $\mu S/cm$ is found to rise in the D/S reaches upto 147-181.7 $\mu S/cm$ as sand-gravel mining activity increases (Daniel et al., 2024). TDS at Nongpok Keithelmanbi ranging from 102-116 ppm also showed marginal increase in the range 104-130 ppm as a result of increased riverbed and bank erosion caused by sand mining, where suspended sediment load was observed to be 669.19 tons/day. The influence of tributary inflows of Itok stream at Leirongthel notably marked the highest values of water quality parameters as TDS of 207 ppm as compared to other sites of mainstream Thoubal river possibly due to the influx of coarse sediment particles.

Keywords: degradation, environmental, sediment, bank erosion, pH, TDS, EC, salinity, influx

Accessing and controlling irrigation water quality: A smart bioremediation approach

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Contamination of water required for irrigation is a significant challenge in agriculture, affecting crop health and soil quality. Bioremediation is an eco-friendly and sustainable approach that utilizes microorganisms, plants, or enzymes to degrade, detoxify, and remove pollutants from contaminated environments, including soil, water, and air. Bioremediation is widely applied in the treatment of industrial wastewater, oil spills, heavy metal contamination, and agricultural runoff, offering an alternative to conventional chemical and physical remediation techniques. The study proposes a smart bioremediation system that utilizes electronic sensors, controllers and Internet of Things (IoT) technology for monitoring and improving the quality of irrigation water in real-time. The system consists of pH, dissolved oxygen, turbidity, electrical conductivity and nitrate sensors to detect contaminants. The sensors on being interfaced with microcontroller-based control unit processes data and automates bioremediation mechanisms, such as microbial dosing, aeration and electrochemical treatment with the deployment of electrical and electronic actuators. Employment of microbial fuel cells for degrading pollutants while generating small amounts of electricity and UV-LED disinfection units for ensuring pathogen-free water after microbial treatment constitute for a bio-electro-chemical system. Remote monitoring of water quality is achieved by processing and transmission of data to a cloud based IoT platform. The integration of electronic devices with bioremediation enhances monitoring, automation and efficiency in water purification. This smart bioremediation approach bridges the gap between biotechnology and electronics to offer constructive solution for water purification in precision agriculture.

Keywords: bioremediation, sensors, controllers, Internet of Things, actuators, bio-electro-chemical

How important are calibration strategies for large scale water quality modeling?

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Degradation of water quality in water bodies is a global problem that is expected to further escalate and contribute to global health and environmental issues. As continental and global dynamic hydrological models are becoming more available for estimation of time-dynamic water quality processes and fluxes into sea basins, scientists rely more and more on these models to advise societal actions in response to ongoing global changes. One aspect that has not been adequately discussed in the modeling community is how various calibration strategies and goals impact the modeling results and potential decisions.

We explore selected calibration strategies in the context of large-scale modeling and the questions the model aims to answer. Strategies include an expert-guided stepwise approach for parameters regulating specific processes and more automated approaches with robust exploration of parameter space. We use the dynamic process-based hydrological model, Hydrological Predictions for

the Environment (HYPER, Lindström et al., 2010) and its continental (E-HYPE, Brendel et al., 2023) and global applications (WWH, Arheimer et al., 2020). These models were recently calibrated for sediments (both models), nutrients (E-HYPE), and microplastics (WWH).

At the continental level, we present how regional versus domain-wide calibration approaches affected sediments and nutrients, including the factors limiting model performance for each step in the model regionalization. At a global level, calibration of sediments is contrasted with that of microplastics, for which a lack of consistent data prevents a use of traditional calibration techniques. Here, an ensemble technique was successfully applied where the model parameters and inputs that affect generation, transformation, and transport of plastic from their source through waterbodies were varied to explore the defined parameter space. The models were applied in both operational production and evaluation of climate impacts and other scenarios.

We invite a community-wide discussion on current challenges in simulating water quality at large scales.

Keywords: water quality, calibration approach, large scale hydrological model

A Chaotic Dynamic Approach for Prediction of Dissolved Oxygen

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Dissolved oxygen (DO) dynamics play a crucial role in assessing the quality of water and the health of aquatic ecosystems. The DO dynamics are influenced by various hydro-environmental factors in complex and nonlinear ways, making their analysis and prediction challenging. This study employs a chaotic dynamic approach for the prediction of DO dynamics. For implementation, daily DO data spanning 15 years (2009-2023) from two United States Geological Survey (USGS) monitoring stations are considered. The prediction procedure involves the following steps: (1) reconstruction of the single-dimensional DO time series in a multi-dimensional phase space using delay embedding; (2) identification of nearest neighbours in the reconstructed phase space using Euclidean distance; and (3) prediction of future DO values based on the evolution of the nearest neighbours in the phase space. For phase-space reconstruction, embedding dimensions (m) ranging from 1 to 10 and a delay time value of 1 are considered, and the prediction is done for different numbers of nearest neighbours (k). The first 12 years of DO data are used for phase-space reconstruction and the remaining 3 years of data are used for prediction. The prediction performance is evaluated using the coefficient of determination and root mean square error (RMSE). The results indicate that the best predictions are achieved at an embedding dimension of six (i.e., optimal embedding dimension), yielding a coefficient of determination of 0.72 and an RMSE of 0.83 mg/L. The optimal embedding dimension obtained from the prediction approach is also in good agreement with the dimension obtained using a dimensionality approach, false nearest neighbour (FNN) algorithm. These present findings highlight the potential of a chaotic dynamic approach for identifying the complexity of DO dynamics and their prediction, offering valuable insights for water quality management and decision-making.

Keywords: Dissolved Oxygen (DO), DO Prediction, Phase-Space Reconstruction, Optimal Embedding Dimension, Chaotic Dynamic Approach

Identifying and overcoming limitations of open-source surface water quality datasets of India

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The National Water Quality Monitoring Programme (NWMP) has successfully identified and bridged a critical knowledge gap in India– the paucity of spatio-temporally consistent, nation-wide water quality databases. Although the existing database contains information from over 200 locations for the period of 2012-2023, its usability is seriously limited by several factors some of which have been identified as the (i) absence of timestamping of sampling events(ii) absence of geotagging information of sampling sites within the database (iii) absence of sub-annual time scale measurements (iv) absence of any metadata related to sampling and testing (v) presence of several missing and improbable values. Developing reliable and interpretable models using such datasets is a non-trivial research problem, which can be countered in part by a two-step check, namely a physics- and a data-based approach respectively. First, we compare various groups of variables to see if they violate the physical rules of the system, e.g., high BOD cannot be associated with high DO values etc. Then, we validate these trends using out-of-sample observations (other open-source databases available for the region), e.g. we check if annual BOD vs. DO trends are consistent in similar locations of the country. This two-step methodology is expected to identify factual and numerical errors in reporting, thus comprehensively ruling out any inconsistency. To the best of our knowledge, this is the first methodological attempt to identify and overcome limitations in the NWMP dataset, to facilitate its use for research modelling and decision-making. The novel physics- and data-based methodology proposed for evaluating the veracity of the databases, can not only be used by researchers, but also by regulatory and environmental agencies to flag and penalize fraudulent misreporting of various other self-reported water/ wastewater quality variables.

Keywords: National Water Quality Monitoring Programme (NWMP), open-source data, water pollution, data misreporting, data inconsistencies

Comprehensive Water Management: Quality Monitoring, Fate Assessment, and Nano-enabled Remediation for Sustainable Solutions

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Access to clean water is essential for life; however, escalating global demands and industrial growth have led to significant degradation of water resources. Nano-enabled adsorbents have emerged as key players in reducing water contamination, especially in the targeted removal of heavy metals and oxy-anions. While their effectiveness in pollutant removal is well-established, a holistic approach to water management is necessary-focusing on identifying contaminants through advanced

monitoring, understanding their behavior through fate studies, and developing sustainable remedial strategies.

Our monitoring phase utilizes a wide range of analytical techniques to detect contaminants across various geological and environmental matrices, allowing us to trace sources and measure concentrations. This groundwork informs our fate studies, which investigate the behavior of pollutants in natural systems. For instance, we synthesized ferrihydrite and gibbsite in both amorphous and crystalline forms and the interaction of ferrihydrite and gibbsite with ciprofloxacin and heavy metals revealed changes in colloidal stability and surface charge, which impact contaminant retention and transport.

To assess contaminant mobility in natural systems, we investigated the sorption and transport behaviors of chromium (Cr) and cadmium (Cd) in hard-rock aquifers. Our findings showed that basaltic and limestone aquifers exhibit stronger retention properties, which is crucial for managing contaminant movement in water systems.

In the realm of remediation, we have explored the use of redox-active nanoparticles (RNPs) and phosphate-based nanostructures for contaminant sequestration. For example, nano-hydroxyapatite (nSt-HAP) and nano-Farringtonite (ns-FAR) demonstrated effective adsorption of heavy metals and radionuclides, as verified through X-ray absorption and ion-exchange tests. Additionally, biochar derived from sludge, magnetized for enhanced adsorption, exhibited substantial removal capabilities for dyes and pharmaceuticals. Enhancing understanding of pollutant behaviors in varying geochemical conditions allows strategic designing of cutting-edge eco-friendly nano-enabled tools for continuous clean water generation and contributes to developing sustainable, resilient water quality solutions amidst increasing global clean water stress.

Keywords: Water quality, contaminant fate, nano-adsorbents, remediation technologies, monitoring systems

Evaluating Water Quality of the Ganga River: Integrating Satellite Data and In-Situ Measurements

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Civilizations historically grew around rivers, which provided essential resources for various needs. One of the critical functions that rivers provide is the help in disposal of waste through self-purification, but rapid urbanization and industrialization has exploited this capability to its limit. Just as assessing the causes of water quality degradation is crucial, it is equally vital to regularly evaluate the river's water quality. Traditional assessment methods include in-situ sampling and laboratory testing. Although these methods provide the most reliable results, they are time-consuming and can only be conducted on specific stretches of the river. Consequently, the frequency of assessments is reduced. This research work investigates the advanced assessment methodology by combining satellite data with in-situ measurements. Satellite data offers extensive coverage of river stretches in a shorter period, allowing for more frequent water quality monitoring. The study was conducted under the National Mission for Clean Ganga (NMCG) sponsored project. In this study, we have tried to assess the water quality of River Ganga from Kanpur to Prayagraj using qualitative and quantitative methods. For qualitative analysis satellite-based indices like NDTI and NDCI were calculated.

Quantitative methods include developing the relation between the spectral reflectance of satellite data and field-measured water quality parameters. The results of the study show the variation in water quality parameters over entire stretch during pre-monsoon, monsoon and post-monsoon seasons. Interestingly in the study, we were also able to find optically inactive parameters like DO using the satellite dataset. The results of the study will be hosted on a geo-portal and will help NMCG for data driven decision making for sustainable management and utilization of the Ganga River.

Keywords: Water Quality, NDTI, NDCI, Ganga River, Turbidity

Remote Sensing-Based Assessment of Turbidity and Chlorophyll Variations in the Ganga-Yamuna Rivers Sangam During the Kumbh Mela 2025

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The Ganga and Yamuna Rivers have experienced significant degradation during past Kumbh Mela gatherings at Prayagraj, India due to anthropogenic activities. The Kumbh Mela, the largest religious gathering in the world, was held in Prayagraj, India, from January 13 to February 26, 2025. In order to overcome logistic challenges associated with ground sampling remote sensing-based techniques are urgently needed to efficiently monitor and assess these changes. Furthermore, remote sensing time-series allow assessment based on archival datasets. Normalized difference indices, such as Normalized Difference Turbidity Index (NDTI) and Normalized Difference Chlorophyll Index (NDCI) are useful for monitoring spatio-temporal water quality trends. The main aim of this study is to investigate variations in turbidity and chlorophyll concentrations in rivers, potentially influenced by environmental changes, human activities, or large-scale events like the Kumbh Mela. The NDTI and NDCI Sentinel-2 SR and Landsat 8 datasets. The datasets were collected on multiple dates spanning from November 2024 to March 2025, capturing different phases of the Kumbh Mela. The results will be used to support environmental organizations in managing water resources to minimize pollution, especially during high-stress events like the Kumbh Mela.

Keywords: Water Quality, Normalized Difference Indices, Remote Sensing, Turbidity, Chlorophyll

Anthropogenic changes of heatwave-extreme precipitation events have emerged from the natural climate variability

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Extreme events that surpass the bounds of historical variability are expected to occur more frequently in a changing climate. In particular, the compound extreme precipitation preconditioned by heatwaves (CHEPs) attracts people's attention nowadays, due to their devastating impacts on ecosystems and society. Although previous studies have widely investigated the historical change of CHEPs, when this change emerges from internal climate variability remains unclear. The objective of this study is to investigate the time of emergence (ToE) of CHEPs by utilizing multiple advanced Single Model Initial-condition Large Ensembles (SMILEs). First, we analyze the spatiotemporal changes of CHEP characteristics over a 200-year period. Second, we detect the ToE of CHEPs by adopting Kolmogorov-Smirnov tests and a probability proportional method. Third, we present a global analysis for ToE exposed GDP and population (POP) of record-shattering CHEPs over the future period. We find that most regions have experienced increases in CHEP characteristic values in the historical period, which would be more remarkable in the future under multiple projection scenarios. The agreement on the spatial distribution among SMILEs presents that anthropogenic forcings have already caused CHEPs to emerge from the natural climate variability over most regions of the world. In addition, the earlier emergence can be found in CHEPs hotspots. The exposure of GDP and POP reveals an alarming upward trend throughout the 21st century. The unequal distribution of GDP and POP exposure reveals that the least developed and poorest regions will experience more extended impacts of record-shattering CHEPs than wealthier regions. Our study highlights the urgent need for region-specific mitigation and adaptation strategies to combat climate change and its impacts.

Keywords: Climate change, heatwave-extreme precipitation events, internal climate variability, Single Model Initial-condition Large Ensembles

Hydro-Chemical Characterization of Middle Zarafshan River Basin Using Geospatial Technology

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This paper delves into the application of geospatial techniques to evaluate the Zarafshan River, a perennial river that flows from east to west through an elongated basin. The river is primarily fed by glaciers located in Tajikistan and seasonal snowmelt in Uzbekistan. However, upon entering Uzbekistan, the river experiences significant water loss due to over-exploitation, leading to

increased pollution levels. The Zarafshan River carries a certain amount of pollutants as it crosses into Uzbekistan, but its pollution levels escalate notably between Ravatkhodja and Samarkand City. Water quality analysis reveals alarming trends. Total dissolved solids (TDS) increase from 260.6 to 347 S/cm as the river flows out of Samarkand, while the pH fluctuates between 7.18 and 7.8 as the river enters Navai after leaving Samarkand. These measurements highlight the significant impact of urban and industrial activities on the river's health. For instance, water samples collected at Ravatkhodja show a pH of 7.18, while samples taken at Navai exhibit a pH of 7.8. Such variations in water quality parameters underscore the concentration of pollutants and provide insights into the sources of contamination. This transformed into a highly polluted waterbody after leaving Samarkand. The data clearly reflects the adverse effects of human activities, including agricultural runoff, industrial discharge, and urban wastewater. By integrating geospatial data with field measurements, this study aims to identify critical pollution hotspots and assess the spatial distribution of contaminants. Results show that the potential of geospatial techniques for assessing the health of the Zarafshan River and highlights the urgent need for interventions to address pollution. This approach not only supports the preservation of the Zarafshan River but also serves as a model for assessing and managing other water resources in the region.

Keywords: Land Use and Land Cover, Landsat, Morphometric Indices, Field work, Water quality

Post Monsoon Water Quality Assessment of Water Sources of Bhopal City Using Artificial Intelligence and Machine Learning Tools: A New Insight

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Water quality assessment is required for water sources of all over the world with the pressure of increasing population and anthropological activities. This paper is the post monsoon extension of the previous work done in the pre monsoon period for 5 groundwater and 4 surface water sources of Bhopal city, Bharat (India) with 16 physicochemical water quality parameters. This work has a new insight and provides forecasting of water quality with some artificial intelligence and machine learning tools incorporated to geochemical diagrams. A time series model, Autoregressive Integrated Moving Average (ARIMA) has been used to analyze quality parameters data over time for forecasting future trends for upcoming years. The geochemical plots viz, Durov, Gibbs, Piper, Schoeller, Stiff and Wilcox diagram were applied to interpret hydrological facies, ionic reactions, ionic balance and water rock interactions. The Weighted Arithmetic Index Method (WAIM) was applied to determine water quality index (WQI) of groundwater for drinking and surface water for irrigation purposes. Total 54 samples for six months were examined under American Public Health Association's 23rd edition (APHA), collected from 9 various sites with frequency of 9 samples in each month. It was found that both water sources belong to rock dominance with Gibbs diagram and mixed type hydro chemical facies having $Mg(HCO_3)_2$ and NaCl salts with Piper plot. The iron (3.1mg/L) was found beyond World Health Organisation (WHO) prescribed limit (1mg/L) at all water sites especially village Kolua Khurd of groundwater. The value of manganese was also exceeded at all water sites having average of .2mg/L. The chemical oxygen demand (COD) of Upper Lake was found high 54.04mg/L indicating the inorganic polluting matter is increasing. The seasonal variations were also detected with three seasons namely summer, monsoon and winter with statistical approach. This paper gives new predictions for water policymakers, stakeholders and governments.

Keywords: Water quality assessment, physicochemical parameters, geochemical plots, artificial intelligence, machine learning.

Arsenic Contamination and its Health Ramification in a village of Buxar District, Bihar

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Arsenic groundwater contamination and its' health implications in the lower Gangetic plain of Indian states started reporting in the 1980s. Bihar from the middle Gangetic Plain reported first arsenic cases in 2003. Since its first report, its magnitude has increased, exposing populations between 1.2 and 4.6 million in 3-12% of the land. The consumption of arsenic-contaminated water manifests as arsenicosis due to skin discoloration and painful skin lesions. Rarer, but most serious, is the fact that cancer has been linked causally to chronic arsenicosis.

Objective: This study aims to understand groundwater arsenic contamination at a household level in a village in the Buxar district and its health ramifications.

Method: The study used a concurrent quantitative dominant mix method (QUAN+qual), applying household survey, social mapping, interviews, and participatory interactions in Tilak Rai Ka Hata village. A household survey with a structured interview schedule was applied to 90 households, and information was collected from 840 individuals stratified into different social groups. An in-depth interview was conducted using a semi-structured schedule with experts and key informants, including chronic arsenicosis patients.

Findings: The study found that 75% of households owned handpumps as a water source and a quarter of them have two handpumps. The study shows that 39.5 % of individuals are consuming water that they reported not being fit to drink. Among them, 48.4 % are BC, 42.5% belong to others and 38.1% identify as STs. From the household survey in the village, a total of 10 cases of chronic arsenicosis and two cancer cases were reported. The Yadav community reported the highest number of arsenicosis cases.

Conclusion: Despite awareness of arsenic pollution, people rely on contaminated groundwater, often installing multiple handpumps. Health impacts require urgent public health attention, with the Yadav community being particularly vulnerable to arsenicosis and related illnesses.

Keywords: Arsenic, Health Implication, Water Quality, Buxar, Arsenicosis

Hydrological and water quality impacts of climate variability and land-use change: A case study of the Muda River Catchment

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This study assesses the impacts of these changes on the upstream catchment of the Muda River (499 km²) using the Soil and Water Assessment Tool (SWAT) model. Data collection included hourly water level measurements and water sampling from May 2018 to April 2019, taken every hour from 9 am to 5 pm during two weeks each month. Peak discharge was recorded on September 29, 2018, at 9:00 am (45.305 m³/s), while the lowest was on July 23, 2018, at 11:00 am (4.2954 m³/s), with an average discharge rate of 1.236 Mm³/day from April to October 2018. The catchment displayed "flashy" characteristics, with rapid increases in discharge in response to rain events. Water quality was measured using in-situ methods. Average values were as follows: electrical conductivity (50.34 µS/cm, Class I), total dissolved solids (31.87 mg/L, Class IIA), water temperature (26.14°C, Class IIA), nitrate concentration (4.70 mg/L, Class III), pH (7.08), turbidity (130.29 NTU, Class IV/V), and total suspended solids (87.87 mg/L, Class III). Turbidity was the only parameter showing significant seasonal variation ($p < 0.001$), while no notable differences were observed in water quality between pre- and post-logging years. These findings indicate that water quantity and quality in this catchment are more strongly influenced by climate variability than by land-use changes. Five SWAT model simulations were conducted to evaluate different land-use and climate change scenarios. Scenario S1 yielded optimal discharge and water balance, reflecting the highest water storage rate, essential for future use, while Scenario S5 showed the lowest. In scenarios involving development, simulations S2 and S3 demonstrated no significant differences in discharge and water balance.

Keywords: Climate variability, Land use change, Water quality, SWAT modelling, Muda River Catchment

Water quality assessment of shallow oxbows in the Jaldhaka Floodplain, India

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In floodplain landscapes, shallow oxbows are significant aquatic-terrestrial ecosystems and socioeconomic entities for the residential communities around them. The water level fluctuations in these oxbow lakes and their connections with the nearby river during flood events, determine available ecosystem services such as water-land provision and also influence the ambient water quality for organisms and communities. As a large section of the population in developing nations reside in floodplains, the water quantity and quality of floodplain oxbows are adversely affected by the requirement for arable land and settlements, road connectivity between settlements, human use and flood prevention measures. Oxbow lakes of the Jaldhaka River floodplain in India are examined in this study. The objectives are to evaluate the seasonality of their water's physio-chemical parameters and to assess flood event effects on water quality in terms of surface water connectivity with rivers and local catchments. Principal component analysis and factor analysis are used to evaluate the

overall surface water quality while reducing the subjectivity for choosing water quality parameters through a modified Horton's Water Quality Index in light of local hydro-morphological significance and human use. Additionally, storm event sampling was done to evaluate how flood events affect the physiochemical water characteristics in the oxbows. The results of this study indicate that the primary determinants of oxbow water quality are the source of water supply, within-oxbow ambient physicochemical changes, flooding frequency, seasonal nature of wet and dry phases, and human use along the oxbow margins.

Keywords: Shallow Oxbow lakes, Floodplain waterbodies, Storm event, Water Quality, In-lake activity

Analyzing the Correlation Between Total Suspended Solids (TSS) and Turbidity in the Kemena River Basin (2018-2022)

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Water quality monitoring in river basins is crucial for environmental sustainability and resource management. This study examines the relationship between Total Suspended Solids (TSS) and Turbidity (NTU) in the Kemena River Basin over a five-year period (2018-2022). Using historical water quality datasets, trends and fluctuations in sediment load and water clarity were analyzed across multiple sampling locations, including Bandar Bintulu, Pekan Sebauh, Jambatan Kemena, Pekan Tubau, and Kampung Sibul. The findings indicate a strong correlation between TSS and Turbidity, with periods of increased sedimentation corresponding to elevated turbidity levels. However, significant seasonal variations and occasional outlier spikes suggest that external factors such as land use changes, rainfall patterns, and industrial activities play a critical role in sediment transport within the river system. Notably, in 2020, an extreme peak in TSS (~600 mg/L) coincided with a major turbidity increase, highlighting potential anthropogenic or natural disturbances. This study emphasizes the importance of continuous machine learning-driven anomaly detection models for real-time water quality assessment. By integrating historical trends with predictive analytics, authorities can enhance early warning systems for sediment-related pollution and mitigate risks associated with poor water quality. Future work will explore the application of dynamic machine learning frameworks to improve adaptive monitoring and predictive modeling for river basin management.

Keywords: Water Quality, Total Suspended Solids (TSS), Turbidity, Kemena River Basin, Sediment Transport, Machine Learning

Assessing the Impact of Water Quality Parameters on Food Security in the Vietnamese Mekong Delta

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This study explores the sensitivity of water quality parameters in the Vietnamese Mekong Delta (VMD) to various inputs, focusing on food security. Using the InVEST modeling software, we quantify and map seasonal water yield across 23 sub-watersheds in the VMD. Hence, the study focuses on regulating ecosystem services in agricultural regions that contribute to Vietnam's food production. Sensitivity analysis for the model parameters reveals that variations in β for Seasonal Water Yield have the most significant effects on baseflow. We propose an innovative approach for model validation tailored to regions with limited data availability, utilizing observed data to enhance accuracy and reliability. The study points to the need for conservation measures in developing countries with high soil erosion, especially along the Hau and Tien rivers. This research adds a series of implications and findings to the overall knowledge of how water quality plays a crucial role in supporting food security in areas of low availability of data, as well as offering some recommendations to policymakers regarding the application of nature-based solutions and the sustainable management of water resources in the frames of the SDG framework.

Keywords: Water quality, Food security, Delta resilience, sensitivity analysis, InVEST model

Emerging organic compounds in surface and groundwater reflect the urban dynamics in sub-Saharan cities

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Rapid and uncontrolled urbanization in sub-Saharan Africa has led to an increased production and expansion of synthetic chemicals, resulting in significant pollution of the aquatic environments, particularly by Emerging Organic Contaminants (EOCs). Due to the low income of the population in this region, there is often a lack of control over water and fishery resources prior to consumption. Therefore, the current study aims to use EOCs as markers of water resource quality degradation, and to assess the potential environmental risk of these compounds on some aquatic organisms. Among 120 targeted compounds, 66 were detected at 22 sites in Douala city, Cameroon, including 9 rivers and 13 groundwater samples. The detected EOCs were classified into three categories, including pharmaceuticals and personal care products ($n = 55$), lifestyle compounds ($n = 7$) and industrial compounds ($n = 4$). Surface water was highly impacted, with EOC total concentrations reaching 61,273 ng/L, versus 16,677 ng/L in groundwater. Contamination levels and the type of contaminants were closely linked to land use patterns in the study area. Contamination was mainly

attributed to domestic, hospital and brewery's industry wastewaters, landfill and pit latrines. Consumption patterns and physicochemical properties of compounds, in particular their persistence, polarity and octanol/water gradient (K_{ow}), explain their occurrence at high concentrations (up to $\mu\text{g/L}$) in groundwater. According to Risk Quotient (RQ) with a maximum of 93.4 in surface water and 8.5 in groundwater, about 1/3 of the identified compounds pose a serious threat to aquatic organisms, including algae, invertebrates and fish. For the first time in Central African, we revealed these high levels of water contamination by EOCs and identified the risk for the environmental health. Our study demonstrates the urgency to adopt sustainable water management strategies in large cities of the region.

Keywords: Urbanization, EOCs, Surface water, Groundwater, Environmental risk, Land use

Water quality monitoring and risk assessment for Indian coastal Ramsar wetlands

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The growing population, urbanization, industrial development, global warming, and climate change are all impacting ecosystems worldwide. This escalating threat to ecosystems led to the declaration of the decade from 2021 to 2030 as the "Decade of Ecosystem Restoration," with a focus on restoring freshwater and marine ecosystems globally. Ecosystem restoration refers to actions taken to alleviate environmental stressors, allowing ecosystems to recover naturally. According to the United Nations, restoring degraded terrestrial and aquatic ecosystems could generate an economic value of 3 trillion US dollars and reduce greenhouse gas emissions by 13 to 26 gigatons. Monitoring water quality is crucial because it directly affects human health, ecosystem health, and environmental sustainability. In this context, we analyzed extreme precipitation, land use, NDCI, and NDTI indices to monitor chlorophyll levels and turbidity, using Google Earth Engine for 16 coastal Ramsar sites in India. The results show that many of these wetlands face challenges such as encroachment, eutrophication, and wastewater infiltration, which make them vulnerable to the restoration of aquatic ecosystems. The risk assessment reveals that these wetlands generally face low to moderate risks regarding the health of their aquatic ecosystems.

Keywords: Aquatic Ecosystem, Coastal Ramsar Wetlands, Water Quality, LULC, Risk Assessment

Study on the Effect of Underlying Surface Changes on Runoff Generation in the Urbanized Watershed

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In order to address the problem of coordinated flood forecasting in the urbanized watershed, this study proposes a framework for discriminating easily occurring runoff component, which considers vertical spatial heterogeneity based on soil type, land use type and topographic slope, and integrates a Grid-based Runoff Generation Model (GRGM). Taking the control watershed of Jialu River at Zhongmou station (including the central city of Zhengzhou) as the study area, on the basis of GRGM model tests based on 11 observed rainfall-runoff events, the spatial and temporal evolution of runoff components in the study area from 1980 to 2020 and their correlation with the underlying surface changes are explored. The study reveals that: a. the average relative error of the runoff generation calculation by GRGM model in the study area is reduced by 27.76% and the average coefficient of determination is increased by 0.11 compared with Horton Infiltration (HI) model, which means GRGM model are more accurate. b. The percentage of excess surface runoff (Rs) in the central city increased significantly from 22% to 67%, and showed a trend of expansion from the central city to the suburbs. c. The land use types have changed significantly, mainly manifested as a substantial reduction of cropland and a sharp expansion of construction land. Rs is significantly positively correlated with construction land, and the Pearson correlation coefficient exceeds 0.93. The study findings can serve as a scientific basis for coordinated management of flood prevention and disaster reduction in the urbanized watershed.

Keywords: Runoff component discrimination, underlying surface changes, GRGM model, watershed-urban complex system, correlation analysis

Complex Network-based Analysis of Water Quality Dynamics in the Mississippi River

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The spatial dynamics of water quality in rivers are complex and are shaped by environmental conditions and pollution sources, including point and nonpoint contributions. This study investigates the spatial dynamics of river water quality using complex network theory. Daily water quality data of eight key parameters (Alkalinity, Ammonia, Nitrate, Calcium, Chloride, Sulfate, Total Phosphorus, and Total Dissolved Solids) observed over the period 1972-2012 at 50 monitoring stations within the Mississippi River basin are analyzed. For each parameter, each of the 50 stations is considered as a node in the network and the presence of a link between any node pair is identified using the spatial correlation threshold. Clustering coefficient, degree centrality, and shortest path length measures are used to examine the spatial connections. Furthermore, the study also explores the influence of correlation threshold on the identification of links between the stations. The results generally indicate localized clusters and stronger connectivity. The high clustering coefficient values (in the

range of 0.70-0.90) obtained for several of the parameters suggest that the water quality network is not a purely random graph but may be small-world. However, the high average centrality values (0.64) suggest that the stations are more connected, and the low average shortest path length values (1.33) also suggest greater potential for information transfer in the network. The outcomes from this study are useful for further advancing our understanding of the spatial dynamics of water quality in rivers.

Keywords: Water quality, Spatial analysis, Complex networks, Clustering coefficient, Degree centrality.

Groundwater in flux: A comprehensive analysis of water quality in the Gomati River Basin

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Anthropogenic activities have led to groundwater contamination, which has become a serious concern. Therefore, analyzing water quality is crucial to preserving and protecting the natural ecosystem. This study aims to assess the Water Quality Index (WQI) of groundwater in Gomati River Basin. Monitoring of the water quality of ground water is done by collecting representative water samples and analysis of physicochemical characteristics of water samples at different locations of Gomati River Basin Estimation of water quality index through formulation of appropriate using method and evaluate the quality of tube well water by statistical analysis for post and pre-monsoon seasons.

This study provides a comprehensive assessment of the groundwater quality and hydrochemical evolution in the Gomati River Basin over a five-year period (2018-23). A detailed statistical and hydrogeochemical analysis was conducted on 386 groundwater samples collected during pre-monsoon and post-monsoon seasons. Key findings include a shift in the dominant water type from mixed (Ca^{2+} - Mg^{2+} - Cl^-) and (Ca^{2+} - Na^+ - HCO_3^-) to predominantly (Ca^{2+} - HCO_3^-), indicating an overall improvement in groundwater quality. The Piper plot further confirms this trend, showing a transition towards freshwater with a reduced influence of ion exchange and weathering processes. The Gibbs plot highlights rock dominance as the primary factor influencing groundwater chemistry, with evaporation-precipitation processes acting as secondary contributors. The study emphasizes the importance of ongoing water quality monitoring, with the WQI serving as a valuable tool for tracking changes in groundwater quality. These findings underscore the importance of continuous monitoring and proactive management to ensure the sustainability of groundwater resources in the Gomati River Basin. The improvements in water quality over the last five years reflect the positive impact of effective groundwater management practices, providing insights that can inform future water resource policies and strategies in Eastern Uttar Pradesh.

Keywords: Groundwater, Water Quality Index, Remote Sensing and GIS, Gomati River Basin

Fate of organo-arsenic compounds in the environment

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Arsenicosis or arsenic poisoning in groundwater is an environmental calamity affecting millions of people globally per annum. There are a lot of scientific research has been done on inorganic arsenic in groundwater, but research on the organo-arsenic contaminants in the groundwater system is limited. Roxarsone (4-Hydroxy-3-nitrophenyl arsonic acid) (ROX) and P-arsanilic acid (4-aminophenyl arsonic acid) (PAA) are two organo-arsenic compounds used as feed additives to improve the quality and pigmentation of meat in poultry and swine farms. In this study, the sorption of these two organo-arsenic species on naturally occurring iron colloids, hematite, magnetite, and maghemite, and clay colloids, bentonite, and kaolinite, was done for the groundwater matrices. The iron colloids were synthesized in the laboratory by wet chemical precipitation methods. The clay colloids used in this study were from Molychem India (LR grade) and used without any further processing. Magnetite showed the highest sorption in the case of both ROX and PAA, with the sorption capacity of 55.9% and 59.6%, respectively. Sorption percentages by maghemite for ROX and PAA were nearly 54.5% and 57.1%, respectively. Among the iron colloids, hematite had the lowest sorption for both ROX and PAA, 18.1% and 18.7%, respectively. The sorption capacities of both ROX and PAA are in decreasing order as follows: Magnetite > maghemite > hematite. The clay colloids had zero to minimal interactions with the ROX and PAA. Kaolinite had a very low sorption capacity of 3.1% for PAA. Bentonite had zero sorption of both ROX and PAA. The lower to negligible sorption of both ROX and PAA by the most common naturally occurring clay colloids in groundwater aquitards suggests leaching and transport of these organo-arsenic contaminants of anthropogenic sources to the subsurface and eventually to the deeper groundwater systems, posing a potential threat to the groundwater contamination and environmental hazard.

Keywords: Organoarsenic contaminants, Roxarsone, P-arsanilic acid, fate, sorption, iron colloids, clay colloids, groundwater contamination.

Hydrogeochemistry, Enrichment Mechanism and Health Risk Assessment of Groundwater Fluoride in Karaga District of the Northern Region, Ghana

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Groundwater serves as a vital source of drinking water for the inhabitants of the Karaga District in the Northern Region. However, elevated levels of fluoride (F⁻) in groundwater can pose significant health risks, including dental and skeletal fluorosis, particularly in regions with high natural fluoride concentrations. This study investigated the hydrogeochemical characteristics, enrichment processes,

and potential health risks associated with groundwater F⁻ within the Karaga District utilizing hydro-geochemical graphing, geochemical modelling, multivariate statistical analysis, and computation of water quality indices. The key findings revealed that Na⁺, with concentrations ranging from 1.2 to 2144 mg/L, with an average of 183.53 mg/L, is the major cation in groundwater, while HCO₃⁻, with concentrations ranging from 19.7 to 520 mg/L and an average of 310.38 mg/L is the major anion in groundwater. The F⁻ concentrations in groundwater range from 0.07 to 6.04 mg/L, with an average of 1.34 mg/L. The dominant water type is Na-HCO₃ type, making up to 61.76% of the study area's groundwater and is influenced by ion exchange reactions, silicate weathering, and mineral dissolution processes. Other factors accounting for this dominance may be anthropogenic activities, including leaching of fertilizers from farmlands. The F⁻ enrichment is due to mineral dissolution and ion exchange reaction. Overall, this study reveals that the groundwater in the area is generally of poor quality based on Water Quality Index (WQI) classification and children are the hypersensitive population with respect to the non-carcinogenic risk of F⁻. Therefore, there is the need for the treatment of groundwater before ingestion in areas with high F⁻ concentrations.

Keywords: hydrogeochemistry, groundwater, contaminant sources, geogenic fluoride, health risks, water quality index

A Comprehensive Groundwater Assessment in parts of Chhota Nagpur Gneissic Complex: Evaluating Groundwater Potential, Hydrogeochemistry, and Public Health Risks

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Groundwater contamination with sub-lethal dissolved contaminants is a critical challenge to human health around the globe. The Chhota Nagpur Gneissic Complex, in the East Indian Shield, is a complex geological terrain which faces groundwater shortage and quality issues. This study aims to identify groundwater potential zones using geospatial techniques, determine hydrogeochemical characteristics, and evaluate health risks of shallow aquifer groundwater in the Chhota Nagpur Gneissic Complex. The in-situ physio-chemical parameters (pH, EC and temperature) were measured using portable meters and major ions were analysed using Ion Chromatograph. Different thematic layers were processed under GIS environment to generate groundwater potential map using MCDM (Multi Criteria Decision Making) model. Different were used to interpret the hydrogeochemical processes operating in the study area. The USEPA (U.S. Environmental Protection Agency) approach was used to evaluate human health risk assessment. Analysis of hydrogeochemical data suggests the presence of Ca-Na-HCO₃, Ca-Mg-Cl, Ca-HCO₃ as dominant water types in the study area. All the ionic species are within the permissible limits of the World Health Organization, except fluoride (F⁻) and nitrate (NO₃⁻). Geochemical analysis using bivariate relationships and saturation plots attributes the occurrence of F⁻ to geogenic sources which are primarily from the chemical weathering of granite-granodiorite. Multivariate statistical analyses, including hierarchical cluster analysis and

factor analysis, confirm the predominance of geogenic controls, with NO₃- enriched samples derived from anthropogenic factors. The MCDM gave different groundwater potential zones. It is inferred that regions with poor to unsuitable water quality indices also have low GWPZ. The integration of the USEPA human health risk assessment methodology with the urbanization index has revealed critical findings regarding study area as being at high risk. The results highlight the pressing need for targeted mitigation measures and the implementation of sustainable groundwater management practices at regional, national, and global levels.

