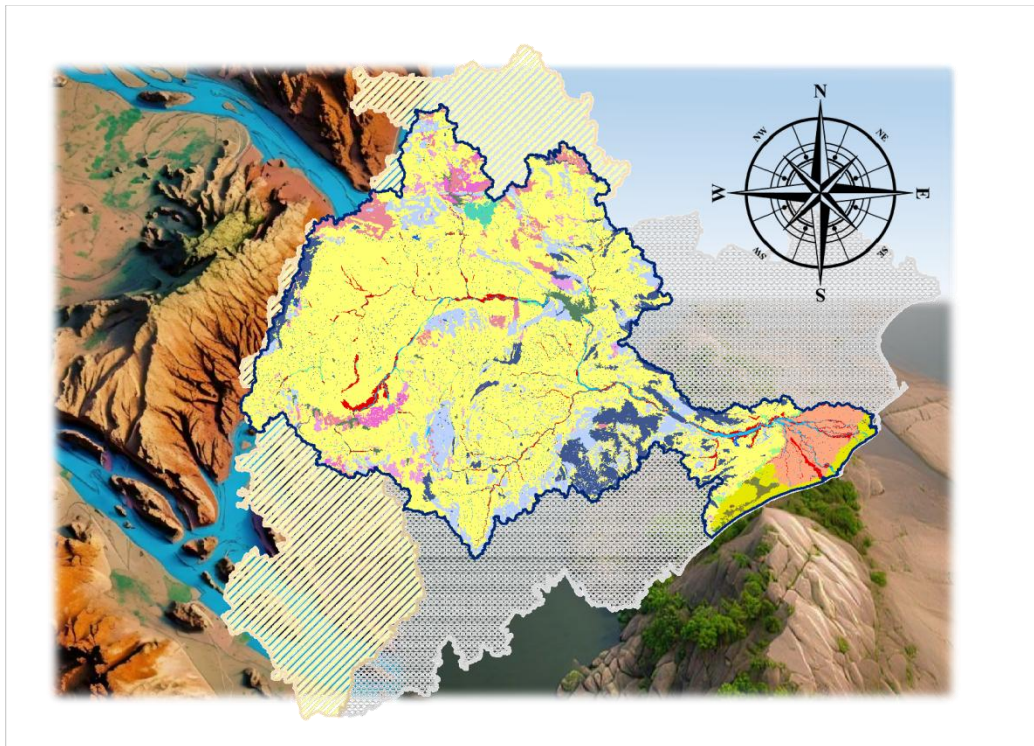




National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Flood Hazard Model

Mahanadi River Basin



December 2025



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Flood Hazard Model

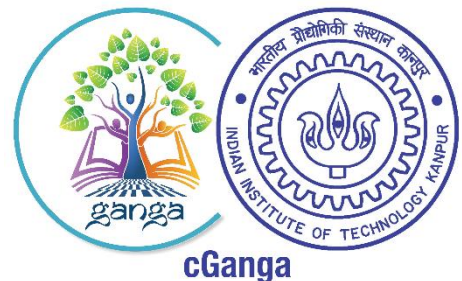
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cMahanadi



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National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development & Ganga Rejuvenation, and Ministry of Jal Shakti providing financial assistance to the State Government for conservation of rivers under the Centrally Sponsored Schemes of 'National River Conservation Plan (NRCP)'. National River Conservation Plan to the State Governments/ local bodies to set up infrastructure for pollution abatement of rivers in identified polluted river stretches based on proposals received from the State Governments/ local bodies.

www.nrcd.nic.in

Centres for Mahanadi River Basin Management Studies (cMahanadi)

The Centres for Mahanadi River Basin Management Studies (cMahanadi) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by NIT Raipur and NIT Rourkela, under the supervision of cGanga at IIT Kanpur, the centre serves as a knowledge wing of the National River Conservation Directorate (NRCD). cMahanadi is committed to restoring and conserving the Mahanadi River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

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Centre for Ganga River Basin Management and Studies (cGanga)

cGanga is a think tank formed under the aegis of NMCG, and one of its stated objectives is to make India a world leader in river and water science. The Centre is headquartered at IIT Kanpur and has representation from most leading science and technological institutes of the country. cGanga's mandate is to serve as think-tank in implementation and dynamic evolution of Ganga River Basin Management Plan (GRBMP) prepared by the Consortium of 7 IITs. In addition to this, it is also responsible for introducing new technologies, innovations, and solutions into India.

www.cganga.org

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Preface

In an era of unprecedented environmental change, understanding our rivers and their ecosystems has never been more critical. This report aims to provide a comprehensive overview of our rivers, highlighting their importance, current health, and the challenges they face. As we explore the various facets of river systems, we aim to equip readers with the knowledge necessary to appreciate and protect these vital waterways.

