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Bihar's Battle Against Flood: Unravelling the Science of Flood Forecasting and the Primacy of Multi-Source Data Integration

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Abstract

The state of Bihar in India is often vulnerable to catastrophic floods during the monsoon season due to its vast alluvial plains and the systematic pattern of transboundary Himalayan Rivers Systems that flow through it, with their origins in the Himalayas. These floods result in the loss of lives, livelihoods, and infrastructure, among other effects, leading to socio-economic losses that affect millions of people. As such, efficient flood prediction and early warning mechanisms are not just a technical wish; there is an urgent need to incorporate flood prediction and early warning systems into disaster risk reduction and climate change adaptation in the region. This article provides a detailed examination of the flood forecasting paradigm in Bihar, particularly its evolution over the years, from traditional empirical forecasting techniques to more advanced hydrological and hydrodynamic models based on data. It cuts across the institutional structure headed by agencies such as the Central Water Commission (CWC) and the Bihar State Disaster Management Authority (BSDMA), which are responsible for making predictions and distributing them. One of the main points of this study is the importance of data in present-day forecasting, which is the lifeblood of the modern era. We examine the complex procedure of incorporating multi-source information streams, including ground-based data, satellite-derived rainfall information, real-time river gauge and discharge data, high-resolution topographical data, and essential transboundary hydrological data provided by Nepal. The paper begins with an examination of the mechanics of popular models, such as MIKE-11, and how these are used to model riverine dynamics by solving the Saint-Venant equations.

Besides, it identifies the technological edge, such as implementing Artificial Intelligence (AI) to map inundation in real-time and creating a more efficient early warning broadcasting infrastructure. Along with, it determines the technological advantage, including the adoption of Artificial Intelligence (AI) to map inundation in real-time and the establishment of a more effective early warning broadcasting system. In spite of the major improvements, there are still some issues such as the complications of transboundary data sharing, gaps in observational networks, modelling uncertainties, and the complications of last-mile connectivity to disseminate warnings. The article concludes by concluding on these points and presenting a roadmap on future efforts to improve flood resilience in the state of Bihar which includes; more long-term investment in technology, international cooperation, and more integrated water resources management.

Keywords: Flood forecasting: Rainfall-runoff modelling: Hydrodynamic models: MIKE-11: Transboundary rivers: Remote sensing: Artificial intelligence: Disaster risk reduction.

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Introduction

Bihar, a state in eastern India, is a rich region of alluvial plains, boasting some of the country's most powerful river systems, including the Ganga, Kosi, Gandak, Burhi Gandak, and Bagmati. On the one hand, such rivers can be considered a key component of the state's agrarian economy, but on the other hand, they are the leading cause of its most frequent natural disaster: floods. With over 73 per cent of its total land area, especially in North Bihar, at risk of flooding, Bihar has gained an unwanted reputation as the most flood-prone state in India (Sharma and Kumar, 2018). Such yearly floods are directly the result of a challenging hydro-geographical environment, where great rivers, born in the geologically young, erosive Himalayas of Nepal, fall abruptly onto the plains of Bihar, their flow enhanced by the heavy rainfall of the Southwest Monsoon (Verma et al., 2020). The sophisticated interaction of monsoon variability, river structure, and anthropogenic elements also increases flood risks in the area (Rao and Patel, 2017).

The socio-economic cost of such floods is phenomenal. Millions of people are displaced every year, vast areas of farmland are flooded, and essential infrastructure, such as roads, bridges, and communication lines, is badly damaged. The massive disasters caused by such events can be illustrated by the notorious 2008 Kosi embankment break, which led to the various cascading impacts, left more than 3 million displaced and significantly altered the region's landscape (Kumar and Ranjan, 2009). The reports indicate that financial damages amount to billions of rupees per year in the region, crippling the state's developmental path and putting at-risk groups in a cycle of poverty and calamity. A 2023 report by the Bihar State Disaster Management Authority (BSDMA) revealed that, on average, 28 districts are affected by floods each year, with approximately 20 million people impacted (BSDMA, 2023).

