A Report on the Minutes of the

Discussion Meeting
on
Hydrology in the Anthropocene

December 06 – 09, 2022
Hassan
India

Interdisciplinary Centre for Water Research (ICWaR)

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Discussion Meeting on Hydrology in the Anthropocene

December 6 - 9, 2022

Hoysala Village Resort, Hassan

The workshop on "Hydrology in the Anthropocene" was conceptualized by Prof. Ana Mijic, Imperial College London (Satish Dhawan Chair) and Prof. P. P. Mujumdar, ICWaR, IISc. The discussions spread over the course of three days and were held in the picturesque Hoysala Village Resort in the quaint town of Hassan, away from the hustle and bustle of Bengaluru city. Several potential science questions related to human interactions with nature and water cycle feedback were collated and prioritized. The discussions were organized in the form of four sessions spread across three days including presentations from participants and brainstorming break-out sessions. The participants (list enclosed in Annexure) comprised Professors, Assistant Professors, and Ph.D. Research Scholars from the University of Texas at Austin, various Indian Institutes of Technology and Universities across the country, C-DAC Pune, and ICWaR (IISc) engaging in stimulating discussions on the impact of humans on various components of hydrology.

दुर्लभान्यपि कार्याणि सिद्यन्ति प्रोद्यमेन हि।
शिलापि तनुतां याति प्रपातेनार्णसो मुहुः॥

Even the hardest of things can be accomplished with small, consistent efforts,
just like a hard rock gets thinner with repeated fall of water on it.

As humongous as it sounds, researching and realistically modeling the human impacts on hydrology can be done with small, meaningful efforts. This workshop was an imperative attempt to bring together researchers from various domains of water resources, forge collaborations, and formulate the future research direction for the study of hydrology in the Anthropocene.

Attendees (Abbreviations)

Ana Mijic (AM), Dev Niyogi (DN), Pradeep Mujumdar (PM), Nagesh Kumar (NK), Rajiv Sinha (RSI), Satish Regonda (SR), Sagar Rohidas Chavan (SRC), Debsundar Dutta (DD), Sanskriti Mujumdar (SM), Rehana Shaik (RSH), Bihu Suchetana (BS), Bramha Dutt Vishwakarma (BV), Athira P. (AP), Abhinav Wadhwa (AW), Gowri R (GR), Shailza Sharma (SSH), Shobhit Singh (SSI), Kannneganti Bhargav Kumar (KB), Sarat Chandra (SC), Subhrasita Behera (SB), Gouri Kadam (GK), Likhitha Pentakota (LP), Saumya Srivastava (SSR)

1. Introduction – Day 1

Prof. Mujumdar welcomed all the participants. He especially thanked Prof. Ana Mijic and Prof. Dev Niyogi for accepting the invitation. He recalled the previous workshop on "Scale Issues in Hydrology" with Prof. Sivapalan at Hoysala and the insightful discussions during the workshop. Prof. Mujumdar mentioned that this workshop is to build connections with fellow mates working in hydrology and to acknowledge and learn from each other's works in the same discipline. He emphasized that this workshop would help young researchers in hydrology to stand out. He also mentioned that the workshop would have team-building exercises, team discussions, and free time for formal and informal interactions and discussions. This workshop would focus on the broad subject of human impacts on natural resources and come up with various scientifically rigorous tools to deal with the emerging problems in hydrology.

Prof. Ana Mijic, who visited IISc Bangalore as Satish Dhawan Visiting Chair Professor, kickstarted the workshop with a presentation titled "Human Impacts on Hydrology".

Humans impact all components of the water cycle! The scientific decade 2013–2022 of the International Association of Hydrological Sciences (IAHS), entitled "Panta Rhei – Everything Flows", is dedicated to research activities on changes in hydrology and society. The purpose of Panta Rhei is to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems.

Human-natural water system interactions will be different depending on the local context and across different spatial and temporal scales, but the problems are very similar. In order to develop a physically based urban catchment water cycle model, components like agricultural demand, urban demand, housing demand, irrigation water use, urban water use, and effluents are gradually added to a basic natural catchment water cycle driven by local climate and physical properties of the water cycle.

There are human water cycle interactions with other systems like climate, transport pollution systems, energy emission systems, and ecological systems. Any changes to the natural water cycle (with additions and subtractions) will have propagations on the entire system. The system gets very complex very quickly. The question we need to ask ourselves is: 'What should the boundary conditions of water system analysis and models be?'

Prof. Ana's research team has worked on including human interventions in the water cycle. She explained three example studies conducted by her students. The first one is understanding the impacts of irrigation water use at the farm scale. Adding human elements to the physical systems helps in effective canal water management in terms of irrigation water use, cropping patterns, as well as monetary issues.

During her presentation, she exemplified a few of the integrated water management systems researched across the globe. The first example is the Indian case study of canal usage to demonstrate the integrated water management framework. This work suggests that canals play an important role in Indian water use, but they need to be managed carefully to avoid flooding and waterlogging. The second example is with respect to water quality aspects where no-cost water infrastructure using AED (Abstraction Effluent Dilution) is the main idea. The third example concentrated mostly on a key element in the integrated framework called, multi-catchment urban-rural load allocation. An integrated water management tool, the CatchWat-SD model, is being developed at the Imperial College London to model multi-catchment urban-rural loadings. This model typically coordinates load reduction between urban-rural systems (space), upstream-downstream (space), and monthly (time) domains. It maximizes the effectiveness of management strategies. As a case study of the urban-rural and headroom-excess concepts, Prof. Ana and her team evaluated the system-wide pollution contributions to the outlet of the Upper Thames regional water system. The results showed an improvement at the checkpoints, temporal steadiness, efficiency, spatial homogeneity, and practical feasibility of the system.

It is important to assess the potential new frontiers with all the tools and methods the researchers have at their disposal. Where do we go next with the analysis of coupled human water systems? Some of the tools that can help in the process are:

- WSIMOD – It is an integrated modeling platform that can simulate a range of physically connected components like water flow and quality. It is highly flexible and can be customized. This model keeps the physical representation of the system simple so that the management options and future planning can be simulated easily.

- Artificial Intelligence (AI) and Machine Learning (ML) – These can be helpful for improving model parameterization, analysis of model-observation mismatches, and replacing the physical models with ML sub-models.
- Water Digital Twins – These can serve as human water systems for modeling, decision-making, governance, and water management.

Some of the challenges in these frontiers are:

- What is the best way to capture the complexity of model components?
- How can the integration of systems-level models with detailed numerical simulations be done?
- What is the level of detail that we need to represent human behaviour?
- There is a need to address the lack of interpretability of ML models in emulating the underlying systems.

Discussion:

RSH to AM:

- How is the model capturing the demands of the reservoir, if the condition of > 99% reservoir storage needs to be maintained for the model? AM - As daily optimization details are not available for reservoir operations; estimation of water allocation is done as per knowledge.