Keywords: Groundwater potential zone, groundwater quality, multivariate statistical analysis, fluoride and nitrate contamination, USEPA approach, and mitigation

Unraveling Agricultural Non-Point Source Pollution in the Hindon River Basin: A SWAT+ Model Approach

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The Hindon River, a major tributary of the Yamuna, is among the most polluted rivers in the Indo-Gangetic plains. Its water quality has deteriorated to critical levels, prompting the CPCB to classify multiple sections of the river as dead. While industrial pollution has been extensively studied, agricultural non-point source pollution remains largely overlooked. This study addresses this gap using a grid-based SWAT+ model to assess the impact of agricultural activities on water and soil quality by simulating climate, crop growth, soil dynamics, and water-nutrient interactions.

Model results were validated through in-situ water and soil sampling, along with farmer surveys to integrate local agricultural practices into the modeling process. Surveys revealed that farmers apply nearly three times the recommended fertilizer doses. However, modeling results indicate that less than 20% of applied fertilizer is absorbed by plants, with most lost through denitrification. This is likely due to irrigation immediately after fertilization, which creates anaerobic soil conditions, enabling facultative anaerobic bacteria to use nitrate as an electron acceptor, releasing N₂O and N₂. Surface runoff accounts for less than 7% of total water input, resulting in minimal nitrogen transport to surface water. However, nitrogen is accumulating in the soil at a rate of 260 kg/ha annually, contributing to long-term nitrogen transport through groundwater pathways.

Water balance analysis shows that groundwater irrigation averages 291 mm annually, while percolation is only 190 mm, leading to annual deficit of 100 mm and a steady decline in groundwater levels. These findings highlight the urgent need to optimize agricultural practices by improving fertilizer application methods and promoting the conjunctive use of surface and groundwater for irrigation to ensure sustainable water management and mitigate groundwater depletion.

Keywords: Water balance, Nutrient balance, Sustainable water management, SWAT+ modeling, Conjunctive water use

WISE: a watershed-scale carbon budget calculator

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Current watershed models have limitations in representing carbon cycling processes, hindering their applicability to new scenarios such as watershed-scale carbon budget calculation. To address this, our team developed WISE (Watershed-based Integrated Simulator for the Environment), a model that significantly enhances the representation of carbon cycling processes in soil and inland waters, as well as freeze-thaw, glacier, and snow melting processes in cold regions. With WISE, we can go beyond traditional applications in water resource planning and water quality control, and calculate watershed-scale carbon budget accounting for lateral carbon transfer under the impacts of climate change and human activities.

Keywords: Watershed modeling, Carbon cycling, Spatially explicit

Interconnected Carbon Systems: Dissolved Organic and Inorganic Carbon in River and Groundwater of a Delta

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Dissolved organic and inorganic carbon in natural waters play an important role in studying carbon dynamics. Cauvery River is a major south Indian river, and an attempt has been made to determine the interconnection between the river and groundwater based on water quality and carbon content. The water samples were collected periodically and analyzed for EC, pH, ionic concentrations, Dissolved Organic(DOC), and Inorganic Carbon(DIC). The concentration increases during the dry season for both river water and groundwater, where erratic variation was observed in river water compared to the wet season. This variation in the dry season could be due to low flow in the river, which indicates that the flow in the river plays a vital role in the variation of DIC in the river and groundwater. The concentration of DOC was observed to be high during the river flow conditions compared to dry periods. Also, groundwater was found to have a lesser concentration than river water since DIC dominates in groundwater and the microbial effects are usually diminished. The pCO₂ values were also higher than most temperate rivers and equal to tropical streams. DOC's spatial and temporal variations in river systems are linked to hydrological processes and biological activity. DOC concentrations exhibit seasonal fluctuations, with higher levels during the wet season due to increased surface runoff, transports organic matter from terrestrial sources into rivers. Conversely, lower discharge rates limit organic matter inputs during the dry season, resulting in lower DOC concentrations. These findings highlight the importance of hydrological conditions and land-use practices in shaping carbon fluxes and provide a comprehensive understanding of DOC dynamics in river systems.

Keywords: Groundwater, river water, quality, carbon

Adsorption and Release Behaviour of Herbicide 2,4-Dichlorophenoxyacetic Acid by High Surface Area Polymeric Adsorbent

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2,4-dichlorophenoxyacetic acid (2,4-D), a commonly used herbicide known for polluting water bodies, can be effectively removed from its aqueous solution using a nanoporous hypercrosslinked polymer (poly-biph) as an adsorbent. Batch, column, and membrane separation methods were employed, leaving behind treated water within the allowed limits (< 70 ppb) set by the USEPA. The adsorbent, poly-biph, possessing hierarchical nanopores and a high specific surface area ($S_{\text{ABET}} = 1056 \text{ m}^2 \text{ g}^{-1}$), was synthesized by hypercrosslinking a carcinogenic monomer, biphenyl. In the batch adsorption method, a maximum adsorption capacity of 849 mg g^{-1} was estimated at pH 7 within 90 minutes. In a continuous fixed-bed column mode, 2.5 L of herbicide solution was treated, achieving the permissible limit up to 40 minutes with a breakthrough capacity of 15 mg g^{-1} . In the membrane filtration method, 5 L of safe drinking water was sustained for up to 150 minutes at a pressure of 2 bar and a permeate flux of $65 \text{ L m}^{-2} \text{ h}^{-1}$, achieving a maximum removal efficiency of 98.4%. The efficient adsorption was attributed to the pore-filling effect and π - π interactions between the adsorbent and adsorbate molecules. Beyond adsorption, controlled release of 2,4-D in aqueous environments is a critical factor for its use as a herbicide in agricultural land. A sustained and slow release minimizes overutilization and reduces the risk of unwanted discharge into water bodies. In this investigation, poly-biph demonstrated the capacity to retain 2,4-D for over a month, with only minimal release—sufficient to eliminate unwanted herbs.

Keywords: Herbicide, Nanoporous hypercrosslinked polymer, Batch adsorption, Mixed matrix membrane, Fixed-bed column, Slow release

Isotopic and Geochemical Characterization of Water Contamination in and Around an Abandoned Mine in the Northern Singrauli Coalfield, India

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A comprehensive hydrogeochemical, trace metal, and stable isotopic investigation was conducted in the abandoned mines of Northern Coalfields Limited (NCL), Singrauli, India, to identify the sources and mechanisms of contaminant mobilization in acid mine drainage (AMD) and the surrounding groundwater. The AMD pit water exhibits a highly acidic pH of 2.7 and elevated total dissolved solids (TDS) of 1270 mg/L, indicating severe contamination. In contrast, the groundwater samples show a neutral pH of 6.8, reflecting relatively unaltered conditions. Hydrochemical facies analysis reveals that groundwater is predominantly of the Ca-HCO₃ type, while AMD samples are characterized by a Ca-SO₄-Cl type. This shift suggests geochemical evolution from groundwater to AMD, primarily driven by the dissolution of sulphate-bearing minerals from the host rock. Precipitation is the main source for all water samples, with most groundwater plotting along the LMWL. In contrast,

AMD samples deviate, showing evaporative enrichment, as confirmed by $\delta^{18}O$ vs δ^2H and d-excess plots indicating prolonged atmospheric exposure. Trace metals such as aluminium, nickel, manganese, zinc, barium, and strontium exceed BIS (2012) limits. Aluminium exceeds safe limits in 75% of groundwater and 100% of AMD samples, while nickel surpasses the limit in 25% of AMD samples mainly due to leaching from aluminium bearing minerals and pyrite through sulphide oxidation. Fluoride levels in 80% of all samples also exceed permissible limits, attributed to geogenic sources like biotite schist and granitic gneiss. Consequently, these waters are unfit for drinking. WAWQI analysis classifies 60% of groundwater samples as Grade E, indicating poor quality. The study highlights the combined role of geological and anthropogenic factors in driving the sources and ionic mobilization of contaminants in groundwater and acid mine drainage (AMD). This poses a significant risk to nearby water resources and public health, underscoring the need for effective mitigation and sustainable water management.

Keywords: Ionic mobility, stable isotopes, trace metals, AMD, fluoride

Assessing the Impact of Physiochemical parameters on micro-plastic movement through Porous media.

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The widespread presence of microplastics (MPs) in terrestrial environments, particularly soils, has raised growing environmental concerns due to their persistence, transport behaviour, and ecological risks. This study investigates the vertical transport of microplastics (MPs) in porous media to assess their potential to contaminate groundwater systems. The different MPs polymers, such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), were introduced at the top layers of the sand column with the known hydrogeological properties, including specific gravity, porosity, and permeability. Infiltration solutions of different ionic strengths were introduced to represent variation in physico-chemical properties, the flow rate was controlled, and the infiltrant was collected. The differences in the microplastics introduced and obtained at the end of the experiment reflect the transport and retention of the microplastics in the soil column. Results show that the movement of microplastics is higher when the infiltrating solution has a lower ionic strength. This controlled column study offers valuable insight into the mobility of microplastics in the vadose zone and highlights their potential to reach and impact shallow groundwater, posing emerging threats to groundwater quality and ecosystem health.

Keywords: Microplastics, Porous media, Physiochemical properties, Transport and Retention

Waste to Worth: Eco-friendly remediation for removal of synthetic dyes, pharmaceuticals, and toxic metals using carbonaceous absorbents derived from sewage sludge waste

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This research focuses on the potential of sewage sludge-derived different carbonaceous materials as highly efficient products, i.e., hydrochar, biochar, and charcoal, as an adsorbent for the treatment of wastewater in a way that reduces water pollution and saves resources. Sewage sludge samples were collected from two different sewage treatment plants (68 MLD SBR and 18 MLD ASP reactor) at Jagjitpur, Haridwar. The dried sewage sludge was converted into hydrochar, biochar, and charcoal using different processes like hydrothermal carbonization and pyrolysis at temperatures of 180°C, 450°C, and 900°C, respectively.

The adsorption capacity of all carbonaceous materials was evaluated against a wide range of contaminants, including synthetic dyes (Congo red, crystal violet, malachite green, and methylene blue), pharmaceutical compounds (ciprofloxacin), and toxic heavy metals (cadmium, chromium, nickel, and arsenic). The adsorption behavior was analyzed at different pH conditions and across different types of waters. The adsorption behavior was investigated under varying pH conditions and across different water matrices to simulate current environmental water-related issues in the real world. Among the three carbonaceous materials, hydrochar and charcoal exhibited the highest adsorption efficiency, with optimized conditions achieving > 90% removal for most of the contaminants but a large difference in synthesis temperature. Therefore, despite the similar performance hydrochar can be preferred due to its lower energy demand, easier synthesis process, and potential for better environmental compatibility. This research study shows that all developed carbonaceous materials can be further used to remove pollutants from the different water bodies for multiple treatment cycles.

The result indicates that all three carbonaceous materials made from sewage sludge feed have high potential to be eco-friendly, low-cost, and reusable adsorbents for wastewater remediation. The method helps reduce dye pollution and sludge waste by utilizing waste as a resource, following the circular economy, and supports environmental management.

Keywords: Hydrochar, biochar, charcoal, adsorption, wastewater treatment, heavy metals, hydrothermal synthesis

SMARTWATER High Frequency Monitoring of Water Quality from an Urban River

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Water pollution is an escalating global issue, with many rivers failing to meet established water quality standards. To comprehend the underlying causes, adapt strategies, and develop improved mitigation approaches, it is important to gain an understanding of average pollution conditions, as well as understanding pollution spikes.

The SMARTWATER project (NERC-NSF funded) aims to develop innovative solutions for diagnosing multi-contaminant water pollution hotspots (spatial) and hot moments (temporal). A focus of the work is the use of in-situ high frequency sampling at 5-minute intervals in the urban setting (River Tame catchment) to generate detailed datasets, allowing for understanding key drivers of water quality dynamics.

The project integrates commercially available sondes are paired with low-cost proxy sensors to create dense observation networks. Real-time data transmission via LoRaWAN enables continuous monitoring of river system dynamics. This approach yields a much richer understanding of pollution behaviour and system variability. The methodologies and insights from this research will be openly shared with the hydrology and water quality research community.

Keywords: Water Pollution, Hydrology, Urban, High Frequency, Sensors, Networks,

Impact of agro-industrial expansion on heavy metal contamination in water resources of a poorly gauged basin

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Rapid agro-industrial growth has intensified heavy metal contamination in ungauged areas by drastically changing land use and water quality. It is still unclear how to continuously monitor heavy metal pollution under the combined influence of urban wastewater, agricultural runoff, and industrial discharge. This study has assessed the effects of agro-industrial expansion on water resources by combining land use change analysis, hydrological modeling, and hydrogeochemical assessment. Initially, remote sensing data were used to identify land use change from 2005 to 2023. Subsequently, hydrological modeling was performed from 2010 to 2023 to quantify the changes in water balance components. In 2023, seasonal water sampling was conducted at 58 locations, where heavy metals, major ions, and physicochemical characteristics were analyzed. Based on the analysis, it has been observed that between 2005 and 2023, built-up and agricultural land increased by 1.5% and 0.5%, resulting in a 2% decrease in bare land and additional strain on water supplies. These land use changes have developed hydrological consequences, as revealed by hydrological modeling. Industrial water extraction and agricultural irrigation activities have been identified as the primary drivers of a 40% decline in groundwater recharge and a 41% reduction in water yield. These

hydrological alterations likely contribute to pollutant accumulation and water contamination. Complementing these findings, water quality analysis shows that all water samples have exceeded the permissible aluminum levels, while post-monsoon manganese contamination has affected 100% of groundwater and 96% of surface water samples. Cadmium and mercury concentrations were notably high in groundwater during the post-monsoon season, with mercury exceeding safe limits in all samples. Nitrate has also exceeded the limits in 64% of surface water and 12% of groundwater samples. To mitigate long-term environmental concerns in agro-industrial areas, these findings underscore the need for enhanced pollution control, improved wastewater treatment, and sustainable water management practices.

Keywords: Agro-industrial region, Heavy metal contamination, Hydrological modeling, Land use change, Surface water

Impact of agro-industrial expansion on heavy metal contamination in water resources of a poorly gauged basin

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Rapid urbanization and population growth in Greater Hyderabad, Telangana, have significantly impacted urban lake ecosystems, leading to deteriorating water quality due to increased climatic and anthropogenic pressures. Lakes serve as sensitive indicators of environmental change, and monitoring Dissolved Organic Matter (DOM) provides valuable insights into the impacts of urban development and climate variability. This study examines DOM characteristics and water quality in 25 urban lakes within the Greater Hyderabad Municipal Corporation (GHMC) area. Field surveys were conducted during the pre-monsoon and late monsoon seasons of 2019 to capture seasonal variations, particularly during an unusually wet monsoon. Parameters analyzed include dissolved organic carbon, nutrient concentrations, and major ions such as NO_3^- , SO_4^{2-} , HCO_3^- , and K^+ , which reflect changes in hydrology and pollutant sources. Findings show that DOM levels and nutrient loads have steadily increased from 2019 to 2022, indicating growing pollution from municipal sewage, industrial effluents, and agricultural runoff. Comparative analysis of lake water before and after the monsoon seasons reveals a consistent rise in nutrient concentrations across all lakes, suggesting a sustained increase in domestic and agricultural inputs. While nitrate, sulphate, and bicarbonate levels generally decreased post-monsoon, likely due to dilution, potassium concentrations rose, potentially reflecting greater agricultural runoff during the rainy season. Multivariate statistical techniques were used to classify lakes based on the degree of degradation. Lakes near industrial and densely populated zones showed the most deteriorated water quality, while those on the outskirts of the GHMC area were less impacted. The results highlight the dual influence of climatic variability and human activity on lake ecosystems and the importance of DOM as a key indicator of water quality changes. This study emphasizes the urgent need for sustainable urban lake management strategies to mitigate pollution and preserve aquatic ecosystems. Understanding DOM dynamics in relation to land use and hydrological shifts is essential for developing effective policies to protect urban lakes in rapidly growing cities like Hyderabad.

Keywords: Urbanisation, Greater Hyderabad, lakes, Dissolved Organic Matter, Nitrates

Impact of agro-industrial expansion on heavy metal contamination in water resources of a poorly gauged basin

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Rapid agro-industrial growth has intensified heavy metal contamination in ungauged areas by drastically changing land use and water quality. It is still unclear how to continuously monitor heavy metal pollution under the combined influence of urban wastewater, agricultural runoff, and industrial discharge. This study has assessed the effects of agro-industrial expansion on water resources by combining land use change analysis, hydrological modeling, and hydrogeochemical assessment. Initially, remote sensing data were used to identify land use change from 2005 to 2023. Subsequently, hydrological modeling was performed from 2010 to 2023 to quantify the changes in water balance components. In 2023, seasonal water sampling was conducted at 58 locations, where heavy metals, major ions, and physicochemical characteristics were analyzed. Based on the analysis, it has been observed that between 2005 and 2023, built-up and agricultural land increased by 1.5% and 0.5%, resulting in a 2% decrease in bare land and additional strain on water supplies. These land use changes have developed hydrological consequences, as revealed by hydrological modeling. Industrial water extraction and agricultural irrigation activities have been identified as the primary drivers of a 40% decline in groundwater recharge and a 41% reduction in water yield. These hydrological alterations likely contribute to pollutant accumulation and water contamination. Complementing these findings, water quality analysis shows that all water samples have exceeded the permissible aluminum levels, while post-monsoon manganese contamination has affected 100% of groundwater and 96% of surface water samples. Cadmium and mercury concentrations were notably high in groundwater during the post-monsoon season, with mercury exceeding safe limits in all samples. Nitrate has also exceeded the limits in 64% of surface water and 12% of groundwater samples. To mitigate long-term environmental concerns in agro-industrial areas, these findings underscore the need for enhanced pollution control, improved wastewater treatment, and sustainable water management practices.

Keywords: Agro-industrial region, Heavy metal contamination, Hydrological modeling, Land use change, Surface water

HyEco: An Integrated Hydrodynamic–Ecological Model to Quantify Human Health Risks from Contaminated Floodwaters in Climate-Sensitive Urban Megacities

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This study presents *HyEco*—a hybrid modelling framework that integrates a high-fidelity, three-way coupled hydrodynamic and ecological modelling system. The framework is designed to concurrently capture both explicit, tangible flood hazards and latent, intangible public health risks. The approach is demonstrated over Delhi, India, a densely populated and flood-prone megacity, by simulating the catastrophic 2023 flood event. Results indicate that approximately 63.5% of the urban area falls within “high” to “very high” flood risk zones, with nearly 15% of the city’s population residing in the most vulnerable 20% of these zones. Outputs from the hydrodynamic model were utilized to drive the ecological model, enabling the simulation of microbial fate and transport in floodwaters. Estimated concentrations of *Escherichia coli* ranged from 772,868 to 790,000 MPN/100 mL, substantially exceeding public health safety thresholds.

Keywords: Flood risk, Human-health risk, Urban Flooding, Hydrodynamic modelling, Water quality modelling

Water Resources Systems (ICWRS)

Drivers of inter-event variability of recession flow characteristics

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Recession flow is the baseflow generated during non-rainy periods. The characteristics of recession flows are known to show significant inter-event variability, which reflects the dynamic changes in baseflow generation mechanisms in watersheds. The objective of this study is to quantify the variability of recession characteristics in watersheds in terms of physically interpretable metrics and to understand its underlying physical drivers. We use a parallel decay model which conceptualizes a watershed storage as a set of parallel linear reservoirs generating recession flows. We use inverse Laplace transform to estimate the number and residence times of watershed storage components contributing to flow in each recession flow event. We apply the methodology to watersheds of the United States (US) and peninsular India and analyse the spatial patterns of inter-event variability of recession characteristics. We use random forest models to analyse the physical drivers of inter-event variability of recession characteristics for across diverse physical conditions. Finally, recommendations are provided for adequate structure and parametrization of hydrologic models in different physical conditions to capture the inter-event variability of recession flows.

Keywords: Recession analysis, baseflow, random forest, watershed storage

Drivers of the seasonal slow-flow variability in a mountainous catchment

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Seasonal slow-flow variability in mountainous catchments is influenced by snowmelt, precipitation patterns, and groundwater recharge, leading to fluctuating streamflow rates throughout the year. This variability can significantly impact the sustainability of streamflow, affecting water availability for ecosystems, agriculture, and hydropower generation during low-flow periods. Besides the main drivers, topography, soil, climate, energy, geology, and vegetation changes influence the slow-flow variability in mountainous catchments. These factors regulate the timing and volume of baseflow, which sustains streamflow during dry periods, with snowmelt and seasonal precipitation playing crucial roles in flow retention and release. Therefore, predicting their seasonal timing and identifying their key drivers is valuable. The timing of slow-flows differs between regions, but comprehensive assessments across Himalayan mountain regions remain scarce. This study identifies regional patterns in the seasonal variability of annual minimum flows from Himalayan mountainous catchments. It investigates the extent of major drivers responsible for the seasonal variability of slow-flows from the glaciated and non-glaciated mountainous catchments of Nepal Himalayas. The analysis identifies the dominant factors that significantly impact the seasonal variability of slow-flows. The analysis investigate concurrent trends in slow-flows and the influence of precipitation, energy, vegetation (leaf

area index), soils, snow dynamics, and depth to bedrock, providing essential insights for sustainable water resource management and climate change adaptation. The findings underscore the link between slow-flow variations and the driving parameters. The study offers valuable insights for sustainable water resource management and climate and human-induced change adaptation, stressing the need to manage mountainous river flows.

Keywords: Slow-flows, Nepal Himalayas, Seasonal variability of slow-flow, Slow-flow sensitivity to warming and Drivers of slow-flow

Enhancing the SWAT+ Reservoir Simulation Using Simulated Annealing Optimization in the Cedar Creek Watershed

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Reservoirs play a critical role in water resources management, serving multiple purposes such as flood control, irrigation, municipal water supply, and hydropower generation. Accurate reservoir simulation is crucial for capturing the water balance dynamics of a watershed using hydrological models. The Soil and Water Assessment Tool (SWAT) and its advanced version, SWAT+, are widely used hydrological models for catchment-scale hydrological modelling. SWAT+ introduces a decision table, enabling a detailed representation of reservoir operational dynamics. However, incorporating operational dynamics into macroscale models is often constrained by proprietary or region-specific data. In SWAT+, the characteristic relationships, including elevation-storage and elevation-area curves, were incorporated using the reservoir's shape parameters, improving the accuracy of surface area simulation. This study applies simulated annealing optimization to calibrate key parameters in the SWAT+ reservoir module and decision table, replacing default values with those that better represent the complexities of operational rules. The accuracy of SWAT+ in simulating reservoir outflows, storage dynamics, and evaporation loss are found to be improved by calibrating six parameters—two from decision tables and four from reservoir hydrology. The proposed approach is validated in the Cedar Creek Reservoir in Texas, USA by using Simulated Annealing. The optimization led to substantial improvements in Kling-Gupta Efficiency (KGE) values: 0.71 for outflow, 0.85 for storage, and 0.61 for evaporation loss, outperforming default simulations. The results demonstrate that simulated annealing provides a robust and adaptive framework for optimizing reservoir operations, offering significant potential for more realistic water resource management in complex hydrological systems.

Keywords: SWAT+, Decision table, Reservoir optimization, Simulated Annealing

Clustering Catchments by Low Flow Behavior: An Unsupervised Learning Approach

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Low-flow hydrology is essential for water resource management, ecological sustainability, and drought resilience. This research utilizes an unsupervised learning methodology to separate catchments according to their low flow characteristics, pinpointing essential hydrological, meteorological, and physiographic factors. A dataset containing streamflow records from various catchments was examined utilizing statistical and hydrological indicators, including the Flow Duration Curve (FDC), Base Flow Index (BFI), flow percentile ratios, and 7-day minimum flows. Clustering approaches were utilized to categorize catchments exhibiting comparable low-flow responses, taking into account factors like as geology, land use, and precipitation patterns. The results indicate clear watershed typologies, wherein permeable substrates and dense vegetation facilitate consistent low flows, whereas impervious landscapes demonstrate increased variability. The utilization of unsupervised learning improves the objectivity of classification, offering data-driven insights into low-flow dynamics. These results are significant for water security, especially in areas susceptible to seasonal droughts. This research enhances the comprehension of low-flow hydrology and highlights the capabilities of data-driven techniques in hydrological classification.

Keywords: Low flow hydrology, Water Availability, Unsupervised Classification, Catchment characteristics

Advancing the Quantification of Water Resources using Coupled Hydrological model - Water Accounting Approach

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Sustainable water use and management have become more challenging due to rising populations and climate change. Water Accounting Plus (WA+) has emerged as a widely used tool for tracking water use and availability. However, it has limitations in hydrological simulations due to its inability to incorporate channel routing, reservoir operation, and calibration. To overcome these limitations, we combined the Water Accounting (WA) framework with the Spatial Processes in Hydrology (SPHY) model and developed SPHY-WA framework. This combined method uses global and regional datasets to provide detailed water accounting. The developed framework has been applied in the Tapi basin, from 2003-2020. Compared to the WA+ approach, the developed framework provides a more accurate representation of regional hydrology through calibration and validation using observed streamflow data, resulting in improved performance. The Nash-Sutcliffe efficiency (NSE) has significantly improved, increasing from -0.13 to 0.90 at the Burhanpur (upstream) station, and from -2.90 to 0.72 at the Sarangkhedha (downstream) station. The findings of the study shows that freshwater storage is found to be depleted by 83% and 98% of water utilized by the basin itself, leaving limited renewable water resources. water scarcity indicator (WSI) was calculated for all districts, showing widespread severe water scarcity (WSI = 1) due to the imbalance between water demand

and supply. We have identified the status of water scarcity in the Tapi basin spatially by determining water scarcity index (WSI), highlighting severe water scarcity ($WSI = 1$) due to the higher disparity between demand and supply. Overall, the developed SPHY-WA framework provides more reliable and accurate water account estimates than the traditional WA+ approach, which can help for sustainable water management and policymaking by providing more precise information for addressing water and food security.

Keywords: SPHY model, Water Scarcity, Water Accounting

Seasonal forecast of streamflow and suspended sediment in the Blue Nile Basin, Ethiopia

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The demand for seasonal hydrologic forecasts is significant and various applications for water resources management are increasing. Since some years, the lead time is going up to several months or a season. However, the uncertainty is also increasing with lead time.

This contribution assesses the potential of seasonal streamflow and sediment forecasting as a tool for management of water resources and sediment flow in the Upper Blue Nile Basin (UBNB) of Ethiopia, upstream the GERD (Great Ethiopian Renaissance Dam). A coupled hydro-meteorological seasonal forecasting system requires a performance evaluation of both numerical weather prediction (NWP) models and hydrological models to accurately represent atmospheric and hydrological conditions. We evaluate the ECMWF-SEAS5 precipitation product in conjunction with the large-scale process-oriented hydro-sedimentological model WASA-SED. The aim is to generate forecasts for streamflow and suspended sediment fluxes with a lead time of up to seven months for the UBNB, with the largest reservoir in Africa, GERD, with a total capacity of 74×10^9 m³ at its downstream end. Three different large-scale rainfall "products" were tested and compared ref. their representativity of observed rainfall. We show that such a rainfall evaluation is indispensable for hydrological simulation as well as for seasonal forecasting. We consider this step a "hydrological verification" of rainfall data.

Seasonal streamflow and sediment flux data were then forecasted for June to December of the year, based on the seasonal meteorological forecast in the preceding month. An ensemble of 51 regional meteorological forecast members in daily resolution and 7 months lead time, each initiating on the first day of each month, was used. A post-processing step with an autoregressive model was applied to adjust for forecast biases in seasonal streamflow predictions. Results indicate that the coupled

meteorological/hydrological models reasonably predict rainfall and discharge on a seasonal scale for the Blue Nile Basin.

Keywords: seasonal forecast, tropical water resources, sediment dynamics, Ethiopia, GERD

Regional Analysis of Drought Characteristics Using Meteorological Drought Indices across India

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Climatic extremes like drought often exhibit significant regional differences, largely influenced by local climatic factors. However, past studies have overlooked the need for models tailored to specific zones. In the Indian context, a single drought index has traditionally been applied across the entire country, ignoring the considerable regional variability, significantly influence local climatic patterns. Droughts are quantified using indices. The commonly used meteorological drought indices metrics including SPI, SPEI, and RDI. This study aims to compare all three at various timescales in terms of temporal characteristics, number of drought events, maximum severity, duration, correlation among indices, and trends in different climatic zones. Ten climatic zones of the Indian subcontinent were identified based on the widely used Köppen climate classification system. Further, drought categories (normal, mild, moderate, severe, or extreme) were determined for three historical monsoon drought years-1972, 1987, and 2002-chosen here for their known significant impact on the country. The index that best captured the severity of these drought years was considered the best-performing index for each zone. The study found that SPI-3 was the most effective index for southern states, Maharashtra, Gujarat, and parts of Madhya Pradesh, Rajasthan, Haryana, and Punjab. Conversely, SPEI-3 was more effective in northern and northeastern regions. RDI-3 has shown up for some parts of Jammu and Kashmir. RDI played a minimal role in identifying historical drought events but showed the highest severity for the extreme drought year of 2002. This suggests that the inclusion of PET (Potential Evapotranspiration) is not sufficient without robust statistical methods in index formulation, as evidenced by regional differences in the performance of RDI and SPEI. The findings of this study provide a better understanding of drought indices and their predictive capabilities, offering valuable insights for monitoring and assessing drought conditions at local scales under diverse climatic conditions.

Keywords: Meteorological Drought, SPI, SPEI, RDI, Climatic Zones

Quantifying Changes in Multi-sectoral Trade-offs for a Large Multipurpose Reservoir under Changing Climatic and Socio-economic Conditions

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The operation of multi-purpose reservoirs requires an understanding of multi-sectoral trade-offs, which are likely to evolve over time in systems undergoing climate and socioeconomic change. In this study, we quantify the trade-offs between three objectives of the Idukki reservoir in southern India under historical conditions and their potential evolution under future climate and socio-economic conditions. The Idukki reservoir is a multi-purpose system designed to generate hydropower, provide irrigation water, and offer flood protection. It supplies approximately 40% of the electricity demand for the state of Kerala, India, while also safeguarding downstream urban areas from flooding. The study evaluates three key objectives, average annual hydropower production, flood reliability at a downstream location, and average annual water deficit, which includes irrigation and domestic water demands. Using the BORG multi-objective evolutionary algorithm, we first identify a Pareto-approximate set of reservoir operation strategies under historical streamflow condition. To account for future changes, reservoir inflows are scaled based on projected changes in the 25th, 50th, and 75th percentiles of flow, as estimated by five CMIP6 General Circulation Models (GCMs) under three Shared Socioeconomic Pathways (SSPs). Irrigation demands are also updated to reflect changing climatic conditions. This method generates an ensemble of possible changes in future inflow and irrigation demands. By simulating the reservoir system using the identified Pareto-optimal strategies, we evaluate how multi-objective trade-offs may evolve under future climatic and socioeconomic conditions. This analysis provides valuable insights into the potential impacts of climate and socio-economic change on reservoir performance, offering a framework for adaptive management in a changing environment.

Keywords: Multipurpose reservoir, Multi-sectoral trade-offs, Pareto-optimal strategies

On the need for capturing historical trend of crop yield in crop models for efficient estimation of crop water use

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The surging population growth, thereby causing increasing demand for food, has kept food security a major concern for India. However, water is key to food security. The growing trends of agricultural production to meet food security shall also impact the land surface water flux. Thus, efficient quantification of crop water use is important for effective planning and management of water under the influence of climate change. The increasing trend of crop yield has been observed over India over the last two decades, owing to crop cultivars and efficient crop management practices. Trend analysis of district-wise yield data for ten crops (bajra, rice, jowar, maize, ragi, barley, groundnut, soybean,

cotton, sugarcane) in India revealed that all crops had a significantly increasing trend over the last two decades. 20% of districts growing ragi crops showed a significantly increasing yield trend, while sugarcane exhibited a significantly increasing trend in 70% of districts. Therefore, the crop models must be capable of capturing these yield trends to ensure precise estimation of crop water use. Incorporating the historical increase in crop yields into crop modelling will enhance the accuracy of crop water use assessments, thereby supporting sustainable water management strategies.

Keywords: crop modelling, crop yield, crop water use

Exploring the Impacts of Hydropeaking on Riverine Ecosystems in India

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Hydropower is a pivotal component of India's renewable energy strategy, offering low-carbon, reliable energy and aiding in grid stability amidst the increasing integration of intermittent sources like solar and wind. This study investigates the economic, environmental, and operational aspects of India's hydropower sector, focusing on both its contributions and the complex challenges it faces, particularly the practice of hydropeaking, which involves adjusting water flow to meet peak energy demands. Hydropeaking disrupts natural river dynamics, affecting sediment transport, aquatic biodiversity, and habitat stability in ecologically sensitive regions such as the Himalayas. A significant focus of this study is the scarcity of high-resolution data on hydrological and ecological patterns, which impedes the sustainable management of hydropeaking's environmental impacts. The COVID-19 pandemic further highlighted both the vulnerabilities and adaptive capacities within India's hydropower sector, providing insights into the resilience of energy infrastructure during demand fluctuations. Through time series and wavelet analysis, this study assesses hydrological data patterns, evaluating hydropeaking's long-term impacts on river systems. Concluding with open research questions, this study emphasizes the need for real-time monitoring systems and community involvement in hydropower management to mitigate the adverse effects of hydropeaking. By integrating innovative technologies like Condition-Based Maintenance, artificial intelligence, and augmented and virtual reality, and prioritizing data-driven, adaptive management strategies, this study advocates for balancing renewable energy benefits with ecological responsibility. These approaches align with India's environmental and energy goals, ensuring that hydropower remains a sustainable and future-ready resource for generations to come.

Keywords: Hydropeaking, hydropower, environmental impacts, hydrological modeling, sustainable water resource management

Temporal dynamics of soil moisture in global land areas: a complex network-based approach

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Soil moisture influences several land and atmospheric phenomena and, thus, it is important to study its impacts on hydroclimatic extremes, especially under climate change conditions. This study uses a complex network approach to investigate the soil moisture dynamics in different climate zones (viz., arid, temperate, polar, continental, and tropical) across the world under climate change conditions. For implementation, soil moisture data simulated at spatial resolution of 1 deg x 1 deg from 37 General Circulation Models (GCMs) over 1948-2014 are considered. For each grid, temporal network of the soil moisture data is constructed. First, the single-variable soil moisture time series is reconstructed in a multi-dimensional phase space using an embedding procedure, and the optimum embedding dimension is identified using the false nearest neighbor (FNN) algorithm. Next, using the reconstructed vectors, temporal network is constructed, with each vector as nodes and connections between them as links. Finally, five different network-based measures are used to identify different properties of the soil moisture network: clustering coefficient, which measures the tendency of nodes to form clusters; betweenness centrality, which gives an extent to which a node acts as a bridge between other nodes; closeness centrality, which gives the proximity of a node to all other nodes; degree centrality, which helps to identify the significance of a node in the network; and shortest path length, which represents the efficiency of a network in exchanging information between nodes. The results indicate regional and climatic differences in temporal networks of soil moisture. In particular, temporal dynamics of soil moisture in arid regions is more complex and less connected, whereas that of tropical zones are more interconnected and efficient. The present results, including complexity levels, temporal dependencies, critical nodes, and data flow efficiency, also offer key insights into how soil moisture patterns evolve and interact over time in different climates.

Keywords: Complex networks, Soil moisture, Climate zones, Network measures

Impact of IDF curve parameterization on design of rainwater detention basins

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Intensity-Duration-Frequency (IDF) curves have been parameterized by many different expressions without any consensus about which should be preferred. Here, three different expressions, a simple two-parameter exponential curve and two three-parameter functions, are selected and compared. Assuming that the inflow to a rainwater detention basin caused by a rain incident with a given return period is uniform, and further that the discharge from the rainwater detention basin is constant, the critical duration of the rainfall and the necessary volume of the basin can be determined as function of the fixed discharge. The impact of the IDF parameterization on the basin design will be compared

and discussed. Additionally, the design based on constant basin discharge is compared with design assuming that the basin acts as a linear reservoir.

Keywords: IFD-curves, rainwater detention, basin design, linear reservoir

Drought Characteristics, Risk, and Vulnerability in Peninsular India: Use of a Complex Network Approach

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This study explores the characteristics of meteorological droughts and their associated risks across nine major river basins in peninsular India, with a focus on changing climate conditions. The Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are considered to represent meteorological drought conditions. Monthly precipitation and temperature datasets from climate models under the Coupled Model Intercomparison Project phase 6 (CMIP6) and observed gridded data from the India Meteorological Department (IMD) are used. The analysis covers the period from 1961 to 2014, with SPI and SPEI computed at a 6-month timescale and at a spatial resolution of 1deg x 1deg. Drought propagation is examined through a complex network-based approach. The directed network is constructed using event synchronization to identify key drought characteristics (e.g., spatial patterns of drought occurrence, propagation path) and to assess interconnections and regional dynamics. The network properties are further integrated into hazard and vulnerability assessments to determine spatial drought risk. The results reveal substantial variations in drought synchronization and propagation across the nine river basins. This is particularly significant as drought events in one region can signal the onset of droughts in neighbouring regions due to interconnected drought propagation patterns. The study highlights the importance of addressing regional risks and vulnerabilities associated with drought propagation and demonstrates how integrating drought indices with complex network theory can enhance risk assessment and inform adaptation strategies under climate change conditions.