In such a high-stakes situation, forecasting an events of flooding, its magnitude, and extent becomes paramount. Valid and prompt flood prediction is the key to any successful disaster management. It provides the much-needed lead time before government agencies can mobilise resources, emergency responders prepare to handle evacuations, and communities can take precautionary measures. In this research paper, the complex science and operations architecture of flood forecasting in Bihar is explored. It follows the history of modelling methods, beginning with their simplistic correlations of various empirical parameters, to the complex and physically representative rainfall-runoff and hydrodynamic models that are the workhorses of the contemporary forecasting system. The primary objective of this study is to provide a holistic and in-depth analysis of the flood forecasting ecosystem in Bihar. It aims to:

1. Detail the hydro-meteorological and geographical factors that make Bihar uniquely vulnerable to floods.
2. Examine the institutional framework and the roles of key national and state-level agencies.
3. Unravel the scientific principles behind the current forecasting models, focusing on transitioning towards rainfall-driven models.
4. Highlight the criticality of a multi-data approach for flood risk reduction, systematically exploring the various data types—hydrological, topographical, satellite-based, and transboundary—integrated into these models.
5. Discuss the technological advancements, particularly the role of Artificial Intelligence (AI) and remote sensing, that are revolutionizing flood mapping and warning systems.
6. Critically evaluate the persistent challenges that impede the system's effectiveness and propose a strategic path forward.

Hydro-Meteorological Context of Flooding in Bihar

To understand the flood problem in Bihar, a perspective on its unique geographical and regional climate system interactions is required. The state is a model for how upstream catchments, downstream topography, and heavy seasonal rain combine to form a deadly trifecta of frequent, widespread inundation.

Monsoon Phenomenon and Extreme Rainfall

The Southwest Monsoon, which occurs from June to September, is the primary cause of flooding in Bihar. In this season, the state receives more than 80% of its average annual rainfall of nearly 1,200 mm. The monsoon is not a steady rain; it has bursts and off-burst patterns, with the bursts sometimes involving heavy short spells of rainfall. These events can dump huge volumes of water in a matter of hours or days, overwhelming natural drainage systems. For instance, heavy rainfall in the catchment area can cause rivers to rise rapidly, leading to flooding. Moreover, Bihar is also situated in the monsoon belt of the Indian subcontinent, a volatile region with unstable monsoons that bring erratic rainfall and other extremes. These systems travel northwest ward, carrying massive moisture loads, and result in fairly widespread heavy to heavy rainfall over Bihar and the adjoining catchments of the Himalayas in Nepal. Climate change could make this situation worse as more extreme rainfall events – of both short and long duration – are expected to become increasingly common and severe, further complicating flood management.

Himalayan Connection: The Transboundary River Systems

The landscape of North Bihar is predominantly characterised by a series of rivers originating in the Himalayas. The major rivers Kosi, Gandak, Bagmati, Kamla and Mahananda are transboundary. These rivers can take on two forms, depending on their location. In their headwaters in Nepal, they are steep mountain streams with very actively down-cutting channels and surrounded by geologically young and rapidly eroding Himalayan terrain. As a consequence, it has very high erosion rates, filling rivers with vast amounts of sediment and sand. The Kosi River, for instance, is recognised as having one of the highest sediment loads among rivers worldwide (Rao and Patel, 2017). On leaving the foothills of the Himalayan Range, where they descend onto the flat plains of North Bihar, their fall becomes precipitous. The sudden slowing down of the rivers results in an immediate depletion of energy, and so there is a rapid deposition of them into the riverbed as well as on the plains. Sediment is washed down the river and deposited, which leads to the level of the river bed gradually rising and sometimes flowing higher than the surrounding ground. Consequently, the rivers are confined by natural levees or by artificial embankments. The pressure on these embankments is enormous during floods, and failure can result in catastrophic flooding of low-lying areas, as tragically demonstrated by the 2008 Kosi breach. Its depositional character is also the cause of the shifting course of rivers, resulting in remnants that form an intricate network of islands and marshes (called in the local language 'chairs'), which contribute to a complicated drainage pattern in the sub region.

Plains of Bihar: Low Gradient and Drainage Congestion

Once in Bihar, the river winds slowly down to the Ganga. The land has a very low average slope, averaging less than 1:5000. This gentle gradient hinders the rapid escape of floodwater, resulting in extended periods of flooding that can last for weeks or months. The waterlogged conditions damage standing crops, infrastructure and serve as prime breeding grounds for waterborne diseases. The picture is clouded even more by the "backwater" effect. When the river is in flood, it does not allow its northern feeders to drain into itself because of its higher water level. This amounts to building a hydraulic dam, so the water in the tributaries backs up and overflows their banks, inundating large swathes of land in North Bihar, even if there is no heavy rain locally. This complex interaction between the various river systems makes flood prediction a multi-dimensional challenge.