SRC to AM:

- How are the differential agricultural practices incorporated into the model? AM - The model is flexible, and the source code is openly available on GitHub. This code can be customized using the python platform.

SR:

- Do you consider the calibration of various parameters in the model? AM – Calibration of the parameters depends on the use case and data availability.

DN:

- The current research is focused on the connectivity of hydrology and climate models using Digital Twins.
- DestinE, a Digital Twin of the Earth to aid climate change studies, is an initiative by the European Commission, Copernicus, and ECMWF.
- We can create a monsoon digital twin for the urban cities of India.

- The use of Augmented Reality for Digital Twin studies (Meta World Hydrology) would be helpful for the model runs.
- Explainable AI and interpretable ML should be used to change the parameterization of Digital Twin models.
- Effort is needed on ML and deep learning to bring information down to the user scale.

RSI:

- Canals are indispensable in Indian irrigation systems. They provide easy access to water to farmers. Canal water can be pumped to areas where canals are not available. There is a study conducted by IISc that compares the economic returns from crop production using canal irrigation versus groundwater irrigation.
- The socio-economic uplift of the communities depends on irrigation water availability. Water Control Board officials and water managers should be well aware of the irrigation water requirement needs of the farmers.

NK:

- To look at the bright side, climate change-induced high-intensity rainfall causes extreme flooding that can take care of effluents in the rivers by causing more effective dilution.

BV:

- "All models are wrong, but some are useful."

AM:

- There should be optimization of nature-based solutions for co-benefits across all indicators.

SR:

- There is a need to investigate what is more important at the end of the day: better model calibration, or better representation of processes in the models?

AM:

- Models should be chosen wisely based on the application. Our models enable analysis at different scales, so the modeler can decide which areas require more information and which areas can do with lesser information.

2. Short Presentations and Breakout Session – Day 2

2.1. Short Presentations

Linking Hydrology and Geomorphology: the Anthropocene Context – by Prof. Rajiv Sinha

- Catchment characteristics, geomorphic (sediment) connectivity, river-sediment dynamics, and floodplain topography control the fluxes of water and sediments from the catchment.
- Flux and movement of water and sediment manifest in river form and floodplain topography through time because rivers move water and sediment downslope and in doing so, they expend energy and perform geomorphic work.
- Excess flow over steep slopes, or reduced sediment loads, tilts the balance towards degradation, and incision occurs. This is an example of how anthropogenic interventions impact sediment dynamics and flooding.
- A study of the 18/8 avulsion of the Kosi River in India shows that the past breaches along the Kosi coincide with the hotspots of siltation.
- Siltation results in 'superelevation' of the riverbed and hence increases in lateral slope leading to breach.
- All breaches result in large floods and therefore these hotspots of siltation are also high flood-risk zones.
- Hydrogeomorphic flood risk assessment in the Ghaghra Basin in India using high-resolution UAV data shows variability in the extent and inundation depth - a function of floodplain topography.
- Stage-frequency relationships should be used for flood mapping.
- Flood Management strategy needs a paradigm shift which must integrate geomorphic analysis and river behaviour from a 'historical perspective'.
- Levees - tend to increase the wave speed and reduce the storage of flood water on the flood plain and create 'superelevated' rivers - therefore not an effective strategy.
- The 'Room for river' approach might prove to be a better strategy for Himalayan rivers in the long run.
- Geomorphic setting governs aquifer characteristics – provides a good proxy for a first-order understanding of alluvial aquifers and groundwater dynamics. Comments:

DN:

- What happened in the year 2000 that led to the depletion of groundwater? RSI - The increase in the rate of water extraction due to the advent of mechanized agriculture in the year 2000 led to the massive depletion of groundwater.

PM:

- How was 25 cm DEM obtained? RSI - Ortho images were obtained at 5 cm from drones, a stereo correction was applied, and then the images were scaled to 25 cm.

<u>Understanding Urban Micro-Climate for Vadodara – by Dr. Sanskriti Mujumdar</u>

- In Vadodara, the monsoon is moving to October.
- The rainfall in the city decreased in June and July and increased in the later months.
- The onset of the monsoon is delayed by two weeks for the city.
- A deeper understanding of the role of urbanization in impacting the climate patterns of cities is essential.
- The years 2000 to 2002 saw rampant climate change impacts because urbanization started then, and it was seen that a massive earthquake led to a change in the rainfall patterns.
- The flooding pattern within the city has been mapped and the impacts of climate change on health and socio-economic aspects have been studied.
- The rise of cases of dengue and chikungunya has increased in the past 15 years, especially for the low-income groups.
- The mid-income and high-income groups face increased stress levels, and skin and hair issues.
- Energy consumption based on income and the type of appliances was studied in detail and an increasing pattern was seen.
- In general, future rainfall intensities will be 17% to 48% higher than the observed rainfall intensities.

<u>Urban Hydrology in the Anthropocene – by Dr. Satish Regonda</u>

- There is a need for information on finer spatial and time scales for use in water resources modeling and the development of innovative products/tools.

- Flood definition with little more clarity, techniques to develop a flood database, and a reliable flood database with fair accuracy are the needs of the hour.
- The study of Hyderabad city included analysis of geopotential height at 500 hPa, identification of atmospheric drivers, the interaction between low-pressure systems, and back trajectory analysis for certain events.
- Besides, the study showed season-specific synoptic patterns and hinted at the possibility of local scale mechanisms for all seasons including monsoon and post-monsoon seasons. The findings have great potential to improve rainfall estimation algorithms and WRF modeling efforts.
- Also, the sequence of tasks, i.e., identification of multiple flood events, application of SOM on Integrated Vapour Transport, and analysis of results build a framework, which can be adapted for other cities.
- Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (GPM) (IMERG) should be used to enable precise rainfall measurements in cities.
- Statistical distribution of rainfall and then the statistical distribution of runoff using the climatological data and invoking the rainfall-runoff estimation should be done.
- The use of information from IoT and the application of AI/ML techniques to develop snap flood products will help in the better development of flood inventory.
- Community-based data networks using smart devices can result in better modeling of climate in cities.

<u>The Impact of Climate Change on Water Resources – by Dr. Rehana Shaik</u>

- Hydrology under climate signals at various spatial and temporal scales can be effectively studied using driving forces along with global circulation model outputs/ reanalysis data/ gridded data/ remote sensing data/gauging station data.
- Climate change impacts on regional evapotranspiration flux and variability of climatological and hydrological droughts can be assessed by drought indices like the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Actual Evapotranspiration Index (SPAEI).
- The SPAEI can provide more insight into capturing the severe and extreme drought characteristics at catchment scales compared to the SPEI due to the inclusion of hydrologically induced AET in the drought characterization instead of PET.