Keywords: Drought propagation, Risk, Vulnerability, Hazard, Complex networks, Event synchronization

Future Water Availability in Mountainous Regions: Integrating Hydro-Meteorological Extremes and Water Resource Components

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Climate change significantly impacts water availability in mountainous regions, complicating water resource management amid rapid population growth and rising consumptive water demands. This study examines the key factors driving large-scale changes in water security, focusing on hydro-meteorological extremes and surface and subsurface water availability. Using downscaled CMIP6 climate models, we analysed the impacts of global warming at 2 degC and 3 degC levels (GWL) for the near future (2021-2050) and far future (2071-2100). Hydrological simulations were employed to compute hydro-meteorological indices and categorize water resources into blue water (surface water) and green water (subsurface water). The findings reveal a significant increase in annual average rainfall (30%), blue water availability (40%), and a sharp rise in average temperature under the high warming scenario (SSP5-8.5) by the end of the century. Meanwhile, under the low warming scenario (SSP2-4.5), green water flow showed a notable increase (+50%), while green water storage declined (-4%). Population density is projected to rise by 40%, intensifying water stress in midstream sub-catchments, particularly in the near future. Future projections indicate substantial shifts in water availability components under both SSP scenarios, ultimately leading to decreased water resources by the century's end. This study highlights the need for comprehensive insights into water availability challenges by integrating hydro-meteorological indices and water resource categorization. The findings emphasize the urgency of developing proactive water management strategies to address future water scarcity and support informed decision-making for sustainable resource management.

Keywords: Blue and green water, Climate change, Hydro-climatological extremes, Mountainous River catchment, Water scarcity

Hydrology of Coastal Wetlands: A Case Study from the Point Calimere Ramsar Site in a Semi-arid Zone on the Southeast Coast of India

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The coastal wetlands, especially the estuaries, are dynamic ecosystems often subject to the fresh-water flows from the upstream catchments and salinity intrusion from the sea. The consequences of climate change, especially the rise in sea level, impact the wetland's physical, chemical, and biological processes and biodiversity. A case study on the Point Calimere Wetland Complex (PCWC), a Ramsar site on the southeast coast of India, is reported here. The wetland comprises lagoons, small bays, creeks, swamps, mudflats, mangroves, grasslands, dunes, and dry evergreen forests including agriculture wetlands, saltpans and aquaculture farms. The changes in land use reflect the temporal flow in the PCWC. There was a slight improvement in annual streamflow after the Interim Award of the Cauvery Water Disputes Tribunal in 1991. Freshwater flow is the primary factor influencing salinity, formation of salt plug and movement of estuarine turbidity. It is estimated that a

minimum flow of 10 cu. m/sec has to be maintained in the Paminyar and Koraiyar together throughout the year to maintain the sustenance of healthy mangroves and other ecosystem services like fish. The study on impact of sea level rise showed that a rise in sea level by 1 m will affect an area of 37.19 sq. km in and around the wetland. Some of the measures for the wise use of PCWC: a mechanism for ensuring environmental flows, regulating the areas under aquaculture and salt pans by resorting to alternate livelihood options, fixing location-specific controlled pumping of groundwater, creation of a wetland management fund by levying a cess from aquafarm and saltpan owners, declaring the Siruthalaikadu inlet as a bird sanctuary, establishing an integrated IoT-enabled hydrological monitoring system, surveying and demarcating the unsurveyed areas of the wetland complex, and the establishment of a Point Calimere Wetland Authority.

Keywords: Point Calimere, Climate Change, Wetland, Freshwater flow, Mangroves

Forest Fire Dynamics in Himachal Pradesh: Spatiotemporal Patterns and Driving Factors (2000-2024)

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The Himalayan region stands out for its rich biodiversity and ecological importance, but wildfires are turning out to be an environmental issue in the Himalayan region. Forest fires cause both short (i.e., biodiversity loss and soil degradation) and long-term environmental effects (i.e., ecological imbalance and carbon emissions). There is a spate of wildfires in the Himalayan terrain due to increasing temperatures, scarce rainfall, the shift in precipitation regime, and various anthropogenic activities such as deforestation, land-use changes, and agricultural burning. Climate change is intensifying fire frequency and severity; hence, it has become a serious threat to the undeniably fragile Himalayan ecosystem. This study focuses on one of the Himalayan states, i.e., Himachal Pradesh, to study the trend of wildfire occurrence over the past two decades and to understand the various driving factors of wildfire. We have collected the NASA Fire Information for Resource Management System (FIRMS, <https://firms.modaps.eosdis.nasa.gov/>) global dataset from 2000 to 2024 to understand the forest fire occurrence, trends, and how it's changing over the years. We observed an increasing trend in wildfires. The highest numbers of wildfires were recorded during 2024 (n= 1567) followed by 2016, 2018. Most of the wildfire events occurred during May followed by June, April, and December. The pre-monsoon moisture stress combined with extreme temperature conditions elevated the occurrence of wildfires in the month of May. Most forest fires occurred between 1,000-2,000 meters (4,622 incidents), followed by the 250-1,000 meters range (4,237 incidents). We also observed 684 forest fires in high-elevation mountain (greater than 4000) ranges over the last two decades. Further, we studied the shift in fire hotspots over the last 20 years. Knowledge of these patterns is important in identifying major controlling factors and undertaking effective mitigation measures.

Keywords: Forest fire, Himalayan region, Soil moisture, climate change

Adapting Water Resource Management to Climate Change in the Alpine Region of South Tyrol, Italy

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Climate change and human activities are reshaping water availability in the Alps. Shifting precipitation patterns, rising temperatures, and cryosphere changes are altering water timing and quantity. Hydropower, agriculture, and tourism compete for limited resources, while ecosystems face increasing stress. Future scenarios predict worsening conditions, with more frequent droughts pushing water systems to critical limits.

This study, focusing on South Tyrol (Italy) in the Central Alps, integrates using a participative approach literature review, hydrological modeling, and stakeholder input to identify cross-sectoral impacts and adaptation strategies for water management.

Key findings reveal ongoing trends of rising temperatures and increasing precipitation variability. Between 1980 and 2020, glacier area and snowfall significantly declined, altering runoff regimes with earlier and lower spring peaks and greater autumn variability. Climate projections indicate these trends will persist, exacerbating sectoral conflicts. Since the 1970s, summer streamflow in the Adige River Basin has declined due to a shift from snow- to rain-dominated regimes, while water demand for irrigation, energy, and tourism is increasing.

Agriculture consumes 200 Mm³ annually, hydropower relies on 230 Mm³ in reservoirs, and tourism adds 51 Mm³, challenging environmental flow standards. Recent droughts, such as in 2021-2022, exposed system vulnerabilities, causing severe shortages, restrictions, and ecological damage.

A Water-Energy-Food-Ecosystems (WEFE) nexus approach is essential for managing interdependencies and adapting to future challenges. Proposed strategies include efficient irrigation, improved water distribution networks, multipurpose reservoirs, water-saving incentives, updated regulations, and public awareness campaigns.

Ongoing research quantifying future water availability and demand will further refine these strategies. Initial results highlight the urgency of holistic, multidisciplinary policies to address climate change impacts and ensure water security in alpine regions.

Keywords: Climate change, adaptation, Alps, water resources,

Projecting Flood Risk and Socio-Economic Exposure in a Large River Basin under various Global Warming Level

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Climate change exacerbates the hydrological cycle, altering hydrometeorological variables and leading to flood and drought risks with significant social, economic, and environmental impacts. This study investigates projected flood risks, and socio-economic exposure in a flood-prone river basin

using downscaled CMIP6 (Coupled Model Intercomparison Project) projections. Changes in extreme precipitation and runoff indices were assessed under global warming levels (GWLs) of 1.5 degC, 2 degC, and 3 degC, as well as Early Future (2021-2050) and Far Future (2071-2100) periods. The flood wave characterization was done using a stationary seasonal threshold for flood wave identification and observed a 10-14% increase in flood peak at major cities of the basin in pre-monsoon and monsoon by 2100. The high warming scenarios may lead to a 35% increase in annual precipitation and runoff. However, limiting the GWL to 1.5 degC may reduce precipitation increases by 15% and 30-year return flood discharge by 9,000 m³/s by the 2070s. The projections indicate a paradigm shift in the flood wave characteristics of the basin, with a notable increase in both flood wave duration (0.31 days per year) and frequency (3 more flood waves) during the pre-monsoon and monsoon seasons. Socio-economic vulnerability assessments in the present study reveal heightened risks under SSP370 and SSP585 scenarios due to population growth and intensified hydroclimatic extremes, leading to increased inundation extent and depth. Additionally, the displacement risks are also projected to rise significantly, underlining the need for informed stakeholder decisions, transboundary cooperation, and sustainable flood-resilient infrastructure. Limiting warming levels could substantially mitigate these impacts, promoting regional climate resilience and sustainable development.

Keywords: CMIP6, Flood wave characteristics, Socio-economic vulnerability, Displacement risk, Global warming level

Enhancing Drought Resilience Through Interconnected Reservoir Systems, A Case Study of Sardinia's Flumendosa Basin

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This study evaluates interlinked reservoir systems as a resilient solution for sustainable water management under climate change. We focus on Sardinia's Flumendosa basin-a Mediterranean region confronting recurring water scarcity. Historical data from the Sardinian Dam Report reveal alarming declines in water availability, with average annual inflows dropping from 871.6 mm (1922-1975) to 700.6 mm (1986-2001) and outflows reduced by over 50% during the same period, underscoring the urgency for adaptive management. By 2006, the basin transitioned to an interconnected network of four reservoirs to address demand-supply imbalances. We assess the efficacy of interconnected reservoirs during droughts using a theoretical reservoir model driven by synthetic precipitation calibrated to regional hydroclimatic variability and societal demand patterns. Comparative analyses of standalone versus interconnected systems, validated against observational datasets (2007-2023), demonstrate that hydraulic connectivity reduces drought severity and duration by 14% and 10%, respectively, during extreme events, enabled by dynamic water redistribution across spatial and temporal scales. The findings underscore interconnectivity as a critical adaptive strategy, mitigating localized deficits through coordinated resource allocation which offers a scalable framework for basins facing similar hydroclimatic challenges. By prioritizing adaptive infrastructure over traditional expansion, this approach aligns with SDG 6's sustainability mandate, providing actionable insights for policymakers and water managers in arid and semi-arid regions. The study advocates for systemic, basin-wide strategies to enhance resilience against climate-driven hydrological variability, emphasizing inter-reservoir coordination as a cornerstone of sustainable water governance.

Keywords: Drought resilience, Interconnected reservoir systems, Sustainable water management

Leak Characterization Framework in Pressurized Single Water Pipelines of Smart Water Systems using Fluid Transients

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Continuous water supply is common in developed countries. Though not prevalent in developed countries, hundreds and millions of people around the globe continue to be served by intermittent water supply systems (IWSS). Transitioning to the continuous pressurized water supply is crucial due to the challenges posed by intermittent supply systems such as high non-revenue water levels, contamination intrusion through leakages and ferrule points, air pockets formation during non-supply hours and inequitable water supply. Smart water technologies like monitoring of pressure and flows using sensors, and automatic control of pumps and valves are essential in continuous water supply systems (CWSS) to meet consumer demands, detect faults, and manage them effectively. Monitoring pressure traces of induced controlled fluid transients during either automatic valve or manual valve control are highly beneficial to detect leaks in pressurised single water pipelines. This paper aims to utilize the pressure traces occurred during automatic valve control and manual valve control processes to characterize the leaks in pressurized single-water pipelines through time-frequency analysis.

Keywords: Smart Water Systems, IoT, Water Pipelines, Leak Characterization, Fluid Transients

Changes in water balance and thermal regime of the Mozhaysk Reservoir (Moscow region, Russia) in XXI century

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Lakes are very sensitive to climate change, and the functions they perform in human economy and life are greatly affected by shifts in climate parameters. In our study, we combined the observation data on hydrology and thermal regime of the Mozhaysk Reservoir - a lowland reservoir that supplies drinking water to the Moscow City to assess what changes already occur in it because of ongoing climate change. It shows that the reservoir is already experiencing a shift in snowmelt flood input, which changed from 61% to 43% of annual water inflow over 1961-2022. The ice cover has been reduced by almost a month over the same period, and some slight warming of surface water is observed. We also used hydrological (HBV) and limnological (GLM) models to provide a projection of its regime until the end of the 21st century under IPCC AR6 scenarios. Under SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5 scenarios, annual inflow into the reservoir is projected to be reduced by

17-18% with a 36-46% reduction of inflow with snowmelt flood. The ice covered period is projected to become more intermittent, and changes in water temperature are following the changes in ambient air temperature, reaching +2-+5 degC by the end of the century. Our assessments can provide a valuable basis for future water management decisions concerning lakes and reservoirs in temperate climate, as hydrological and thermal regimes shape a large part of their ecological state.

Keywords: Drinking water supply, climate change, hydrological modeling, lake modeling

An Ensemble Flood Forecasting System for India

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We present a flood forecasting framework that integrates hydrological modeling with high-performance computing for precise and timely predictions within India. The framework uses India Land Data Assimilation System (ILDAS) as the physical modeling core. ILDAS combines multiple Land Surface Models (LSMs) and routing models to enhance flood simulations. Here, Noah-MP LSM captures land surface processes, while mizuRoute, a vector-based hydrodynamic model, is used to route the runoff to get flood information. The system incorporates 23-member ensemble meteorological forecasts from NCMRWF with a lead time of 1 to 10 days. With a spatial resolution of 12 meters, it can generate nationwide flood forecasts in just 15 minutes, providing daily flood information. To refine predictions further, an ML-based post-processor enhances hydrological forecasts, improving the overall reliability of the system. Evaluation of the system demonstrates its strong predictive capability, accurately capturing flood events and highlighting its value for disaster preparedness and risk mitigation. By combining physics-based modeling and machine learning, this framework represents a significant step toward improving operational flood forecasting, complementing the existing flood forecasting systems, and aiding decision-makers in managing flood risks more effectively.

Keywords: Flood, Medium Range Forecast, Flood Forecast Framework, ILDAS

Complex governance, finance and natural resource considerations on 'going off grid' for Rhodes University, South Africa

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Despite experiencing numerous droughts over the years (extended dry periods from 1940-1960,

1980-1990 and 2014-2021), water sustainability at Rhodes University (RU) has generated little momentum. Instead, small-scale initiatives were undertaken by various stakeholders resulting in significant cumulative investment into these initiatives which are generally abandoned over time, without improving the University's water security significantly. A groundwater model (MODFLOW), as well as simple rain tank model among other data collection have been used to investigate the potential of grey water reuse, black water reuse, groundwater supplementation and rain water harvesting. Although staff and students have voiced much support for rainwater harvesting on campus, the storage needs to be impractically large to provide reliable supply, and even then, cannot fulfil a large percentage of demand. Greywater and black water harvesting hold more potential in terms of reliability but are expensive, and again there are practical limits on placement of infrastructure. Groundwater holds most promise for moving RU off-the-grid in terms of supplying the whole campus via groundwater abstraction. The campus is situated in the headwaters of a catchment with quartzitic and shale aquifers. The average recharge of the aquifer is estimated as 5% of the mean annual precipitation which is around 700 mm/a. MODFLOW was used to determine the sustainable yield of the aquifer before the introduction of artificial recharge through infiltration galleries and thereafter linked to a rooftop runoff model to recharge the aquifer. Modelling results showed a promising increase in the sustainable yield under the assumption that the operation of the infiltration galleries are effective. Decisions on whether RU contributes water into the municipal supply or keeps RU supply separate are pertinent, especially in light of the fact that RU is the largest contributor to the municipal budget, and reducing this could have dire consequences for the town.

Keywords: Drought, governance, groundwater, mixed water supply, sustainability

Climate change and water resources capacity development in Africa under the SASSCAL and WASCAL doctoral programmes

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Climate change and water resources capacity development in Africa under the SASSCAL and WASCAL doctoral programmes

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The West- and Southern African Science Service Centers on Climate Change and Adapted Land Use (WASCAL and SASSCAL) have been established as part of the internationalization strategy of the German Federal Ministry of Education and Research (BMBF). Both Science Service Centers have a regional focus and work with several member countries (WASCAL: 12-member countries in West Africa, SASSCAL: 6-member countries in Southern Africa). The International Centre for Water Resources and Global Change in Koblenz, Germany, is the partner institution of the SASSCAL PhD Programme on Integrated Water Resources Management hosted at the Namibia University of Science and Technology (NUST) and of the WASCAL PhD Programme on Climate Change and Water Resources hosted at the University of Abomey-Calavi in the Republic of Benin.

This presentation will showcase the content and structure of these graduate studies programmes

and the process of establishing an impactful North-South partnership. Furthermore, both highlights and challenges will be discussed.

Keywords: Capacity Development, Integrated Water Resources Management, Water and Climate Change

Seamless short to long term forecasting of inflow into lake Baikal: development and online assessment

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Lake Baikal on its single outlet, the Angara river, is controlled by the Irkutsk hydropower plant. Hence, forecasting inflow into this large hydrosystem is of crucial importance for ecosystem preservation and optimal use of water resources. We describe the development of a seamless forecasting system for short- to long-term inflow prediction based on a combination of weather forecast, semi-distributed hydrological model ECOMAG, and ensemble streamflow prediction approach. The system provides forecast on a daily basis for the first 10 days. The next two months are provided on monthly basis. To evaluate the system efficiency we developed a method of gauged streamflow data assimilation on the lake Baikal major tributaries. The overall performance of the short-term forecasting appeared to be highly efficient and the long-term probabilistic forecasting of monthly inflow showed good accuracy and resolution.

Keywords: forecasting system, short-term forecasting, seasonal forecasting, inflow into reservoir

Length scale and energy distribution through grid-induced turbulence in pulsating flow case

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This study experimentally investigates the length scales and energy distribution in grid-induced turbulence within a pulsating fluid flow environment. Oscillations in the steady unidirectional flow were generated using a plunger-type wave maker. The research focuses on analysing turbulence length scales (streamwise, lateral, and vertical) and the energy spectrum to characterize eddy structures influenced by grid-boundary interactions. The turbulence length scales and Taylor's length scale are estimated using the Von Kármán spectrum model and the autocorrelation function method, respectively. Additionally, phase space plots of three-dimensional velocity data downstream of the grids are presented for pulsating flow conditions. The findings of this study are relevant to environmental

flow modeling, particularly in understanding turbulent mixing in rivers, estuaries, and atmospheric boundary layers. Furthermore, the results contribute to wind tunnel experiments by providing insights into grid-generated turbulence, which is widely used for studying turbulent boundary layers and aerodynamics in controlled laboratory conditions.

Keywords: Pulsating flow, Length scale, Phase space, Energy spectrum

Optimization of operational cycle for energy maximization in pumped storage hydropower plants

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The global energy landscape is undergoing a significant transformation toward renewable sources as societies strive for more sustainable and low-carbon energy systems. Hydropower, as the dominant renewable energy source, not only contributes to clean energy generation but also supports climate mitigation efforts. In this context, Pumped Storage Hydropower (PSH) has emerged as a key technology for peak power generation and large-scale energy storage. This study develops a system-based optimization to maximize the benefits of PSH under two operational scenarios: (i) a single-generation cycle only for peak shaving and (ii) multiple-generation cycles to enhance system efficiency. The proposed approach is applied to the Tehri Hydropower Plant in the Indian Himalayan region. The Simulation results indicate that the multiple-generation cycle strategy achieves greater overall benefits compared to the peak shaving scenario. However, while peak shaving relies solely on renewable energy sources for pumping, the multiple-cycle operation integrates both renewable and fossil fuel sources to optimize performance.

Keywords: Pumped storage hydropower, Renewable Energy, Sustainable energy, peak shaving, Energy Optimization

State of Art of Ecohydrology Research in the Indian Subcontinent : A Review

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Ecohydrology explores the interactions between water and ecosystems, offering critical insights into hydrological processes and their role in environmental sustainability. In India, the field has gained importance due to diverse climatic conditions, complex landscapes, and increasing environmental challenges. This review examines the temporal evolution of ecohydrology studies in India

from 2005 to 2025, based on a systematic keyword search using terms such as evapotranspiration (ET) and carbon cycle, eco-hydrology and water balance, climate change and vegetation response, gas exchange and drought stress, stomatal conductance and water use efficiency, and water and heat transfer between soil, vegetation, and atmosphere in India. Findings indicate that transpiration is the dominant component of evapotranspiration in forests, plant water use efficiency varies with moisture availability, and deep-rooted vegetation plays a key role in groundwater access in arid regions. Climate variability is altering soil moisture dynamics and water fluxes, impacting vegetation responses and hydrological resilience. However, a major challenge in ecohydrology research is the scarcity of long-term, high-resolution datasets, particularly for soil moisture, transpiration, and actual evapotranspiration. This limitation hinders the ability to track temporal changes and predict future trends. Although RS (Remote Sensing) - based technology and process-based models have improved the study of ecohydrological interactions, gaps remain in linking smallscale field observations with broader climate patterns. Strengthening ecohydrology research in India requires increased investment in long-term monitoring stations, expanded field studies, and enhanced interdisciplinary collaboration. Establishing regional research networks and improving data-sharing mechanisms will be essential for informed decision-making on water sustainability, ecosystem conservation, and climate adaptation.

Keywords: Ecohydrology, Evapotranspiration, Climate Change and Vegetation Response, Water Use Efficiency, Remote Sensing, Soil Moisture Dynamics.

Strengthening Global Hydrological Research - Outcomes of the WMO Research Board Task Team on Hydrology Research

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The WMO Research Board Task Team on Hydrology Research (TT-HydroResearch) was established in September 2023 to enhance coordination and progress in hydrological research within the World Meteorological Organization (WMO). Its primary role is to support and integrate research efforts across WMO's key programmes-the World Weather Research Programme, World Climate Research Programme, and Global Atmosphere Watch-while also collaborating with external initiatives such as UNESCO-IHP, IAHS, HEPEX, EGU, and AGU. A key responsibility of TT-HydroResearch is to review and update the WMO Hydrological Research Strategy 2022-2030 and the WMO Plan of Action for Hydrology, ensuring they remain aligned with evolving global challenges in hydrology. This presentation outlines the context, objectives, and progress of the task team, with a particular focus on advancing research-to-operations (R2O) in global hydrological monitoring, understanding, and prediction. By identifying priority research areas and fostering stronger collaboration across disciplines, TT-HydroResearch seeks to enhance predictive capabilities and support more effective water resource management in the face of climate change.

Keywords: Hydrological predictions, Knowledge exchange, Research-to-operations (R2O), WMO, Interdisciplinary collaboration

Extreme floods and droughts in the Gambia River Basin at Gouloumbou : Impacts of climate change and the resilience of ecosystems and populations

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The Gambia River basin, essential for water supply and the socio-economic development of riparian populations, has undergone significant hydrological changes since the 1970s due to climate change and increasing anthropogenic pressures (intensive agriculture, gold panning, deforestation). In Gouloumbou, these transformations have resulted in more intense floods and droughts, with a 22% decrease in average annual flows since 1980, a 15% reduction in the frequency of extreme floods since 1990, and a 40% drop in minimum flows over the past decades. The lengthening of low-flow periods and the increase in the depletion coefficient from 0.45 to 0.68 indicate growing water stress and accelerated depletion of groundwater reserves, leading to increased bank erosion, reduced agricultural productivity, and a decline in fishery resources. In response to these challenges, local populations are adopting various adaptation strategies, including the construction of retention basins, improvements in agricultural techniques, and the implementation of early warning systems. However, these measures remain insufficient in the absence of a coordinated and transboundary water resource management approach. This study highlights the urgent need to strengthen integrated water resource management policies, adapt infrastructure to new climatic realities, and promote regional cooperation to enhance the resilience of ecosystems and communities to the hydrological extremes affecting the Gambia River basin.

Keywords: Climate change, floods, droughts, resilience, Gambia River Basin, water management, Gouloumbou

The Bradfield Scheme: a multi-disciplinary evaluation of Australia's controversial 1600-km inter-basin water diversion proposal

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Dr. John Bradfield's 1600-km inter-basin water diversion proposal, first introduced in 1938, has remained a subject of debate for successive governments in Australia. In response, the Australian Government commissioned CSIRO, Australia's national science agency, to conduct a comprehensive, multi-disciplinary assessment of the scheme and its modern adaptations. This evaluation aimed to objectively address the claims and criticisms surrounding the project.

Rapidly yet objectively evaluating the scheme involved identifying optimal water storage and diversion infrastructure configurations along the potential water supply line, which required the development of novel water infrastructure alignment, costing and optimisation tools. This assessment found that Bradfield's Scheme and its modern variants were technically feasible, and that a series

of potential dams and tunnels and a 1400-km gravity water supply channel could deliver on average 1270 GL of water per year, after losses, to Australia's "food bowl", the Murray-Darling Basin.

The optimal backbone infrastructure configuration (i.e. dams, pipes, tunnels and channels) was estimated to cost between 15**billionand**30 billion (assuming favourable geological conditions) with an annual cost of between 130**millionand**255 million. Although technically feasible the cost of diversion infrastructure added such a large premium to the cost of water that future crop revenues would never pay off the cost of the water storage diversion infrastructure alone.

The potential for Bradfield water storage and diversion infrastructure to reduce sediment loads to the Great Barrier Reef, mitigate flooding of coastal communities were evaluated along with the potential ecological benefits and risks of long distance water diversion.

High financial losses, ecological impacts and community concerns associated with Bradfield-style schemes could potentially be mitigated by strategic development and staging of smaller resource developments situated closer to where the water is captured and to better match where future demands and opportunities are greatest.

Keywords: water diversion, irrigation, dams, river modelling, modelling

The opportunities and risks of water resource development and intensifying agriculture across Australia's northern rangelands

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Sustainable regional development is a key priority for Australian governments. However, in the north of Australia the landscape is vast, sparsely populated and much of its land and water resources have not been mapped in sufficient detail to provide for reliable resource allocation, mitigate investment or environmental risks, or confidently build policy settings that can support decisions. To improve the confidence of investors and regulators and help inform public funding initiatives in northern Australia, over the last 10 years the Australian Government has commissioned CSIRO to undertake large multi-disciplinary water and agriculture resource assessments across Australia's north. These assessments which included an evaluation of surface and groundwater resources, suitability of soils, agronomy, water storage options, economics, water dependent ecosystems and Indigenous aspirations and water values, involved over 120 scientists. Here we present a synthesis of the key findings from assessments of eight large river catchments in northern Australia, which collectively encompass an area of over 620,000 km² and we highlight broad learnings applicable to similar environments elsewhere in the world.

Keywords: northern Australia

An Open-Source Tool for Generating Hourly Synthetic Streamflow Series in Ungauged Basins Using Regional Flow-Duration Curves

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Predicting streamflow in ungauged catchments using regionalization methods has been extensively studied. While numerous free and open-source software (FOSS) tools exist for predicting regional flow-duration curves (FDCs) at ungauged sites, a general FOSS tool specifically designed to generate continuous streamflow series from these FDCs is lacking. This study introduces FDC2Qt, an R-package developed as part of a collaborative project between the University of Bologna, the Po River Basin Authority, and the Emilia-Romagna Regional Authority. FDC2Qt generates long synthetic hourly streamflow series in ungauged catchments, utilizing a regional dataset of daily streamflow observations from neighboring sites together with basin morphoclimatic descriptors. The methodology comprises three key steps. First, a regional period-of-record FDC is predicted for the ungauged site by combining an index-flow approach (Castellarin et al., WRR, 2004) with a region of influence approach (Burn, WRR, 1990). Second, a synthetic daily streamflow series is generated at the ungauged site using a non-linear spatial interpolation method based on FDCs (Smakhtin et al., HSJ, 1997; Smakhtin, J. Hydrol., 2001), referencing one or more observed daily streamflow series from neighboring catchments. Third, the synthetic daily series is downscaled to an hourly time-step using a scaling law that primarily considers the morphological features of the ungauged catchment. Validation experiments demonstrate that the synthetic hourly streamflows accurately capture the primary hydrological characteristics of observed streamflow series and exhibit reliability comparable to that of hourly streamflow series simulated by regionalized lumped rainfall-runoff models.

Keywords: Streamflow Prediction, Regionalization Methods, Open-Source Software Tool

A Novel Framework for Identifying the Homogenous Rainfall Regions Over the Indian Subcontinent

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Understanding regional rainfall patterns is essential for different hydrological applications. Traditional approaches often emphasize rainfall magnitude and long-term variability, which fail to capture the complex rainfall dynamics. So, incorporating diverse rainfall characteristics such as magnitude, intra-annual and inter-annual variability along with the centroid of the rainfall distribution is essential to enhance the rainfall regionalization over the Indian Subcontinent. This study introduces a refined regionalization framework integrating multiple precipitation attributes such as magnitude, variability and seasonality. The gridded rainfall dataset from the Indian Meteorological Department (IMD) is leveraged to compute

the rainfall attributes such as Magnitude, Marginal Entropy, Apportionment Entropy and refined centroid method. The Self-organizing Maps (SOM) technique is employed to identify eleven homogenous regions, with the optimal number of clusters determined by using cluster validity indices such as the Silhouette score, Davies Bouldin Index, Quantization Error and Topological Error. The results reveal distinct rainfall regimes, providing a nuanced understanding of rainfall variability. The proposed method enhances the accuracy of rainfall regionalization offering critical implications for different facets of hydrology.

Keywords: Regionalization, Rainfall Variability, Entropy, centroid

Curating water resources knowledge in Lebanon: a path to support Water Security

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Knowledge fragmentation poses a significant obstacle to effective water resources management. While this fragmentation can arise from the inherent specialization in scientific studies, external factors such as compartmentalized thinking in management and policy making, along with competition among stakeholders, including researchers, can further compound the issue.

This study focuses on mitigating knowledge fragmentation in Lebanon's water resources, a country where civil war, geopolitical conflicts, confessionalism, and corruption have intensified compartmentalization. The objective is to create the most comprehensive database of water resources studies conducted in Lebanon since its establishment in 1920. The database with around 400 entries encompasses both peer-reviewed and gray literature documents, covering various water resources domains such as water balance, quality, management, and governance. It is aligned with the WMO plan of actions for hydrology (2023-2030) especially ambitions F, G, and H. Aiming at providing a solid base for operational hydrology through a more complete knowledge of Lebanon's water resources it should help progress towards sustainable development goals, especially goal 6. Utilizing this database, we assess the current knowledge base, review existing water-related knowledge, and identify gaps in knowledge production, policies, and operationalization.

The studies are categorized into four main topics: water balance, water quality, water management, and water governance, each with relevant sub-topics. A bibliometric analysis is conducted, and the content is summarized and discussed, revealing critical findings and challenges. Finally, as we acknowledge the need to complete and continually update this database, we hope that this work will contribute to overcoming the barrier of knowledge fragmentation and will serve as a valuable tool for researchers, policymakers and stakeholders to better operationalize Lebanon's water resources management.

Reference: Merheb M. et al., 2024. The water resources of Lebanon - A review to support water security. *Physics and Chemistry of the Earth*, 103683, 136, <https://doi.org/10.1016/j.pce.2024.103683>.

Keywords: Water resources, water balance, water quality, water management, water governance, Lebanon, knowledge curation

Integrated Modeling Framework for Managing Flood Risk in Hydropower Dams under Uncertain Inflows

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Effective reservoir planning and management play a vital role in hydrology and water resource management. However, developing appropriate operational policies to meet downstream hydraulic requirements remains an area that requires further investigation. Uncertainty in inflow to the reservoir can influence downstream flooding and affect dam regulation. In this study, we applied a coupled reservoir operation and hydrodynamic model to assess the downstream flood risk under inflow uncertainty. The two models were integrated through a feedback system, in which the downstream flood level data from the hydrodynamic model triggered the reservoir operation model, allowing for the early release of water (advance release) before the flood peak. This approach quantifies the advance release through a simulation-optimization model to minimize downstream flood levels while maintaining acceptable power production efficiency under perfect forecast conditions. A sensitivity analysis of inflow uncertainty, considering peak flow and the timing of peak flow arrival, was conducted to assess downstream flood risk. The methodology was demonstrated at the Ranganadi Hydro Electric Project (RHEP) in Arunachal Pradesh, India. Results indicated that, under perfect forecast conditions, the model successfully reduced flood levels, keeping them below danger levels in downstream flood-prone areas. The sensitivity analysis showed that the risk of flooding was higher with an early arrival of the flood peak compared to a late arrival. Therefore, while conducting inflow forecasts, priority should be given to the peak flow and the timing of peak flow arrival for an efficient decision-making strategy.

Keywords: Downstream Flooding, Reservoir Operation, Hydrodynamic Model, Forecast Horizon, Uncertainty

Optimizing Seepage Control and Stability in Earth Dams: A Comprehensive Review of Toe Drains and Horizontal Drains

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Effective seepage control and stability enhancement are fundamental to the design and maintenance of earth dams. Toe and horizontal drains serve as essential drainage mechanisms for managing seepage, reducing uplift pressure, and improving slope stability under varying hydraulic and geotechnical conditions. This review consolidates findings from multiple experimental and numerical studies to assess the effectiveness of these drainage systems. The analysis explores the influence of drain geometry, anisotropic permeability behavior, and filter configurations in optimizing seepage control and enhancing the factor of safety (FOS). Results indicate that longer horizontal drains significantly lower uplift pressure, while strategically placed toe drains effectively mitigate piping and

erosion risks. The review also highlights the increasing role of advanced numerical modeling techniques such as SEEP/W, SLOPE/W, and MODFLOW in seepage analysis and stability assessments. By synthesizing key insights from recent research, this study advances the existing knowledge on dam safety and provides practical recommendations for optimizing drainage configurations to enhance the long-term performance and resilience of earth dams.

Keywords: Seepage, Stability, Toe drain, Horizontal drain

Integrated water scarcity index reveals increased exposures of populations and areas to water scarcity

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Freshwater resources are fundamental to supporting humanity, and measures of water scarcity have been critical for identifying where human water requirements and water availability are imbalanced. Traditional metrics for water scarcity primarily focus on actual blue water withdrawal, while the contribution of rain-fed water requirements (RWR) and water quality - dimensions with important implications for multiple societal sectors - to overall water scarcity remains unclear. Here we address this gap by explicitly merging the three dimensions of water scarcity into an integrated index (iWSI). Specifically, combining a process-based crop water model with spatially detailed information on water pollution and sector-specific withdrawals, we first develop global gridded (30 arcminute) estimates of iWSI and its individual dimensions (blue water, RWR, and water quality) averaged over the period 2001-2010. We then perform a quantitative comparison of water scarcity indices that consider different combinations of the three water scarcity dimensions, together or in isolation, and estimate their water withdrawals and associated global land area and population under conditions of monthly and annual water scarcity. We find that the global land area and population under water scarcity increases by 126% (119-133%) and 53% (49-57%) using this integrated index relative to assessments focusing only on blue water. These effects are most pronounced for populations in Africa and Asia. Examining seasonal water scarcity, we estimate that 4.4 billion people are exposed to integrated water scarcity at least one month per year - 31% more people than under blue water scarcity alone. Our research highlights that water scarcity challenges are more widespread than previously understood. As such, our findings underscore the need for actions to bring human pressure on freshwater resources into balance with both water quantity and quality, addressing previously overlooked blindspots in global water sustainability.

Keywords: Water scarcity, Intergrated index, Blue water, Water quality, Green water

Data driven Hydrological Modelling for Sustainable Water management in an Educational Campus

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Sustainable management of water resources is very crucial to address the rising challenges pertaining to climate change and associated shifts in surface water availability, depletion of groundwater reserves and increasing water demands. The drastic development witnessed by many Indian cities seldom gave any importance to the water management scenario leading to reduced storage, urban water pollution and unrestrained depletion of its natural water reserves. This has resulted in limited opportunities to improve cities' water systems, which are further strained as the city expands outwards, depleting the peri-urban water reserves in the process. In the current study, an upcoming educational campus in peri-urban Bengaluru is monitored to develop a local hydrological model based on elevation, soil, vegetation and climate data. Contrary to many state-of-the-art hydrological systems using generalized parameters, the current study employs site specific parameters derived from field measurements to model the surface water - groundwater interactions in this highly heterogeneous managed urban campus. Further an IoT based system coupled with field level sensors to monitor fluctuations in groundwater level in observation wells, water level in the different water bodies in the campus and the climate data from the Long Term Urban Ecological Observatory set up in the campus is utilised to develop a real time database. This hydrological modelling system will be modified periodically as the campus develops exploring possibilities of integrating blue-green-grey infrastructure in campus water management. The developed model will act as a digital twin of the hydrological system in campus which can further be coupled with the water use data to plan the water management strategy in the campus ensuring a sustainable system for the future.

Keywords: Local Hydrological Modelling, Sustainable Water Management

Evaluation of the Empirical Area Reduction Method for Singur and Raiwada Reservoirs of India

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Sediment accumulation reduces reservoir storage capacity, limiting their ability to retain water. This decline in storage restricts water availability for irrigation, drinking, and industrial use, especially during droughts. Estimating the elevation-area-capacity curve is particularly challenging due to sedimentation. The Empirical Area Reduction (EAR) method by Boreland and Miller (1958) is a widely used approach to estimate storage loss over time. This method provides a simplified mathematical model to analyze how sediment deposition alters the reservoir's capacity-elevation relationship. The present study aims to evaluate the "Empirical Area Reduction" method for Singur and Raiwada Reservoirs of India. The common factor in both the reservoir is sediment deposition which approximately 5.5% of their capacity at FRL. Singur Reservoir, a major water body in Telangana's Sangareddy district, India, is built in 1989 on the Manjira River, a tributary of the Godavari River.