Institutional Framework for Flood Management and Forecasting

Responding to Bihar's immense flood vulnerability requires a well-structured and coordinated institutional mechanism. The framework for flood forecasting and management in the state is a multi-tiered system involving national and state-level agencies, each with specific mandates and responsibilities.

Central Water Commission (CWC)

The Central Water Commission operates under the Ministry of Jal Shakti. This Ministry is part of the Government of India. The Central Water Commission is the top technical organisation in India for managing water. Its main job is flood forecasting, and they are indeed responsible. The CWC's Flood Forecasting Network started in 1958. Since then, it has evolved into a sophisticated system. This system watches all important river basins that flood, which span multiple states (CWC, 2022).

In Bihar, the CWC operates numerous hydrological observation stations. These stations do important work. The stations fall into two types of levels: Some forecast water levels. These are the Level Forecasting stations. The others forecast water volume. That volume flows into a reservoir or barrage, a necessary part. Key stations dot the Ganga, Gandak, Kosi, and Bagmati. From June 1st to October 31st, which is the monsoon season, they collect data frequently. It is concerning regarding water levels, as well as the discharge of water, which can occur multiple times. The information moves fast. Data is transmitted to divisional and central control. In control rooms, hydrologists make the forecasts. The CWC then releases daily flood updates, including data. These bulletins contain observations and expected levels for the future, which are sent to everyone important in both local and central governments, which is also important (CWC, 2022).

State-Level Department and Agencies

At the state level, three bodies play very crucial role:

- The Disaster Management Department (DMD) of the Government of Bihar plays a crucial role in the flood management process, which involves a holistic approach that focuses on preparedness, mitigation, response, and recovery. Some of the tasks of the department include ensuring that plans to respond to floods are developed and implemented, as well as the development of early warning systems and regular training and awareness programs to equip communities and officials with the basic knowledge and skills necessary to respond to floods. It also collaborates with agencies on weather forecasting to monitor the weather and provide timely alerts on floods, thereby minimising life and property losses. The department is also involved in flood control, which involves the construction of river embankments, the improvement of the drainage system, and the planting of more trees to mitigate the effects of floods. It coordinates rescue and relief efforts in the event of emergencies, such as floods, by providing basic services to victims, including shelter, food, and health care. The department is responsible for the recovery and rehabilitation of the community following floods, assisting the community in restructuring their homes and infrastructure. Community participation and awareness campaigns are also key elements of community preparedness and resilience at the grassroots level. The Disaster Management Department, in close partnership with other government agencies, non-governmental organisations, and other stakeholders, will strive to achieve an effective and mutually beneficial response to any flooding, which will ultimately reduce its adverse impacts on human livelihood, property, and the environment.
- Bihar State Disaster Management Authority (BSDMA): The BSDMA was established in accordance with the Disaster Management Act of 2005, and it serves as the coordinating body for disaster management activities in the state of Bihar. On the one hand, the CWC is mandated to produce technical river predictions; on the other hand, the BSDMA is mandated to produce predictions and deliver them effectively and on time to the last mile. It can translate technical projections into comprehensible and implementable warnings of administrative authorities and citizens. The BSDMA is based on creating awareness, training local populations, and organising the efforts of different departments, such as Health, Education, and the State Disaster Response Force (SDRF).

- Water Resources Department (WRD), Government of Bihar: The WRD is primarily responsible for the structural aspects of flood control, including the construction and maintenance of embankments, barrages, and drainage networks. In the WRD, a dedicated technical cell is located within the Flood Management Improvement Support Centre (FMISC). The FMISC was formed with the assistance of the World Bank, and it plays a crucial role in flood management modernisation. It operates its advanced forecasting systems, especially in the Kosi basin, which in many cases provide a longer forecast lead time (up to 72 hours) compared to traditional CWC forecasts. The FMISC is also very active in creating inundation maps and providing technical decision support to the WRD.