- Actual evapotranspiration can be promising toward drought intensity, extreme drought areal extents, shorter-time scale drought frequencies, and longer-time scale drought durations for water-limited zones (P<PET) compared to energy-limited zones (P>PET).
- Validation of water quantity-quality modeling results is challenging due to the spatiotemporal mismatch between hydrological, meteorological data, and pollution monitoring networks for Indian rivers.
- A holistic approach to integrating water quantity and quality to identify the possible contamination levels and measures for policymaking is required.
- For every 1 °C rise in river water temperature due to climate change, there will be about a 2.3% decrease in dissolved oxygen saturation level concentrations over Indian catchments under climate signals.

Climate Resilience in the Urban Water Cycle – by Dr. Bihu Suchetana

- There are various components of the urban water cycle – stormwater runoff, wastewater, drinking water, reclaimed water from water reclamation plants, etc.
- Each component of the urban water cycle must be managed judiciously for reliable, climate-resilient performance of the urban water system.
- IIT Roorkee has a 3 MLD wastewater treatment plant that sees high influent volumes following a rainfall event due to stormwater ingress, despite having a separate sewer system.
- Due to a strict policy devised by the government for the wastewater treatment plants, rampant false reporting of data has started that interferes with scientific research.
- There is a need for a reliable, unified multi-treatment plants database that disseminates daily data on inflow, nutrient concentrations, process failures, etc.
- There is also a need for technologically feasible regulations rather than unscientific regulations that are climate-informed. There should be rigorous monitoring and enforcement to avoid false reporting of data and provide upgraded support with process modifications for the wastewater treatment plants.
- Wastewater studies should be done for monsoon and non-monsoon periods separately.
- There is a need to acknowledge that separate sewers cannot protect the wastewater treatment system from large rainfall events.

Characterization of Tails of Precipitation over India under Changing Climate – by Dr. Sagar Chavan

- Tail behaviour assessment of precipitation is very important because extreme events lie in the upper part of the probability distribution known as the 'tail' of the distribution.
- Characterization of the tails of probability distributions can be done in two ways - tail fitting approach and empirical/data-based approaches.
- Empirical/data-based approaches include graphical methods such as mean excess function, discriminant moment ratio plot, Zenga plot, etc., or scalar measures such as the Obesity index, Gini index, etc.
- Characterization of tails of precipitation over India using various techniques reveals interesting details. Eight categories of severity are proposed by considering an increase or decrease of average rainfall above the threshold and a change in tail heaviness over the period from pre-1970 to post-1970.

Open Discussion:

AM:

- Are precipitation and temperature data available for India as a harmonized resource?
- Is it time to move away from event-based studies as the use of large-scale data and climate models is rampant?
- Can we explore downscaling of data at spatial and temporal scales to solve the problem of data availability?

NK to SRC:

- Is the heavy-tail distribution phenomenon India-specific or is it a global issue? SRC – It is a global phenomenon.
- Does heavy tail mean an increase in flood frequency or an increase in flood magnitude? SRC – Heavy tail means flood frequency has increased. It does not say anything about flood magnitude.

KB to SR:

- How reliable are newspaper articles and social media for flood studies? SR – It is a good starting point to observe old newspaper archives using AI/ML techniques or manually and then validate with observed data, although this approach has its own uncertainties.

DN:

- There is a need to develop methods and tools for the characterization and quantification of human impacts on the water cycle.
- This can be done either by parametric representation in models or through detailed statistical analyses.
- It will be interesting to figure out why are we doing this or what are the applications at the outset itself.

NK:

- There is the advancement of technology to an extent that the speed of windscreen wipers on cars and the number of water droplets on cameras are being used to determine the amount of rainfall.

AW:

- Natural language processing tools are being employed for data inventory.

GR:

- Crowdsourcing should also be used for data inventory and qualitative validation of it should be done.

2.2. Breakout Session

The participants were divided into 4 groups to discuss hydrology in the Anthropocene. The discussions were focused on the characterization, representation, tools, models, products, future directions, and applications in hydrology.

Discussion Topics -

- **Group 1:** River systems and groundwater: water availability, demands - streamflow, evapotranspiration, groundwater recharge/baseflow
- **Group 2:** River systems: geomorphology, water quality, ecology, environmental flows, etc.

- **Group 3:** River systems: hydrologic extremes (floods, droughts) and climate change
- **Group 4:** Urban water systems - urban floods, urban droughts, water quality, water reuse

Breakout Groups-

	Group 1	**Group 2**	**Group 3**	**Group 4**
Convenor	D Nagesh Kumar	Rajiv Sinha	Dev Niyogi	Sanskriti Mujumdar
Rapporteur	Sarat Chandra	Saumya Srivastava	Gowri R	Subhrasita Behera
Day 2	Bramha Dutt Vishwakarma	Rehana Shaik	Sagar Chavan	Satish Regonda
	Athira P	Bihu Suchetana	Shailza Sharma	Gouri Kadam
	Debsunder Dutta	Shobhit Singh	Kanneganti Bhargav Kumar	Likhitha P
				Abhinav Wadhwa
	Ana Mijic			
	P P Mujumdar			

Discussion Outcomes

Group 1: River systems and groundwater: water availability, demands-streamflow, evapotranspiration, groundwater recharge/baseflow

- Proper estimation of evapotranspiration is important to understand the feedback between evapotranspiration and other hydrological parameters. An optimal density of flux towers network can assist in more accurate evapotranspiration estimation.
- A major problem is the quantification of baseflow to understand groundwater interactions with river systems. This can be done either by groundwater modeling techniques or by using isotope analysis. Both approaches are interspersed with various uncertainties and sampling issues.
- Vertical disintegration of GRACE data can be done to estimate groundwater fluxes.

- Modeling the ISMR and the ITCZ in the context of changing precipitation patterns due to climate change is essential.
- Near-accurate modeling of monsoons and estimation of glacial water conversion is essential to determine water availability.
- Water demand in India is mostly agricultural. Change in cropping patterns causes a change in water demand.
- There is a need for high-resolution crop mapping by developing more accurate spectral unmixing algorithms.
- There should be consistent efforts in stopping losses at the source to meet the growing water demand.
- Irrigation practices should be updated, and the use of genetically modified climate-resilient crops should be increased.

Group 2: River systems: geomorphology, water quality, ecology, environmental flows, etc.

- Proper estimation of evapotranspiration is important to understand the feedback between evapotranspiration and other hydrological parameters. An optimal density of flux towers network can assist in more accurate evapotranspiration estimation.

The discussions revolved around three questions in particular.

What are the drivers for water quality studies?	What are the alternative data sources instead of actual ground measurements?	What are the parameters to be accounted for in calculating e-flows?

What are the drivers for water quality studies?

- There is a need to couple hydrology and hydraulic modeling studies with water quality models to identify the connection between the quality and quantity of water.
- Mapping of non-point sources is difficult. Efforts should be made to start with the inclusion of point-sources pollution rather than waiting for the data about nonpoint sources.
- There is a need to develop methods to quantify non-point sources.