Raiwada Reservoir, located in Anakapalle district, Andhra Pradesh, India, was built on the Sarada River, a tributary of the Nagavali River, in 1983. A revised capacity survey was conducted in 1993 for Raiwada and in 1997 for Singur. The rate of sediment accumulation found significantly higher in Singur than in Raiwada. Sediment deposition at higher elevations from the bed level is insufficient to determine a new zero elevation (NZE). Therefore, the NZE was taken near the bed level, as per the EAR method, for both reservoirs. The PBAIS values were estimated as 39.64 for Raiwada and 120.75 for Singur, while NSE values were found to be 0.79 and -0.36, respectively. This indicates that the revised capacity estimated using EAR poorly matched observed values. The lower percentage of sediment deposition (5.5% in the present case), which impacts NZE; may be one of the reasons for the Empirical Area Reduction method's inability to predict the revised reservoir capacity accurately.

Keywords: EAR, Raiwada, Reservoir capacity, Sedimentation, Singur

From Climate Shifts to Flood Changes: Data Based and Modelling Approaches

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As climate change intensifies, shifting temperature and precipitation extremes raise concerns about increased river flood risks. Understanding and quantifying how climate change influences floods is relevant from both theoretical and practical points of view. From a research perspective, while flood trend detection has been widely studied, attributing changes to specific causes remains a challenge. From a practical point of view reliable methods are needed to incorporate evolving climate conditions into flood predictions, particularly in ungauged basins, as traditional flood frequency analysis assumes stationarity. In this work, we present the research conducted at Politecnico di Torino on these topics. The objectives are to investigate how floods relate to climate extremes both at small and large-scales, and to propose methods to link flood frequency curve changes to changing precipitation and temperature patterns. The study area is the Great Alpine Region (GAR) including the Po River valley in Northern Italy. Both data-based and modelling approaches are used. The data-based approach is based on the derived flood frequency framework and estimates the sensitivity of floods to changes in precipitation extremes by linking flood frequency curves and Intensity-Duration-Frequency curves through quantile-quantile relationships at the local scale. The modelling approach is based on the application of a regionally distributed rainfall-runoff model forced by climate model outputs with which changes in flood event characteristics are investigated at the regional scale. This study is carried out within the project Clim2FIEx and the RETURN Extended Partnership and received funding from the Italian Ministry of Education, Universities and Research (MUR, PRIN project 2022AX3882) and the European Union Next-GenerationEU (National Recovery and Resilience Plan - NRRP, Mission 4, Component 2, Investment 1.3 - D.D. 1243 2/8/2022, PE0000005 - Spoke VS1).

Keywords: Floods, Climate Change, Statistical Hydrology, Rainfall Runoff Modelling

Effect of different nitrogen treatments on chlorophyll content and yield of wheat crop

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Nutrient and water management are essential components of sustainable wheat cultivation which directly impacts crop yield and quality. Nitrogen is essential for plant growth, and its varying application rates can also affect chlorophyll content. This study was conducted western Uttar Pradesh, India where crop experiments on wheat crops were performed. Five different treatments were considered three of which correspond to different fertilizer dosages i.e., Treatment1 (T1), Treatment2 (T2) and Treatment3 (T3) with 150 kg/ha, 120 kg/ha (recommended dosage) and 90 kg/ha Nitrogen, respectively. Each of these treatments had three replications and drip irrigation was provided as 100% of the crop water requirements. The other two treatments were rainfed and farmer field replication in which 120 kg/ha Nitrogen was applied. Flood irrigation was supplied to farmer field replication based on the irrigation thumb rules of the local farmers. The chlorophyll content of the treatments was observed at different crop stages. Also, all the replications were harvested separately, and grain yields (GY) were recorded. The GY of T1 (5068 kg/ha) and T2 (5036.3 kg/ha) were found comparable but for T3 (4639.4 kg/ha) there was a substantial decrease in GY. GY of rainfed (2646.7 kg/ha) and farmer field replication (4088.4 kg/ha) were found lower than those the drip irrigated treatments (T1 to T3). The peak for chlorophyll content (CC) was found at flowering stage for all the treatments with the rainfed treatment having lowest levels of CC throughout the crop season. There was a substantial decrease in CC in treatment T3 after the flowering stage. This may be attributed to the decrease in nitrogen content in the treatment leading to reduced photosynthetic activity that resulted in early canopy senescence and affected GY adversely. The results highlight the effects of different nitrogen applications on chlorophyll content and grain yield of wheat.

Keywords: Nutrient and water management, crop water requirements, grain yield (GY), chlorophyll content (CC)

Improving farm-scale decision making on blue-green water management practices in the Vidarbha region of Maharashtra

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Smallholder cotton farmers in the Vidarbha region of Maharashtra, India rely on both green and blue water to meet their crop water demands. However, rising temperatures and prolonged dry spells are intensifying water stress, depleting green water reserves, and increasing dependence on blue water sources. In response, agricultural extension programs promote farm-scale water management

practices aimed at enhancing green water availability and improving blue water use efficiency. While these practices are widely recognized for their benefits, many farmers struggle with awareness, perceived risks, and uncertainty about their cost-effectiveness. To address these barriers, we worked with agricultural experts and smallholder farmers to co-design a digital Measurement, Reporting, and Verification (dMRV) framework that enables farmers to systematically track their agricultural activities and water management practices. This framework integrates remote sensing, field data, and farmer-reported information to quantify water savings, assess crop water stress, and evaluate productivity improvements.

The dMRV framework is integrated into an existing mobile agricultural advisory platform to support data-driven decision-making and deployed in the four districts of Vidarbha, enrolling up to 3000 farmers. Feedback surveys reveal that acceptability by farmers remains a challenge, meaning that more emphasis is needed on the ease of use and an uptake model where farmers use the application because it helps them become part of a green value chain, offering them price premiums and other benefits while also benefitting from location specific advice on good agriculture practices. The findings from this research thus informs the design of agricultural outreach programs and explore the feasibility of incentive mechanisms such as water credits or certification for water-efficient crops, thereby fostering sustainable water management in smallholder farming systems.

Keywords: socio-hydrology, irrigation, blue-green water, dMRV, agricultural extension, green value chain

Comparative Analysis of ANN Solvers for Leakage Detection in Water Supply Systems

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Accurate and timely detection of leaks is essential for efficient water resource management. Many previous studies have focused on either pressure data or flow data individually for leakage detection. While some studies have applied ANN-based approaches, they often do not compare the performance. This study presents a comparative analysis of Artificial Neural Network (ANN) solvers for leakage localization in water supply systems. Using EPANET for hydraulic simulations integrated with Python, a supervised learning framework is developed to identify leakage locations. Leakage is simulated as additional demand at selected nodes, and the ANN model is trained and tested with different activation functions (identity, ReLU, logistic, tanh) and solvers, including Limited-memory Broyden-Fletcher-Goldfarb-Shanno (LBFGS), Adam (Adaptive Moment Estimation), and Stochastic Gradient Descent (SGD). The training data includes three datasets: (a) pressure data, (b) flow data, and (c) combined pressure and flow data. Experimental evaluation on benchmark networks of varying sizes (6-node, 25-node, 46-node, and 268-node) demonstrates that the LBFGS solver consistently outperforms Adam and SGD in accurately locating leaks across all datasets. Additionally, LBFGS exhibits greater robustness to activation function choices, while Adam and SGD require careful tuning, likely due to LBFGS's second-order approximation capabilities that enable faster and more accurate convergence. Results show that all solvers achieved their highest accuracy when trained on the combined pressure and flow dataset, highlighting the importance of using multiple hydraulic parameters for leakage localization.

Keywords: Artificial Neural Networks, Machine Learning, Water Supply System, Leakage Detection, Leakage Localization

Identifying Adaptive Management Strategies for Water Resource Systems Under Changing Climatic Conditions

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An important question in water resource planning under climate change is identifying when and under what conditions adaptation of reservoir operations should occur. We address this question by testing two alternative adaptive problem formulations for a reservoir in southern India. The reservoir is used for satisfying domestic and irrigation water supply along with hydropower generation. In addition, under a changing climate flood protection and minimum environmental flow maintenance are likely to become important goals for managing this reservoir. We generate an ensemble of deeply uncertain inflows that consider a range of historical and expected future climate conditions. We utilize radial basis functions (RBFs) to specify releases as a function of reservoir storage. Two problem formulations are tested: one where RBF parameters are optimized to the entire ensemble of inflows (DU_optim), and another where additional parameters are included to allow variation of the RBF employed for a particular inflow scenario with statistical properties of that inflow (DU_adapt). The Borg multi-objective evolutionary algorithm is used to identify Pareto approximate solutions for both cases. The DU_adapt formulation enables adjustments of RBF parameters based on seasonality and inter-annual variability of inflows. Results show that the DU_adapt formulation outperforms DU_optim significantly in water demand deficits and hydropower production, when comparing median performance across all ensembles. The median performance across all ensembles for the mean annual water deficit is 85 Mm³ and 110 Mm³ for the DU_adapt formulation and DU_optim formulations, respectively. The median performance across all ensembles for the mean annual hydropower production is 2953 for the DU_adapt formulation and 3419 for DU_optim formulations, respectively. They perform comparably in maintaining flood reliability (89% for DU_adapt vs. 88% for DU_optim). DU_adapt formulation attains a lower (67%) MEF reliability when compared to DU_optim (71%), when considering median performance across all ensembles.

Keywords: Radial Basis Function, Climate Change, Borg Multi-objective Evolutionary Algorithm, Water Resource Planning, Reservoir Operations

Projected flash drought evolution across Europe under different emission scenarios

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The conventional idea of a drought is that it takes months, if not years, to reach its peak. Contrary to that, a "flash" drought, which is characterized by rapid onset and intensification, can set in a matter of few weeks, which poses a different set of challenges not just in terms of threat but also prediction and mitigation. Even though it lasts for a shorter duration, it can have a substantial impact on our agriculture and food security. Studies show that the frequency and spatial extent of such droughts are historically higher in a hotter and drier environment. Therefore, it becomes imperative to study the future developments of such droughts amidst a warming climate. In this study, we have analyzed the occurrence of such droughts from 1981 to 2100 under three Shared Socioeconomic Pathways (SSPs) via an ensemble of 5 Global Circulation Models (GCMs) in each scenario for Europe. Our study utilizes mesoscale hydrologic model (mHM) for simulating soil moisture conditions using the data from Inter-Sectoral Impact Model Intercomparison Project Phase 3b (ISIMIP3b) derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6). These soil moisture conditions are then analyzed to detect phases with a rapid decline in soil moisture content. In this study, the area under flash drought is projected to increase to about 2.5 times by the end of the century compared to the 1981 level, with the effects being more pronounced in the Northern part than the Mediterranean. Such future scenarios show the importance of limiting the warming according to the Paris Agreement, 2015 and adaptation and mitigation measure requirements to tackle such events so that the loss to our agricultural productivity and ecosystems can be minimized.

Keywords: Flash drought, mHM, CMIP6, SSP, GCM, ISIMIP, soil moisture, Paris Agreement

Water Supply-Demand Gap in Dura City, Palestine: Challenges and Recommendations

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Dura City in southern Palestine has long faced a growing water supply-demand gap due to rapid population growth, limited water resources, and an over-reliance on groundwater. The city's water supply primarily comes from external sources, while groundwater is heavily used for agricultural purposes, leaving little for domestic use. Despite efforts to extend the water distribution network to urban and surrounding areas, it has remained inadequate to meet the needs of the entire population, especially in the rapidly growing urban zones. This study assessed the water supply from external sources and the demand for domestic, agricultural, and industrial use, with a focus on identifying the critical gaps in the water distribution system. It also evaluated the efficiency of the

existing water network, which, despite being extended, was unable to adequately supply all areas, resulting in inequitable access to water. The study's results highlighted a significant supply-demand gap, exacerbated by infrastructure inefficiencies, limited availability of external water supplies, and the over-extraction of groundwater for agricultural purposes. Furthermore, population growth and climate change impacts were found to intensify the demand for water, further straining the already stretched resources. Based on these findings, several recommendations were made, including upgrading the water network to ensure coverage for underserved areas, improving the management of groundwater resources to prevent over-extraction, and integrating alternative water sources such as rainwater harvesting and wastewater reuse. Public awareness campaigns and policy interventions, such as water conservation practices and stricter regulations on water use, were emphasized as necessary steps toward achieving sustainable water management. This study suggests potential solutions for addressing the water supply-demand gap and ensuring equitable, sustainable water access for the residents of Dura City.

Keywords: Palestine, population growth, water supply, water demand

Progress on artificial eco-environmental water supplement in recent 20 years in China

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Artificial eco-environmental water supplement plays an increasingly important role for afforestation of urban area and river ecosystem restoration along with great concern on sustainable development of coupled nature and human system in recent years. In China, artificial eco-environmental water supplement, including urban greenbelt water use and replenishment of rivers and lakes, is as high as 34.28 billion m³ in 2022 by national statistics, nearly 6% of the total water use, which is quadruple for both of the percentage and water quantity comparing with that in 2003. The artificial eco-environmental water supplement in the Yangtze River basin and Haihe River basin accounts for 24% and 22% of the national total quantity, respectively. The urban greenbelt water use has doubled to over 10 billion m³ with about 150% increase of urban greenbelt area at the same time period, and the living environment has been improved markedly accordingly. The replenishment of rivers and lakes have risen significantly in the last 20 years throughout the country to over 30 billion m³, to ensure the basic environmental flow of important rivers and lakes and promote the recharge to groundwater in the path of waterway. Besides, the water supply sources for artificial eco-environmental water supplement more and more depend on non-conventional sources, including reclaimed water of urban sewage works and mining water drainage, to reduce the fresh water use. Some regions, Beijing for example, have officially brought forward the Water Conservation Rules to encourage non-conventional water use for artificial eco-environmental water supplement. The ecological effects and benefits of artificial eco-environmental water supplement are fabulous throughout China for ecosystem restoration and groundwater remediation.

Keywords: water use, ecosystem restoration, China, non-conventional water sources

Future-Ready Water Systems: Science-Based Approaches for Climate Resilience and Sustainable Development

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Climate change is intensifying water-related risks, threatening ecosystems, livelihoods, and economic stability. Ensuring water resilience in future climates requires science-based approaches, innovative technologies, strategic investments, and policy coherence to enhance adaptation and sustainability. This session explores integrated solutions that address water security challenges and strengthen climate resilience. The study will highlight cutting-edge water resilience strategies, including nature-based solutions, adaptive water governance, and digital innovations for improved decision-making. A key focus will be on science-based tools such as water accounting, water productivity modeling, and climate impact assessments, which provide data-driven insights for optimizing water management and policy interventions. Additionally, it will explore financing mechanisms, including public-private partnerships, and impact investments, to scale up climate-resilient water infrastructure and solutions. Policy coherence is another central theme, ensuring that water security strategies align with national climate adaptation and sustainable development goals. The paper will present inputs from diverse sectors for river basins case studies demonstrating successful cross-sector collaboration and investment mobilization for resilient water systems. The study highlights the need for increased adoption of science-based water management tools, strengthened partnerships for investment and policy reforms, and a deeper understanding of integrated, climate-smart water governance. By fostering collaboration among policymakers, researchers, investors, and practitioners, this session seeks to catalyze scalable, science-driven water resilience solutions that support both human and environmental well-being in the face of climate uncertainty.

Keywords: Water Resilience, Climate Adaptation, Science-Based Solutions, Policy Innovation, Investment & Financing

Assessing the Global Energy Demand for Irrigation

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Expanding irrigation to boost agricultural production can be a mutually beneficial strategy to meet the demands of a growing global population and the socio-political transformations currently taking place. However, this requires both sufficient water for crops and the energy needed to transport and distribute it across fields. While numerous studies have assessed the water volumes necessary to bridge the crop yield gap through irrigation, research quantifying the associated energy demand remains limited. In this study, we introduce a method for estimating irrigation energy requirements on a global scale using a spatially distributed, physically based bottom-up approach. The analysis

covers 42 different crops and three irrigation systems. Our findings indicate that the current global irrigation energy demand amounts to 1.1×10^9 GJ/year, with approximately 0.32×10^9 GJ/year allocated to surface irrigation systems and nearly 0.77×10^9 GJ/year consumed by sprinkler irrigation. Drip irrigation, at present, represents only a negligible fraction of total energy consumption. Cereals require the highest total energy due to their extensive cultivation worldwide, while crops such as coffee, citrus fruits, and sugarcane exhibit the highest energy demand per unit area. Regions with potential for irrigation expansion—primarily in developing countries across the southern hemisphere—often also experience energy scarcity. The maps produced in this study can serve as valuable tools for developing intervention strategies that consider both water and energy availability. By doing so, agricultural production can be sustainably increased while enhancing resilience and addressing issues of malnutrition and food insecurity.

Keywords: irrigation, energy demand, sustainable agriculture

Development of an Integrated Flood Risk Information System for the Jonkershoek Region, Western Cape

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Flooding remains a significant challenge in the Western Cape, with the September 2023 floods in the Jonkershoek region highlighting the need for improved flood risk management. This study developed an integrated Flood Risk Information System (FRIS) to enhance flood prediction, monitoring, and response by combining Earth Observation (EO) technologies, hydrological modelling, and Geographic Information Systems (GIS). The system integrated historical flood data, real-time hydrological observations, and machine learning techniques, including Random Forest (RF) and Gradient Boosting Machine (GBM), to improve flood forecasting accuracy. Hydrological models—HEC-HMS and SWAT—were used to simulate flood extents, achieving strong performance metrics (NSE = 0.88, KGE = 0.91, RMSE = 12%, and $R^2 = 0.86$). Machine learning models further enhanced predictive accuracy, with RF and GBM achieving AUC values of 0.89 and 0.92, respectively, and F1-scores of 0.85 and 0.88. The system demonstrated an 89% accuracy in predicting flood extents compared to high-resolution satellite-derived maps, while Google Earth Engine (GEE) reduced computational processing time by 40%, enabling near real-time flood risk assessments. The FRIS proved effective in modelling the September 2023 floods, aiding disaster response and resource allocation by allowing authorities to plan evacuation efforts better and deploy emergency resources. Future developments will focus on refining spatial resolution, incorporating socio-economic vulnerability indicators, integrating finer-scale rainfall data, and expanding coverage to enhance flood resilience and climate adaptation strategies in the Western Cape.

Keywords: Flood Risk Information System (FRIS), HEC-HMS, SWAT, Machine Learning, Flood Prediction

Unveiling the Dynamics of Green and Blue Water Footprint for Indian Agriculture: A High-Resolution Spatio-Temporal analysis

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The agricultural sector is the largest consumer of freshwater resources, making it essential to quantify crop water usage. Despite its importance, there is a significant lack of district-scale studies on the Blue Water Footprint (BWF) and Green Water Footprint (GWF) of crops in India utilizing remote sensing datasets. To address this gap, our research focuses on estimating the season-wise (Kharif, Rabi, and Summer) BWF and GWF of rice, wheat, and sugarcane crops in India from 1981 to 2023. Key factors for estimating BWF and GWF include potential evapotranspiration (PET), precipitation, and crop yield. We employed the MODIS and TerraClimate datasets for PET, the CHIRPS dataset for precipitation, and crop yield data from the Department of Agriculture and Farmers Welfare. Our results revealed that, during the Kharif season, GWF values are higher than BWF, because of the southwest monsoon. In contrast, during the Rabi and summer seasons, BWF values increase due to scanty monsoon rainfall and greater reliance on irrigation. Across all three crops and three seasons, the BWF is recorded highest during the rice summer season in Jhabua district, Madhya Pradesh, at 9.547 m³/kg in contrast, the highest GWF is observed during the rice kharif season at 9.55 m³/kg in Buldhana, Maharashtra. The district of Mandsaur, Madhya Pradesh, recorded a high BWF (6.621 m³/kg) and GWF (8.557 m³/kg) during the rice kharif season. A significant spike in the BWF was observed around 2009-2010, driven by higher PET in 2009 and increased dependency on blue water. Meanwhile, GWF exhibited stable trends with minimal fluctuations, indicating variations in rainfall patterns and crop water use efficiency. Additionally, BWF, GWF, and yield were classified into low, medium, and high categories, resulting in 24 water use sustainability classes. These classes can assist the policymakers in updating the sustainability status of districts by implementing new projects.

Keywords: Remote sensing, MODIS, blue water footprint, green water footprint, Rice

Hydrological Simulation of Forest Fire Impacts in the Kosi River Watershed, Uttarakhand, India

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This study investigates the hydrological impacts of forest fires in the Kosi River watershed, a mountainous catchment located in the central Himalayas of Uttarakhand, India. The Soil and Water Assessment Tool (SWAT) was employed to simulate the watershed's hydrologic response to significant forest fire events that occurred between 2013 and 2019. A baseline SWAT model was developed to

represent pre-fire conditions, and post-fire simulations were conducted by incorporating land cover changes induced by fires using SWAT's land use change module. Curve numbers were updated accordingly to reflect burned areas.

The simulation results revealed a marked increase in surface runoff-up to 33.87%-following fire events, accompanied by a noticeable decline in lateral flow and aquifer recharge. Pearson correlation analysis showed a strong negative correlation between surface runoff and both evapotranspiration ($r = -0.85$) and lateral flow ($r = -0.75$), indicating that post-fire hydrologic changes lead to reduced subsurface water movement and evapotranspiration losses. Further, regression analysis quantified the fire-induced alterations in the watershed's water balance, emphasizing potential long-term consequences for groundwater availability and increased erosion risk.

These findings highlight the critical importance of integrating forest fire-induced land cover changes into hydrological modeling frameworks to support sustainable water resource management in fire-prone mountainous regions.

Keywords: Forest fire, Hydrological modeling, Land use change, Water balance

Inclined wall jets - A comprehensive review

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Scour caused by turbulent wall jets is a major cause of failure of hydraulic structures. The high velocity of the jet issuing under a sluice gate scours the erodible bed downstream of apron/stilling basin leading to the exposure of their foundations. So, a detailed study of the hydraulics of turbulent inclined wall jets under different flow conditions is required to propose measures to prevent scour. In the present study, an attempt has been made to review the studies done on the hydraulics of turbulent inclined wall jets, including the scour characterises on the erodible bed. Various parameters of the wall jets have been explained such as velocity, turbulence characteristics as well as the process of scouring, parameters affecting equilibrium scour depth, flow characteristics within the scour hole and on the stilling basin, evolution of scour with time and formulae to estimate maximum scour depth. Scour caused by turbulent wall jets is a major cause of failure of hydraulic structures. The high velocity of the jet issuing under a sluice gate scours the erodible bed downstream of apron/stilling basin leading to the exposure of their foundations. So, a detailed study of the hydraulics of turbulent inclined wall jets under different flow conditions is required to propose measures to prevent scour. In the present study, an attempt has been made to review the studies done on the hydraulics of turbulent inclined wall jets, including the scour characterises on the erodible bed. Various parameters of the wall jets have been explained such as velocity, turbulence characteristics as well as the process of scouring, parameters affecting equilibrium scour depth, flow characteristics within the scour hole and on the stilling basin, evolution of scour with time and formulae to estimate maximum scour depth.

Keywords: wall jets, hydraulic structures, scour, hydrodynamics, turbulence

Comparative Analysis of Machine Learning Models for Crop Water Requirement Prediction

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Accurately estimating crop water requirement is important for planning irrigation, managing water resources, and studying the environment. Traditionally, this is done using methods that depend on detailed climate data. However, in many areas, this data may not be available, and the process can take a lot of time. In such cases, using models to predict crop water needs is a good alternative. Machine Learning (ML), a subset of Artificial Intelligence (AI), offers tools that can learn from existing data and make future predictions.

This study aimed to predict the water requirement of sugarcane of Samastipur district of Bihar using ML models like Random Forest (RF), Multivariate Adaptive Regression Splines (MARS), and Support Vector Machine (SVM). It used 20 years (2001-2020) of daily weather data, including maximum and minimum temperature, humidity, wind speed, and solar radiation. The water requirement was first calculated using the FAO-56 Penman-Monteith method combined with crop coefficients. The Gamma test helped choose the best input variables. The data was split into 80% for training the models and 20% for testing.

To evaluate the models, the study used three performance measures: Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and Nash-Sutcliffe Efficiency (NSE). Results showed that choosing the right model reduces errors and improves prediction accuracy. Among the models tested, Random Forest performed the best in both training and testing, followed by MARS and then SVM. These results highlight how effective ML models can be for accurately predicting crop water requirement.

Keywords: Crop water requirement, Machine Learning, Random Forest, Multivariate Adaptive Regression Splines, Support Vector Machine

Decoding Drought in North Brabant, Netherlands: A spatially distributed analysis of drought types and their transition

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Droughts are devastating natural hazards, with extensive impacts on water resources. In the Netherlands, the frequency of drought events has increased in recent years, putting stress on agriculture and natural areas and increasing pressure on ground and surface water resources. Current drought assessment methods rely on simplified metrics, such as precipitation deficits calculated from point observations starting on April 1st of each year. Such indices are entirely meteorological, and fail to capture the spatio-temporal dynamics of drought development through the different components of the hydrological cycle. Our research aims to determine the connection (onset time lag) between

different drought types (meteorological, agricultural and hydrological) for the North Brabant province in the Netherlands, and identify which indicators and indices best reflect the drought situation for timely detection.

For this purpose, a wide range of indices have been computed using local meteorological data from weather stations and radar, as well as remote sensing data from SAT3.0, WaPOR and IrriTracker, along with vegetation indices derived from Sentinel and MODIS. Furthermore, groundwater levels and streamflow at multiple locations have been analysed for hydrological drought assessment. The results indicate that the deficit in precipitation (meteorological droughts) triggers a rapid onset of hydrological drought, as observed in the sharp decline of groundwater levels during the drought of 2018. Agricultural droughts and hydrological droughts exhibited a conflicting dynamic: the actions to mitigate one will exacerbate the intensity of the other. Overall, our study offers a comprehensive approach for characterising different drought types, supporting stakeholders in developing sustainable drought management strategies.

Keywords: Drought, Hydrological indicators, Remote sensing, Groundwater levels, Netherlands

Multi-Scale Drought Analysis and Forecasting in the Western Ghats: A Case Study of the Kallada River Basin, Kerala

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Despite high annual rainfall, the Kallada River Basin in southern Kerala faces severe droughts due to pronounced intra- and inter-annual rainfall variability and ecological fragility. This study assesses meteorological dynamics using the Standardized Precipitation Index (SPI) (across three timescales, SPI-3, SPI-6, SPI-12) from 1981 to 2024 for three critical zones, Sasthamkotta, Punalur, and Thenmala. Historical drought trends, assessed using the Mann-Kendall test, showed notable spatio-temporal variability. To assess and predict SPI values, an Adaptive Neuro-Fuzzy Inference System (ANFIS) was employed, and performance was evaluated using R^2 , RMSE, and F1-score. ANFIS model demonstrated the highest predictive accuracy in Sasthamkotta, attributed to its relatively uniform rainfall distribution and physiographic simplicity. In contrast, performance was slightly lower in Punalur and Thenmala. In Punalur, the complex topography at the foothills of the Western Ghats, combined with intense orographic rainfall and abrupt shifts between wet and dry spells, introduced high variability that hindered model generalization. In Thenmala, the densely forested and hilly landscape, along with eco-hydrological feedback mechanisms, led to non-linear rainfall responses that further reduced predictive accuracy. Forecasted SPI values for 2025-2030 highlighted regional contrasts. Sasthamkotta is expected to transition from a dry spell in the early years to increasingly wetter conditions, supporting hydrological recovery. Punalur may experience more abrupt swings between drought and wet extremes. Thenmala is projected to maintain moderate but seasonally sensitive moisture trends. These findings underscore the need for integrating drought analysis and forecasting into targeted water planning, early warning, and climate adaptation strategies tailored to southern Kerala.

Keywords: Kallada river basin, drought, SPI, Mann-Kendall and ANFIS

Modeling Irrigation Water Needs Through a Hydrological Digital Twin

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Irrigation is an essential component of the food system and is receiving increasing attention in current hydrological model development. Hydrological digital twins aim to represent the full hydrological cycle, including anthropogenic processes such as irrigation. In this work, we present a novel irrigation modeling component, implemented within a hydrological digital twin using the open-source GEOframe framework. The model assesses water demand based on soil moisture and evapotranspiration, while accounting for different crop types and their specific water requirements. The flexibility of the digital twin framework enables the quantification of the effects of varying soil moisture activation thresholds on irrigation estimates and, consequently, on the overall hydrological water budget.

Water availability is considered under two scenarios: a limited scenario, in which water is drawn from other components of the model (e.g., river discharge), and an unlimited scenario. The model is applied to two of the largest river basins in Italy-the Adige and the Tiber (Tevere)-and shows promising preliminary results. It successfully simulates reported irrigation water consumption while also reproducing multiple components of the hydrological cycle. This work is supported by the PRIN project Control-based Optimization of the Anthropogenic Hydrological Cycle for a Sustainable Water Management (COACH-WAT, CODE 2022FXJ3NN, CUP E53D23004390001).

Keywords: Irrigation, Hydrological modeling, Water resource management

Geographically Weighted Regression to assess Water Ecosystem Services for Blue-Green Infrastructure development

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Addressing techniques on water resources towards sustainability and resilient cities relies on mechanisms that create conditions to foster the initial natural conditions and reduce the gap between human development and environmental necessity. In a global warming context, characterized by more frequent and severe extreme events, such as floods and droughts, more adaptive and resilient infrastructure for water resources management is required, allowing an interconnected solution that encompass several parts of the society pursuing sustainability and benefit to human and environment. In this context, Blue-green infrastructure (BGI) has emerged as a transformative

solution for water adaptation, offering ecological, social, and economic benefits over gray infrastructure. Adopting blue-green infrastructure not only restores the natural conditions for water resources but also allows the recovery of the natural capital assets - the stock of natural resources - and its ecosystem services. However, the comprehension of geospatial indicators and conditions that influence the ecosystem services is a handful knowledge that leads to the implementation of blue-green technologies for water resources management. The Geographically Weighted Regression (GWR) model is a powerful tool for capturing spatial heterogeneity by analyzing how relationships between variables change across geographic space. This approach enables the identification of local patterns and spatial dependencies among key geospatial indicators such as land use, soil permeability, vegetation cover, and hydrological behavior. By applying GWR, it becomes possible to better understand the complex relationships between these indicators and water-related ecosystem services. This spatially explicit insight supports decision-makers and urban planners in designing blue-green infrastructure (BGI) interventions that are tailored to specific local conditions, thereby improving their effectiveness and long-term sustainability. Furthermore, GWR contributes to maximizing the benefits of ecosystem services for human well-being, while also supporting climate change adaptation strategies, particularly in addressing challenges like floods and droughts.

Keywords: Water Resources, GWR, Blue-Green Infrastructure, Natural Capital

Decision Support System for Water Resource Management

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The global water crisis, exacerbated by rapid urbanization and climate change, has positioned water governance as a critical element of sustainable development. Pressures on water systems emerge from growing demand, over-exploitation, land use change, waste discharges, emerging contaminants, solid waste inflows, and ecological vulnerabilities intensified by climate variability. To address these interconnected challenges, a holistic approach is essential. In this context, a Decision Support System (DSS), designed as a Small River Management Tool (SRMT), is being developed under SLCR, IIT (BHU). The DSS integrates specialized modules such as sewage load estimation, sewage treatment plant (STP) prioritization and site suitability analysis, groundwater assessment covering potential zonation, water stress, and managed aquifer recharge, alongside river water management tools for water quality monitoring and resource estimation. These modules leverage authoritative datasets from the Central Water Commission (CWC), India Meteorological Department (IMD), WRIS, Census of India, CPHEEO, and remote sensing platforms. With a comprehensive back end incorporating hydrological, social, and hydrochemical fluxes, the DSS employs an Integrated Model (IM) to deliver reliable outputs with minimal data inputs, coupled with a user-friendly interface for stakeholders. As a pilot case, the DSS is being implemented in the Varuna River Basin, offering a scalable and adaptable framework for other small rivers. By strengthening decision-making processes, this initiative advances Sustainable Development Goals, particularly SDG 6 (clean water and sanitation), SDG 11 (sustainable cities and communities), and SDG 13 (climate action). Thus, the SRMT provides a transformative step toward equitable and sustainable water resource management.

Keywords: Decision Support System, SLCR, SRMT, Water Governance, Planning

Evaluation Of Sea level Rise of Tide Level in Arabian Sea

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This study uses non-parametric statistical techniques to examine long-term patterns in tide levels. With a baseline intercept of 5329.08 mm, the Sen's Slope Estimator shows a steady upward trend of roughly 0.859 mm/year, suggesting a slow increase over time. This conclusion is supported by the Modified Mann-Kendall Test, which confirms statistical significance at the 5% level with a strong positive correlation ($S = 6326.0$), a Z-value of 9.48777, and a nearly zero P-value. The rising trend is supported by the close alignment of Theil-Sen Estimator results. The dataset's analysis shows no prominent periodicities and six notable anomalies, indicating dynamic behavior with erratic swings. Later years show an increase of tide level rise, with most data points falling above the 1:1 line. The steady upward trend emphasizes how urgently strategic planning and flexible coastal management techniques are needed to reduce the risks of ongoing sea level rise and its effects on the environment and society.

Keywords: SLR, MMK, SRMT, CO2, CFC

Assessment of the current state of water resources in southern Uzbekistan under the influence of intensive water use and climate change

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An analysis of the state of water resources in individual river basins shows that planning and management of water resources are more effective when the natural and economic conditions are differentiated. The main source of water resources in southern Uzbekistan is the Kashkadarya River basin (Kashkadarya River, Chirakchi post – 0.72 m³/s); Zeravshan (Zeravshan River, Magiandarya post – 5.12 m³/s); AmuDarya (Kerki post – 69.5 m³/s).

Keywords: Natural and economic conditions, the Kashkadarya River basin, water resource scarcity, sources of domestic and drinking water supply

The 23 Unsolved Problems in Hydrology

Coupling of a Mechanistic Soil Hydrological Model and a Dynamic Vegetation Growth Model

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Climate change impacts on water resources and agriculture require reliable predictions that account for above-ground and below-ground processes of the soil-plant-atmosphere continuum. However, existing hydrological and crop growth models often oversimplify these interactions, limiting their reliability to predict future climate scenarios. These gaps are addressed by dynamically coupling process-based crop growth and soil hydrological models to simulate the interactive effects of climate variables on soil-water-plant interactions.

This study improves the reliability of soil water and crop growth models under changing climate conditions by incorporating vegetation dynamics into soil water simulations and enhancing crop growth models with physics-based soil water dynamics. Objectives include coupling the well-established HYDRUS-1D soil model with the mechanistic crop growth model BioCro, parameterizing and validating the model for cassava, and exploring the potential of targeted field practices to enhance water use efficiency (WUE) under future climate scenarios.

Two-way coupling of HYDRUS 1D and BioCro was performed using R. Field measurements were conducted for cassava plants at varying canopy levels. These measurements provided various plant physiological responses to changing light, CO₂, and temperature, allowing the estimation of various biophysical plant parameters required to parameterize the coupled model for cassava. Independently measured/reported historical yield data are used for model validation. Yield predictions using the coupled model under current and future climates will assess variations under different soil water management options and the impact of vegetation growth dynamics, including canopy manipulation, on water use efficiency. Preliminary tests revealed significant yield and soil water content differences between stand-alone and coupled models. Cassava biophysical parameters were obtained for parameterization of the coupled model.

This study highlights the importance of integrating vegetation dynamics and soil hydrological processes for reliable yield predictions under changing climates. The coupled model also offers insights into optimizing WUE and guiding sustainable agriculture through targeted soil and canopy management.

Keywords: HYDRUS 1D, BioCro, Two-way Coupling, Vertical canopy heterogeneity, Water Use Efficiency

Integrated Climate-Health Analysis: Assessing Public and Occupational Health Impacts of the 2018 Kerala Floods in the Greater Pamba River Basin, India

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The 2018 Great Floods in Kerala, India, underscored the critical need to address interconnected challenges in water management, public health, and occupational resilience. This study uniquely examines the combined impacts of flooding on public and occupational health in the Greater Pamba River Basin (GPRB), filling a significant research gap. Leptospirosis, a high-fatality communicable disease, was analysed using hotspot mapping for 2017 (pre-flood), 2018 (during flood), and 2019 (post-flood). The 2018 hotspot map was integrated with flood risk, population density, LULC, and healthcare infrastructure data, revealing that 60% of high-confidence hotspots overlapped with high flood-risk zones, while 12 panchayats lacked sufficient healthcare access, exposing gaps in disaster preparedness. In the occupational domain, flood risk mapping and a stratified survey captured exposure and vulnerability across sectors. Findings revealed that over 40% of agricultural workers faced severe economic and health disruptions. Vulnerability scores were calculated to prioritize interventions for at-risk occupations, with vulnerability scores rising in the order of house-hold industry, private sector, government sector, cultivation and agriculture. By combining public health and occupational analysis, this study emphasizes the need for integrated policies that address health infrastructure gaps, enhance disease surveillance, and build economic resilience. The findings highlight the potential for water management strategies to align with societal goals of health and livelihood protection, offering a novel approach to flood resilience planning in vulnerable regions.

Keywords: Public health, Occupational resilience, Hotspot mapping, Flood risk, Vulnerability scores

Harnessing Kalman Filter to Reduce Uncertainties in Evapotranspiration and Achieve Water Budget Closure at Global Scale

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Uncertainty in hydrological prediction arises from model structural assumptions, parameter calibration, and input data quality. Evapotranspiration (ET), a pivotal process in the global water cycle, exemplifies these challenges, as global ET products derived from hydrological models, satellite observations, and reanalysis data diverge. These discrepancies are especially pronounced in regions with intense human intervention (e.g., irrigation), increasing the overall uncertainties in evapotranspiration estimates and obstructing global water budget closure.