Inter-Agency Coordination and Information Flow

Seamless coordination between agencies is what makes the whole system successful. The CWC has a river level forecast. The IMD gives a rainfall forecast. That is basically what they do, and their responsibility is to coordinate well with each other. Technical data now goes to the FMISC and the BSDMA. The FMISC executes the models with the data. Inundation maps and all that are value-added. Other effective products, too. BSDMA is the primary distributor. It warns them judiciously in packaged form. Then, BSDMA distributes them in different channels. Official channels are available, and District Magistrates and other departmental heads utilise them. We should be aware that BSDMA uses these processes, to name a few. Mass media is one channel—even social media aids in their communication process, along with the new CAP alerts. Maintaining coherence on all sides is the single challenge: consistency. We also do not want any interruptions at all.

Evolution of Flood Forecasting Models in Bihar

The science of flood forecasting has undergone a significant transformation over the past few decades, moving away from simple empirical methods towards complex, physically-based models that provide greater accuracy and longer lead times.

Traditional Empirical Methods: Gauge-to-Gauge Correlation

For many years, the mainstay of flood forecasting in Bihar was the gauge-to-gauge correlation method. This purely empirical technique relies on establishing a statistical relationship between the water level (gauge height) at an upstream monitoring station and a downstream forecasting station. By observing the water level at the upstream station and knowing the average travel time of the flood wave between the two points, forecasters could predict the water level at the downstream station.

While simple and computationally inexpensive, this method suffers from several critical limitations:

- Short Lead Time: The forecast lead time is limited to the travel time of the flood wave between the two gauges, which is often only 12 to 24 hours.
- Inflexibility: The relationship is based on historical data and assumes that the river channel characteristics remain constant. It cannot account for dynamic changes like embankment breaches or unprecedented rainfall in the intervening catchment between the two stations.
- Limited Scope: It only predicts water level at a specific point and cannot provide information on the volume of floodwater or the extent of inundation.

Paradigm Shift to Physically-Based Models

Recognizing these limitations, forecasting agencies have progressively transitioned towards physically-based models. Unlike empirical models, which treat the system as a "black box," physically-based models attempt to simulate the physical processes governing water movement. These models can be broadly categorized into rainfall-runoff models and hydrodynamic models.

Rainfall-Runoff (RR) Modelling

Rainfall-runoff models are the essential first step in any forecast aiming to have a longer lead time than the river's travel time. These models simulate the transformation of rainfall over a catchment area into river flow. When rain falls, a portion of it is intercepted by vegetation, another portion infiltrates into the soil, and some is stored in surface depressions. The remaining water, known as excess rainfall or direct runoff, flows over the land surface (overland flow) and into river channels.

An RR model mathematically represents these processes. It requires several key inputs:

- Observed and forecasted rainfall data (Quantitative Precipitation Forecasts - QPF).
- Catchment characteristics like size, shape, and slope are derived from a DEM.
- Land use data determines interception and surface roughness.
- Soil type data, which determines the infiltration rate.

The output of an RR model is a hydrograph—a graph showing the flow rate (discharge) versus time at the outlet of the catchment. This output hydrograph becomes a crucial input for the next stage: hydrodynamic modelling.

Hydrodynamic Modelling in Bihar: A Closer Look at MIKE-11

Once the runoff enters the river system, its movement is governed by fluid dynamics principles. One-dimensional (1D) hydrodynamic models simulate this flow in river channels. One of the most widely used software packages for this purpose in Bihar, by both the CWC and FMISC, is MIKE-11, developed by DHI (DHI Water and Environment, 2017).

MIKE-11 solves the full dynamic wave equations, also known as the Saint-Venant equations, which are a set of partial differential equations that describe unsteady open-channel flow. These equations are:

1. The Continuity Equation (Conservation of Mass):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (1)$$

Where A is the cross-sectional area of flow, Q is the discharge, t is time, x is the distance along the channel, and q is the lateral inflow per unit length.

2. The Momentum Equation (Conservation of Momentum):

$$\frac{\partial Q}{\partial t} + \frac{\partial (\alpha \frac{Q^2}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + gAS_f = 0 \qquad (2)$$

where, h is the water depth, g is the acceleration due to gravity, Sf is the friction slope, and α is the momentum correction coefficient.

To solve these equations, the model requires:

- Geometric Data: Detailed river cross-sections along the river's length at regular intervals.
- Boundary Conditions: The upstream boundary condition is typically the inflow hydrograph from a rainfall-runoff model or an upstream gauging station. The downstream boundary condition is often a known water level (e.g., the water level of the Ganga where the tributary meets it).
- Model Parameters: A key parameter is Manning's roughness coefficient (n), which represents the frictional resistance of the channel bed and banks. This parameter must be carefully calibrated using historical flood data.