- It would also be interesting to see how catchment similarity influences pollutant output. For example, slope and land use determine the time of pollutant travel.
- Sediment flow can also be used as a proxy for pollutant flow.

What are the alternative data sources instead of actual ground measurements?

- There should be a digital support system that collates and disseminates observed as well as reanalysis datasets.
- A high-resolution DEM for India will help in more accurate modeling studies. Planet M provides global DEM data at 4 m resolution.
- Connection between flow magnitude and water quality should be studied to estimate water quality data from flow data instead of actual measurements.

What are the parameters to be accounted for in calculating e-flows?

- E-flows should be decided based on not just water quantity but also water quality, along with socio-cultural aspects, habitat requirements for species, and geomorphic characteristics.
- Dilution is not the solution to manage the quality of water downstream of dams because it will become a big issue for water managers if users start demanding more water to reduce pollution.
- Better management of e-flows is required in low-flow periods as compared to high-flow periods.
- The best way to manage e-flows is to maintain longitudinal and lateral connectivity of the river water. Often, this ensures that every other condition is also met.
- The use of areal high-resolution remote sensing should be employed for water quality monitoring.

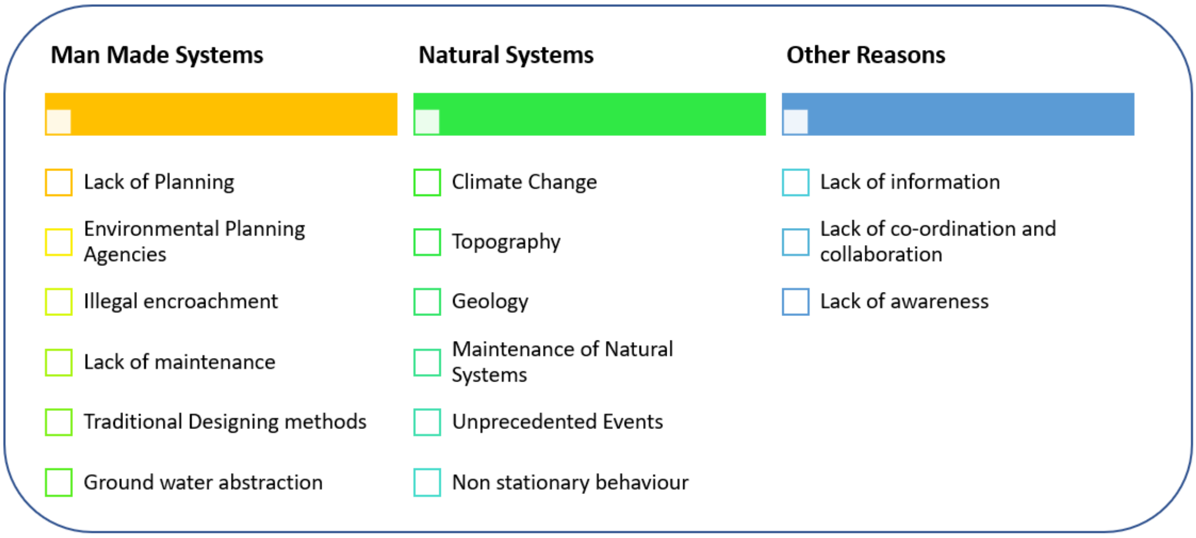
<u>Group 3:</u> **River systems: hydrologic extremes (floods, droughts) and climate change**

- There is a disconnect between stochastic and physics-based modeling approaches.
- Efforts should be made to bridge the gap between stakeholders and researchers.
- It is important to address data issues like reliability, duration, the scale of availability, etc.
- A few pertinent questions about the mechanisms/ processes under human-dominated landscapes that demand attention are:
    - Are there common drivers for natural and human-affected landscapes?

- What is the best way to address the non-linear relationship between the causative factors of extreme events?
- How to disentangle the complex interactions between various components of the hydrological cycle?

- There is a need for proper technological representation of available information and correct transfer of information. Such studies will benefit from a common platform that integrates different disciplines.
- With the advanced methods available, the natural processes can be represented in a better way. To make near-accurate predictions, studies must incorporate all human interventions.

<u>Group 4:</u> Urban water systems - urban floods, urban droughts, water quality, water reuse



- Water systems suffer from several problems that need immediate attention.
- Some of the products/ tools/ solutions that can tackle these problems are:
  - Integrated, coupled Hydro-Met science-based decision support system – short-range and long-range forecast, Hydro-Met model development.
  - Increase in instrumentation including sensors
  - Open-source data availability – data sharing treaty, real-time systems, alert systems
  - Engineered and non-engineered solutions – low-impact development, interconnection of lakes/water bodies, recharge of lakes, pumping systems
  - Stakeholder feedback mechanism

3. Short Presentations and Breakout Session – Day 3

3.1. Short Presentations

Water Resources Modeling in the Anthropocene – by Prof. D. Nagesh Kumar

- The impact of subjective modeling decisions on the simulation of flood events can be tested by using a flexible modeling framework like SUMMA (Structure for Unifying Multiple Modeling Alternatives). Model simulations are performed using the Param Pravega supercomputer at IISc.
- Soil moisture retrievals using passive microwave satellite data (CKDEMI & SPRA)
- The ability of hydrological models to simulate the processes can be improved if model calibration is carried out at multiple locations for multiple variables like streamflow, evapotranspiration, soil moisture, etc.
- It is essential to characterize and quantify the various sources of uncertainties to give a complete picture of the water resources of a river basin when communicating the results of any hydrological modeling exercise.
- Correct identification of bare soil pixels prior to soil mapping is essential. Hyperspectral remote sensing data for the estimation of clay content can be used to develop composite clay mapping algorithms.
- Chlorophyll content prediction of pear trees can be done using convolutional auto-encoder features of hyperspectral data. This technique can also be extended to other crops to determine their health, yield prediction, and irrigation requirements.
- HiROS (Hindon Roots Sensing) is a DST WTI – NWO sponsored project of Rs. 11.5 crores, led by IISc and Wageningen University. It involves river rejuvenation through scalable water- and solute-balance modeling and informed farmers' actions. Farmer-level interventions are to be implemented and the plan is to upscale from fields to the entire river basin scale.

Comments:

PM- Why did you select pear fruit for chlorophyll content prediction? NK - This work is currently being carried out in Spain and it is observed that a small fluctuation in the chlorophyll content of pear trees changes the yield to a large extent. Pear fruits are also very profitable economically.

Calibration of Hydrological Models Considering Process Interdependence: A Case Study of SWAT Model – Dr. P. Athira

- It is important to account for the interdependence of parameter perturbations in multi-variate hydrological model calibration.
- Correlations in parameter perturbations can be found using pedotransfer functions.
- The addition of soil moisture in model calibration causes a decrease in Nash-Sutcliffe efficiency for streamflow due to the adjustment of parameters for both variables.
- It would be interesting to see how parameters are related to the geographical attributes of the river basin.