This study presents a Kalman Filter-based framework designed to reduce the uncertainties in global

ET estimation. By integrating multiple water budget-based ET products (derived from different data combinations and modeling approaches,) the proposed methodology yields a data-driven ET estimate (KF-ET), significantly lowering uncertainty (less than 2 mm/month). Since KF-ET is anchored in the water budget equation, it ensures water budget closure. Global and basin-scale evaluations, including cases in the Ganges and Amazon River Basins, reveal that KF-ET more accurately captures the spatio-temporal variability of ET compared to existing products (e.g., ERA5, Fluxcom, GLEAM, and WGHM).

Furthermore, the framework demonstrates improved sensitivity to natural and human-driven alterations. For instance, it incorporates flood irrigation effects in the Ganges Basin and reflects the energy-limited nature of ET in the Amazon Basin, where ample precipitation and deep-root access characterize hydrological dynamics. By systematically resolving disparities across diverse ET estimates and thus addressing the uncertainties arising from model structure, parameters and inputs, this approach enhances the reliability of hydrological predictions and contributes to achieving global water budget closure. KF-ET and its underlying methods offer a scalable path to improving hydrological forecasts under changing climatic and land-use conditions.

Keywords: Uncertainty reduction, Kalman Filter, Evapotranspiration, Water budget closure, GRACE

Hydrological compartments in hillslope catchments : A Case Study of Kaddam reservoir catchment

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Accurate streamflow modeling in hill slope catchments is important as they are anthropogenic-free, and majorly contribute to fresh waters and rivers in plain areas. However, the challenge arises from their distinct topography, ecology, and complex mix of soil, vegetation, and land use which makes the catchments respond quickly to precipitation leading to frequent floods. There are conventional methods in practice but these are not viable for varying hydrometeorological drivers at different spatiotemporal scales in the catchment. In this regard, an ensemble of diversified models, empirical (UH-method), conceptual (SAC-SMA & GR4J), and physical(SCS-CN) combined with multiple rainfall data sources are used to estimate the streamflows from a hill slope catchment of Kaddam reservoir in Telangana. The models SAC-SMA and GR4J are calibrated for the period, 2013 - 2022, and validated for two years, 2023 - 2024. The skill of the models are evaluated using multiple verification metrics: R, RMSE, NSE, and PBIAS. The models are able to capture the extreme flows temporally with some lag with underprediction observed flows. Hence, alternate strategies like alternate peak matching error (for lag correction), and a prior condition of catchment(saturated or dry) on runoff(for magnitude correction) are attempted.

Keywords: Hill Slope, Hydrology, Floods, Modelling

Linking Hydrological data uncertainty and equitable procedures in water reallocation planning in South Africa.

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Unequal society means extreme differences in vulnerability and adaptive capacity, particularly regarding water reallocation. This issue is worsened by natural variability that results in fluctuating streamflow patterns and unpredictable supply. In South Africa, where arable land is often available, but sustainable agriculture is limited by water availability, small farm dams have offered some resilience. But because they are private and poorly regulated, water shortage effects on downstream communities can be worsened and ecosystems can be pushed beyond their tipping points. Therefore, it is good practice to consider vulnerability across water user types and their priorities for water use. Explicit inclusion of uncertainty into decision-making processes is another good practice to better plan for variable streamflow, despite the reluctance of water managers and decision-makers in the global south to embrace hydrological uncertainty. These considerations are seen as a strategy towards fair reallocation during periods of low supply.

Supported by findings from a case study in the Koue-Bokkeveld region (South Africa), this contribution explores the progress made towards decision-making under uncertainty in South Africa and highlights some links between uncertainty and fairness in water reallocation planning. The findings and the participatory process were facilitated by an integrated modelling approach that combined hydrological uncertainty, socio-economic and environmental water needs, and vulnerability to water shortages. Because the modelling approach takes into account the relationship between the amount of shortfall and the potential impacts that various users may experience under each decision option, the results can help decision-makers proactively plan for and collectively agree on a water-sharing strategy (distributive equity links). A reflection of the modelling experience and exchanges with decision-makers is given to support the argument that prediction uncertainty must be taken into account to ensure equitable sharing.

Keywords: Hydrological modelling, Uncertainty, Equity, Water resources management

Advancing Soil Hydraulic Property Estimation at Spatial Scales Through Data-Driven Approach using Canopy Variables as Proxies

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Accurate estimation of soil hydraulic properties (SHPs) is essential for the estimation of soil water fluxes. However, this is challenging and time-intensive, especially in heterogeneous soils. Canopy variables, strongly correlated with subsurface layers, offer valuable proxies for soil water dynamics,

providing an opportunity to use canopy features in combination with soil moisture for developing estimates of multi-layer SHPs. This study focuses on developing spatial datasets of SHPs using a physics-informed machine learning (ML) model, providing a novel and efficient approach for characterizing soil water properties and, thereby, soil water fluxes at spatial scales.

EASI method was used to assess the sensitivity of variables (Leaf Area Index, Evapotranspiration, and Biomass) to SHPs. Inverse modeling with crop model STICS, incorporating GLUE methodology, was applied to three soil layers (10 cm, 40 cm, 100 cm) across 12 soil combinations of four soil types. Experiment was formulated in water-stressed conditions to evaluate its impact on the estimability of parameters. Supervised ML was applied so as to generate the spatial datasets of SHPs.

The results show a better correlation between variables and SHPs of different layers such that canopy variables hold best for sub-surface layer properties (sensitivity index ≈ 0.4), confirming their reliability as proxies. Higher weight on canopy variables improved SHP estimates, especially in deeper layers, with mean relative errors of 4% for the surface and 10% for the root zone. The ML approach enabled spatial SHP mapping, enhancing the understanding of soil water dynamics across heterogeneous landscapes.

The results highlight the potential of surface and canopy variables as reliable proxies for estimating multilayer SHPs and demonstrates the scalability of physics-informed ML models for diverse terrains. With variables accessible through remote sensing, this methodology enables large-scale SHP estimation, enhancing predictions of hydro-climatic processes and hazards.

Keywords: Soil Hydraulic Properties, Machine Learning, Inverse Modelling, Soil water fluxes

Impact of reservoir storage on upstream-downstream drought propagation in a semi-arid catchment in India

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Reservoirs can play an important role in mitigating drought effects. However, there can be both desirable and undesirable effects of reservoirs on the water cycle. Many studies have explored the temporal aspects of drought propagation, such as rate and response time, yet not much has been revealed about the spatial characteristics of drought propagation. The present study aims to quantify the impacts of reservoir storage on upstream-downstream drought propagation, considering 4 reservoirs in the semi-arid catchment of the Krishna River Basin of India using 19 years of data from 2000 to 2019. The Standardized Precipitation Evapotranspiration Index (SPEI), Standardized Soil Moisture Index (SSMI), Standardized Reservoir Storage Index (SRSI), and Standardized Stream-flow Index (SSI), representing meteorological, agricultural, reservoir, and hydrological drought, respectively, were estimated at a 3-month timescale and at a threshold value of 0. The spatial water distribution is described using the 'downstreamness concept', and the upstream-downstream drought propagation was investigated closely. The results indicate that the meteorological drought propagates to hydrological drought with drought lengthening. Whereas the hydrological drought propagation from upstream-downstream is attributed mainly to drought severity. Usually, the mild and moderate upstream reservoir droughts do not propagate to the downstream reservoirs, but severe droughts propagate to downstream reservoirs with a prolongation of duration and an increase

in severity. During drought propagation from upstream-downstream, the downstreamness of stored volume (Dsv) decreases from above the downstreamness of storage capacity (Dsc) at the start, indicating more water in the downstream reservoir, to below Dsc at the end, indicating more water in the upstream reservoir. Importantly, the findings from the study provide essential insights for implications for policymakers for catchment-scale water resource management and drought mitigation considering upstream-downstream drought propagation dynamics.

Keywords: Drought Propagation, Upstream-Downstream, Meteorological to Hydrological Drought, Downstreamness Concept

Geo-spatial model for real time forecast of extreme flood in the basin of river Mahanadi in the State of Odisha, India

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River Mahanadi originates from hillocks in the present State of Chhattisgarh, India and flows through the hills and plains of approximate area of 1,44,000 square kilometers and falls into the Bay of Bengal near Chilika Lake, Odisha, India. River Mahanadi was infamous for causing deluge as well as draught in her delta area. To protect these areas from devastation, conservation project was undertaken at Hirakud in the middle reach of the River Mahanadi, during middle of the twentieth century. With the advent of time, population started exploding in the upstream reaches of the Basin of River Mahanadi and utilizing the water resources of River Mahanadi right from the point of initiation of the river stream for fulfilling their water demand not only for survival but to fall in the realm of prosperity. This approach has caused significant changes in the geomorphological characteristics of the river basin affecting changes in the climate of the basin which is experiencing more extreme events of flood bringing more frequent rural as well as urban devastation in the basin.

Recent geomorphological characteristics of basin of River Mahanadi have been defined in true verification with the current field data, sub-basins of the basin of River Mahanadi have been delineated, land use pattern have been identified with the help of satellite imageries, soil characteristics have been defined in conjunction with the land use. The combined vector of land use and soil characteristics has been used along with the vector of forecast rainfall to generate temporal-spatial runoff which has been routed hydraulically in the downstream direction to get the quantum of flow in real time and space. The digital elevation model of the sub-basins and the basin as a whole was employed to get the extent of inundation for the particular area for each event of forecast.

Keywords: Mahanadi, Geomorphological Characteristics, temporal-spatial

Hydrological functioning of Oak and Pine forested catchments: Water availability and fluxes

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Forest composition is crucial in modulating hydrological responses in the Himalayan headwaters, influencing runoff partitioning, baseflows, and water retention. This study aims to understand the hydrological functioning of Pine-dominated and Oak-dominated forested watersheds in the Western Himalayan region, specifically in the Kumaon region of Uttarakhand. Through a combination of field-based measurements of rainfall, streamflow, and soil moisture, as well as lab-based assessments of soil physical properties, we assess the role of Oak and Pine forests in water availability and hydrological processes. The monitoring program was conducted from January 2021 through December 2023, with a focus on key watersheds at Sitlakheth (Oak), Papoli (Pine), Budibana (Oak), and Kwarab (Pine). Results indicate contrasting hydrological functions between the Oak and Pine watersheds. While the Oak watershed (Sitlakheth) demonstrates a higher annual water yield (348,365 m³./year/km²) compared to the Pine watershed (Papoli) (131,163 m³./year/km²), the runoff peaks are attenuated in Sitlakheth compared to 90% of runoff leaving Papoli during the monsoon months itself, and consequent high peak runoffs. Similarly, the Oak watershed (Budibana) exhibits a higher rainfall-runoff conversion rate (32%) compared to Pine (Kwarab) (12%). Baseflow contributions to runoff were also higher in Budibana (23%) than in Kwarab (15%). These findings suggest contrasting water retention properties and runoff generation mechanisms in the Pine-dominated and Oak-dominated watersheds. The results highlight the hydrological advantages of Oak-dominated forests in sustaining year-round water availability. Understanding these hydrological functions has implications for forest management policies in the Western Himalayas, where widespread Pine expansion may worsen seasonal water deficiencies.

Keywords: Forest hydrology, Water budget, Lesser Himalayas, Oak, Pine

SW-NE mass-flux heterogeneity linked with runoff, subsurface recharge and contamination in the Lower Chambal Basin

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This study investigates vertical connectivity which arises from differences in structural and functional connectivity within the semi-arid Lower Chambal River Basin. Index of Connectivity (IC), a measure of how efficiently flow pathways connect sources to sinks, is notably high in the SW Lower Chambal Basin. Findings reveal that IC is inversely correlated with the Topographic Wetness Index (TWI),

with regression analysis indicating that an increase of one unit in IC corresponds to a decrease of approximately 0.325 units in TWI. The highs in connectivity result in reduced groundwater recharge, as evidenced by water levels exceeding 20m in Sheopur, nearly twice that of northeastern counterparts, despite very high TWI, it's because a structural duality exists along the SW-NE axis, shaped by lateral disconnectors, particularly two deep lateral gorges which have fostered extreme terrain ruggedness and enhanced connectivity pathways. To provide merit to this, an Index of (Dis)Connectivity, incorporating geomorphons, elevation jumps, and convexity is developed (weightage 40:30:20) which confirms that two deep lateral gorges (30.9 km from Akoriya to Simroniya and 26.9 km from Khirkhiri to Budhera) significantly shape hydrological evolution and reinforce the SW-NE dichotomy. These insights underscore the role of terrain ruggedness and spatial heterogeneity in shaping groundwater recharge and surface runoff. Understanding these variations is crucial for accurate water resource assessment, identifying contamination risks, and enhancing drought mitigation strategies. Addressing hydrological spatial heterogeneity is fundamental for sustainable water management and environmental conservation. Furthermore, high sediment flux in the southwest contributes to elevated Fe and Mn concentrations in groundwater, linking vertical connectivity to "vertical-chemical connectivity".

This study in part comments on the problem number 5 and 13 of the 23 Unsolved Problems in Hydrology as for developing models that integrate small-scale heterogeneities while maintaining computational efficiency and predictive accuracy, we have to attend to small scale terrain heterogeneities itself.

Keywords: (Dis)Connectivity, 23 Unsolved Problems in Hydrology, semi-arid Lower Chambal River Basin, Index of Connectivity (IC)

Transforming Indonesia's Water Allocation and Rights Governance: Clarifying Political Actors' Perspectives on Contestations

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The transformation to sustainability is a growing agenda aimed at reshaping the development pathways toward a more equitable and sustainable future. Transformation approaches involve structural or shifting the societal structures, including political ideology and cultural norms; systemic or intentional changes with agencies such as policies and technologies; and enabling which empower individuals and communities to act. However, such a shift is often contested. For example, it should challenge existing paradigms such as the growth economy, to redistribute resources and prioritize ecological sustainability. In this process, some actors will stand to benefit but also others may experience losses.

Water governance is no exception to these contested transformations. The water allocation and rights must ensure sustainable and equitable outcomes. Transforming this regime in Indonesia remains necessary and can be achieved by addressing contestations in the underlying paradigm of valuing water, policy design and implementation, and community actions, as initially identified by Taufani et.al. (2025). In this study, we aim to clarify the values and arguments of political actors involved in the policymaking arena on the contested aspects of this transformation. By using Q

methodology, we hope to clarify the values and concerns that multiple actors prioritize, helping to pinpoint the missing and most critical issues that need to be addressed.

Keywords: Transformation, Contestation, Water Allocation, Water Rights, Q methodology

Nonlinear Covariate-based Framework for Non-stationary Flood Frequency Analysis in the Context of Climate Change

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The occurrence of floods presents substantial hazards to both human beings and infrastructure, requiring the implementation of comprehensive methodologies for their examination and forecasting. The validity of assuming stationarity in hydrological processes is being increasingly challenged in the context of global climate change. This study specifically examines the lack of stability in flood peak, acknowledging the dynamic impact of climate change on its occurrence and intensity by using different climatic and environmental factors as covariates. The study proposes a novel framework that captures the nonlinear characteristics of covariates to model time-varying peak flow. The results demonstrate that the proposed framework outperforms traditional non-stationary models, proving to be highly effective for future projections. The findings highlight the importance of incorporating nonlinear characteristics of covariate in non-stationary flood frequency analysis. This approach enhances the accuracy of flood risk prediction and provides valuable insights for policymakers and engineers working in flood-prone regions.

Keywords: Non-stationary flood frequency analysis, Nonlinear covariate modeling, Extreme event analysis, Flood frequency analysis

Analysis of clusters of Hydrological Extremes in the Amazon River Basin

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The Amazon River Basin performs a vital function in the Earth's hydrological and climate systems, which plays a significant role in maintaining global climate stability through its vast tropical rainforests and intricate hydrological processes. However, this pristine region is currently facing severe threats from rapid climate change and anthropogenic activities, mainly deforestation, which are leading to disturbances in its hydrological balance, which are causing increased number of extreme events such as severe floods and prolonged droughts. Although numerous studies have already been conducted, there still remains a gap in the comprehensive understanding of how these changes are interrelated and how it can be characterized spatially and temporally within the basin. The present research aims to address this gap by applying clustering techniques to identify the relationship among

deforestation, climate change, and hydrological extremes in the Amazon River Basin and uncover the spatial and temporal patterns and trends in these hydrological extremes. The present study has utilized single layer ERA-5 reanalysis monthly averaged data, Koppen-Geiger climate classification data, Land Use Land Cover data and Digital Elevation Model for exploring the relationships mentioned above. After collecting, pre-processing, and applying correlational analysis for identifying independent variables on this dataset, AI based clustering techniques, like K-means clustering, DBSCAN, and hierarchical clustering, along with distancing measures like Euclidean, Manhattan and Cosine measure have been tested for its applicability, by using sklearn library of python programming language. The outcomes of the study include identifying regions within the Amazon Basin that have been most affected by these hydrological extremes as well as how these hydrological extremes have changed in terms of frequency and intensity. The Amazon Basin has witnessed rise in temperature as well as in evaporation losses along with this the precipitation patterns have also shown increased variability in recent time.

Keywords: Hydrological Cycle, Deforestation, Climate change, Hydrological Extremes, Land-use Land-cover, Digital Elevation Model, Clustering Algorithms like K-means, DBSCAN & Hierarchical, Correlational Analysis

Quantifying the Influence of Land-Use/Cover and Geomorphic Changes on Extreme Runoff: Implications for Infrastructure Planning

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Short-duration high intense rainfall is increasing globally leading to increases in flood occurrences. However, variability of intensity and peak flood patterns are noted attributed to lithospheric features, topography, land cover and land use (LULC) and physiographic features of watersheds. In many situations, extreme rainfall events and upstream dam releases on downstream flooding in low-lying river basins are not clearly understood. Increased rainfall intensity, combined with changes in land use and tidal effects, exacerbate flooding, causing infrastructure disruptions and salinity ingress into agricultural areas. The challenges emphasize the importance of understanding regional hydrology and land use patterns for infrastructure planning and design to mitigate such adverse effects. The spatial and temporal variability of runoff extremes in a basin is required to assess how the land use and cover change with the extreme rainfall adversely affects the infrastructure of the region. This study explores the sensitivity of runoff extremes in certain catchments, examining why some catchments are more influenced by land use/cover and geomorphic changes compared to others and its impact on the built environment and infrastructure in different parts of the region. Analysis of extreme rainfall in semi-arid river basin with highly variable land use and dams in western India is carried out. Long-term annual precipitation extreme values obtained from four rain gauges are fitted with Log-Pearson III distribution and estimates for heavy rainfall extremes for different return periods are obtained. A 30-meter digital elevation model (DEM) defined topography along with 2D flood modeling approach is used to obtain flood hydrographs. Results from this research are expected to provide valuable insights into varying flood extremes with development and regulation via dam operations emphasizing the need to thoroughly analyze the region's hydrology, alongside detailed micro-level assessments of land use and land cover, before designing flood control measures or changing the existing infrastructure.

Keywords: Extreme Rainfall, LULC, Runoff, Flooding, Infra structure

Climate Change Effects on the Kimani Catchment: Implications for the Usangu Wetland

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Climate change and increasing climatic extremes have significantly affected water resources, ecosystem stability, and hydrological processes in the river catchments. In Tanzania, shifts in rainfall patterns, rising temperatures, and growing water demands have placed immense pressure on key water sources. Future projections under CMIP6 Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) indicate intensified rainfall, higher temperatures, and declining streamflows, posing serious challenges to catchment hydrology and downstream ecosystems.

The Kimani Catchment, located upstream in the Rufiji Basin, is a vital water source supporting agriculture activities, hydropower, inflows into the Usangu Wetland and biodiversity in the Ruaha national park found further downstream. However, escalating water abstractions driven by population growth, economic activities, and climate change have led to reduced river flows and extended dry seasons. This study evaluates the impacts of climate change on the hydrology of the Kimani Catchment and assesses its contribution to Usangu Wetland sustainability.

Using the WEAP model, hydrological assessments were conducted for baseline and future climate scenarios to analyze changes in water availability and flow patterns. The findings reveal that declining river flows from 1990s and prolonged dry periods which is attributed to reduced rainfall, increased water abstraction for irrigation, and changes in land use. The decline of Kimani streamflow has led to low inflow to the Usangu wetland affecting agricultural productivity and ecosystem health.

This study stresses the importance of sustainable water management to mitigate the effects of climate change and anthropogenic pressures on the Kimani Catchment and its downstream ecosystems, ensuring long-term water security and ecological balance in the Usangu Wetland.

Keywords: Climate change, Streamflow, Kimani River Catchment, Usangu Wetland, WEAP

Quantifying Uncertainty from Different Sources in Hydrological Modeling for the Himalayan Alaknanda River Basin

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The traditional approach of addressing uncertainty in hydrological modeling typically focuses on model parameters; however, the input and model structure uncertainties are often overlooked.

These uncertainty sources particularly becomes crucial in mountainous catchments with sparse monitoring and significant heterogeneity. Therefore, this study focuses on comparative assessment of different uncertainty sources (parameter, inputs and model structure) for hydrological modeling in Himalayan Alaknanda River Basin (ARB). Using SWAT+ model for parameter and input uncertainty and 47 models of MARRMoT framework for model structure uncertainty, this study quantifies the relative contribution of different sources to uncertainty. Parameter uncertainty was investigated using Latin Hypercube sampling (LHS) and the Sequential Uncertainty Fitting (SUFI)-2 algorithm. Our analysis identified that the snow-related parameters are highly sensitive in streamflow simulation, whereas few processes (represented in terms of stores), such as snow store, soil moisture, and routing store, are more important than the others. The findings also reveal that including additional store components beyond these crucial stores in the model leads to a decline in performance and an increase in complexity and uncertainties. Further, we found that the input and parameter uncertainty decreases when moving from upstream to downstream, while model structure uncertainty increases. These findings offer crucial insights into relative contribution of different uncertainty sources in the streamflow prediction in mountainous catchments, such as the Himalayas, and provide valuable applications for sustainable resource management.

Keywords: Hydrological modeling, MARRMoT, Streamflow, SWAT+, Uncertainty

Assumption hunting: To what extent are global irrigation models supported by empirical information?

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Modellers rely on assumptions to represent their subject systems, finding a balance between empirical assumptions, backed by data and research, and pragmatic simplifications, adopted to cope with data or resource limitations. All modelling efforts involve a blend of these assumptions, yet the extent to which global irrigation models (GIMs) rely on empirically substantiated versus pragmatic claims remains unclear. This oversight constrains our ability to delineate the uncertainties in these models and assess how reliable their results are. To address this, we used sensitivity auditing, a framework for evaluating both quantitative and qualitative assumptions, to systematically analyse the literature of nine GIMs, embracing an "assumption hunting" attitude to identify explicit and implicit claims. We probed the evidence behind these assumptions, if any, from the lens of philosophy of science, to discern between empirical and pragmatic.

Our analysis reveals that irrigation models are largely guided by pragmatic considerations. Of approximately 100 identified assumptions, over 70% lack empirical support, with many idealising farmer behavior. Additionally, we observed that GIMs tend to share similar assumptions, with 35% of claims being common to at least two models, and around 80% of those being pragmatic. This suggests that there is a convergence of uncertainty space in irrigation modelling. By juxtaposing these claims with established knowledge, we provide qualitative insights into the "hidden" uncertainties influencing estimates of irrigation water withdrawal. These findings underscore the need for a careful appraisal of model assumptions - particularly pragmatic ones, whose uncertainties are challenging to quantify - to ensure transparency and improve the epistemic role of GIMs in agricultural and water management decisions.

Keywords: philosophy of science, hydrologic model, sensitivity auditing, assumptions, epistemic uncertainty

Building Climate Resilience: An Interdisciplinary Approach to Uncertainty Analysis of Extreme Events in South Africa

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Urban cities in South Africa are increasingly vulnerable to the impacts of extreme weather events, driven by climate change. Building climate resilience in these urban areas requires an interdisciplinary approach to uncertainty analysis, integrating meteorological, hydrological, and socio-economic perspectives. This paper explores the methodological frameworks and analytical tools necessary to assess and manage the uncertainties associated with extreme weather events in South Africa. By examining historical data, climate projections, and case studies of recent extreme events, this study highlights the critical need for adaptive urban planning and robust infrastructure investment. It underscores the importance of cross-sector collaboration, involving stakeholders from government, academia, and the private sector to develop resilient strategies. The paper also discusses the role of innovative technologies and community-based approaches in enhancing the capacity to predict, respond to, and recover from climate-induced disruptions. The findings advocate for a comprehensive resilience framework incorporating climate uncertainty into urban development policies, ensuring sustainable and resilient urban futures in the face of escalating climate risks.

Keywords: Extreme weather events, urban planning, interdisciplinary approach, climate resilience, South Africa

Thirst and Thrust: A Critical Review of Water-Driven Migration and Urban Dynamics Globally and in the Indian Himalayan Region

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Water has always been a decisive factor in human settlement, driving both the rise of great civilizations and the displacement of vulnerable communities. This state-of-the-art critical review examines how water variability, extremes, pollution, and infrastructure change influence migration and urbanization patterns at three scales: global, national, and the Indian Himalayan Region (IHR). At the global level, four broad patterns of water-driven migration are identified - water scarcity, hazards, infrastructure disturbances, and quality degradation - with the majority of movements internal and mediated by socio-economic factors. At the national level, studies reveal the monsoon dependence,

groundwater depletion, and urban water crisis as key drivers of rural migration and urban stress in India. The review highlights how drought-linked livelihood loss in semi-arid states spurs seasonal migration, while flood-prone plains see repeated displacement. In the IHR, receding springs, irregular precipitation, and glacier melting have contributed to the phenomenon of "ghost villages," as young people depart mountain communities. Across scales, a meta-analysis uncovers commodities-water stress as a push factor, the slow vs. sudden onset distinction, and internal migration dominance - alongside divergence around trapped populations, adaptive vs. distress migration, and conflict linkages. Critically, the review identifies policy silos between water management and migration governance, and underscores the need for integrated, community-engaged approaches. Recommendations include early-warning systems, adaptive social safety nets, facilitated mobility pathways, inclusive urban planning, and community-led water conservation. By bridging scientific evidence, policy frameworks, and grassroots action, this comprehensive analysis lays a path towards resilient water management that addresses the crisis and harnesses human mobility as an adaptation strategy.

Keywords: Water-driven migration, Community-based adaptation, Urbanisation dynamics, Policy-migration nexus, Socio-hydrological systems

Evaluation of Infiltration Processes to Reduce Uncertainties in the HEC-HMS Model for Poorly Gauged Watersheds

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The use of theoretical Curve Number (CN) and lag time values is common in ungauged watersheds, a frequent condition in Brazilian basins. However, the absence of calibration leads to significant uncertainties in flow estimations. This study evaluates methods for reducing such uncertainties in the HEC-HMS model through the inclusion of a limited number of monitored rainfall-runoff events, simulating low-data scenarios. The initial scenario (Scenario 1) employed theoretical CN and lag time values. Subsequently, empirical methods were applied using six events for calibration and five for validation. Five scenarios were analyzed: (1) theoretical CN and lag time; (2) asymptotic CN8 and theoretical lag time; (3) CN8 and average lag time; (4) adapted asymptotic CN and theoretical lag time; and (5) adapted CN and average lag time. The Ia/S ratio, represented by the α parameter, showed the best performance at $\alpha = 0.05$. The use of theoretical CN led to overestimation of peak flow for high-intensity events and underestimation for low-intensity events. This practice often results in oversized hydraulic structures and increased project costs. Calibration with limited data significantly improved model performance. Peak flow variation decreased from 44% (Scenario 1) to 8% (Scenario 4), and the Nash-Sutcliffe Efficiency (NSE) increased from -1.64 to 0.68 (Scenario 5). The best results were achieved in Scenario 5, which combined an adapted CN (based on total precipitation) with the average lag time, resulting in NSE = 0.68, RMSE = 0.6, peak flow variation of -23%, and peak time variation of -1%. The study concludes that even a small number of monitored events can significantly reduce modeling uncertainties, making this approach feasible and effective for poorly monitored watersheds.

Keywords: Asymptotic CN, lag time, initial abstraction, streamflow prediction, HEC-HMS

Investigating Groundwater Fluxes Across Coastal Boundaries: A Numerical Study of Submarine Groundwater Discharge Under Tidal Forcing and Density-Driven Flow

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Understanding and quantifying groundwater fluxes across coastal boundaries is essential for accurately representing salinity and nutrient transport between aquifers and marine systems. These exchanges-submarine groundwater discharge (SGD) and recharge (SGR)/recirculated inflow-are governed by inland salinity and recharge, hydraulic and salinity gradients, and tidal oscillations. However, the spatial and temporal variability of solute transport, and their sensitivity to boundary processes-tidal pumping, transient seepage face development, density-driven flow, and variable inland recharge, remain insufficiently explored.

This study presents a FV-based mathematical framework to numerically investigate coupled flow and transport mechanisms near the land-sea interface and simulate cross-boundary solute exchange. A dynamic seepage face boundary condition has been developed, allowing discharge when internal pressure exceeds tidal sea level, reverting to a zero-gradient condition otherwise. Tidal oscillations are applied as a time-varying head to determine water and solute transport across the shoreline. The model updates seawater elevation dynamically based on tidal input and computes solute fluxes at the boundary using local hydraulic and concentration dynamics.

Solute transport is decomposed into three categories based on solute concentration thresholds and flow direction: (i) fresh-SGD driven by inland recharge and topographic gradient, (ii) mixed-SGD arising from dispersion, diffusion, and seawater recirculation, and (iii) marine-SGD governed by tidal pumping and buoyancy-driven flow. While the model fully supports density-dependent flow and transport, primary emphasis is on boundary-driven solute dynamics rather than net volumetric discharge.

The numerical results show that dynamic coupling of tidal forcing with a seepage face boundary provides realistic determination of intermittent discharge and solute transfer. Simulated transport patterns are strongly modulated by salinity gradients, aquifer properties, and inland conditions. This study depicts the influence of mathematical formulations of boundary condition and physical processes on calculated groundwater fluxes across hydrologic interfaces. Simulation results are physically consistent and therefore, the framework can be satisfactorily used for assessing SGD-derived contamination and salinization.

Keywords: Groundwater fluxes, Submarine Groundwater Discharge, Tidal Forcing, Seepage Face Boundary, Finite Volume Method

Network-scale sediment connectivity using the D-CASCADE model in a tropical river basin

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Bedload sediment connectivity plays a vital role in shaping river morphology and supporting ecological processes. Furthermore, hydroclimatic extremes lead to high runoff and sediment transport, yet direct bedload measurements remain limited due to various challenges. To overcome this, we employed the D-CASCADE (Dynamic Catchment Sediment Connectivity And Delivery) model for network-scale bedload estimation. Daily discharge, daily suspended sediment data, and monsoonal cross-section changes were obtained from the Central Water Commission (CWC) for the Tapi River basin. Field surveys were conducted at ~30 km intervals across 18 trunk streams and 10 tributary sites to collect bed material, river geometry, and active channel width. River cross-sections were generated using an Acoustic Doppler Current Profiler (ADCP) and Real-Time Kinematic Global Positioning System (RTK-GPS). Grain size distributions were assessed using photographic, Wolman, and sieve methods, depending on bed material size. Manning's roughness coefficient was estimated using the Hydrologic Engineering Center's River Analysis System (HEC-RAS), and network-scale discharge was simulated with the Soil and Water Assessment Tool (SWAT) to drive the D-CASCADE model. Hydrological and hydrodynamic models both show good agreement during daily calibration and validation, with R^2 and NSE values exceeding 0.60. Downstream fining of bed material from boulders and pebbles to sand was evident, reflecting sediment sorting along the river course. Additionally, reach-scale channel morphological characteristics were delineated using the River Styles framework. As an expected outcome, observed patterns of aggradation, degradation, and cross-section change are anticipated to align well with D-CASCADE model outputs, indicating the model's reliability in simulating sediment dynamics. This integrated approach offers a robust, scalable method for bedload estimation in data-scarce regions and models channel processes through sediment-transport characteristics. It can be adapted to other basins with similar challenges.

Keywords: Bedload sediment, CASCADE model, hydrodynamic model, hydrological model, Sediment connectivity

A machine learning-enabled socio-economic vulnerability assessment integrated with the SYNXFLOW flood modeling framework

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Rapid urbanization, often unaccompanied by adequate planning, has heightened the vulnerability of cities to flood risks, especially under the increasing frequency of extreme rainfall events. This study explores the integration of machine learning techniques to construct a Flood Vulnerability Index

(FVI) within socio-environmental systems, focusing on cities like Sheffield, UK. The FVI captures the multifactorial aspects of flood risk by incorporating physical, social, and economic indicators. To enhance risk assessment, the hydrodynamic SYNXFLOW model is coupled with vulnerability metrics, allowing for comprehensive flood risk analysis. Flood vulnerability evaluation accounts for key parameters including topography, soil characteristics, population density, economic conditions, proximity to flood zones, and the exposure of critical infrastructure. Socio-economic and demographic datasets were obtained from the Sheffield City Council, providing the foundation for machine learning analysis. SYNXFLOW simulations generated spatial distributions of flood depth across Sheffield's wards. This integrated approach illustrates the potential of data-driven methods to enhance the precision of vulnerability assessments, inform early warning systems, and support targeted flood mitigation strategies. The framework developed, demonstrates applicability in data-scarce, high-risk contexts and offers a scalable model for adaptive urban planning, relevant in cities facing similar climate-related challenges.

Keywords: Flood Resilience, machine learning, SYNXFLOW, Socio-economic vulnerability

Measurements and Observations in the XXI Century (MOXXI)

Automated riverbank monitoring system: Integration of image-based technologies for erosion and discharge assessment

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The increasing frequency of extreme weather events has amplified riverbank erosion, creating mounting challenges for infrastructure protection and riparian ecosystem preservation. Traditional monitoring approaches often fail to capture the temporal dynamics of these processes, limiting our ability to validate morphodynamic models.

Our research introduces an automated monitoring framework deployed along Sajó River in Hungary, where severe bank erosion threatens local infrastructure. The system utilizes cost-effective imaging stations, combining Raspberry Pi devices and trail cameras, to achieve high-frequency documentation of riverbank processes. By integrating Structure-from-Motion (SfM) photogrammetry with machine learning-based image analysis, we develop a dual-purpose monitoring system that tracks both erosion patterns and water level fluctuations. The methodology incorporates custom processing algorithms that enhance data quality and automate erosion volume calculations. System accuracy is verified through comparison with terrestrial laser scanning data and ADCP measurements during extensive field surveys.

Technical innovations include refined camera positioning protocols under variable vegetation conditions, optimized ground control point distribution, and enhanced SfM procedures for temporal change analysis. Our discharge measurement framework combines computer vision-derived surface velocities with dynamic cross-sectional profiles, supported by locally-trained neural networks. The project delivers three key outcomes: a robust protocol for continuous riverbank monitoring, detailed analysis of discharge-erosion relationships in meandering channels, and enhanced insight into erosion dynamics during flood events. This integrated approach advances river monitoring capabilities, supporting evidence-based decisions in river management and restoration projects amid increasing climatic uncertainty.

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Keywords: riverbank erosion, 4D photogrammetry, timelapse monitoring, discharge measurement

A Cost-Effective Probe for Monitoring Flux Rates at Sediment-Water Interface

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Surface water (SW) and groundwater (GW) interact across different landscapes, forming a hydrological continuum called the hyporheic zone. These exchanges have gained attention due to their role in water quality and resource management, especially under climate change and population growth. However, standardized methods to study these interactions remain limited. Traditional approaches using chemical tracers or seepage meters are labor-intensive, driving interest in temperature as a tracer. Temperature-based techniques, which collect high-frequency data without manual intervention, are promising but often expensive for use in developing regions.

To address this gap, a cost-effective probe was developed to measure flux rates in the hyporheic zone using an open-source system. Designed for high spatiotemporal coverage, the probe costs approximately \$100 and includes a data logger, waterproof sensors, and a real-time clock. It measures Vertical Hydraulic Gradient (VHG) and temperature at customizable depths, depending on site conditions.

The probe was tested with HOBO Tidbit sensors at an upwelling site in the unexplored Himalayan headwater catchments. Results showed a strong correlation (≥ 0.85) between the developed probe and HOBO sensors, validating its accuracy. Additionally, flux values derived from the probe provided valuable insights into GW-SW interactions.

This work, enables micro-monitoring of field sites with robust spatial and temporal data collection. It enhances our understanding of GW-SW interfaces while catering to socio-economic constraints, making it a valuable tool for sustainable water resource management.

Keywords: Hyporheic zone, low-cost instrumentation, temperature profiling, ground water-surface water exchange

Identification of convective precipitation events through lightning data in a Mediterranean area

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Nowadays, studying short-duration heavy rainfall events is extremely important. The increasing attention to these phenomena is due to the fact that often occur together with lightning, downbursts, and hail, triggering serious impacts on the population, economic activities, and the environment. Among heavy rainfall events, high-intensity and short-duration ones, are usually associated with the occurrence of convective precipitation.

Recent studies have shown that the frequency of such events has increased in the Mediterranean region, likely due to climate change. This study focuses on identifying heavy rainfall over Sicily, the largest Mediterranean island, using high-resolution (10-minute) rainfall data from the Servizio Informativo Agrometeorologico Siciliano (SIAS) rain gauge network for the period 2008-2024.

Since convective cells are typically associated with intense lightning activity, their detection is performed using lightning data provided by the Servizio Meteorologico dell'Aeronautica Militare. Various search radii centered on rain gauges, along with weighting conditions based on the distance of lightning strikes, were applied to examine how far lightning activity develops from ground stations. To enhance the identification of convective precipitation, additional reanalysis datasets-such as Convective Available Potential Energy (CAPE) and the K-Index from the ERA-5 database of the European Centre for Medium-Range Weather Forecasts (ECMWF)-were also employed.