The mathematically determined solution of these equations can thus predict water levels and discharges at any point along the river over the forecast period, providing a dynamic and comprehensive picture of how the flood wave propagates. This physics-based model allows for longer lead times (up to 72 hours or more, depending on the predictability of rainfall). It can mimic the results of interventions such as a barrage being deployed.

Data as the Cornerstone: A Multi-Source Integration Approach

The axiom "garbage in, garbage out" is particularly true for flood forecasting. No matter how sophisticated, the input data quality fundamentally constrains any model's accuracy and reliability. Modern flood forecasting in Bihar is a data-intensive enterprise that relies on the seamless integration of multiple data streams from various sources.

Primacy of Rainfall Data

Rainfall is the primary driver of floods, and its accurate measurement and prediction are the most critical elements for providing meaningful forecast lead times.

- Ground-Based Networks: The initial data is provided by the rain gauge networks that the IMD and the Government of Bihar run. The tools offer exact point measurements of rainfall. The state government's effort to publicise this data by posting it on its e-Statistics portal improves access to the data for various stakeholders. The spatial density of these gauges, however, can be a limitation. Flash floods are usually very localised, and a sparse network of rain gauges may not record the centre of the storm, hence underestimating the quantity of rainfall.
- Satellite Rainfall Estimates (SREs): Forecasters are now increasingly using Satellite Rainfall Estimates to overcome the spatial gaps of ground networks. Rainfall measurements such as the Tropical Rainfall Measuring Mission (TRMM) and its successor, the Global Precipitation Measurement (GPM) mission IMERG product, involve a constellation of satellites operating with microwave and infrared sensors to give estimates of rainfall across the entire globe at a high spatial and temporal resolution (e.g. 10km, half an hour). Although SREs are very useful in data-sparse areas of rainfall, such as the Himalayan catchments of Nepal, SREs are indirect estimates and can be subject to bias. Thus, they are typically applied when calibration and data correction are performed using ground-based rain gauges.
- Numerical Weather Prediction (NWP) Forecasts: Beyond a few hours, forecasts need to be based not upon observed rainfall but upon forecasted rainfall. The IMD operates sophisticated international and regional Numerical Weather Prediction models which give up to 10 days of Quantitative Precipitation Forecasts (QPF). These QPFs are directly input into rainfall-runoff models to produce flood forecasts with a lead time of three days or more. The accuracy of the flood forecast is, therefore, highly dependent on the accuracy of the QPF, which is likely to diminish with longer forecast horizons.

Hydrological and Geomorphological Data

- The River Data: As noted, the CWC network offers real-time discharges and water level data. This information is not only used in empirical forecasting, but also in the operation of hydrodynamic models. It is the boundary that distinguishes river reaches and serves as the primary source of information for model calibration and validation. The calibration procedure is a process that determines the values of the model parameters (such as the n in the Manning equation) until the model's simulated water levels for past flood events match the historical data.
- Topographical Data: A Digital Elevation Model

(DEM) is a key pillar of flood management in contemporary times. It can be utilised in defining catchments and stream networks of RR models. The most important use of it, however, is in post-processing the results of hydrodynamic models to produce inundation maps. Using the predicted maximum water surface level of the model in combination with the high-resolution DEM of the floodplain, it is possible to produce a map of the actual extent and depth of the anticipated inundation. This map is highly sensitive to the accuracy of the DEM resolution. Although publicly available DEMs, such as the 30m SRTM, are helpful, the results of more detailed DEMs, like CartoDEM or aerial LiDAR surveys, are much more precise, particularly in flat areas like those in Bihar.

- Geospatial Data Layers: Land Use and Land Cover (LULC) and soil maps are essential for parameterising rainfall-runoff models. LULC maps, which are typically based on the processing of satellite images, such as Landsat or Sentinel-2 sensor images, are used to estimate parameters, including the number of curves (when using the SCS-CN method) or roughness. Similarly, digital soil maps will provide data on soil texture, which can be used to estimate infiltration capacity.