Characterizing Water and Carbon Fluxes over Terrestrial Ecosystems using High-Resolution Remote Sensing and Modeling – Dr. Debsunder Dutta

- Predicting how increasing CO_2 due to climate change will affect the global hydrologic cycle is important and challenging.
- Land surface typically adjusts to hydrologic changes driven by precipitation and radiation changes due to climate change.
- CO_2 physiological response has a dominant role in evapotranspiration and evaporative fraction changes.
- This highlights the key role of vegetation in controlling future terrestrial hydrologic response and emphasizes that carbon and water cycles are intimately coupled over land.
- Utilizing high-resolution observations to characterize ecosystem attributes and further constrain the dynamics of ecosystem functioning can improve the predictive power in the future.
- There is a non-uniform distribution of ground (tower) based flux observing stations, the regions around and south of the tropics are especially lacking.
- Solar Induced Fluorescence (SIF) can be used to estimate evapotranspiration and it can track crop productivity and monitor water stress in evergreen forests. Absorption of sunlight by chlorophyll molecules drives it all – SIF is an instantaneous indicator of plant functioning.

- A major challenge going forward is to incorporate these observations in process-based models – for improving parameterization and/or improving the process understanding and representation, especially in cases of water limitation.

Geodesy for Earth System Science - Dr. Bramha Dutt Vishwakarma

- GRACE (Gravity Recovery And Climate Experiment) data has many applications in hydrology. GRACE satellite output is sensitive to the changes in gravity 8^{th} digit after the decimal, which is due to the changes in water resources.
- Careful processing of GRACE level 2 data is essential to obtain level 3 products (Equivalent Water Height (EWH) or Terrestrial Water Storage (TWS)) with improved accuracy.
- GRACE satellite data should be used carefully while data analysis as filtering causes large differences.
- GRACE is used to detect groundwater losses, but several studies report over-estimation of groundwater losses as compared to the in-situ trend. This is due to different post-processing methods of raw GRACE data.
- The spatial resolution of GRACE satellite products for hydrology is approximately 65000 square kilometers (Vishwakarma et al., 2018).
- Current endeavours focus on temporal hindcast before 2002, spatial downscaling, and filling GRACE data gaps.

Flood forecasting using Coupled Hydro-Met Modeling System - Ms. Gouri Kadam

- Flood forecasting can be done using coupled Hydro-Met modeling system. One such project was undertaken by National Supercomputing Mission for Pune city.
- Urban integrated modeling system framework consists of weather, air quality, CFD, and hydrology elements.
- Coupled Hydro-Met framework has WRF with HEC-HMS, HEC-RAS, and SWMM.
- Coupled Hydro-Met quasi-operational runs achieved 70% accuracy in flood volume and spread estimation.
- Two important questions that must be addressed are:
    - In the absence of required datasets for hydrological modeling, how can the reliability of the system be improved?
    - How to integrate impact assessment with the existing framework to make it more useful?

Digital Twin Model for Bangalore Floods – Dr. Abhinav Wadhwa

- Bangalore city has an advantage for flood model development as it has good data availability.
- A 1-D flood model for Bangalore was created in PCSWMM and a 2-D model in HEC-RAS.
- WRF forecasts with 3 km and 1 km domains were obtained and compared with observed rainfall for heavy rainfall events from 4th to 6th September 2022 in Bangalore.
- The flood spread for 4th September 2022 was validated with social media and newspaper reports and was found to be fairly accurate.

Open Discussion:

AM:

- What are the key challenges in data and tools to analyze the effects of the Anthropocene on both river and urban hydrology? What are the frontiers in tools, data, and integrated modeling? Is this the right time to focus on a multi-model approach?

RSI to AW:

- What approach has been used to validate the flood inundation? AW - Inundation validation was done using 80 water level sensors (15 min temporal resolution) distributed across Bangalore city and social media reports.
- What are the validation techniques for river-based flood models? AW – It can be done by satellite products like SAR.
- Can drone be used for flood extent validation? AW – There are some restrictions on flying drones in urban areas.

SR to AW:

- What is the model run time for WRF? AW - WRF forecast is given 24 hours prior, at 8:30 am every day for the next day's forecast, and it takes nearly 12-14 hours to run the WRF model. Currently, we run WRF on the ICWaR cluster (20 nodes, 4 processors).

- How can we get building and elevation data for model development? AW - Bangalore city building data is procured from Bangalore Development Authority. Drones, satellite data, and manual surveys can be used to get this data.

DN to AW:

- What is the definition of a digital twin? For Bangalore, efforts are underway toward the development of a digital twin.
- There is global building height data set GLOBUS: GLObal Building heights for Urban Studies. Open-source building height data for Bangalore and Hyderabad is available already.

DN to DD:

- What are your plans for the next three years? DD - Bridging the spatial scales, disentangling the physiological and structural signals, and exploring the role of SIF in understanding ET.

SR to BV:

- Where is the depleted groundwater going? BV – It goes as ET to dry areas.

SR to AW:

- Can the Bangalore flood model tell which buildings in the low-lying areas are more prone to flooding? AW - Yes, building heights are added in the 2D model and an average flood depth of 1.5-2 m was observed for the recent heavy rainfall event in September 2022.

AP:

- There is a need to optimize the data required for hydrological model calibration.
- There should be spatial coherence in the parameter space.

3.2. Breakout Session

The participants were again divided into 4 groups to discuss hydrology in the Anthropocene. The discussions were focused on the characterization, representation, tools, models, products, future directions, and applications in hydrology.

Discussion Topics -

- **Group 1:** Hydrologic Modeling (including physical, conceptual, statistical, machine learning, and uncertainty modeling)
- **Group 2:** Technologies (including remote sensing and satellite data, sensors, IoT, etc.)
- **Group 3:** Data Issues (including field observations, open access to hydrologic data, etc.)
- **Group 4:** Integration of Human Natural Systems through Systems Thinking (hybrid/ integrated modeling, future planning, water digital twins)

Breakout Groups-

	Group 1	Group 2	Group 3	Group 4
Convenor	Sanskriti Mujumdar	Dev Niyogi	Rajiv Sinha	D Nagesh Kumar
Rapporteur	Shailza Sharma	Likhitha P	Kannneganti Bhargav Kumar	Shobhit Singh
Day 3	Debsunder Dutta	Athira P	Bramha Dutt Vishwakarma	Rehana Shaik
	Saumya Srivastava	Bihu Suchetana	Subhrasita Behera	Sagar Chavan
	Gowri R	Sarat Chandra	Gouri Kadam	Satish Regonda
		Abhinav Wadhwa		
	Ana Mijic			
	P P Mujumdar			