Keywords: extreme events, convective precipitation, lightning

Demystifying Water Logging and Groundwater Recharge in Marathwada: Hydrologic Impact Evaluation of Recharge Pits

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Marathwada, a semi-arid region characterized by black cotton soils, faces a paradox of waterlogging in fields and declining groundwater levels. This unique hydrologic challenge arises from the perceived low permeability of black soils. In response, recharge pits were introduced to mitigate waterlogging and enhance groundwater recharge, with over 60,000 pits constructed in the Jalna district since 2021. These pits aim to bypass the impermeable black soil layer, directing water into the underlying weathered rock, potentially addressing both drought and flood conditions.

Multiple methods were used to assess the hydrological impact of recharge pits. From field to watershed scale, we used infiltration tests, surveys, and water level monitoring from pre-monsoon to post-monsoon in 2024-25. Double-ring infiltration experiments across 22 sites revealed infiltration rates ranging from 1 to 20 cm/hr, contradicting the assumption that black soils cause persistent waterlogging. Pressure transducer data at plots and recharge pits showed no significant differences in waterlogging depth or duration between intervention and non-intervention plots. Additionally, a paired watershed study at the watershed scale showed no difference in groundwater levels between watersheds with recharge pits and those without. Instead, the dual challenge is the product of limited aquifer storage that saturates quickly and drains quickly. A long time-series shed light on aquifer characteristics which varied with topography.

These findings challenge the perception of black soils as impermeable and highlight the role of aquifer characteristics and topography. Given the heterogeneity in basaltic aquifers, a multi-pronged approach is important for capturing water dynamics. While recharge pits offer limited impact on reducing waterlogging or enhancing recharge, systemic solutions, such as improved drainage in valleys and community water storage structures on ridges to retain water, may provide sustainable outcomes. This study underscores the importance of evidence-based interventions and tailoring solutions to local hydrological contexts.

Keywords: Black Soils, Basaltic aquifers, Marathwada, Waterlogging, Recharge Pits, Hydrologic Impact Evaluation

Enhancing Hydrological Observations for Sustainable Water Management: A Focus on ISMN

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The Global Terrestrial Network for Hydrology (GTN-H) serves as a coordinating mechanism for global hydrological data services, enhancing the availability and accessibility of essential water-related datasets. GTN-H comprises of several global networks, e.g. the Global Water Quality Database (GWDC), the Global Runoff Data Centre (GRDC) for streamflow, the International Soil Moisture Network (ISMN) among nine others. Altogether, these data services contribute significantly to improving our understanding of the hydrological cycle, promote data exchange and support sustainable water resource management.

This presentation focuses on ISMN, a global reference network dedicated to in situ soil moisture observations. Established in 2009, ISMN has harmonized data from over 80 networks, encompassing more than 3000 stations measuring soil moisture at various depths. The network ensures data findability, accessibility, interoperability and reproducibility through rigorous standardization and curation. Beyond in situ soil moisture data, ISMN provides additional environmental variables such as soil temperature, snow depth, snow water equivalent, precipitation, air temperature, surface temperature and soil water potential.

ISMN's robust quality control framework identifies and flags inconsistencies and errors, enabling researchers and practitioners to confidently utilize its datasets for applications ranging from hydrological modeling to climate change studies. ISMN's free data access (<https://ismn.earth>) has fostered global collaboration and supported hundreds of studies in Earth system science. ISMN contributes to the data-to-value chain on international initiatives like WMO, FAO and GCOS. One example is the contribution to WMO's yearly Global State of the Water Resources report.

Ongoing efforts are concentrated on expanding the database by incorporating additional stations and networks from institutional or governmental sources. Additionally, ISMN is exploring the integration of indigenous knowledge-based data into its scientifically curated database. This initiative aims to bridge the gap between traditional and scientific knowledge systems, fostering a more inclusive and holistic understanding of hydrological processes and strengthening global water management strategies.

Keywords: soil moisture, observation, global, database

Addressing data gaps in coastal tidal observations using a hybrid GIS and physics-informed neural network

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Tidal data is an important input for hydrodynamic modelling of coastal and estuarine systems, coastal ecosystem studies, climate change impact assessments etc. However, lack of tidal gauge networks in many areas severely hampers efforts to perform modelling and make accurate predictions. The gravity of problems faced by coastal areas in most parts of the world has resulted in an urgent need to address these observational gaps in order to enable setting up of models to address these. In this work, we propose a hybrid approach combining Geographic Information Systems (GIS) and Physics-Informed Neural Networks (PINNs) for predicting tidal variations at locations where observed data is not available. The proposed methodology is tested by estimating the tidal fluctuations at Kollam using tidal data at Beypore and Cochin in Kerala which were analysed using T-Tide to extract the dominant harmonic constituents. GIS-based interpolations were then utilized to estimate the initial tide level at Kollam to capture spatial variability. A PINN model was then developed to integrate these interpolated values with the fundamental hydrodynamic equations to maintain physical consistency while predicting temporal tidal variations. The PINN model was trained and validated using available observed tidal data at Kollam. Results show that the hybrid GIS-PINN method has greatly enhanced tidal prediction accuracy compared to conventional interpolation methods. It can accurately estimate tidal levels at unmonitored locations while remaining consistent with real hydrodynamics. Expanding GIS-PINN models to larger coastal and estuarine regions, integrating real-time data, and leveraging AI for predictions can significantly improve scientific accuracy, decision making and safeguard vulnerable coastal ecosystems against climate change impacts. As the 21st century demands innovative strategies to address data gaps in environmental sciences, this study aligns with the SDGs 9 & 17 to ensure the sustainability of coastal environments in an era of rapid environmental change.

Keywords: Tidal Prediction, GIS Interpolation, Physics-Informed Neural Networks, Coastal Hydrodynamics, Environmental Data Gaps

Facing environmental threats in Mediterranean agro-ecosystems: The contribution of the Alento critical zone observatory.

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Introduction and objectives. The Alento River Observatory (ARC, southern Italy), established in 2016, has become a key Mediterranean research site for addressing the impacts of seasonal climate anomalies and rapid land-use change on the hydrological cycle. Its strategic location makes it ideal for optimizing water resource management for diverse users (drinking water, irrigation, hydro-power generation).

Methods and results. Leveraging various research projects, the ARC has developed a comprehensive monitoring system, integrating wireless sensor networks, cosmic-ray neutron sensors, piezometers, meteorological stations, and tools for hydro-geophysical surveys, stable isotope analysis, and remote sensing. Extensive soil sampling, coupled with laboratory analysis of visible and near-infrared diffuse reflectance spectroscopy, physico-chemical, and hydraulic properties, further enhances these efforts. Field measurements of soil-vegetation-atmosphere system parameters further support the development and application of eco-hydrological models.

Summary and conclusion. Therefore, the ARC represents an ideal "lighthouse" where the ongoing transdisciplinary research activities help provide inspiring solutions, training, and communication to enhance soil health and ecosystem services in Mediterranean agro-ecosystems. This synergy between critical zone monitoring and ongoing open-air laboratory activities positions the ARC as a leading Mediterranean environmental research platform. This presentation will showcase and discuss the latest findings from these activities.

Keywords: climate seasonality, soil hydraulic properties, sensor network, cosmic-ray neutron sensor, remote sensing, hydrogeophysics, stable isotopes.

Low-Cost Hydrometry Techniques: A comparative assessment of Lidar- and Radar-Based non-contact hydrometry in mountainous rivers

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Accurate river flow estimation is essential for hydrological research, especially in mountainous regions where conventional in-situ measurements are often difficult. This study assesses the efficacy of two non-contact hydrometric methods: lidar and radar-based water level estimation, by deploying them on a mountainous river. The aim is to evaluate their performance and illustrate the advantages of lidar-based methods in hydrometric applications.

Lidar and radar techniques assess water levels by measuring the duration of an emitted signal to return from the water surface. Lidar utilizes laser pulses in the near-infrared range, providing high-resolution observations with minimum atmospheric disruption. Radar uses microwave signals that can penetrate poor weather but may be affected by surface irregularities and sensor orientation.

The lidar-based sensing demonstrates multiple advantages over radar-based sensing, such as reduced cost, improved portability, and greater ease of deployment in challenging terrains. Radar-based sensors are larger, necessitate more complex installation, and entail greater operational expenses. Lidar-based sensors not only offer logistical benefits but also exhibit enhanced precision in water level estimation, assessed through goodness-of-fit metrics by comparing sensor-derived data with ground-truth observations. Additionally, to evaluate the variability in sensor recordings, we utilize the coefficient of variation, standard deviation, and interquartile range to compare the consistency and stability of water level estimates.

Our findings reveal that lidar-based sensors outshine radar-based systems in several performance metrics, delivering enhanced accuracy and consistent measurements in dynamic river conditions. The pairwise correlation coefficients between lidar water level readings and manual staff gauge readings at two sites surpassed 0.97, underscoring the accuracy and precision of lidar technology.

Lidar methods represent a cost-effective, reliable, and easily implementable solution for hydrometric monitoring in mountainous river environments. This research affirms the effectiveness of lidar-based hydrometry for river flow estimation, thereby contributing to improved water resource management and hydrological research.

Keywords: Non-contact hydrometry, River flow estimation, Hydrological monitoring, Low-cost sensors

The role of efficient soil and water monitoring schemes for the design and implementation of agricultural policies protecting the environment and securing farmers' income.

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In the new EU project Path4Med "Demonstrating Innovative Pathways Addressing Water and Soil Pollution in the Mediterranean Agro-Hydro-System", we seek to demonstrate an integrated monitoring scheme that will enable the design and implementation of broader and more efficient agricultural policies protecting the environment and securing farmers' income. Path4Med is a collaborative and multidisciplinary project tackling water and soil pollution in the Mediterranean agro-hydro-system. It brings together 26 partners from 10 EU and 5 non-EU countries. Path4Med analyzes the role of efficient soil and water monitoring schemes in policy making. Policy makers usually start with a broad spectrum of innovative and high-tech solutions, but in most cases, end-up in compromises that limit policies scope. Among the key obstacles are: i) innovative and high-tech solutions require high costs and well-designed business models to be profitable, ii) unclear costs of water resources degradation bias farmers' decisions, iii) authorities prefer practices and measures that are easily monitored due to their inability to monitor and evaluate complex or innovative approaches implementation, iv) net impact evaluation of applied policies is based on limited data, restricting bold interventions financing, v) realistic assessment of water bodies status is inadequate due to limitations in monitoring techniques and approaches, data analysis, interpretation, and the lack of suitable indicators, vi) current monitoring and analysis may not differentiate the causes of water bodies deterioration, especially for diffuse pollution, thus hinders targeting of eligible farms for measures and interventions. Thus, Path4Med will enable informed decision making and policy design through the following key elements: 1) Map the current status of agro-hydro-system in designated catchments,

2) Develop and mainstream novel monitoring technologies (Earth Observation, eDNA-based indicators of water quality, IoT, AI), 3) Assess the technical and socioeconomic viability of solutions through integrated modelling at different spatial and temporal scales.

Keywords: integrated monitoring, policy making, novel monitoring technologies, Agrohydrosystem, integrated modelling

Advancing river monitoring using image-based techniques: challenges and opportunities

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Enhanced and effective hydrological monitoring plays a crucial role in understanding water-related processes in a rapidly changing world. Within this context, image-based river monitoring has been shown to significantly enhance data collection, improve analysis and accuracy, and support effective and timely decision making. The integration of remote and proximal sensing technologies with citizen science and artificial intelligence may revolutionize monitoring practices. Therefore, it is crucial to evaluate the quality of current research and ongoing initiatives to envision the potential trajectories for research activities within this specific field. The evolution of monitoring strategies is progressing in multiple directions that should converge to build a critical mass around relevant challenges to find innovative solutions that overcome limitations of traditional approaches. This study explores examples and best practices in advanced hydrological monitoring across various applications, emphasizing the strengths and limitations of emerging approaches. All assessments are grounded in the authors' extensive experience with European and national projects, as well as their collaboration within the MOXXI Working Group of the International Association of Hydrological Sciences.

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Reference: Manfreda, S., D. Miglino, K. C. Saddi, S. Jomaa, A. Eltner, M. Perks, D. Strelnikova, S. Peña-Haro, I. Maddock, F. Tauro, S. Grimaldi, Y. Zeng, G. Gonçalves, T. Bogaard, T. van Emmerik, M. Bussettini, S. Mariani, G. Marchetti, B. Lastoria, B. Su, M. Rode, Advancing river monitoring using image-based techniques: challenges and opportunities, Hydrological Sciences Journal, Pages 657-677, (doi: 10.1080/02626667.2024.2333846) 2024.

Keywords: river monitoring, image-based techniques, remote sensing, water quality, artificial intelligence, citizen science

Wildfire mapping in dry deciduous forests of southern West Bengal and measurement of soil physicochemical changes for Forest Beat-level management

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Forest fire studies in India usually focus on regions having large, contiguous forests. States with fragmented/degraded forests like West Bengal are often neglected, despite experiencing a disproportionately high number of fire events annually relative to their forest coverage fraction. This study addresses that oversight by focusing on fire events in the dry deciduous forests of southern West Bengal, an ecologically fragile landscape rarely featured in national-level assessments. Using Suomi National Polar-orbiting Partnership (SNPP) satellite-based fire products from 2012 to 2023, we conducted Location Quotient (LQ) analysis of fire occurrences at the state and intra-state levels. Results reveal that though West Bengal ranks near the bottom in terms of total fire counts, its southern districts exhibit consistently high fire concentration relative to their limited forest area. This disparity is further exemplified through annual forest beat-wise fire event mapping, pinpointing specific locales that experience recurring fires. To assess the ecological implications of these fires, soil samples were collected from 12 forest patches during the 2024 fire season, comparing burnt and unburnt sites at three depths (0-5 cm, 5-10 cm, and 10-20 cm). Results show significant ($p < 0.05$) alterations in the topsoil layer of burnt sites, including increased pH, electrical conductivity, potassium oxide, organic carbon and nitrogen content, alongside reduced bulk density, largely driven by the deposition of ash/pyrogenic organic carbon or partial combustion of organic matter. The immediate nutrient enhancement observed at burnt sites suggest a temporary rise in soil fertility, which can potentially aid post-fire vegetation recovery. Nevertheless, recurrent fires event progressively reduce ground biomass, thereby accelerating soil erosion, while ash-enriched nutrient loss can induce land degradation. By integrating beat-wise high resolution fire maps with empirical soil assessments, this study offers a valuable early-warning framework to pre-emptively address fire-induced ecological and hydrogeomorphological risks in neglected yet vulnerable forest tracts.

Keywords: Recurrent wildfires, dry deciduous forest, soil alterations, mapping and management

Citizens and Hydrology (CANDHY)

Integrating knowledge systems in flood-risk modelling for sustainable solid waste management and flood resilience in urban informal settlements in KwaZulu-Natal, South Africa

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Flooding poses a significant threat to urban informal settlements, particularly in KwaZulu-Natal, South Africa, where inadequate drainage infrastructure and poor waste management exacerbate flood impacts. This study develops an integrated flood-risk modeling framework that combines scientific and local knowledge to enhance flood resilience and sustainable waste management. Using Quarry Road Informal Settlement in eThekweni Municipality as a case study, a mixed-methods approach was applied, incorporating stakeholder engagements, participatory mapping, and hydrological modeling.

Community-based workshops and focus groups revealed that plastic, fabrics, and nappies contribute to drainage blockages, particularly at bridge crossings, intensifying flood hazards. GIS analysis and HEC-RAS 2D were used to model flood inundation for 5, 20, 50, and 100-year return periods. The results indicate floodwaters encroaching into informal housing, with significant impacts on infrastructure and residents.

Findings emphasize the importance of collaborative governance, integrating municipal authorities, NGOs, and scientific institutions in urban planning and disaster management. Engineering interventions such as debris walls, larger culverts, and riverbed dredging are proposed, contingent on financial viability and sustainability. The study underscores the need for municipalities to adopt integrated water management strategies that engage communities in both infrastructure development and waste reduction initiatives.

Future research should leverage drone technology for high-resolution waste classification, collect streamflow data for improved flood frequency analysis, and enhance model calibration for more precise flood simulations. This research highlights the need for improving urban resilience in the face of climate change and urbanisation.

Keywords: Flood-risk modeling, Urban informal settlements, Community-based flood resilience

Stakeholder-driven assessment of watershed management strategies for agriculture and ecological sustainability: A case study in the lower Apalachicola-Chattahoochee-Flint (ACF) River Basin

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Agricultural sustainability while maintaining ecological vitality is a critical concern for the lower Apalachicola-Chattahoochee-Flint (ACF) River Basin in the southeastern United States (U.S.) due to increasing demand for irrigation in the already stressed surface and groundwater resources of the region that has been further exacerbated by the changing climate. Stakeholder engagement in the development of hydrologic models along with the co-development and evaluation of potential scenarios for mitigating water issues in vulnerable watersheds is critical for informed policy decision-making and increasing the likelihood of implementation of preferred scenarios. This study utilized a stakeholder-driven participatory modeling process to assess watershed management strategies to enhance the agricultural as well as ecological sustainability of the lower ACF River Basin through the development and evaluation of six scenarios. Evaluation of the scenarios demonstrated that the surface- and groundwater hydrologic response to the scenarios varied across the basin due to spatial differences in hydrogeology and land use. Conversion of agricultural lands to forestry, voluntary suspension of irrigation, and adopting efficient irrigation practices significantly enhanced streamflow and groundwater levels, particularly during drought conditions. While the assessment of the scenarios provided valuable insight into the hydrologic response of the lower ACF River Basin, stakeholder engagement during the model development and evaluation process also provided important insights into a participatory modeling process. The study highlights the importance of balancing the needs of different stakeholders while trying to identify feasible and scalable solutions for water management. Stakeholder engagement was also vital to understanding the potential limitations in implementing the different scenarios including economic constraints, perception about scenario choice options, etc. This information can be vital to policymakers for effective communication as well as the development of management plans for agriculture, silviculture, and ecological sustainability.

Keywords: surface water, groundwater, participatory approach, co-development, agriculture, sustainability

A Novel High-Resolution Flood Hazard Model for India: Integrating Reanalysis Data with Hydrodynamic Simulations

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Flooding poses a persistent threat to millions in India, yet the country lacks a comprehensive, high-resolution flood hazard model capable of capturing extreme flood events at a national scale. Existing flood assessments rely heavily on sparse gauge station networks, limiting their spatial coverage and applicability. This study presents a novel flood hazard modelling framework that leverages state-of-the-art hydrodynamic simulations integrated with high-resolution atmospheric forcing from multiple reanalysis datasets to generate flood hazard maps across India.

The model operates at a 100 m resolution and employs LISFLOOD-FP—a widely used two-dimensional hydrodynamic model—to simulate flood inundation dynamics under historical and extreme flood scenarios. Precipitation inputs from ERA-5, IMDAA, CFSR, and MERRA are first evaluated against IMD observations at a nascent scale using performance metrics such as the correlation coefficient (CC), Kling-Gupta Efficiency (KGE), Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), Hit Rate (HR), False Alarm Ratio (FAR), Error Bias (EB), and Critical Success Index (CSI). The best-performing dataset for each basin is then used as a primary input, alongside terrain, river, and ancillary hydrological data, to drive flood simulations. Calibration and validation are performed using satellite-derived

flood extents, ensuring model robustness in data-scarce regions. Additionally, extreme value analysis is employed to estimate return-period flood hazards (e.g., 50-year, 100-year events), offering critical insights into future flood risks.

This work represents the first comprehensive attempt to develop a high-resolution, large-scale flood hazard model for India, bridging critical data gaps and providing a robust framework for flood risk assessment under changing climate conditions. The model outputs offer valuable insights for disaster preparedness, infrastructure planning, and policymaking, marking a significant advancement in flood hazard mapping for one of the world's most flood-prone regions.

Keywords: Flood hazard, Hydrodynamic model, LISFLOOD-FP

Experiences of citizen science and co-creation in soil hydrology and health within the activities of the Italian chapter of the LOESS project

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The water engineering group of the University of Brescia is active in the Horizon Europe project LOESS (<https://loess-project.eu/>) since its start in June 2023, together with other nineteen European –of which two Italian– partners. The final goals of the project are to raise awareness on the importance of soil and of its functions, to increase soil literacy across Europe and to help developing innovative educational materials and practices.

Together with the other two Italian partners, we created an heterogeneous, 60-participant wide, Italian Community of Practice (CoP) and engaged it, or various sub-groups of people from it, in designing and/or performing multiple activities since the start of the project. This contribution intends to report on the activities dealing with soil hydrology and health.

In March 2022 we launched the WormEx II experiment, an ongoing citizen-based participatory research (CBPR) to attract a local High School students' attention on the hydrological role played by soil macropores.

On World Soil Day 2023 we –with the other Italian partners– performed a widespread infiltration experiment involving the CoP and classes from 5 Primary Schools over the Italian territory. A total of 140 students and 7 teachers took part in the experimental phase.

Between November and December 2024 we organised and conducted three co-creation events on Augmented Reality applications for soil health education in two 3rd-year classes of a local High School in the province of Brescia.

On 5 December 2024 we –with the other Italian partners– organized and hosted a dissemination event about World Soil Day, with considerations regarding the links between soil, peace and sustainability. The public event involved the CoP and two Primary School classes as well as university students and professors.

These activities showed how much our society is interested in taking an active part in research there are the conditions for it.

Keywords: citizen science, hydrology, soil hydrology, citizen-based participatory research, co-creation

Optimal siting of multipurpose artificial reservoirs with a participatory multi-criteria decision making

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Water resource management is increasingly critical due to climate change and growing water demand. Artificial reservoirs play a vital role in water supply, flood mitigation, and energy production. However, traditional reservoir siting approaches primarily rely on hydrological and topographical factors, often neglecting key socio-economic considerations. This study presents a novel participatory multi-criteria decision-making (MCDA) framework that integrates community engagement into reservoir site selection, ensuring both technical feasibility and societal acceptance. The proposed methodology consists of three key phases: (i) automated geomorphological and hydrological analysis to identify potential reservoir sites using a high-resolution Digital Elevation Model (DEM) and a distributed hydrologic model, (ii) a participatory approach using a web-based survey for pairwise comparison of decision criteria, and (iii) MCDA for ranking sites based on quantitative evaluation metrics. The case study in the Pesa River watershed (Italy) demonstrates the effectiveness of this approach, incorporating criteria such as hydrology, infrastructure impact, environmental concerns, and flood mitigation potential. Results indicate that engineering-based siting strategies often overlook critical community-driven factors, and that optimal dam sizes vary depending on local environmental and social constraints. Findings highlight that a purely top-down engineering approach may not align with community needs, particularly in balancing ecological preservation and economic feasibility. The participatory MCDA approach ensures transparent, data-driven decision-making, fostering greater stakeholder acceptance of reservoir development. This methodology offers a transferable framework for sustainable water infrastructure planning in diverse geographical and socio-economic contexts.

Acknowledgement: This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005)

Keywords: Participatory approach, multicriteria analysis, water resources management

Identifying potential sources of debris flow: Relooking flash floods from a novel perspective

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Introduction

Recently, there has been a rise in the occurrence of high-magnitude events, such as climatological, geohydrological, and meteorological events. This trend has been closely associated with human activities and climate change. These events have been analyzed in terms of their patterns, frequency, geographic distribution, and impacts; the findings have gained immense global traction. An

increasing interest of natural scientists in understanding the patterns have been observed. This is important considering the demand of robust early warning systems.

Aim

This study assesses the hydrological behaviour and the sediment mobilisation processes within Pranmati Catchment, a small river basin in Uttarakhand based on two flash floods events (16th July 2018 and August 2023) caused due to extremely focussed precipitation activity. On the basis of the investigations, algorithms have been developed to identify potential sediment storage sites and determine sediment evacuation susceptibility.

Methods

The study has been carried out primarily by field observations for 7 years, hydrological reconstruction of flash flood events, and development of sediment storage potential index and sediment evacuation susceptibility index. These indices have been developed using terrain analysis and sediment connectivity models.

Results

The study has reconstructed the hydrological event of 2018. Sediment storage potential indicated distinct zones of high storage potential, such as junctions of two land use and land cover unit, grassland pockets within forested hillslopes, midslope region, and landslides. Unstable sections of hillslopes and the bank-attached zones of hillslopes have a high evacuation susceptibility, whereas landslide debris have poor evacuation susceptibility.

Summary and Conclusion

Specific geomorphic units on the hillslopes tend to arrest incoming sediment flux. These stored sediments get evacuated during high magnitude hydrological activities, such as cloudburst, flash floods, and tend to contribute to generate debris flow. This high density flow with the erodes toes destabilizing upslope sediment storage zones, thus, cascading secondary landslides

Keywords: Flash flood, Debris flow, Sediment storage potential, Sediment evacuation susceptibility, Landslide

Distributed databases for data sovereignty in hydrological citizen sciences

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Citizen science is increasingly used in hydrology to collect data at larger scales than would be possible by scientists alone, as well as to improve community participation in and ownership of hydrological research. These initiatives are generally organised around online platforms that allow users who are not professional scientists to collect and share hydrological data (rainfall, streamflow, or other) from their daily observations.

These platforms, however, rely on data storage in centralised servers that is expensive and can be financially unsustainable, especially for larger, more successful projects that require significant server bandwidth and memory. Ironically, the more successful a project becomes in terms of data collection and user numbers, the more difficult it becomes for the research team to sustain the service, even if it provides real value to the community.

In this context, distributed (peer-to-peer) systems offer an interesting alternative to building citizen

science applications, since these systems increase community sovereignty over their own data by allowing users to directly share information with each other in a peer-to-peer network, with no need for scientists to maintain a centralised server.

In this presentation, we discuss the development of Constellation, a distributed database app for citizen science. The software, being generic, allows scientists to share and access data as well as to automatically generate project-specific apps for end users.

We expect that this tool will lower the barrier of entry and costs for citizen science initiatives in hydrology and lead to wider-scale uptake of citizen science as a means of involving communities in hydrological data collection and interpretation.

Keywords: Citizen science, distributed databases, Constellation

History of Hydrology

Development of runoff generation models in the former USSR and Russia: a historical overview

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A historical overview of the development of hydrological models in the former USSR and Russia since the 1930s is presented. An overwhelming number of hydrological papers were published in Russian, and they are not sufficiently familiar to the world hydrological community. Our purpose is to fill the gap and present the main achievements, some of which were pioneering for their time. The period under consideration is divided into three subperiods. Pre-computer 1930-1950s were associated, first of all, with the development of models of unsteady water flow in river channels and linear flood-routing models; in 1960-1980s, many theoretical and practical foundations for modeling the processes of the hydrological cycle and the formation of river runoff were developed; and the Russian era following 1991, when several notable advancements in the considered field were also made.

Keywords: mathematical models, hydrological processes, river runoff formation, Soviet-Russian hydrologists

Bringing out the logical error in the development of kinematic wave equation

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The study delves into the theoretical basis of the development of the kinematic wave (KW) equation, widely used in hydrological studies dealing with rainfall-runoff modelling and flood wave movement in channels, both of which fall under the category of unsteady flow. The development of the KW equation uses the concept of a one-to-one relationship between the stage and the corresponding unsteady discharge, approximated to steady discharge $Q(y)$, where y is the flow depth. This concept describes unsteady uniform flow, which is difficult to exist in nature. However, the distributed hydraulic continuity equation used in unsteady flow studies implies discharge Q as a function of flow depth y and longitudinal water surface gradient $\partial y / \partial x$, however small it may be. This contradicts the one-to-one relationship assumed in the development of the KW equation. The use of the continuity equation in the development of the KW equation leads to wave diffusion due to the presence of $\partial y / \partial x$. The well-known Jones formula uses the KW equation to convert the recorded flood stage hydrograph at a river section to the corresponding estimated discharge hydrograph. Henderson (1966) argued that although the Jones formula serves the purpose of converting unsteady flow stage to discharge, there exists a logical error in its development, as it uses the KW equation which cannot exhibit diffusion and, therefore, the loop-rating curve. However, Perumal et al. (2004)

proved, based on hydraulic principles, that there is no logical error in the development of the Jones formula if the form of the KW equation used in its development is considered as the approximate diffusive equation as proposed by Perumal and Ranga Raju (1999). In a similar manner, Perumal and Price (2013) developed the Variable Parameter McCarthy–Muskingum (VPMM) method based on the use of the hydraulic continuity equation and simplified momentum equation, without resorting to the matched diffusivity approach as advocated by Cunge (1969) and Todini (2007). Analysis of the governing equation of the VPMM method results in a weak-diffusive wave equation, which is a specific case of the diffusive equation, and it can replace the KW equation developed based on inconsistent hydrodynamic principles. The study describes these aspects in detail.

Keywords: kinematic wave, Jones formula, Muskingum method

Hydro-history of Lebanon from antiquity to modern times

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This study explores Lebanon's hydrological history, a key component of the broader Levant and Middle East. With its Mediterranean climate and semi-arid conditions, Lebanon has a rich history shaped by various civilizations since the Neolithic era. The research integrates mythology, toponymy, archaeology, historical texts, maps, and scientific literature to examine hydrological knowledge and water management advancements. Divided into pre- and post-mid-19th-century periods, the study first investigates ancient water interactions through language, mythology, manuscripts, and infrastructure. The later period highlights modern hydrology, marked by universities, hydro-meteorological measurements, and infrastructure development. Preserving and curating hydrological data from antiquity to the present is essential for managing information in data-scarce regions. Insights from Lebanon's hydrology offer lessons in sustainable ancient techniques and past hydro-climates, with potential applications across the Middle East and other regions facing climate challenges. By emphasizing key achievements and human-water interactions, this study aims to inspire future research that leverages historical knowledge for sustainable solutions.

Reference: Merheb M. et al. 2025, Evolution of hydrological knowledge and water management systems in Lebanon from antiquity to modern times. Hydrological Sciences Journal, accepted.

Keywords: Lebanon, Levant, hydrology, water management, knowledge, history, UPH 17, UPH 23, HELPING

On Ancestral Art of Making Dams: Transforming Science into Engaged People

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This contribution addresses the question on how ancestral water knowledge, ranging from history of arts to formal water education, could have influenced the process, lifetime and transformation of making dams. The working hypothesis starts with timelines of the global learning from past failures, dam-breaks and coevolutionary historic marks into challenging storage services in times of global changes and planetary health problems. Hence we state Ancestral Human-Water Feedbacks (AHWF) archetypes including anthropogenic effects and interactions of arts and dams with local communities, thereby postulating a "Ancestry-Dam-Art" nexus (ADA). From revisiting cases in Asia, Africa, Americas and Europe we point the ADA nexus as a result of regional styles of living under unprecedented water extremes and social constraints affected by culture, formal and non-formal education, and water partitioners' and artists' cooperative creativeness. We discuss preliminary ADA evidences from lessons learned and experiences gained from building up societal resilience to changing droughts. Also, we analyse global multidimensional indicators to explain in what manner enhancing water resilience and vulnerability assessment of small communities can be shaped by inherent ADA factors of beliefs, norms and governance which historically prioritize higher dams than proactive pathways of water reuse, hydrological heritage, and water demand management. In the transition of the IAHS' scientific decades, from Panta Rhei to HELPING, we postulate how the integration of education is regarded into a broader discourse of water security and adaptive management for disaster risk reduction, as a more people-centered as humanist approach for bottom-up approaches. Our ADA nexus debate brings feasible pathways, for IAHS/HELPING, WG History in Hydrology, IAHS Academy, and training courses like the Intl. Centre of Excellence in Dams (ICED), Roorkee with recommended references: NHESS, 2024, <https://doi.org/10.5194/nhess-24-2165-2024>; IJDRR, 2024, <https://doi.org/10.1016/j.ijdr.2024.104616>; SSRN, 2024, <http://dx.doi.org/10.2139/ssrn.5069129>; HSJ, 2025, <https://doi.org/10.1080/02626667.2024.2446272>; HSJ, 2025; <https://doi.org/10.1080/02626667.2025.2469762>

Keywords: ancestry, arts, dams, history, water-resilient communities

Rediscovering Probability and Statistics: Robert E. Horton's Forgotten Contributions

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Robert E. Horton's pioneering contributions to hydrology are widely recognized, but his deep and original engagement with statistics and probability theory-particularly in climate time series-remains underappreciated. In his 1922 and 1923 works, Horton independently derived probabilistic formulas to quantify the clustering of wet and dry years in annual rainfall records. Without access to modern probability theory or the benefit of later stochastic formalisms, Horton's approach resembled a Bernoulli process and anticipated the development of autocorrelation and Markov models. Remarkably, his ideas predate or parallel those of Yule (1927) and Bartlett (1946), who are credited with foundational work on autocorrelation and spectral analysis. Horton's sole known statistics reference was Charles Davenport's 1914 *Statistical Methods*, a text that lacks advanced probabilistic treatments. Yet, Horton developed recurrence formulas and probability-based grouping strategies that captured temporal dependencies in binary event sequences. These "group distributions" functioned similarly to lag-based analysis in autocorrelation, revealing Horton's intuitive grasp of persistent behavior in hydrologic records. Drawing from his rich library of mathematical classics-from Dedekind and Chrystal to Eisenhart-Horton built a rigorous quantitative framework decades ahead of hydrology's stochastic turn. His unpublished writings, including philosophical reflections on probability interpretations in a semi-fictional 1938 story collection, reveal his nuanced understanding of the epistemological debates between classical, frequentist, and subjective views of probability. This paper revisits Horton's statistical insights in light of the historical evolution of probabilistic thought. It suggests that Horton deserves renewed recognition not only for his physical hydrology but also for his contributions to the mathematical modeling of uncertainty and persistence in environmental systems. His work illustrates a flexible and context-sensitive use of probability, unfettered by dogma, that offers lessons even for today's divided statistical schools. Horton's early climate statistics may remain among the most rigorous and creative efforts in the field to date.

Keywords: Horton, Probability, Statistics, History

Global and Local Interactions (HELPING theme 1)

Investigation of Characteristics, Drivers, And Predictability of Compound Dry and Hot Extremes

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Compound drought and hot extremes (CDHE) are periods of prolonged dry and hot weather exhibiting adverse impacts on nature and humankind than their counterparts. Understanding compound extremes is in its infancy due to complex dynamical climate systems involving interactions and feedback with the different processes at different scales. A multitude of studies have investigated the characteristics, drivers, and future trends of CDHE. However, most of this research has focused on the hottest three-month period, with limited attention given to the Indian Summer Monsoon and its intraseasonal variability. This study has investigated the characteristics, drivers, and predictability of CDHEs during the ISM, considering intra-seasonal variation. Our detailed investigation of the last seven decades of CDHE during the Indian Summer Monsoon has shown alarming observations. Our results confirmed a threefold increase in CDHE frequency for the recent period (1977-2019) relative to the base period (1951-1976), exhibiting a strong spatial pattern. Further investigation revealed that CDHE likelihood and spatial diversity in CDHE occurrence is a function of the strong negative association between precipitation and temperature and soil moisture-temperature coupling, respectively. Investigation into the temporal evolution of CDHE confirms the strengthening of the negative association between precipitation and temperature, indicating a higher number of CDHEs in the future. Our complexity-based approach outperformed traditional and contemporary approaches in predicting CDHE at a seasonal scale on a grid resolution across India's mainland.

Keywords: Compound Extremes, Hot and Dry, India, Prediction, Teleconnections

Landholders leverage over moisture flows and forest resilience in South America

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The moisture that evaporates from the Amazon rainforest plays a crucial role in sustaining rainfall

over downwind natural and human-managed land systems across South America. However, the accelerating pace of deforestation and wildfires, driven by human activities, poses a dire threat to regional water cycle. On the one hand, diminishing forest moisture undermines forest's resilience to withstand hydroclimatic fluctuations (e.g., droughts), pushing these ecosystems toward a tipping point. On another, the decreased moisture threatens the yields of rainfed agriculture. Understanding the influence humans have on rainfall will help us realise the full extent of land-use-change impacts on the regional water cycle and ecosystems sustained by them. In this study, we analyse landholders' leverage over atmospheric moisture flows and the resilience of forest ecosystems in South America. Using the remotely sensed MapBiomas land-use dataset and the output of an atmospheric moisture tracking model - UTrack, we track moisture flows from different spatial explicit landholder-dominated regions over to natural and anthropogenic land systems. Our findings reveal that a 43-56% of moisture originating from small ($3.0 \times 10^3 \text{ km}^3/\text{yr}$), medium ($0.6 \times 10^3 \text{ km}^3/\text{yr}$) and large ($4.7 \times 10^3 \text{ km}^3/\text{yr}$) landholders contributes to forests rainfall. Intriguingly, forests within these landholder-dominated regions contribute to nearly half of their total evaporation, with smallholders having a disproportionately higher influence on these forest's rainfall (19-39% greater than other landholders). Whereas large landholders exert higher influence over agricultural land systems (29-116% more than other landholders), but are likely to drive more forests towards their tipping point. The results from this study emphasise the need for more stringent forest policies to factor in the influence of deforestation on downwind rainfall to promote effective ecosystem stewardship.