Transboundary Data Conundrum

For rivers like the Kosi, Gandak, and Bagmati, a significant portion of their flood-generating catchment lies within Nepal. Without timely and reliable hydrological and meteorological data from these upstream areas, any forecast for Bihar is inherently reactive. Recognizing this, India and Nepal have a long-standing cooperation and data exchange framework governed by joint committees. Nepal shares data from key hydrological stations on these rivers with India. However, significant challenges persist. The density of the observational network in the mountainous regions of Nepal is sparse. Data transmission can sometimes be delayed due to technical or logistical issues. Furthermore, the shared data is often raw, which needs to be processed and quality-checked before it can be used in models. Enhancing this transboundary data sharing mechanism—by investing in more real-time telemetry stations in Nepal and ensuring faster, more robust data transmission protocols—is widely recognized as the single most important step for increasing the lead time and reliability of flood forecasts in North Bihar.

Frontier of Flood Forecasting: Technology and Innovation

Advancements in computing, remote sensing, and artificial intelligence are rapidly transforming the field of flood forecasting. Bihar is slowly becoming a testbed for some of these cutting-edge technologies.

Inundation Modelling and Visualization

The output of a forecast is no longer just a number (the expected water level). The focus has shifted to providing spatially explicit information. The FMISC and other agencies are now routinely generating inundation maps based on model outputs. These maps are not static; they can be dynamic, showing the progression of flooding over time. These visualizations are far more intuitive for disaster managers and the public than a simple warning level. They can be overlaid with administrative boundaries, village locations, and critical infrastructure data to create a powerful tool for planning evacuations and positioning relief supplies.

Rise of Artificial Intelligence and Machine Learning (AI/ML)

AI and ML are emerging as powerful tools to complement and enhance traditional forecasting models.

- Data-Driven Modelling: ML models, such as Artificial Neural Networks (ANNs), Recurrent Neural Networks (RNNs), and Long Short-Term Memory (LSTM) networks, are adept at learning complex, non-linear patterns from historical data. They can be trained on long-term rainfall records, river levels, and other parameters to generate forecasts. These data-driven models can sometimes outperform or be used with physical models, especially for error correction.
- Real-Time Inundation Mapping: A groundbreaking application of AI has been used to analyze satellite data for real-time flood mapping. In a collaboration between Google and the BSDMA, AI algorithms are used to rapidly process satellite imagery (both optical and SAR) to detect the presence of water on the ground. This allows for generating highly accurate inundation maps during an ongoing flood event, which can be disseminated to affected populations via smartphone alerts. This provides people with a visual understanding of the situation around them and helps them find safer

routes.

- Nowcasting: AI is also used for "nowcasting"—predicting rainfall at very high resolution for the next few hours. By analyzing the movement and development of storm clouds in recent satellite and radar images, ML models can provide crucial warnings for impending flash floods.

Early Warning Dissemination Systems (EWS)

The best forecast is useless if it does not reach the right people at the right time in an understandable format. There has been a significant push to improve Early Warning Dissemination Systems. The BSDMA utilizes a multi-channel approach that includes:

- Traditional media (television, radio, newspapers).
- SMS alerts to registered users and officials.
- Social media platforms.
- The Sachet mobile application for disaster alerts.
- The Common Alerting Protocol (CAP) is an international standard that allows a single warning message to be simultaneously disseminated over multiple platforms, including mobile network alerts that can reach everyone in a specific geographic area.

Persistent Challenges and the Path Forward

Despite the remarkable progress, the flood forecasting system in Bihar faces several persistent challenges that must be addressed to build a truly flood-resilient state.

1. **Data Gaps and Quality**: The observational network, particularly for rainfall and automatic river gauges, needs further densification, especially in the transboundary catchments. The quality and continuity of data also need to be rigorously maintained.
2. **Model Uncertainty:** All models are simplifications of reality and have inherent uncertainties. These uncertainties arise from input data errors, model structural limitations, and parameter estimation errors. There is a need to move towards ensemble forecasting, where multiple models are run with slightly different initial conditions or parameters to generate a probabilistic forecast that quantifies this uncertainty.
3. **Transboundary Cooperation**: As emphasized earlier, strengthening the mechanism for real-time data sharing with Nepal is non-negotiable for improving forecast lead times. This requires sustained diplomatic engagement and technical collaboration.
4. **Last-Mile Connectivity and Community Response**: Ensuring that warnings reach the most marginalized communities and that these communities have the capacity and resources to act on them remains the ultimate challenge. This requires a bottom-up approach, strengthening community-based disaster management committees and integrating local and indigenous knowledge into the formal EWS.
5. **Integration of Structural and Non-Structural Measures**: Flood forecasting (a non-structural measure) must be better integrated with the planning and maintaining structural measures like embankments. For example, forecasts can inform emergency embankment strengthening work, while data on embankment performance can be used to refine hydrodynamic models.