Discussion Outcomes

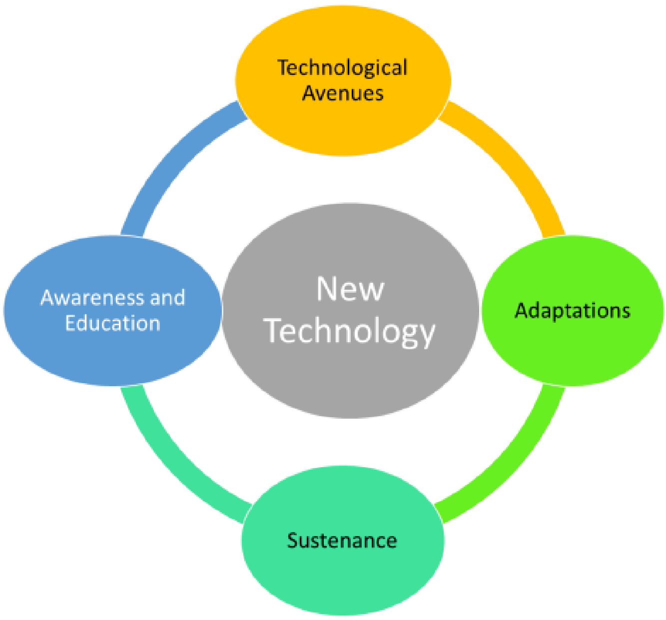
Group 1: Hydrologic Modeling (including physical, conceptual, statistical, machine learning, and uncertainty modeling)

- The group discussion focussed on
  - Where exactly does the research community stand in terms of hydrological modeling?

- What are the challenges and uncertainties that researchers face during the model development stage?
- What are the ways to tackle these challenges?
- How can we better use emerging technologies like Machine Learning in hydrological modeling?

Hydrological Modeling			
Where are we now?	**Challenges**	**Ways Forward**	**Can Machine Learning help?**
• Physical and conceptual models • Separate models for urban/rural environments. • Different models for extremes/water availability • Conventional calibration approaches and stationarity assumptions	• Model reliability • Interpretation/communication of results • Problem of equifinality • Data issues at finer scales • Reducing parameter dimensionality • Why do we need calibration at all? • Temporal evolution of parameters in modeling • Model parameter and structure uncertainties are key challenges	• Creating a framework for data optimization • Aggregation of various uncertainties to tackle predictive uncertainties • Focus on model structure along with parameterization • A robust unified modeling framework	• Conceptual and physical models are not for extremes • Hybrid modeling – outputs of physical model goes as input into ML- for prediction of extremes • Use of entire time series rather than providing extremes alone

<u>Group 2:</u> Technologies (including remote sensing and satellite data, sensors, IoT, etc.)



- Technologies like AI, ML, IoT, cloud computing, and metaverse are emerging. Using robotics, hyperspectral and remote sensing images for modeling, high-performance computing, and fit-for-purpose tools are the current technological avenues.
- Object-based classification to extract the necessary information, clubbing of various satellite products with different spatial as well as temporal resolutions, and development of modeling platforms are some of the ways to utilize newer technology for water resources research.
- There is a need for the development of open data platforms to educate people about new data and technologies.
- Spreading awareness to the public through talks, seminars, social media (Facebook, Instagram, YouTube, Twitter), advertisements, dashboards, conferences, open-source patents, apps (like Bengaluru's Megha Sandesh), workshops, and conducting surveys can bridge the gap between the scientific community and common people.
- Some of the main problems with sensors-based data collection are the quality of data, long-term performance of the sensors, and uncertainty in data. There is a need to develop measures to reduce tampering with the sensors and increase the quality and reliability of the sensors.
- System-based approach that integrates private sectors and NGOs working on definite projects with the community is needed for adapting to new technologies. Incubating a greater number of start-ups or collaborating with start-ups that are working on specific projects would be helpful for sustenance.
- Educating peers on the methods of adopting new data into the models would help.
- There is a need to bring societal aspects into the modeling framework.
- Developing awareness tools and integrating workshops as credits in the student curriculum would help in exposing students to new technologies and data.
- Setting up specialized centres for hydrological science at premier institutes in the country would go a long way.
- Does finer-resolution data always give better results?

<u>Group 3:</u> Data Issues (including field observations, open access to hydrologic data, etc.)

- The group divided the data used for hydrological modeling into 4 categories - remote sensing data, meteorological data, socio-economic data, and in-Situ data. The focus was on the aspects of quality control, availability of the data, open-access data, and reducing data issues.
- Some of the data issues in hydrologic in-situ data are inappropriate details of gauge stations, improper maintenance of hydrologic sites, and unavailability of gauge stations in major parts of India.

Major outcomes from the discussion are:

- There is a need for an automated package for data quality checks like integration of AI/ML-based methods with the double mass curve. This automated package should also be able to check the stationarity and non-stationarity of the data.
- Creation of a single window system for river/basin/country scale data portals like the Indian Open Earth Observatory will be helpful in accessing multi-scale data at a single platform.
- Uploading Readme/Help videos for data downloading or data usage of remote sensing products will also be helpful.
- A common platform or data repository is necessary to give information on the country-level local interventions, like flood control structures, large shifts in crop dynamics, and shifts in irrigation techniques.

<u>Group 4:</u> Integration of Human Natural Systems through Systems Thinking (hybrid/ integrated modeling, future planning, water digital twins)

- The first question that needs to be answered is 'how exactly do we represent human influence in the hydrological system?' For example, the changes in LULC due to urbanization and its impact on the hydrological aspects of the system should be modeled as a part of every hydrological modeling exercise.
- This could also be achieved by using ML techniques to develop data-driven models. ML can also be used for the identification and quantification of the human role on various parameters like rainfall, ET, temperature, LULC, topography, etc.
- Two of the major things that must be answered while integrating human influence into hydrology are:

    - How do we characterize the human impacts on hydrology?
    - How do we quantify them?
- The next step is to identify the problem which the modeler is trying to address (water quality/floods/drought) and selection of object-based models to identify the human roles in each component.
- Selection of models based on the human system approach like lumped, semi-distributed, or distributed models is the next action. A combination of physics-based and ML-based models (hybrid models) can also be used to increase the efficiency of the modeling exercise.
- The selected model should be validated to check the qualitative and quantitative performance of the system.
- While using the current models for the future, new indices/ reliable indicators need to be developed to measure human influences.
- Development of digital twin: An integrated system must be developed to incorporate multiple events – A system that can be updated, can be used as an interface to observe the human influence, can collect data, or can take human feedback to the model.
- The newly developed system should be ready for unprecedented events including compound extremes and it should be resilient, adaptive, and dynamic.

Discussion:

RSI:

- Identification of tipping points that mark the arrival of human intervention in water resources systems is important.

SM:

- How do we take care of issues in using gridded datasets?

NK:

- There is a need to see how well a system can behave in the case of unprecedented extreme events.