Keywords: Atmospheric moisture flows, deforestation, human influence, moisture recycling, rain-forest

CAMELS-IND: hydrometeorological time series and catchment attributes for 472 catchments in Peninsular India

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CAMELS-IND (Catchment Attributes and Meteorology for Large-sample Studies - India) is a dataset containing hydrometeorological time series and catchment attributes for 472 catchments across Peninsular India, with streamflow data available for 228 catchments over at least 30% of the 1980-2020 period. CAMELS-IND provides 41 years of catchment-averaged meteorological time series and 211 catchment attributes capturing topographic, hydroclimatic, soil, geology, land cover, and human influence characteristics. The meteorological data includes 19 variables such as precipitation, temperature, radiation flux, wind components, humidity, evapotranspiration, and soil moisture. Catchment attributes also encompass dam statistics, population density, and urban/agricultural land cover changes. The dataset includes observed streamflow data sourced from the India Water Resources Information System (India-WRIS), and predicted streamflow time series from a regionally trained Long Short-Term Memory (LSTM) based hydrologic model. Following standards established by prior CAMELS datasets from the USA, Chile, and other countries, CAMELS-IND enables cross-regional hydrological comparisons and global studies. CAMELS-IND aims to advance research on

Indian hydrology, watershed management, hydrological extremes, and climate change impacts. The dataset is openly available at <https://doi.org/10.5281/zenodo.11118408> (Mangukiya et al., 2024).

Keywords: CAMELS, India, Watersheds, Streamflow

Deep Learning-Based Approach for Daily Streamflow Prediction in Watersheds with Aggregated and Intermittent Observations

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Accurate daily streamflow estimates are essential for water resources management. Yet, many regions lack high-temporal-resolution data due to limitations in monitoring infrastructures, often relying on monthly aggregates or singular observations. Disaggregation of such monthly and intermittent observations to a daily scale remains challenging. This study proposes a deep learning-based approach, utilizing their capabilities of learning long-term dependencies within hydrological variables and processes, for streamflow disaggregation. The proposed approach is evaluated for simulating daily flow patterns from monthly or weekly intermittent observations and monthly aggregates for two contrasting hydrological settings: near-natural watersheds and human-influenced watersheds with varied anthropogenic activities in each. The results demonstrate the capabilities of the proposed approach in reliably predicting daily flows from monthly or weekly intermittent observations, achieving a median Nash-Sutcliffe efficiency (NSE) of 0.70 for near-natural watersheds and 0.55 for human-influenced watersheds. The proposed approach also demonstrated reliable performance for daily flow predictions from monthly aggregates, with median NSE values of 0.61 for near-natural watersheds and 0.48 for human-influenced watersheds. The findings show that the proposed approach is robust across different seasons and hydrological conditions, with a median percentage bias within $\pm 5\%$, except in arid regions. Moreover, the proposed model trained on intermittent and aggregated observations reasonably predicted daily streamflow in ungauged watersheds. Overall, this study demonstrates that the proposed approach provides a robust and accurate representation of daily streamflow patterns from aggregated or intermittent observations, offering hydrological insights and promising solutions for improving water resource management in regions with limited monitoring infrastructures.

Keywords: deep learning, disaggregation, gap-filling, sparsely sampled watershed, streamflow

Assessing the Impacts of Landscape Change on Riverine Ecosystem Services in the Upper Beas Catchment

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Rivers are essential elements of the hydrological cycle and provide numerous Ecosystem Services (ES) that support human well-being. However, the rising demand for these services, combined with significant anthropogenic stresses, risks the long-term availability of riverine ES. For example, floodplains provide significant ES such as flood peak reduction, sediment and nutrient retention and habitat regulation. Yet, these floodplains are often utilized for grazing, agriculture and urban development, disrupting the river's natural processes and reducing the ES provision. Our study analysed the long-term impacts of landscape changes on one provisioning ES (freshwater provision) and three regulating ES (flood retention, habitat regulation, and erosion control) in the Upper Beas catchment. A representative indicator was selected and quantified for each ES using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Spatial and temporal changes in the ES potential of the riverine ecosystem of Upper Beas were analyzed over two decades: 2001-2010 and 2011-2020 for a 1-km buffer zone along the Beas riverbanks. It can be observed that Water Yield (WY) and Sediment Retention (SR) increased in the two decades, with WY increasing from 230 mm in the first decade to 301 mm in the second decade and SR from 81 tons/pixel to 84 tons/pixel. On the contrary, the Habitat Quality Index (HQI) decreased from 0.53 to 0.51, and the Flood Retention Index (FRI) also decreased from 0.83 to 0.80 from one decade to another. These findings highlight the critical trade-offs between urbanization and ecosystem services in riverine landscapes.

Keywords: Ecosystem Services, River, Beas Catchment, Landscape, InVEST

When rivers dry out: an intermittency analysis for Central Europe

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The runoff regime of most rivers in central-northern Europe is characterised by perennial flow due to the rather homogenous seasonal distributions of rainfall, wherein all months generate substantial rain. However, in the recent past it became noticeable that more and more rivers dry up completely for some periods over the year. As terrestrial Europe has been warming twice as fast as the global average and climatic gradients across Europe are expected to shift significantly, intermittent runoff regimes may become more prominent. However, a thorough analysis to which extent this climate shift might have already affected runoff regimes was pending. In this study, the flow regime of Germany is assessed for occurrence, trends and emerging behaviour of intermittency. For this purpose, the CAMELS-DE data set (Catchment Attributes and Meteorology for large-Sample studies) with daily discharges from 1555 discharge stations across Germany for the period 1951 to 2020 is used to investigate persistent and emerging intermittent runoff behaviour. Only one percent of all stations showed a high intermittency regime; these stations are distributed throughout Germany, but there is a focus on the eastern and north-eastern stations. There was a clear increase of zero

flow periods (in frequency and extend) during a recent drought period, and more than 6 % of all stations became highly intermittent, at least temporarily, for several, consecutive years. A random forest analysis showed no conclusive variable importance, which might explain intermittency using 90 key influencing catchments parameters from the CAMELS-DE data set covering typical topographic, climate, hydrological, land cover, soil, hydrogeological and anthropogenic attributes. The study confirms the increasing occurrence of intermittency, present trend test results for different intermittency categories and tests to which extend droughts have affected intermittency regimes.

Keywords: intermittency, drought, catchment analysis

Analysis of the compound impact of antecedent dry periods and rainstorm events on urban diffuse pollution and resulting surface water pollution

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Diffuse pollution in urban surface water bodies originates from multiple urban surfaces accumulated over dry periods and transported with urban runoff. The compound impact of a long, dry period followed by a large rainstorm is known to increase this, however no quantitative studies are available to assess their importance. This study aims evaluated the impacts of dry periods on water pollution through big data analysis examining the impact of individual rainstorms on water quality at nine urban stations across Central Europe. Dry period lengths were derived using two definitions, a classic definition using a fixed rainfall threshold and an advanced one based on events wash-off potential. To include the dynamics of high-intensity rainfall-runoff events, 1-min rainfall station data and sub-daily oxygen content data as a proxy for water quality were used. Wash-off potential of rainstorms were assessed with the urban rainfall-runoff model SWMM. A serious impact was identified as a minimum of 30% drop in the oxygen-content of the water body after a rain event.

For the nine water bodies, the mean annual frequency of the pre-defined serious impact on its oxygen-content varied from one to four. The 'simple definition' underestimated dry spell length with fewer events having dry period greater than a week. With the advanced definition, the impact of rain events was seen as a function of dry period length and rain magnitude. Evaluating the importance of rainfall magnitude and dry period length showed despite having high magnitude, many rain events with shorter dry period did not show any impact on water quality.

The study emphasises the need for sub-daily or even better sub-hourly monitoring of water quality of urban water bodies. It was shown that pollutants accumulated during long dry period length play a major role in urban diffuse pollution and need to be managed as such.

Keywords: diffuse pollution, water quality, urban rivers

Optimizing raingarden performance with smart, low-cost sensor networks

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Climate change and urbanization are altering water cycles and increasing flood risks, making stormwater management a challenge. Raingardens help reduce runoff and improve water quality, but require regular maintenance. Low-cost sensors enable real-time monitoring, improving raingarden performance through predictive maintenance. This study investigates the use of sensors for real-time monitoring of raingardens to optimize maintenance and improve system efficiency. It aims to develop a framework for detecting changes in soil moisture, assess sensor reliability in detecting anomalies, and establish performance indicators for proactive management.

The experiment involved 15 columns replicating a typical raingarden stratigraphy. These were divided into three groups: a control group representing optimal conditions, a preferential flow paths group simulating surface erosion, and a surface clog group representing sediment accumulation. Each column was equipped with a network of low-cost sensors, including Chameleon Soil Water Sensors and Truebner SMT 100, to continuously measure soil moisture and temperature. Simulated rainfall events based on historical weather data were used to analyze hydrologic responses. The study found that low-cost sensors, particularly the SMT 100, reliably monitored volumetric water content (VWC) and identified different hydrological behaviors among the three column groups. Key performance indicators such as peak span and delay time proved useful in diagnosing hydraulic failures. While the Chameleon sensors showed degradation over time due to soil drying and root growth, the SMT 100 sensors provided consistent and accurate data, demonstrating their potential for long-term field use.

This study explores the use of affordable sensors for real-time raingarden monitoring, focusing on their role in reducing manual inspections and supporting predictive maintenance strategies.

Low-cost electronic sensors provide a practical and cost-effective solution for continuous raingarden monitoring, improving system efficiency and supporting proactive maintenance in urban stormwater management

Keywords: Stormwater management, Raingarden, Real-time monitoring, Low-cost sensors, Urban water management, Bioretention systems

Balancing Productivity and Climate Impact: Quantifying the Climate-Smart Potential of Irrigation Practices

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Climate change increasingly undermines global crop productivity, particularly in regions with limited

water availability. Climate-smart agriculture seeks to enhance productivity while minimizing greenhouse gas (GHG) emissions, especially biogenic emissions from soil microbial activity. From an irrigation perspective, this underscores the need for a framework to evaluate irrigation practices, moving beyond traditional objectives of merely maximizing yield and water use efficiency to consider their climate impact. Framing climate-smart irrigation as a multi-objective optimization, here we develop a dual-index framework for assessing irrigation practices across productivity, water consumption, and climate impact dimensions. We first demonstrate the application of this framework by analyzing field studies of different crops (such as wheat and rice), irrigation practices and soil greenhouse gas (GHG) emission compositions, showing how the new indices jointly identify optimal irrigation practices. Additionally, using an ensemble of crop model simulations for corn production using irrigation across major U.S. production regions under varying climate and soil conditions, we explore trade-offs between productivity and climate impact goals. Results reveal a spectrum of Pareto-optimal irrigation practices that balance these dual objectives. These insights underscore the importance of holistic approaches in CSI and are critical for providing actionable insights into nature-based climate solutions in agricultural ecosystems.

Keywords: climate-smart irrigation, soil biogenic emissions, multi-objective optimization, crop productivity

A global dataset of near-natural basins for climate change detection - ROBIN

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Hydrological extremes are intensifying due to climate change, impacting livelihoods, infrastructure, and economies. To study trends in floods and droughts, we analyse observed river flow data. However, to attribute these trends to climate change, we must exclude human influences like dams, land-cover changes, channelization, and water abstraction. These activities can obscure climate change signals and distort river flow trends.

Many studies have examined long-term changes in river flows globally. However, confidence in observed trends remains low due to human disturbances. Integrating results from various regional and national studies is challenging because of differing methodologies, hindering consistent assessments at continental and global scales. To address this, many countries have established 'Reference Hydrometric Networks' (RHNs) to monitor river flows in catchments with minimal or no human impact. However, these networks are disparate and sparse and ROBIN spearheaded a unified approach to enhance international assessments of hydrological changes consistently.

With partners from 30 countries, covering diverse climates and geographies, ROBIN has established the first global RHN. This network comprises over 3,000 near-natural catchments worldwide, consistently defined to aid in hydrological climate change detection. Around 2,400 of these catchments are available in an open-access dataset for the hydrological community to exploit.

Here we present the results of a first global-scale analysis using ROBIN, quantifying trends in low flows and drought indicators highlighting regional and global variability.

Moving forward we are embarking on an ambitious Phase 2 of the initiative. This phase aims to expand the network by incorporating more countries and diverse geographies, further developing this unique resource of river flow data.

With the support of international organizations such as the WMO, UNESCO, and IPCC, ROBIN has established the foundations for a lasting network of people and catchments. This will support future global assessments of climate-driven trends and variability.

The ROBIN international Team: <https://www.ceh.ac.uk/our-science/projects/robin>

Keywords: stream flow, river flow, hydrology, climate change, reference hydrological networks, data, observations

Global-Scale Uncertainties in Hydrologic Modeling: The Role of Precipitation and Temperature Forcings

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Uncertainties in precipitation and temperature forcing play a critical role in hydrological modeling, yet their global-scale impacts remain underexplored. This study integrates an ensemble meteorological dataset (i.e., EM-Earth) with process-based hydrologic models to assess the magnitude and propagation of uncertainties across ~3 million global subbasins. This work was performed as part of the IAHS HELPING Working Group on "Development & application of river basin simulators". For the first time, we systematically quantify and reveal novel insights into hydrologic modeling uncertainties that were previously uncharacterized, providing a comprehensive understanding of their spatial and scale-dependent behaviors.

The results demonstrate significant spatial and process variability in uncertainty responses. For example, strong uncertainty propagation is observed in regions like tropical rainforests and Europe, while arid and high-latitude areas exhibit weaker signals, partly due to differences in hydrologic processes such as baseflow contributions. Precipitation uncertainties dominate in most basins, but temperature uncertainties also play a critical role, particularly in snow-influenced processes. Cryosphere basins exhibit smaller runoff uncertainties partly due to the buffering impacts of snow-pack. In some cases, uncertainties exceed 100% of the magnitude of the output variables, highlighting the substantial impact of meteorological forcing errors. Additionally, uncertainties exhibit distinct scale effects, influenced by factors related to spatiotemporal averaging and hydrologic variables. This study provides valuable insights into uncertainty mechanisms in basin-scale and global-scale hydrologic modeling. Our findings highlight the critical need for enhanced global meteorological datasets that incorporate explicit uncertainty quantification, especially in regions where observational data is sparse or insufficient.

Keywords: Hydrologic modeling, Uncertainty, Precipitation, Temperature, Global scale

Integrated simulation server for the Aral Sea Ecological Restoration Solution

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Aral Sea's ecological disaster could be the biggest ecological catastrophe of our time and is called for international cooperation to save it. Chinese scientists focused on the ecological research of the Aral Sea, and set up research on the causes of Aral Sea drying, salt and dust storms, water and ecological synergy, Aral Sea ecological restoration solutions, water-saving irrigation and salt plant breeding technology demonstration.

We jointly established a database, remote sensing monitoring system, and salt and dust analysis system, which can analyze the salt and dust of the Aral Sea and ecology and environment changes. We developed a model of the spatial and temporal distribution of salt dust storms and bare lake bottom and found that the main source of salt dust storms is located in the eastern region of the Aral Sea. If the eastern salt and dust source area is covered with water bodies, vegetation and other materials, the salt and dust storms will be reduced by 70% and can be restored to the state of the Aral Sea in 2005. We believe that this goal can be achieved in 10 years with our efforts. We studied land use changes from 1960 to 2015 using remote sensing technology, revealing the reason for the Aral Sea drying up in the last 30 years is not a problem of increasing cropland. To identify the key factors of water resources utilization, we set up more than 1000 scenarios of future climate change and water use, and simulated the optimal distribution of water-energy-food-ecology in the Aral Sea basin. The demonstration of integrated water-saving irrigation system for cotton in Uzbekistan from 2021 to 2024. Finally, we proposed the Aral Sea ecosystem restoration roadmap.

Keywords: Aral Sea, International cooperation, Dust storm, Remote sensing, Ecological synergy

Vegetation Response to Soil Moisture Drought: Regional Variations and Contrasts Across Different Descriptors

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Soil moisture (agricultural) droughts occurring on a seasonal or inter-seasonal scale exert a profound influence on natural ecosystems, substantially disrupting their intricate stability to maintain water availability and biophysical activities. During periods of soil moisture deficit, plants experience reduced water uptake, which results in decreased photosynthesis, impaired growth, and potential mortality. Thus, such prolonged and intensive dry events significantly affect the overall ecosystem functioning, such as plant growth, flowering, and microbial activity. These disruptions also affect the process of nutrient (primarily carbon and nitrogen) cycling and organic matter decomposition in the soil, thereby influencing carbon sequestration and greenhouse gas emissions. Therefore, it is crucial to investigate how different biophysical processes (biomass production, photosynthetic

efficiency and carbon and water uptake) are affected during the dry-down (wet-up) phases of soil moisture drought development (recovery).

This study initially investigated the perturbations in three distinct vegetation descriptors (leaf area index: LAI, gross primary productivity: GPP, vegetation optical depth: VOD) observed during seasonal, annual and multi-year droughts. The research examines the significance of antecedent effects on these vegetation descriptors in two distinct phases (development and recovery) of drought events. Remote sensing and reanalysis datasets were acquired at 0.25° resolution for the period 2003-2021, and the study was conducted for various plant functional types (evergreen and deciduous forests, grassland and shrublands).

The outcomes of this comprehensive study, examining the ecosystem responses to soil moisture drought, will facilitate the development of strategies to mitigate the effects of extreme dry events, potentially aiding in climate change adaptation. Furthermore, this research will contribute to the establishment of a regional-level prediction system for more effective water conservation and allocation strategies, as well as ecosystem management practices to prevent biodiversity losses.

Keywords: ecosystem response, soil moisture drought, vegetation optical depth, gross primary productivity, leaf area index

The Coupled Root-Soil Interactions Modeling: A Gateway to Resolving Hydro-biological Complexities of the Land Surface

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Root water uptake (RWU) models have long been constrained by static representations of root systems, limiting their utility in watershed simulators and Earth System Models (ESMs) tasked with simulating hydro-biological processes under climate change and human activities. This talk presents a paradigm-shifting framework that couples dynamic root growth with soil moisture variability through cost-benefit optimization, addressing critical gaps in ESM land-surface modules.

By integrating pipe model theory and Richards' equation, the authors put forward a theoretical framework that simulates root plasticity-dynamic rooting depth and moisture-driven fine-root allocation, and applied it in China's Loess Plateau, a semi-arid region where artificial afforestation has triggered irreversible drying soil layers (DSLs). Key advancements include:

- (1) Root-Soil Feedbacks: Deep roots mitigate short-term drought but deplete deep soil moisture, worsening DSLs.
- (2) ESM Integration: The framework reduces biases in evapotranspiration (30% error reduction) and soil carbon-water coupling, critical for climate projections.
- (3) Geobiological Relevance: Root-mediated nutrient redistribution and microbial activity shifts highlight the role of roots in soil biogeochemistry.

Validated against field data ($NSE > 0.7$), the model demonstrates that even minimal deep-water uptake (6.2%) drives DSL formation due to limited recharge below 2 m. These insights are scalable to global ESMs, offering improved predictions of biome shifts, drought resilience, and carbon sequestration.

This work has quite a few implications for policy:

- (1) Dynamic RWU models inform sustainable afforestation in drylands, balancing carbon capture

with hydrological trade-offs. (2) Enhanced ESMs support SDGs on climate action (SDG 13) and ecosystem restoration (SDG 15).

Future Directions:

(1) Embedding dynamic RWU into ESMs (e.g., CLM, ORCHIDEE) for IPCC AR7. (2) Cross-disciplinary fusion with remote sensing and genomics to resolve trait-based root plasticity.

This work underscores the urgency of advancing RWU dynamics in ESMs to unravel geobiological complexities and guide global sustainability efforts.

Keywords: Root Water Uptake, coupled root-water interactions, watershed simulator, Earth System Models

Statistical methods and climate models jointly analyze the impact of climate change in large river basins

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Affected by the continuous impact of climate change, the natural hydrological processes in the upper mountainous areas of inland rivers have changed, and the trend characteristics of water cycle elements have changed, exacerbating the uncertainty of water resource systems in arid areas. When analyzing the impact of climate change, the GCM data of CMIP6 have been widely used and have become the data basis for supporting future global and regional climate assessments. However, when applying it, we found that 1) the error estimation of GCM historical data and remote sensing precipitation products GPM in Xinjiang was overestimated by 2-5 times in the Karakoram Mountains and the Altun Mountains, indicating that the use of GCM in these areas should be cautious; 2) If a medium- and short-term assessment (10 years) is conducted, the overall water resources in the Tarim River Basin will increase under the GCM method; but in the periodicity analysis method, the next 10 years will be dry years, and the average annual water resources in the Tarim River Basin will decrease by 0-200 million cubic meters. Therefore, we recommend that when using large-scale models to analyze future changes in water resources, GCM must be used in conjunction with periodicity analysis.

Keywords: GCM, periodicity analysis, water resources

Multiple-Scale Variation and Driving Factors of Snow/Ice Melting Floods in Yarkant River Basin, Karakoram Mountains

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Snow/Ice melting runoff is crucial in the alpine mountain-oasis-desert system. The timing, magnitude, and frequency of Snow/Ice Melting Floods (SIMFs) have changed due to climate warming, yet remain poorly quantified. In this study, we use multi-source data to extract the SIMFs occurring in the Yarkant River Basin, and analyze its multi-scale characteristics and driving factors. The results indicate that, (1) Over the past 70 years, the flood peak of SIMFs has increased. The duration of floods has decreased by 0.8 days/decade, and the burstiness (variability) of SIMFs has significantly increased over the past 30 years. Simultaneously, there is a trend towards earlier occurrences of SIMFs. In a sub-basin(KLK) characterized by extensive glaciers, the peak discharge of SIMFs has increased by 25 m³/s per decade, with the occurrence date advancing by 1.6 days/decade. On the hourly time scale, the peak flow time of SIMFs significantly lags behind, tending to occur during the daytime. (2) The driving factors of flood characteristics exhibit temporal scale effects. Precipitation promotes the generation of snowmelt runoff at multiple time scales. Given significant increases in summer precipitation and extreme temperatures, flood burstiness warrants greater attention than continuity. Temperature, at the seasonal scale, advances the occurrence dates of floods rather than causing an increase in flood duration. At the daily/hourly scales, temperature is the main factor influencing flood runoff and diurnal variability. Notably, compared to daytime temperatures, nighttime temperatures have a stronger promoting effect on SIMFs. (3) Diurnal runoff curves vary across flood stages and snowmelt seasons. In the rising stage of the flood, the time of diurnal runoff peak is generally synchronous with the time of diurnal temperature peak. In contrast, in the recession stage of the flood, the runoff peak lags behind the temperature peak. The diurnal variations can roughly indicate the stage of the flood.

Keywords: Climate Change, Yarkant River, Snow/Ice Melting Floods, Driving Factors, Diurnal Variation

CASCADE-3C: Collaborative Climate Change, Risk and Adaptation

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The CASCADE-3C project is a joint effort by the Indian Institute of Technology Roorkee, Indian Institute of Technology Bombay, University of São Paulo, São Carlos, Brazil, and Tsinghua University, Beijing, China. The project aims to address the challenges of forecasting and responding

to cascading climate-related disasters, emphasizing early warning systems and effective early action. The project is divided into three main work packages (WPs): (i) Understanding and quantifying extreme-weather-induced hydrological disasters: This involves identifying the causative mechanisms of meteorological extremes, quantifying changes in extreme hazards over future periods, and assessing the associated risks. (ii) Assessing the cascading and compound impacts of climate risk: This includes examining the temporal dimension of cascading impacts, such as how excessive rainfall can lead to flooding and landslides, and how extended droughts can result in heatwaves. The project also focuses on the intricate interplay of the Food-Energy-Water Nexus. (iii) Analyzing how hazards intersect with exposure and vulnerability in a socio-ecological system: This involves using computational techniques to relate flood hazards to ecological and societal responses and building adaptation and mitigation scenarios. The project highlights the importance of early action in mitigating the devastating consequences of cascading climate hazards. It emphasizes the need for robust geo-hydrological modeling tools and early warning systems to prevent disasters, even in regions with limited resources. The project also underscores the urgency of fostering early response mechanisms and learning from cross-boundary experiences to develop effective strategies and solutions for climate adaptation, mitigation, and resilience-building efforts. The project is funded by the national research agencies that participates in the BRICS countries Science, Technology, and Innovation Framework Programme (STI-BRICS): the Department of Science and Technology (DST) of India, the Ministry of Science and Technology (MOST) of China, and the National Council for Scientific and Technological Development (CNPq) of Brazil.

Keywords: Climate Threats, Cascading and Compound Events, Hydrological Climatology, Extreme Events, Society

Research on Intelligent Monitoring and Sensing of Water Resources in Inland River Source Areas

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The formation of inland river water resources is greatly influenced by the source area. However, the transformation of water resources in the source area is relatively complex, and the slope runoff in this area not only comes from rainfall, but also from snow and glaciers. The diversity of water resource monitoring objects and the lack of communication signals greatly constrain the timeliness and accuracy of downstream hydrological forecasting. This study takes inland rivers in Xinjiang as an example to explore the method of IoT monitoring multiphase water resources, and through automatic identification and simulation technology, real-time reflection of the distribution of water resources in the basin. Provide technical support for water resource management.

Keywords: Intelligent monitoring, Water resources, Hydrologic forecast, Water resource management

Linking hydrology with grassland dynamics for sustainable management of the tiger habitat in Terai Arc Landscape, Nepal

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Understanding the hydrogeomorphology in the Karnali river in the Nepalese and Indian Terai Arc Landscape at the foot of the Himalayas is vital considering the importance of streamflow downstream for irrigation and nature conservation. The Terai Arc Landscape is one of the most important conservation areas of tigers. Here, the grasslands seem to play a pivotal role as the tigers hunt for deer in these floodplains. The interdisciplinary project "Save the tiger! Save the grasslands! Save the water!" has as overarching objective to sustainably provide habitat for a viable tiger population in the socio-economic context of the TAL. However, the complex interaction between river morphodynamics, flood and drought, shallow groundwater, wildfires and grassland dynamics in these landscapes are poorly understood and mapped out. This is not only a scientific, ecohydrological novelty but also crucial in combining preservation of the tiger habitat with sustainable water resources management in the Terai Arc Landscape and upstream Himalayas.

The set-up of the project and the first results after 2 year of research will be presented in which the interrelationships between river dynamics, groundwater, land cover and land use, and grazing ungulates will be assessed. The dual approach will be presented: fundamental, multi-disciplinary research at Bardia National Park and the associated Karnali River in Western Nepal and applied research to identify essential similarities and differences in the current hydrological and ecological conditions of the grasslands in the 15 nature reserves present at the foot of the Himalayas. From the perspective of wildlife conservation by rural communities the concept of stewardship is introduced as an integrated environmental management approach.

Keywords: Hydrology, ecology, tiger habitat, Nepal, India, stewardship

Assessing the role of spatial variability in climate forcing on soil moisture simulated using a hyper-resolution land surface model at the farm scale

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Land Surface Models (LSMs) can resolve land surface processes with spatiotemporal and physical consistency. However, uncertainty from input meteorological data and model parameters affects the accuracy of the LSM simulations. Traditional LSMs, operating at coarse resolutions (tens of kilometers), have limited performance at a farm scale, where representing subgrid heterogeneity of soil, topography, and meteorological variables is crucial. As such, improving the spatiotemporal accuracy of input meteorological data is critical for LSMs to be able to resolve local processes. Although the influence of meteorological forcing data on LSMs has been studied at large scales,

its impact at the farm scale has been less explored. HydroBlocks, a hyper-resolution LSM using Noah-MP, simulates land surface processes at 30-meter resolution in non-contiguous clusters of hydrological similarity. Meteorological forcings are one of the key drivers of soil moisture variability. However, the spatial scale differences between forcings and target soil moisture resolution can impact the outcomes. To determine the optimal and practical spatial scale of meteorological forcings for accurately simulating farm-scale soil moisture, this study utilizes HydroBlocks to assess the impact of spatial heterogeneity in meteorological inputs on surface and root zone soil moisture simulations. For this purpose, we obtained meteorological forcings required to run HydroBlocks from three sources: 1) the state-of-the-art ERA5-Land product, 2) statistically downscaled ERA5-Land variables and 3) Weather Research and Forecasting (WRF)-based dynamically downscaled variables with ERA5 boundary conditions. We considered the Upper Bhima Basin in India as the case study region for this work. Meteorological forcings from all three cases are validated against in situ observations. We evaluated the performance of HydroBlocks soil moisture simulations using in-situ data and analyzed the spatial scale effects in soil moisture simulations by varying the resolutions of meteorological forcings in each simulation

Keywords: soil moisture, high-resolution, precipitation, scale-effects

Decadal Predictability of Indian Summer Monsoon Rainfall: Influence of SST patterns across distinct oceanic regions

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There is an increasing exigency for skilful predictions on seasonal to decadal time scales over India to improve policies and decision-making for agricultural and infrastructural development countering climate change. Due to the nested variability of the Indian summer monsoon rainfall (ISMR) during June to September (JJAS), decadal predictions have remained a longstanding scientific challenge for decision-makers. In this study, we explore leading machine learning algorithms and statistical methods to enhance the decadal predictability of Indian summer monsoon rainfall. We identify a few dominant decadal SST signals that explains 50% of global SST variability and replicate key oceanic modes, such as Atlantic Meridional Mode (AMM) and the Pacific decadal oscillation (PDO) or El-Niño southern oscillation (ENSO) decadal signal. The clustering algorithm on the dominant decadal signals helps to assess its robustness and applicability to the predictability of ISMR and related regime shifts. Our finding suggest that a few optimal SST-based clusters can serve as useful predictors of ISMR seasonal anomalies in the coming decades. The study emphasizes decadal predictions that could improve preparedness for challenging droughts and water security, aiding policy makers.

Keywords: Indian summer monsoon, decadal predictions, PDO, ENSO, AMM

How to deeply communicate with hydrological changes-DEEPHY examples

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Changes in space and time are very important topics in hydrology. Given complicate aspects involved in hydrological changes, for making related sustainable decisions, it is also important but difficult to mine the drivers and explore the effects of the changes, especially for those hidden behind. Three example methods are shown for Deep Explanation & Evaluation for Practices in Hydrological Changes (DEEPHY) Working Group in HELPING decade. One is the model-based Factor Separation method to quantitatively attribute regional trends of hydrological changes with Vegetation Interface Processes (VIP) eco-hydrological distributed dynamic modelling. The relative contributions of climatic change, CO₂ fertilization, and management to trend of the evapotranspiration (gross primary productivity) trend in the North China Plain amounted 56 (-32) %, -28 (25) %, and 68 (108) %, respectively. Second is physical mapping method between hydrological changes and teleconnection indices, such as polar motion and Length of Day. A strong relationship has been found between tipping points of polar motion in 1990s and the change of terrestrial water storage changes, and between extreme signals in the variation of LOD and giant flooding and drought events. The third is Driver-Pressure-Status-Impact-Response (DPSIR) framework used to analyze the legislation behind land, fertilizer and water usage in greenhouse agriculture through a comparison between China and Denmark. Most responses were found to target only the pressure component of the framework. Additional response (policy) mechanisms including economic, informative and administrative instruments were shown more effective, more quickly, and highly in need. More policies generally exist in Denmark than in China at both the national and local levels. China needs a higher degree of environmental policy integration. The mentioned three methods, together with others, help people to communicate with hydrological changes in depth.

Keywords: DEEPHY, HELPING, hydrological changes, explanation, evaluation, practice

Implementing deficit irrigation systems – differences and similarities across world regions

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The challenge of producing more food and using less water is exacerbated by the increasing scarcity of water resources due to climate change, population growth, and other factors. One of the crucial problems to solve is intra-seasonal irrigation scheduling under a limited seasonal water supply. This involves distributing a finite amount of water across multiple irrigation events throughout the growing season while considering the crop's response to water stress at various growth stages. Effective

management of this process using a deficit irrigation (DI) strategy can lead to improved water productivity and crop yields, thereby addressing the dual goals of food security and conservation of water resources in agriculture. However, the resulting optimization problem is high-dimensional and thus requires multiple trials. Thus, crop growth models complement deficit irrigation experiments and support the optimal planning and operation of irrigation systems. Knowledge about adequate irrigation scheduling strategies and resulting yield security is essential for implementing DI systems to improve water productivity and adapt to changing climate conditions. This study considers climate variability within a probabilistic DI framework for irrigation scheduling based on Monte Carlo simulations to support informed decisions. The framework implements optimizers such as evolutionary algorithms, decision tables, and deep reinforcement learning to implement deficit irrigation strategies. To derive the best deficit irrigation strategy for a considered climate region and data availability, we apply the DI framework for a global numerical deficit irrigation experiment, which allows for the analysis of the impact of the selected irrigation strategy on water productivity. The results show a strong dependency on choosing the DI strategy for increasing water productivity in different climate regions. Thus, the results can enable and support the site-specific transformation of low-efficient rainfed and irrigated systems, achieving higher water productivity and food security on a local scale.

Keywords: deficit irrigation, machine learning, management, water productivity

Establishing an operational Flood Early Warning System in Zambia

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Zambia is increasingly vulnerable to extreme flood events, exacerbated by climate change and land-use changes. The lack of a robust Flood Early Warning System (FEWS) has heightened the risks to communities, infrastructure, and agricultural productivity. Establishing FEWS in data-scarce regions has challenges like complexity of accurately predicting flood events. Many African nations face significant data limitations, with hydrometeorological monitoring systems often falling short of global standards. This paper outlines the development of FEWS framework for Kafue river basin in Zambia. The FEWS uses bias-corrected GPM-IMERG real-time rainfall for real-time model inputs, NOAA GEFS data as weather forecast model inputs, calibrated and validated Deltares-wflow hydrologic model for flood simulations, calibrated and validated LISFLOOD-FP model for inundation modelling. The framework is operationalized using Amazon Web Service (AWS) cloud, and Python programming language to control operations and automations. The real-time flood early warning includes decoded severity by several visualized information methods. It provides real-time flood forecast with 10-days lead time at river locations overlaid with return period levels to reflect the flood severity. It also shows a daily normal flood range made from 75-25 percentile of historical observations (2001-2024) to simplify flood severity interpretation and encourage human-centric approach. The system incorporates real-time inundation maps for selected flood-prone areas exceeding thresholds, providing representations of potential flood extents. Additionally, it also shows potential zones where extreme rainfall could occur at different durations (1-10 days) using GEFS weather forecasts. The integration of FEWS onto a cloud platform ensures seamless service delivery by mitigating disruptions caused by power outages, hardware failures, and system malfunctions.



By leveraging open-source datasets and models, the FEWS provides a scalable and cost-effective solution, making it particularly well-suited for data-scarce environments. This study demonstrates scalable FEWS framework which can be adopted for flood-prone regions in Africa and Asia.

Keywords: Flood Early Warning System (FEWS), Kafue River Basin, Flood Forecasting, Hydrological Modelling, Inundation Mapping

Holistic Solutions for Water Security (HELPING theme 2)

HyPeak: A science-policy network to promote sustainable hydropeaking

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Hydropeaking is the term used to define rapid and frequent artificial flow fluctuations in rivers caused by flexible hydropower production. The Network on Hydropeaking (HyPeak) was founded during the 13th International Symposium on Ecohydraulics in 2020 to propose a framework for discussing interdisciplinary perspectives on hydropeaking. Today, HyPeak has evolved into an established international non-profit, volunteer-based network aiming to translate the findings of hydropeaking research into practical applications and policy recommendations. However, bridges across disciplines remain to be developed, particularly regarding the social and economic sciences, whose links with ecohydraulic research are still weak. Additionally, HyPeak emphasizes the importance of a transnational perspective for researchers, policy makers, and practitioners, as effective river management and collaboration in electricity markets require cross-border cooperation and knowledge exchange. HyPeak focuses on several key research topics: i) assessing environmental effects and related socio-economic issues at various spatio-temporal scales; ii) improving mitigation measures and management strategies; iii) advocating for environmentally sustainable approaches to hydropeaking; and iv) offering recommendations for national and international policies, and the support for their integration. To address these goals, six high-priority tasks have been identified: i) providing an overview of the localization and typology of hydropeaking at a continental scale; ii) standardizing tools characterizing hydropeaking regime, iii) identifying the most informative indicators for assessing hydropeaking impacts, iv) promoting the development of technical approaches to limit the negative impacts of hydropower plant operation on river ecosystems, v) elaborating inter- and transdisciplinary approaches to find a compromise between ancillary, balancing and flexibility services to the grid and ecological sustainability, vi) enhancing the efficiency of knowledge and tool transfer between researchers and practitioners. The HyPeak Network welcomes new members at various levels of commitment. For any questions do not hesitate to contact us (hypeaknetwork@gmail.com) or register directly to stay informed about our activities (<https://forms.gle/CsahIE6dWB5SuLaAA>).

Keywords: Hydropeaking, Ecohydrology, Hydropower, Sustainability

Long term river discharge simulation by an integrated hydrologic model in Kyusyu Island, Japan

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Hydrological extreme has opposite characteristics such as flood and drought. Therefore, hydrologic models tend to have been developed especially focusing either on flood or on drought. This causes that some models report future change of flood, and the other models report that of drought. Even if both shows river discharge status, different models were utilized. To avoid this situation, an integrated hydrologic model was developed. The developed model consists of land surface model, river routing model and groundwater model. The river routing model is generally utilized to simulate river discharge especially steep topography and then shows good performance on flood situations. The land surface model, which is usually used for simulating land surface fluxes, calculates runoff component considering evapotranspiration. This might be mean that the combination of the river routing model and the land surface model enables to simulate both flood and drought more accurately. Moreover, one of the most important factors for drought is groundwater. Therefore, groundwater model was incorporated into an integrated hydrologic model in this study. This integrated hydrologic model was applied to evaluate and represent past drought situation in Kyusyu Island, Japan. The results shows that the model enables to represent annual maximum hourly discharge with 10% relative errors on average and the 355th highest daily discharge, which is one of the drought indices in Japan, with 30%. Based on the sensitivity analyses, it was found that the groundwater has an important factor in these basins.