The path forward requires a multi-pronged strategy focused on continued investment in technology and infrastructure, fostering international cooperation, improving scientific modelling capabilities, and, most importantly, empowering local communities to be active participants in their safety.

Conclusions

The fight against the deluge in Bihar is an annual struggle rooted in the state's complex hydro-meteorology and topography. The state's attitude towards the problem over the decades has changed; it is no longer a reactionary and post-disaster intervention, but an active model developed based on scientific predictions. This study has demonstrated that contemporary flood forecasting in Bihar is a complex and data-driven initiative that has long surpassed the use of gauges alone. It is a system that combines massive amounts of data, including rain gauges on the ground, radars and satellites in the sky, and hydrological sensors in rivers, into complicated mathematical models that represent the physics of a flood. Data on rainfall, and especially quantitative forecasts of precipitation, have played a crucial role in increasing the lead time of warnings, providing a decisive preparation time. The simultaneous combination of topographical, land-use, and real-time river information has enabled the transition from level forecasts to full-scale inundation maps, providing practical intelligence to disaster operators. The limitations of AI and satellite technologies are even more advanced, allowing individuals to be notified about the situation and receive personalised alerts in real-time. Nevertheless, the system does not lack weaknesses. The issues of data sparseness in key upstream catchments, the complications of cross-boundary information exchange, the unpredictability's of inherent models and the old challenge of the last-mile warning communications are still worthy of concern and resources. Achieving flood-resilient Bihar is a long-term goal, not a short-term one. It will entail a long-term commitment to enhancing the entire chain of the early warning system, from data observation and modelling to dissemination and community response. With the adoption of modern technology, the development of community level teamwork, and the empowerment of its people, Bihar has an opportunity to enhance its scientific capabilities to mitigate the wrath of the monsoon and turn the repetitive tragedy into a controlled natural disaster.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bihar State Disaster Management Authority. 2023. Bihar State Disaster Management Plan. Government of Bihar.

Bihar State Disaster Management Authority. 2023. Annual flood report 2023. Bihar State Disaster Management Authority.

Central Water Commission. 2022. Manual on flood forecasting. Ministry of Jal Shakti, Government of India.

Chakraborty, A. and Seshasai, M. V. R. 2020. Geospatial assessment of flood hazard in the Kosi River basin, India. Geomatics, Natural Hazards and Risk, 11(1): 817–841.

DHI Water and Environment. 2017. *MIKE 11:* A modelling system for rivers and channels — User guide. DHI.

Government of Bihar, Water Resources Department. 2019. Report of the Flood Management Improvement Support Centre FMISC. Government of Bihar, Water Resources Department.

India Meteorological Department. 2021. Annual monsoon report. Ministry of Earth Sciences, Government of India.

Kumar, S. and Ranjan, P. 2009. The Kosi embankment failure: Causes and consequences. Journal of Indian Hydrology, 15(3): 45–58.

Mishra, V. and Shah, R. 2018. Hydroclimatological perspective of the 2017 floods in South Asia. Hydrology and Earth System Sciences, 22(9): 4837–4843.

Rao, S. and Patel, A. 2017. Flood dynamics and management in Bihar, India. Journal of Hydrology and Water Resources, 35(2): 123–135.

Sanyal, J. and Lu, X. X. 2004. Application of remote sensing in flood management with special reference to DEM generation. Natural Hazards, 33(3): 283–301.

Sharma, P. and Kumar, R. 2018. Flood vulnerability and resilience in Bihar: A socio-hydrological perspective. Indian Journal of Flood Studies, 12(4): 45–60.

Singh, R. and Kumar, R. 2021. A review of transboundary flood management: A Gandak River basin case study. International Journal of River Basin Management, 19(4): 495–506.

Verma, S., Singh, A. and Joshi, N. 2020. Monsoon patterns and river flooding in North Bihar. Journal of Climate and Environment, 8(3): 78–92.

Webster, P. J., Toma, V. E. and Kim, H.M. 2011. Were the 2010 Pakistan floods predictable? Geophysical Research Letters, 38, L04806.

World Bank. 2015. Bihar Kosi Flood Recovery Project: Implementation completion and results report. World Bank.