GR:

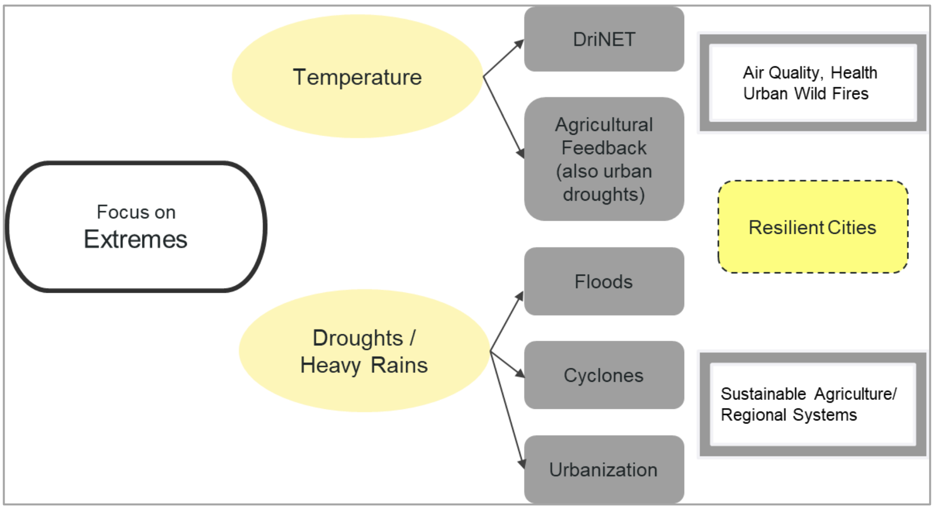
- Attention should also be given to moderate and low extremes, and not only very high extremes.

AM:

- Efforts should be directed toward the creation of a data repository.
- There is a need to design a framework for better usability of models.
- Carbon footprint of nature-based solutions needs to be quantified.

4. Impressions and Way Forward

Urban Digital Twin - Prof. Dev Niyogi



- It is a framework to model cities resilient to climate extremes – extreme temperatures and droughts/ heavy rains.
- The impacts of extreme temperatures on air quality, health, and urban wildfires are studied.
- The increase in the frequency of floods and cyclones due to droughts and heavy rains is assessed and sustainable agricultural and regional systems are established.
- Integration Field Laboratory, a community-driven science project, is funded by the Department of Energy.

Final Discussion Session Coordinated by Prof. Ana Mijic and Prof. Dev Niyogi

Prof. Ana Mijic:

- There is a clear categorization in the areas requiring greater efforts to model hydrology in the Anthropocene: data, models, and applications for rural and urban hydrology, focussing on floods and droughts.
- There is a need for an integrated platform for data sharing.
- Outcomes from this workshop should be divided into three categories –
  - Publications/Writing
  - Education or Training
  - Collaborations
- Publications may be in the form of a white paper or a synthesis paper, a benchmarking paper, and a modeling-data expertise paper.

Prof. Dev Niyogi:

- There should be two key takeaways for the participants:
  - What are the outputs from the workshop?
  - What are the long-term outcomes of the workshop?
- Model setup, data sharing, and individual collaborations are welcome from this workshop.
- Involving young experts/ students in the follow-up work would ensure continuity.
- An open working group like CUAHSI may be set up to foster collaborations.

Actions

Summary Report – Lead: P P Mujumdar

Meeting Minutes – Likhitha, Saumya, Abhinav, Gowri (IISc)

Facilitate the collaborations (maybe online) – Lead: Bramha Dutt, Debsunder

Papers

- Short editorial – to highlight the idea (1-2 pages) – Lead: Rajiv Sinha
- White paper – Lead: Bihu Suchetana
- Review paper – Lead: D Nagesh Kumar
- High-end paper (India-centric) – Lead: P P Mujumdar

Core group members (to sustain the momentum)

- Bramha Dutt
- Debsunder Dutta
- Satish Regonda - Lead
- Athira P
- Gouri Kadam
- Sagar Chavan
- Rehana Shaik

SSR:

- Dividing the entire workshop group into smaller groups with specific expertise might be helpful.

KB:

- We must first write down the various problems raised and discussed in the workshop. This would help us identify the areas that need greater research efforts.

BS:

- We need to find out alternative data sources as work will get limited because of data discrepancies.
- We must try to tackle the challenges of using different hydrological, ecological, and meteorological datasets, etc.

GR:

- Strict follow-up is needed when it comes to collaborative work.

- Scheduling regular meetings or monthly paper readings on a YouTube channel would help to revise and revisit the discussion.

AW:

- Creating an umbrella project for "Anthropocene Hydrology" and a special book publication will help spread the word.

BV:

- Preparation of a skeleton or an outline immediately for future outcomes from this workshop is necessary.
- An IAHS working group on Anthropocene hydrology must be set up. This group may participate in AGU / EGU conferences.
- There should be an open data portal and tutorials to help in data downloading, data analysis, and usage. An in-situ data repository or archive development will also be helpful.
- India's Open Earth Observatory – a platform to put research products must be developed. There must be a Model Inter-Comparison Project for Peninsular India.

NK:

- One-to-one collaborations among young researchers are very important.

RS:

- We must persuade government agencies to undertake large activities. There must be a creation of grants and programs for collaborative work.
- There must be a publication based on the workshop discussions.

PM:

- Land surface processes are often ignored in Earth science. Indicators for identifying human impacts are very different for different parts of the country.
- A page or two write-up about the workshop's proceedings is very important.
- Reports of the workshop, like minutes of the meeting, technical reports, etc. will be documented soon.
- Participants must aim to publish in a high-end journal on "India-Centric Anthropocene Hydrology".
- The white paper should identify the research gaps and focus areas very carefully.

5. Annexure

5.1. Annexure A: Agenda

Day 1: Tuesday, December 6, 2022 **Venue: Hoysala Village Resort, Hassan**		
9:30 AM		Start from IISc, Bangalore
1:30 PM		Arrive at the Venue
1:30 PM	4:00 PM	Check-in; Lunch; Rest
4:00 PM	4:10 PM	Welcome Note: Prof. P P Mujumdar, IISc Bangalore
4:10 PM	5:00 PM	Participants' Self-introduction (2 minutes each)
5:00 PM	5:30 PM	Human Impacts on Hydrology: Prof. Ana Mijic, Imperial College London
5:30 PM	6:00 PM	Open Discussion
6:00 PM	6:30 PM	Coffee @ **Restaurant**
7:00 PM	8:00 PM	Cultural Program & Socializing @ **Lawn** (**Near Swimming Pool**)
7:30 PM	10:00 PM	Networking Dinner @ **Restaurant**