Keywords: drought, Kyusyu, land surface model, river routing model, ground water model

Global River Basin Classification Framework Based on Water Security Metrics

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Water security has gained high popularity as a critical solution to the global water crisis. Its scope has evolved over time, expanding its border from the physical availability of freshwater resources to hydroclimatological, ecological, societal, and socioeconomic dimensions. River basins significantly contribute to water security by acting as natural units for integrated management of freshwater resources, balancing ecological systems, and addressing human demands. Therefore, understanding the multidimensional nature of water security across the river basin is crucial in identifying global water management challenges. However, studies that adopt socio-hydrological perspective to explore

the interplay of drivers affecting water security remain limited. Furthermore, traditional methods relying on absolute thresholds overlook dynamic changes, reducing their effectiveness for monitoring and management. The main objective of this study is to explore water security metrics across major global river basins and delineate distinct spatial management units that reflect the complex interplay of diverse and influential drivers of water security. This study incorporates an unsupervised machine learning approach for classifying the major river basins in terms of their water security metrics, enabling the identification of distinct patterns of similarity and dissimilarity in water security states. The identified river basin clusters represent distinct spatial management units, each with unique hydro-climatological, ecological, societal, and socio-economic characteristics. The findings show how the major global river basins experience disturbances at different hierarchical levels across each driver. Furthermore, the study provides valuable insights into the socio-hydrological dynamics influencing water security across river basins. These insights can guide stakeholders and policymakers for more effective and specific solutions that enhance water security across the river basins.

Keywords: Socio-hydrology, Spatial Management units, Water Security Metrics

Optimization of Crop Patterns at a Regional Scale Using Metaheuristics Algorithms

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Food and water security are closely related because of their significant effects on the population. Both resources are witnessing mounting pressure from the supply and demand sides, leading to major challenges for agriculture. Therefore, optimizing present land and water resources with maximum coordination is one of the significant priorities worldwide. In this context, metaheuristics offers a fresh perspective to address these issues due to its advanced problem-solving capabilities. This study presents an optimization model based on crop pattern optimization for appropriate land use allocation. The optimum crop patterns were proposed using SWAT and metaheuristics such as particle swarm optimization (PSO) algorithm and genetic algorithm (GA) by modifying the cultivated areas for different crops in the irrigation-fed region. The model aims to optimize agricultural land with respect to different crops, thereby optimizing water allocation in the region. The results revealed that the optimized patterns indicated better land use efficiency and water efficiency. The proposed framework can be a crucial decision-support for framing water and agricultural policies, thus reinforcing practical decision schemes and promoting sustainable development in the region.

Keywords: crop management, PSO, SWAT, water allocation

Use Artificial Intelligence to Improve Water Demand Forecasting: Bridging Data, Models, and Uncertainty

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Accurate water demand forecasting is essential for sustainable water resources planning and management, yet it is increasingly challenged by rapid urbanization, climate variability, and shifting water use patterns. Traditional projection methods often overestimated water demand, leading to inefficiencies in infrastructure investment and resource allocation. To address these challenges, an innovative approach that integrates machine learning, scenario analyses, and optimization techniques to enhance forecasting accuracy and adaptability is proposed.

Key factors influencing water demand will be analyzed to identify the most significant predictors. The proposed methodology leverages advanced data analytics and machine learning models to detect nonlinear relationships, capture emerging trends, and improve predictive performance. The approach will be tested using real-world datasets to evaluate its robustness and applicability. This study aims to provide a reliable framework for water demand forecasting, supporting more resilient and efficient water resource management.

Keywords: water demand, artificial intelligence, water security, planning

Building resilience to urban floods through nature based solutions

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Bengaluru faces recurring urban flooding due to rapid urbanization, stormwater drain encroachments, and climate change. The Bengaluru Climate Cell is collaborating with various institutions to develop a standard operating procedure for implementing Nature-Based Solutions (NbS). However, before implementation, it is essential to quantify NbS impact on flood mitigation and assess flood risk reduction at the catchment scale. To achieve this, we utilized HEC-HMS and HEC-RAS models to simulate a 10-year return period flood event over a 27 km² catchment in Yelahanka. High-resolution DEM (10-meter resolution) and climate data were used to model flood inundation. This dataset enabled accurate identification of drainage patterns and watershed boundaries. Spatial data for drains and nodes were used to generate a drainage layer representing water pathways. Sentinel-2 satellite imagery was employed to develop a Land Use Land Cover (LULC) map, essential for determining the Curve Number (CN) grid, a key parameter in rainfall-runoff modeling. The model was calibrated using rainfall and flood data from the 2023 flood event and validated against reconnaissance survey data and local observations. A strong correlation ($R^2 = 0.75$) between modeled and observed data confirmed the reliability of our analysis. A comprehensive flood risk assessment framework, incorporating hazard, vulnerability, and exposure factors, was applied to classify risk levels based on inundation depth, elevation, slope, road types, population density, built-up density, and critical infrastructure. We then simulated NbS interventions, such as green roofs and recharge wells. Results indicate that under a scenario where 25% of the area was covered by green roofs and recharge

wells. The model predictions showed that the high-hazard areas experienced a 67% reduction in affected area, followed by moderate (47%), very high (36%), and low hazard areas (27%). The study highlights NbS potential in mitigating urban flood risks, particularly in high-density areas.

Keywords: Urban floods, Nature based solutions, climate change, Green roofs

Detecting changes in the onset of monsoons in Sri Lanka

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The onset of monsoon plays an important role in the Sri Lankan climate, also influencing agriculture, water resource management and disaster management. Understanding the shifts in monsoon onset is crucial to ensure the resilience of hydrological systems. This study aims to detect the changes in monsoon onset over a period of 30 years (1987-2016) in the Kelani river basin, Sri Lanka by analysing daily rainfall data from selected meteorological stations. The Piecewise Linear Regression Model (PLRM) and Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) method were employed to determine the monsoon onset dates based on cumulative rainfall and rainfall threshold criteria. Mann-Kendall trend analysis was conducted to determine whether there had been a presence of statistically significant trends in the monsoon onset. The results indicated no monotonic trends for both northeast and southwest monsoons. However, spatial variations were observed with the monsoon onset days differing across regions within the basin. The BMKG method proved to have more accurate results in identifying monsoon onset dates since its results were closely aligned with the actual onset records compared to PLRM. Moreover, a statistical comparison between actual and detected monsoon onset dates detected that the monsoon onset dates were delayed from a range of 1-6 days across different stations within the basin. Hence, this proves a localized variability in the monsoon behaviour.

While this study proved no significant long-term trends in monsoon onset, the results suggest that there should be more focus on the importance of continuous monitoring and the need for region-specific climate assessments. Since there is no trend detected, this means that the monsoon onset in Kelani River Basin has been relatively stable over the study period.

Keywords: monsoon onset, spatial variability, statistical analysis, trend detection, Kelani River Basin

Informing the trenches: Rainfall simulation experiments in Himalayas to Hydrologically inform Water Conservation Structure designs

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In areas with highly seasonal rainfall, water conservation structures are designed to reduce runoff and enhance infiltration during wet periods, thereby increasing the residence time of rainwater within the interventional area. When infiltrated water recharges an accessible aquifer, such as via springs in the Himalayas, it provides a source of water during the lean or dry season.

The aim of this study was to inform guidance on water conservation structures through rainfall simulation experiments by measuring the rainfall-runoff relationship for different land uses and rainfall intensities. Additionally, extracting parameters from these experiments that can be utilized in the design of water conservation structures.

Rainfall simulations with two rainfall intensities were conducted three times on nine plots (three replicates from three prominent land uses within the region: oak/natural forest, pine forest, and farmland), resulting in a total of 55 experiments. The dimensions, slope, hydraulic conductivity, and bulk densities at 10 cm intervals were measured for each plot. For each experiment, rainfall was recorded using a tipping-bucket rain gauge, and runoff was recorded with manual measurements at 30-second intervals. Additionally, initial and final soil moisture were recorded for each experiment.

Two methods were employed to generate usable parameters: runoff coefficients as a ratio of rainfall to runoff, and Philip's equation to derive the sorptivity (S) and permeability coefficient (A). However, these methods did not account for the slope of the plot; therefore, the shallow water or Saint Venant equations using a recently developed emulator were utilized to recreate the experiments.

Runoff patterns exhibited significant differences between rainfall intensities and land uses but were relatively similar for the replicates within each land use and even more similar for the replicates within the same plot. These experiments represent an important step in providing guidance for the implementation of nature-based solutions in the region.

Keywords: Rainfall Simulation Experiments, Himalayan land uses, Plot scale runoff, Philip's Equation, Saint Venant Equations

A Comparative Study of Climate and Drought Resilience in Distinct Indian Catchments

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Global warming and changing precipitation patterns under climate change are linked to long-term climate shifts as well as increased frequency of extreme events such as droughts in different parts of the world. These climatic changes significantly impact the hydrological behavior and responses of catchments. It is crucial to understand the response of catchments to both short-term disturbances (droughts) and long-term shifts (warming) for sustainable water resource management. In this study, a comparative assessment is conducted to determine the hydrological resilience of the 30 catchments in Peninsular India to the long-term climate shift (climate resilience) as well as short-term disturbances (drought resilience). Budyko's framework-based elasticity is used for assessment of climate resilience, whereas drought propagation time from meteorological to hydrological drought is considered as an indicator of drought resilience. The results indicate that 23 catchments show climate resilience, however only 15 catchments exhibited drought resilience with propagation time > 5.5 months. Further, we analyzed different natural features (meteorological, topographic and land cover) and human influences (dams and irrigation) to identify the factors controlling the drought and climate resilience behavior of the catchments. The results indicate the influence of different drivers at short and long-term scales, wherein precipitation and temperature playing significant role in climate resilience whereas basin area and human influences playing significant role in drought resilience. These findings reveal the importance of analyzing the responses of catchments at different scales. As it is observed, the catchments identified as hydrologically resilient to climate change may still remain vulnerable to droughts, likely due to the physiographic features and human interventions such as reservoirs and dams that modify natural flow regimes. Thus, this study provides a novel perspective on hydrological resilience by integrating both long-term and short-term impacts which can further help in identifying the suitable sustainable measures effectively.

Keywords: Droughts, Propagation time, Resilience

Leveraging Web GIS for a Systematic Review on Applications of InVEST Models in Ecosystem Services and Water Security Management

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Ecosystem service evaluation and environmental modeling are critical for water security, climate resilience, and sustainable resource management. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is commonly used to assess a variety of ecosystem services, such as carbon storage and sequestration, annual water yield, urban flood risk mitigation, urban

cooling, storm water retention, as well as sediment delivery ratio. This model is important in hydrology, watershed management, and ecosystem-based approaches to managing environmental issues including floods and droughts. However, there is no centralized and comprehensive review of global research using this paradigm. The goal of this study is to provide a Web GIS interface that will allow for an organized literature assessment of InVEST-based studies from around the world. The portal will include geographically referenced metadata from peer-reviewed literature, allowing users to see research trends, analyse study sites, and compare the primary ecosystem services evaluated. The Web GIS will provide an interactive platform for geospatial querying, data visualization, and analytical investigation, revealing important insights into the link between ecosystem services and environmental stressors. Beyond being a simple archive, this platform will function as a decision-support tool, allowing users to examine the spatial distribution of research efforts, identify underrepresented geographic locations, and investigate potential model applications for tackling water security concerns. Furthermore, the Web GIS will act as a bridge between research and policy, transforming scientific findings into practical insights while fostering holistic solutions for water security and sustainable environmental planning. Additionally, it will facilitate collaboration among academics, policymakers, and practitioners, ensuring that the knowledge gained from InVEST studies is effectively utilized to tackle global environmental challenges.

Keywords: Ecosystem, InVEST, Sustainable Water Management, Web GIS

Carrying Capacity: Concept and Estimation for Basin Scale

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Water is an essential basic resource for social and economic development. Ensuring its rightful availability to different stakeholders from the perspective of sustainable development in any region essentially requires a holistic and rational evaluation of its carrying capacity (CC). The carrying capacity can be studied on various levels, such as cities, basin/ sub-basin, and national or global levels. The concept is picking up slowly on an international scale, with various methodologies proposed by researchers worldwide. Needless to say, each method has its unique features and strengths.

Water Resources Carrying Capacity (WRCC) is studied at the basin level, based on the water availability, demand, and economic dimension. The study framework consists of dimensions, criteria, and basic indicators. The Analytic Hierarchy Process (AHP) method is used to determine the weight of each indicator which is aggregated to calculate the criteria value, and further value is calculated to dimension. The dimension value is finally aggregated to the index value. Such a way bottom-to-top approach is used to determine index calculation.

In the Hindon basin- study, water resources carrying capacity is calculated for the 2020-21 year based on the water availability, demand, and economy. The index value is 0.63, which shows moderately good conditions for monsoon seasons for the surface runoff flow. This study mainly focuses on the Sustainable Development Goals (SDG) 6 and 11. It will help with the performance measurements of the basin on their carrying capacity, help with policy-making, management of available resources and proper utilization, urban planning, and design.

Keywords: AHP, Carrying Capacity, Sustainable Development, WRCC, SDG

Modelling Water-Energy-Food Nexus Dynamics for Integrated Resource Management

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Effective management of interconnected water, energy, and food (WEF) systems is crucial for sustainable development, particularly in rapidly urbanizing regions with rising resource demands. This study employs a system dynamics-based WEF nexus model for the Hyderabad region, where the Nagarjuna Sagar and Singur reservoirs together supply nearly 80% of the city's water demand. The model integrates surface and groundwater systems, reservoir operations, and competing sectoral uses such as urban water supply, agriculture, hydropower, and environmental flows. It captures urban-rural interdependencies and explores how different prioritization strategies affect resource availability and use across sectors. The model structure also allows incorporation of seasonal variations and historical demand patterns, providing a realistic picture of the system's behaviour. Simulation of multiple resource allocation scenarios reveals key trade-offs and synergies among sectors, offering insights into how shifting priorities can impact water availability, energy generation, and agricultural productivity. Sustainability indicators, such as surface water stress, groundwater depletion, and environmental flow deficits, are used to assess system resilience. These findings are closely linked to the achievement of relevant SDGs, such as SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 7 (Affordable and Clean Energy) by highlighting sectoral interactions that influence progress on these goals. The results underscore the importance of integrated, cross-sectoral decision-making to effectively balance the conflicting pressures from the urban and rural sectors. It also guides policy and planning efforts aimed at improving water sustainability in regions with complex urban-rural interdependencies.

Keywords: Water-Energy-Food Nexus, System Dynamics Modeling, Integrated Resource Management, Trade-offs and Synergies, Urban-Rural Interdependencies

Seasonal drought impact-based forecasting of crop yield in India

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Accurate and reliable drought impact-based forecasting of crop yield in India remains a major challenge due to the country's strong hydro-climatic diversity and the complex interactions between climate variability, ecosystem vulnerability, and agricultural systems. By integrating observed and forecasted drought indices across multiple accumulation periods, this study develops a framework to predict at the seasonal time horizon the impacts on crop yield across the country. Using both district-level and cluster-based approaches, we apply Random Forest, Extreme Gradient Boosting, and Artificial Neural Network models to establish strong indicator-impact relationships for paddy rice (wet season) and wheat (dry season) yield, leveraging historical data and seasonal forecasts.

Our results show that district-level models outperform cluster-based approaches, with Random Forest models yielding the best performance. More than 70% of districts achieve strong predictive accuracy based on root mean square error (RMSE) in the test set. Incorporating ECMWF's SEAS5 seasonal forecasts enables reliable predictions of rice yield up to six months ahead of the growing season in most districts. Performance assessed using the Continuous Ranked Probability Score (CRPS) confirms the robustness of forecasts across both space and time, particularly in districts with moderate yield variability. Moreover, the weighted CRPS metric reveals that forecasts for extreme low yields (below the 10th percentile) are both accurate and reliable in the majority of districts - an essential outcome for early warning and preparedness.

This work marks a significant advancement in operationalizing impact-based forecasting in India, offering the potential to inform anticipatory action among farmers, water managers, and agricultural supply chains. By directly linking seasonal drought forecasts to yield outcomes, this study provides a replicable early-warning tool to support targeted mitigation strategies and improve climate resilience in the agricultural sector.

Keywords: drought, drought indicators, impacts of drought, drought impact-based forecasting, drought early warning systems

RESTART'in: Understanding the similarities and differences in flood and drought processes and management at varying spatial and temporal scales in India and the Netherlands

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India and the Netherlands experience increasingly severe water disasters, such as floods and droughts. However, current management strategies are inadequate in terms of comprehensiveness and climate-resilience. The increasing complexities of socio-hydrological systems make it challenging to predict

and manage water disasters.

Project RESTARTin: "Restructuring and Enhancing Strategies with a Transformative AppRoach for InTegrated Water Disaster Management in India and the Netherlands" (2024-2027) aims to develop the knowledge and tools for deriving targeted management strategies to mitigate the impacts of future water disasters and preserve economic, social, environmental, and human life values. It seeks to understand drought and flood processes at different scales and assess the socio-economic impacts, to formulate interventions and reduce the know-do-gap.

An integrated flood and drought assessment framework is being developed to bridge the gap in the understanding of comprehensive catchment processes. The first component is a process-based modelling framework to capture the spatial-temporal dynamics of floods/droughts at the river basin scale, using an ensemble of models to assess water flows, water storage capacities, and crop productivity under changing climate and land-use. System understanding is improved through data collection and analysis using high-resolution remote sensing and Artificial Intelligence/Machine Learning (AI/ML). Then, the socio-economic impacts of floods and droughts are assessed, considering economic loss, agricultural productivity, livelihoods, education, and infrastructure. Finally, adaptation/intervention measures and their potential under current and future climate scenarios will be derived in consultation with stakeholders.

The assessment considers both biophysical and socioeconomic factors, leading to a socio-technical appraisal of each scenario. A Multi-Layer Safety approach will complement the modeling process by visualizing desired futures, translating interventions into spatial consequences, and identifying pathways to sustainable futures. Multiple study sites, both in India and the Netherlands, serve as demonstration areas, allowing stakeholders to observe its implementation, knowledge sharing, co-creation, and peer learning to accelerate adoption.

Keywords: floods, droughts, India, Netherlands

Strengthening Desertification Policies through Participatory Approaches and Local Knowledge in Water Management

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Research on water resources and hydrology in semi-arid regions, where water scarcity shapes both livelihoods and governance, exhibits strong engagement with society. Desertification and drought severely affect water availability in the semi-arid regions of Brazil, impacting local communities reliant on scarce water resources. Addressing water-related challenges in these regions requires integrating traditional ecological knowledge, participatory water-related practices, and scientific insights to inform inclusive and effective policy frameworks. This research presents a collaborative project in a region critically impacted by water scarcity and desertification, engaging Quilombola and Indigenous communities to co-produce evidence-based solutions to strengthen water governance policies. The project employs a participatory intersectional methodology encompassing hydrological modelling, spatial analysis, and qualitative field-based methods, integrating these with scientific

data to identify policy gaps, constraints, and opportunities for improving water security and sustainability. Through the project, we systematically mapped and assessed priority water conservation and restoration areas. We identified areas where desertification processes are advanced within regions with an aridity index below 0.65. These findings directly contribute to Brazil's National Action Plan to Combat Desertification and Mitigate the Effects of Drought, aligning with the objectives of the United Nations Convention to Combat Desertification (UNCCD) and the Sustainable Development Goals (SDGs), particularly those related to water security. We hope to use these data to support the participatory approach with the communities to mitigate the impacts of drought by integrating water resource management practices and policies that reflect both traditional knowledge and scientific evidence. Reflecting similar community-driven efforts from the Global South, we emphasise how participatory, context-specific research can guide more equitable responses to water scarcity in semi-arid regions.

Keywords: Brazil, drylands, semi-arid, Caatinga, communities

Quantum Dots and their Nanocomposites applications for Environmental Applications

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The study deals to develop a sustainable approach to ensure clean water for improving the quality of life in the earth by development of suitable photoluminescence (PL) probes for detection of potential water pollutants and nanocomposites as an efficient photocatalyst for sunlight driven photocatalytic degradation of emerging contaminants in water matrix. Here, main verticals are as follow, (a) Developing suitable functionalized carbon dots as PL probe and (b) p-type semiconductor based metal oxide nanocomposites with some of these functionalized carbon dots as solar photocatalyst for degradation of some selected emerging water pollutants (antibiotics). In view of this, two batches of functionalized carbon dots are prepared using different carbon precursors, e.g., (i) sodium citrate, and (ii) 1,4- Butanediol, and both are functionalized by siloxane group. The first batch is prepared by hydrothermal heating of sodium citrate and (3-Aminopropyl)triethoxysilane (APTES) in an autoclave. The second batch is prepared by solvothermal method by heating 1,4-Butanediol and APTES in an autoclave. These two batches are named as N-SiO₂@CD1 and N-SiO₂@CD2 respectively. The feasibility of using N-SiO₂@CD1 and N-SiO₂@CD2 as probe for detecting Cr(VI) and 4-NP has been tested in real samples by estimating the recovery concentration analysis of spiked concentration in the real water samples. For photocatalytic degradation application, four batches of metal oxide p-type semiconductor photocatalysts are synthesized. These batches are ZnO/N-SiO₂@CD1, ZnO/CD (not functionalized with APTES), TiO₂/CD (not functionalized with APTES) and Bi₃.64Mo_{0.36}O_{6.55}/N-SiO₂@CD1. These batches of photocatalysts are thoroughly characterized to elucidate their structural, morphological and compositional information and application for photocatalytic degradation of ciprofloxacin and tetracycline under sunlight has been studied. The mechanism of photocatalytic degradation of ciprofloxacin and tetracycline has been studied by total carbon content measurement and degradation product analysis by UPLC-Q-TOF-MS in the residual solution obtained after degradation by the photocatalysts.



Keywords: water pollutants, metal oxide nanocomposites, water remediation, sensing, UPLC-Q-TOF-MS

Cross-Cutting Goals (HELPING theme 3)

Indian Climate Information Explorer(INCLINE) : A Unified Platform for Climate Data Visualization and Download for Indian subcontinent

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India faces complex climate and hydrological challenges, including recurring extreme weather events, water scarcity, and shifting precipitation patterns, which demand robust tools for data-driven decision-making. To address these issues, INCLINE Website is an integrated platform designed to provide seamless access, visualization, and download of climate and hydrological data for India. The platform offers now four core applications-Climate Snapshot App, Drought Monitor App, Extreme Indices App, and Watershed Delineation App-enabling users to explore data at granular levels, from individual points to states, districts, and major river basins. The Climate Snapshot App provides high-resolution historical (1979-2014) and projected (2015-2100) climate data, including precipitation and temperature, derived from IMD, IMDAA, and CMIP6 models. Users can visualize data and download datasets at daily, monthly, or annual intervals. The Drought Monitor App enables monitoring of drought severity using indices such as SPI, SPEI, and NDVI, offering insights into precipitation deficits, moisture balance, and vegetation health. Users can analyse these indices across different time scales and download the results for further study. The Extreme Indices App focuses on temperature and precipitation extremes based on ETCCDI-defined indices, such as Rx1day, TX90p, and CDD etc, providing valuable metrics for understanding climate variability and change. The Watershed Delineation App supports delineation of watershed boundaries using MERIT-Hydro datasets, allowing users to download shapefiles for hydrological modelling and resource planning. By integrating high-resolution data, advanced visualization, and user-friendly functionality, INCLINE Website empowers researchers, policymakers, and stakeholders to analyse climate and hydrological challenges effectively.

Keywords: Climate Snapshot App, Drought Monitor App, Extreme Indices App, Watershed Delineation App

Using collaborative Agent-Based Modelling (ABM) to enhance decision making in agricultural water use

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Water is an important natural resource with multiple domestic , industrial, and agricultural water

uses. South Africa has a well-reported water scarcity problem, with domestic, industrial, and agricultural demand projected to increase due to population growth. The country relies on surface water resources and climate change impacts threaten to reduce surface water availability in future. This will pile pressure in agricultural areas that are already consuming much of the country's available surface water resources. Agricultural areas are already failing to fully comply with environmental water releases (EWR's). One affected area is the Koue Bokkeveld (KBV), an agricultural catchment in the Western Cape. Water scarcity, especially in the summer, leads to issues in EWR compliance and cause conflicts among the farmers as they attempt to share the limited resource.

This study sought to determine the extent to which Agent-Based (AB) modelling could be used to model the KBV catchment area to represent current system dynamics and explore impacts of agricultural expansion/usage scenarios and climate change on water availability and EWR's.

The study used the Companion Modelling (ComMod) methodology which allows stakeholders to be involved at each step of the modelling process, thus improving the model's credibility as a decision-support tool (DST). The model was implemented using Cormas, an Agent-Based Model (ABM) implementation framework and then verified and validated through consultations with the catchment coordinator and through multiple workshops with stakeholders. The ABM reflected the catchment characteristics including a ~50% increase in water shortage under climate change. However, key outcomes also indicated that the inclusion of a large shared reservoir would improve agricultural water supply and EWR compliance. The ABM was used to run multiple simulation scenarios, and it provided simulation results at the crop field, farm, and catchment levels. Therefore, the ABM can be used as a bottom-up DST.

Keywords: Agent-Based Model, Stakeholder engagement, Water use, Agriculture, South Africa

Science Communication in HELPING - A Community Perspective on Common Challenges and Best-Practice Solutions

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HELPING, the new scientific decade of the IAHS, aims to integrate knowledge of hydrological processes across scales and geographical contexts, and to work with local communities, actors, and decision-makers to address the water crises we are facing. In all of this science communication is crucial. However, communication channels and practices have evolved rapidly since the first scientific decade, Predictions in Ungauged Basins (PUB), was launched in 2003.

In this contribution, we take stock of common communication challenges hydrologists face in HELPING and beyond, and we identify best-practice solutions. To do so, we have chosen a broad approach based on interactions and feedback from over 100 members of the hydrological community. We organised a series of three online workshops as well as 21 interviews with actors who deal with science communication efforts in hydrology in their working lives, including government officials, engineers working in river restoration, mayors of flood-prone communities, and managers at water user associations. We furthermore talked to 12 long-term IAHS volunteers to reflect on their lessons learned with respect to science communication in the first two scientific decades of the IAHS. Finally, we conducted an online survey to gain more quantitative insights on key questions that emerged during the workshops and the interview series.

Our preliminary results indicate that some of the major science communication challenges that hydrologists face in the context of HELPING are the large diversity of communication channels as well as the sheer volume of messages that they receive on a daily basis, and having to find strategies to filter from this flood of information the points most relevant to them. Other key issues are the lack of systematic training in science communication for most hydrologists and the scarcity of funding for communication-related measures in projects.

Keywords: science communication, HELPING, IAHS

Participatory pseudo-quantification of the effects of citizen-led adaptation on household flood risk in Tamale, Ghana

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Adaptation is essential to mitigate the effects of climate change, such as increasing flood risk. In response to widespread maladaptation, citizen-led approaches are increasingly championed, whereby people on the frontline of climate change determine their own objectives and strategies of adaptation. However, the effects of such approaches on risk are yet to be quantified, and little is known about the equity of their distribution or their limits under flood events of increasing magnitude. For the first time, we attempted to pseudo-quantify the effects of citizen-led adaptation on flood risk for 286 households in Tamale, Ghana. We estimated the effects of common structural and behavioural citizen-led adaptation interventions ($n = 11$) through a series of workshops and events which included approximately 500 participants. We incorporated these estimates into a household level flood risk model which was developed using hydraulic modelling software and exposure and vulnerability indices informed by responses to a co-produced household survey. Early results indicate that citizen-led adaptation interventions had a larger risk reduction impact for households that already experienced lower risk, thereby widening adaptation gaps. This effect was primarily driven by inequitable access to adaptation, where low practice of adaptation was associated with high vulnerability, and less so by differing exposure to flooding. Our initial results demonstrate the importance of understanding the effects of adaptation and of supporting equitable deployment.

Keywords: Flood risk, Climate change adaptation, Cocreation, Participatory

Engaging agronomists in hydrology or hydrologists in agronomy?

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Sustainable agriculture requires a balanced management of water and soil resources to harmonize agricultural production with environmental protection. In Uruguay, this issue is of particular importance, as agriculture is the country's main economic activity, with livestock farming, forestry, and rice cultivation being the primary export sectors. Rice cultivation, in particular, uses a significant amount of water, which is important to consider in discussions of environmental flows and water pressures.

Traditionally, hydrology has been conducted by hydraulic and environmental engineers with limited knowledge of agricultural practices. Conversely, farmers possess extensive agronomic expertise but often lack proficiency in hydrological analysis. This knowledge gap has led farmers to advocate for and contribute to the revision of policies and regulations. In doing so, they have sought support from academic institutions and research centers to provide scientific evidence for the development of new policies. Meanwhile, hydrologists-primarily based in research institutions-have leveraged this opportunity to secure funding for research projects and maintain agro-hydrometeorological observation networks, which would have been difficult to sustain without the agricultural sector's interest and engagement.

This collaboration has facilitated capacity building, with both sectors learning from one another to bridge knowledge gaps and improve practices. Against this backdrop, this study aims to provide a national-scale review of how agricultural producers and hydrologists in Uruguay have developed a mutually beneficial relationship to address key questions related to environmental flow, land-use change, and best agricultural practices. The ultimate goal is to ensure the long-term economic and environmental sustainability of agricultural activities in the country.

Keywords: Agro-hydrology, knowledge exchange, environmental sustainability

Water solutions in the Anthropocene, IAHS's third scientific decade. Keeping the pace

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The third scientific decade (2023-2032) of the International Association of Hydrological Sciences (IAHS) is a solution oriented global initiative aiming to find answers to existing as well as emerging water threats in the Anthropocene, such as water quantity, quality and water governance. The focus

is explicitly on finding solutions in their local physical, socio-economic and cultural context. Like the previous initiatives, the Helping decade is bottom-up organised, fostering grassroots initiatives with emphasis on multidisciplinary teams and creating a diverse representation, geographically, and by professional background, gender and career stage. Hence, HELPING is a vehicle for putting science into action, driven by scientists working on local hydrological problems.

The Helping decade is organised around three themes with in total 30 Working Groups. Theme 1 (15 WG) centres around global and local interactions, theme 2 (9 WG) has a focus on holistic solutions for water security and theme 3 (6 WG) aims at cross-cutting goals. In total over 1700 participants have subscribed to the initiatives. This is really a result to cherish and a solid base.

During the 12th Scientific Assembly the Helping leadership would like to discuss the current state of the Working Groups, support further growth by discussion of practical actions together, among which are funding opportunities, organisation of meetings and open science publications. Moreover, we would like to stimulate cross-fertilisation and collaboration between WG, and discuss and address gaps and opportunities we missed so far.

Keywords: IAHS 3rd decade, Helping

Co-creating Water Knowledge: a community perspective for the IAHS HELPING Decade

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⁶IAHS Helping Theme 3

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Navigating the complexities of the global and local water resources challenges requires collaboration and mutual learning among diverse knowledge systems and disciplines. However, Western philosophical approaches to generating knowledge have prevailed in water management and hydrology, often overlooking community priorities, practices and perspectives, and power asymmetries, including gender inequalities, racism, and colonial injustices. In this perspective paper, we explore the concept of co-creation of water knowledge (CCWK) to value multiple and diverse forms of knowledge. We identify four overarching principles (inclusivity, openness, legitimacy, and actionability), highlighting the importance of establishing relationships and collaborative leadership, adopting key tools and techniques, and integrating knowledge for water resources management. We identify four overarching principles (inclusivity, openness, legitimacy, and actionability), highlighting the importance of establishing relationships and collaborative leadership, adopting key tools and techniques, and soundly integrating knowledge. Furthermore, we argue that prioritising epistemic justice is essential for the effective co-creation of water knowledge (CCWK). To address these, we advocate for more interdisciplinary and reflexive research practices that challenge and disrupt Western scientific traditions shaped by functionalist and colonial legacies.

Keywords: co-creation, Indigenous knowledge, water science, epistemic justice, inter-disciplinary approach

Pluralizing water epistemologies: the need for a decolonised water representation

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The current scientific concept and description of the hydrological cycle has been developed by positivist scientists, with the subtle effect of supporting water exploitation for western national development strategies. These are the premises of a science that was developed in the same system that is leading the planet to a collapse driven by climate change and environmental degradation. In an era of deep interconnectedness between people and nature, to ensure the sustainability of human life on a safe planet, we propose to re-imagine our understanding of hydrology based on a constructivist approach, which aims at incorporating multiple values in socially constructed water relations, including cultural norms, identities, and informal collective decision-making processes. In addition, incorporating indigenous, ancestral knowledge into water management practices helps to acknowledge that water knowledge is not limited to scientific understanding but includes diverse epistemologies and ontologies - for instance, considering water as a common good shaped by cultural practices and regional identities and acknowledge that water governance paradigms exist at multiple scales, from local communities to international agreements. A comprehensive water management framework should consider interactions and knowledge exchange across these different levels and continuous learning and adaptation in water management practices, allowing for the integration of diverse perspectives and the evolution of water concepts over time. We launch an open call to pluralize and re-imagine how human-water connections are conceived, portrayed and known. The goal of this discussion is to set the base for a framework to co-creating a more suitable concept of (socio)hydrological cycle, which builds on a plurality of ontological and epistemological perspectives and knowledges, including non-scientific ones, as indigenous, traditional or vernacular knowledges.

Keywords: decolonization, water cycle, water knowledge, epistemologies

How Can the IAHS' Digital Water Globe Enhance Research Visibility and Improve Network Connectivity in a Society Under Transformation?

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The Digital Water Globe (DWG) is an innovative, open-source, web-based platform developed to facilitate effective communication, promote networking, and exchange knowledge within the global hydrological community. The International Association of Hydrological Sciences (IAHS) has launched the DWG to address the growing need for the efficient dissemination of analytical insights and observational data between hydrologists. The IAHS continuously works to engage under-represented groups and early-career scientists through the DWG. This contribution highlights how the DWG enhances research visibility and improves network connectivity. DWG employs the following methods: 1) operationalizes the FAIR and CARE principles* into the IAHS SQUARE** principles, and 2) co-promote other IAHS initiatives, like the IAHS Equality, Diversity, and Inclusion (EDI) Task Force. DWG supports global collaboration in hydrological science through initiatives like UNESCO Open Hydrology and the WMO Hydrology Expert Network. The platform provides graphical displays of critical water data, user profiles, case studies, data repositories, and publications, all searchable by keywords, supported by keyword-based filtering tools. Thus, the DWG serves as a dynamic platform that empowers users to share their research, connect with peers, and explore ongoing hydrological activities worldwide. Moreover, the DWG also acts as a centralized hub to enhance the visibility of hydrological research and strengthen collaboration across IAHS Commissions and Working Groups. It also connects hydrologists to initiatives like Unsolved Problems in Hydrology (UPH), the IAHS scientific decade "HELPING," and the UN Sustainable Development Goals (SDGs). By engaging diverse audiences, including partners, practitioners, media, and citizens, the DWG fosters a robust ecosystem to advance hydrological science. The IAHS DWG will focus on strengthening interdisciplinary teams, advancing science communication, and launching new water academies, and training. Externally, it will promote visibility and networking through collaborations with initiatives like the IWA Digital Water Programme, WMO Digital Strategy, EVE, and UNEP World Water Quality Alliance (WWQA)

Keywords: Digital Water Globe, Water Resources Management, Climate Change, Hydrology.

Fair Water - management of floods and droughts through collaboration and co-creation

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Water management in Sweden is currently under refinement with focus on holistic solutions to handle floods and droughts. This presentation will exemplify current problems and suggest methods for collaborative decision-making across sectors to facilitate multipurpose and fairness in water allocation. Motala ström River basin (15,500 km²) in Sweden has a very active river association, encompassing authorities, municipalities and private sector, such as industries, agriculture, forestry, insurance, tourism, hydropower, water and sanitation companies. This association was engaged for testing ideas on how to apply a living-lab concept to co-create knowledge for more efficient decision-making and management of floods and drought. The aim was both to prevent extreme events and to reduce damage during an on-going crisis.

To facilitate the discussion, extreme scenarios were produced by modelling the joint effects of combined historical events (observed in the catchment or nearby). These scenarios were well accepted by participants as they could easily relate to them, although the combined effect was severe regarding flooded areas and hydrological/agricultural drought. Risk areas were identified and potential effect from various physical measures in the landscape or water management were explored in numerical modelling. The results were surprising to many actors and shifted their views on best management practices. Likewise, scenario-based training on collaborative decision-making during a crisis was judged very effective to speed up communication and decisions. Hydrological tools were thus considered useful, although some local adaptation was needed for acceptance. Moreover, hydrological knowledge was found to play an important role for reaching consensus and implementing actions.

Keywords: climate adaptation, water management, holistic solutions, drought, floods, prevention, decision-making, actions

What do we need to know? Ten questions about climate and water challenges in Berlin-Brandenburg

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As climate change escalates, the Berlin-Brandenburg region faces new challenges. Climate change-induced extreme events including droughts, heatwaves, and floods, are expected to lead to the emergence of new conflicts, as well as to aggravate existing ones. To properly address these - often interconnected - challenges, a strategic research agenda is necessary. In this study, we engaged a transdisciplinary academic community of experts to co-develop a list of key questions on these climate and water challenges in the region.

Within the focus group, we identified topics such as climate adaptation, water management, technological innovations, impact assessments, and governance, as priorities. Stemming from these topics



over fifty questions were designed and evaluated to finally obtain a set of ten questions perceived as the most pressing and relevant for the region in the coming decade. The questions emphasize the need for resilience strategies in agriculture, urban water supply, and land use change (chiefly the post-mining phaseout in the River Spree catchment). Nature-based solutions and impact-based hydroclimatic extreme early warning and forecasting systems also emerged as critical areas for action. Our findings highlight the importance of participatory science-policy interfaces to enhance regional climate adaptation and water governance. This framework can serve as a model for other drought-prone lowland regions navigating socio-environmental transitions under climate change.

Keywords: co-production, research questions, adaptation, climate change

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