Day 2: Wednesday, December 7, 2022 **Venue: Hoysala Village Resort, Hassan**		
6:45 AM	7:00 AM	Coffee **@ Reception** (Optional)
7:00 AM	7:45 AM	Village Walk (Optional)
7:30 AM	9:00 AM	Breakfast **@ Restaurant**
Session 1 – Short Presentations (8 minutes presentation + 2 min discussion each) Chair: Prof. Rajiv Sinha, IIT Kanpur		
9:30 AM	9:40 AM	Prof. Rajiv Sinha, IIT Kanpur
9:40 AM	9:50 AM	Dr. Sanskriti Mujumdar, MSU Baroda
9:50 AM	10:00 AM	Dr. Satish Regonda, IIT Hyderabad
10:00 AM	10:10 AM	Dr. Rehana Shaik, IIIT Hyderabad
10:10 AM	10:20 AM	Dr. Bihu Suchetana, IIT Roorkee
10:20 AM	10:30 AM	Dr. Sagar Chavan, IIT Ropar
10:30 AM	11:00 AM	Open Discussion
11:00 AM	11:30 AM	Tea/Coffee Break
Session 2 (11:30 AM – 1:00 PM) – Discussion in Breakout Groups		

1:00 PM	1:30 PM	Report from Breakout Groups & Discussion
1:30 PM	2:30 PM	Lunch
2:30 PM	3:30 PM	Rest
3:30 PM	7:00 PM	Outdoor Sightseeing
7:00 PM	7:30 PM	Break

Day 3: Thursday, December 8, 2022 **Venue: Hoysala Village Resort, Hassan**		
Session 1 – Short Presentations (8 minutes presentation + 2 min discussion each) Chair: Prof. D. Nagesh Kumar, IISc Bangalore		
9:30 AM	9:40 AM	Prof. D. Nagesh Kumar, IISc Bangalore
9:40 AM	9:50 AM	Dr. P. Athira, IIT Palakad
9:50 AM	10:00 AM	Dr. Debsunder Dutta, IISc Bangalore
10:00 AM	10:10 AM	Dr. Bramha Dutt Vishwakarma, IISc Bangalore
10:10 AM	10:20 AM	Ms. Gouri Kadam, CDAC Pune
10:20	10:30	Dr. Abhinav Wadhwa, IISc Bangalore

AM	AM	
10:30 AM	11:00 AM	Open Discussion
11:00 AM	11:30 AM	Tea/Coffee Break
Session 2 (11:30 AM – 1:00 PM) – Discussion in Breakout Groups		
1:00 PM	1:30 PM	Report from Breakout Groups & Discussion
1:30 PM	2:30 PM	Lunch
2:30 PM	2:45 PM	Impressions and Way Forward: Prof. Dev Niyogi, UT Austin
2.45 PM	3:30 PM	Final Discussion Session Coordinated by Prof. Ana Mijic and Prof. Dev Niyogi
3:30 PM	7:00 PM	Outdoor Sightseeing
7:00 PM	7:30 PM	Break

5.2. Annexure B: List of Participants

Name	Institute	Research Areas/ Interests
Prof. Ana Mijic	Associate Professor, Imperial College London	Human impacts on hydrology, Hydroflux project, integrated water systems model development – WSIMOD, water quality, human water system interactions
Prof. Dev Niyogi	Professor, UT Austin	Detection of human interaction on weather forecast variables, integration of models with human impacts and analysis, the effect of urbanization on extreme weather, representation of the urban and agricultural processes in forecast models
Prof. P. P. Mujumdar	Professor, IISc Bangalore	Urban hydrology, compound extremes, impacts of climate change, reservoir operations, and planning
Prof. Rajiv Sinha	Professor, IIT Kanpur	Study of river dynamics, river-GW interactions, human impacts on river hydrology, wetland research, thermal data usage in soil study
Prof. D. Nagesh Kumar	Professor, IISc Bangalore	Remote sensing and stochastic modeling for irrigation operations in reservoir modeling, neural networks, optimization tools for multi-purpose dam projects, hyperspectral remote sensing, monitoring soil moisture, ET, climate change, and LULC impacts
Dr. Sanskriti Mujumdar	Associate Professor, MS University Baroda	Impact of climate change on socio-economic aspects, micro-climate study, Local Climate Zones, urban floods
Dr. Satish Regonda	Associate Professor, IIT Hyderabad	Urban and riverine flood models, rainfall analysis, statistical model and community-based data, modeling and

		tools development for flood study, and stakeholder interactions
Dr. Rehana Shaik	Assistant Professor, IIIT Hyderabad	Statistical DownScaling Model, water quantity and quality research, drought assessment, land, and atmospheric interactions
Dr. Sagar Rohidas Chavan	Assistant Professor, IIT Ropar	Surface water hydrology, frequency of extreme events, impacts of climate change, prediction of hydroclimatic extremes
Dr. Debsunder Dutta	Assistant Professor, IISc Bangalore	Hyperspectral remote sensing application, hydrological modeling using finer resolution sensor data, improve process understanding of ecosystem to improve prediction, LIDAR, and advanced remote sensing tools in research
Dr. Bihu Suchetana	Assistant Professor, IIT Roorkee	Climate change impacts on the water cycle, the effect of climate change on water quality degradation and water-borne disease rise
Dr. P. Athira	Assistant Professor, IIT Palakkad	Climate models for impact analysis study, remote sensing for forest hydrology study, improving the capabilities of hydrological/structural models
Dr. Bramha Dutt Vishwakarma	Assistant Professor, IISc Bangalore	Geodesy for Earth System Science, GRACE satellite products to study TWS, coastal sea level research, and observation, sub-system interactions, global sea level study
Dr. Shailza Sharma	Post-Doctoral Research Associate, Czech University of	Flood forecasting model development, hydro-climatic extremes, multivariate stochastic models

	Life Sciences	
(Dr.) Gowri R.	Research Associate, IISc Bangalore	Understanding catchment scale processes, individual and ensemble model capabilities in hydrological modeling, information theory measures – Mutual Information, Transfer Entropy
Ms. Gouri Kadam	Principal Technical Officer, CDAC Pune	Urban flood model for Pune city, National Supercomputing Mission, SWMM, and HEC-RAS for flood model development
Dr. Abhinav Wadhwa	Post-Doctoral Research Associate, IISc Bangalore	Urban flood modeling for Bangalore city, water distribution system, 1D-2D flood model development, WRF model rainfall forecast, flood mitigation
Mr. Shobhit Singh	Research Scholar, IIT Kanpur	Hydro-geomorphic modeling in flood plains, DEM generation, using high resolution models for flood study
Mr. Kanneganti Bhargav Kumar	Research Scholar, IISc Bangalore	Regional hydrology model, hydrological extremes
Mr. Sarat Chandra	Research Scholar, IISc Bangalore	Understanding the relationship between climate and groundwater, meteorological droughts, and groundwater drought connections
Ms. Saumya Srivastava	Research Scholar, IISc Bangalore	Diagnostic framework for hydrological model calibration based on diverse sources of uncertainties
Ms. Subhrasita Behera	Research Scholar, IISc Bangalore	Coupling of water and urban cycle interaction using high resolution data
Ms. Likhitha Pentakota	Research Fellow, IISc Bangalore	Urban flood modeling for Bangalore city, 2D flood model development using HECRAS, WRF-SWMM coupled flood model runs