Throughout the following pages, you will find an in-depth analysis of the principles and practices that support healthy river ecosystems. Our team of experts has meticulously compiled data, case studies, and testimonials to illustrate the significant impact of rivers on both natural environments and human communities. By sharing these insights, we hope to inspire and empower our readers to engage in river conservation efforts.

This report is not merely a collection of statistics and theories; it is a call to action. We urge all stakeholders to recognize the value of our rivers and to take proactive steps to ensure their preservation. Whether you are an environmental professional, a policy maker, or simply someone who cares about our planet, this guide is designed to support you in your efforts to protect our rivers.

We extend our heartfelt gratitude to the numerous contributors who have generously shared their stories and expertise. Their invaluable input has enriched this report, making it a beacon of knowledge and a practical resource for all who read it. It is our hope that this report will serve as a catalyst for positive environmental action, fostering a culture of stewardship that benefits both current and future generations.

As you delve into this overview of our rivers, we invite you to embrace the opportunities and challenges that lie ahead. Together, we can ensure that our rivers continue to thrive and sustain life for generations to come.

Centre for Mahanadi River Basin
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Abbreviations and Acronyms

cMahanadi	Centre for Mahanadi River Basin Management and Studies
CWC	Central Water Commission
DEM	Digital Elevation Model
GEE	Google Earth Engine
GIS	Geographic Information System
GRBMP	Ganga River Basin Management Plan
GSI	Geological Survey of India
IB	Ib River
IIT	Indian Institute of Technology
MRB	Mahanadi River Basin
NIT	National Institute of Technology
NRCD	National River Conservation Directorate
NRCP	National River Conservation Plan
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
WRIS	Water Resource Information System

1. Introduction

1.1 Basin Significance

The Mahanadi River is one of the most vital hydrological arteries of east-central India, serving as a primary driver of agricultural productivity, industrial development, and ecological sustainability in the states of Chhattisgarh and Odisha. The river drains a total catchment area of 141,589 km², accounting for approximately 4.3% of India's total geographical area (CWC, 2014; WRIS, 2023). The river system exhibits pronounced spatial variability, ranging from seasonal water scarcity in the upper reaches to severe and recurrent flooding in the deltaic region.

Geographically, the Mahanadi basin is bounded by the Central India Hills to the north, the Eastern Ghats to the south and east, and the Maikala Range to the west. The river originates in the Sihawa Hills of Dhamtari district, Chhattisgarh, and traverses a length of approximately 851 km before discharging into the Bay of Bengal at False Point, Odisha (CWC, 2014).

1.1.1 Upper Mahanadi Basin

The upper basin, largely confined to Chhattisgarh, is characterized by undulating terrain, hard rock geology, and a monsoon-dependent hydrological regime. Rainfall variability and limited groundwater storage result in frequent seasonal water shortages, particularly during the pre-monsoon period. Despite these constraints, the upper basin plays a crucial role in supporting rainfed agriculture, paddy cultivation, and emerging industrial centers. The construction of reservoirs and barrages has significantly altered natural flow regimes, influencing downstream water availability and sediment transport.

1.1.2 Middle Mahanadi Basin

The middle basin acts as a critical hydrological transition zone, regulating flows between the upper catchment and the delta. This region hosts major hydraulic structures, including the Hirakud Dam, which is one of the largest earthen dams in Asia. The dam provides flood moderation, irrigation, and hydropower generation; however, it has also contributed to flow regulation, sediment trapping, and ecological modification downstream. The middle basin thus plays a pivotal role in balancing water resource utilization with flood control objectives.

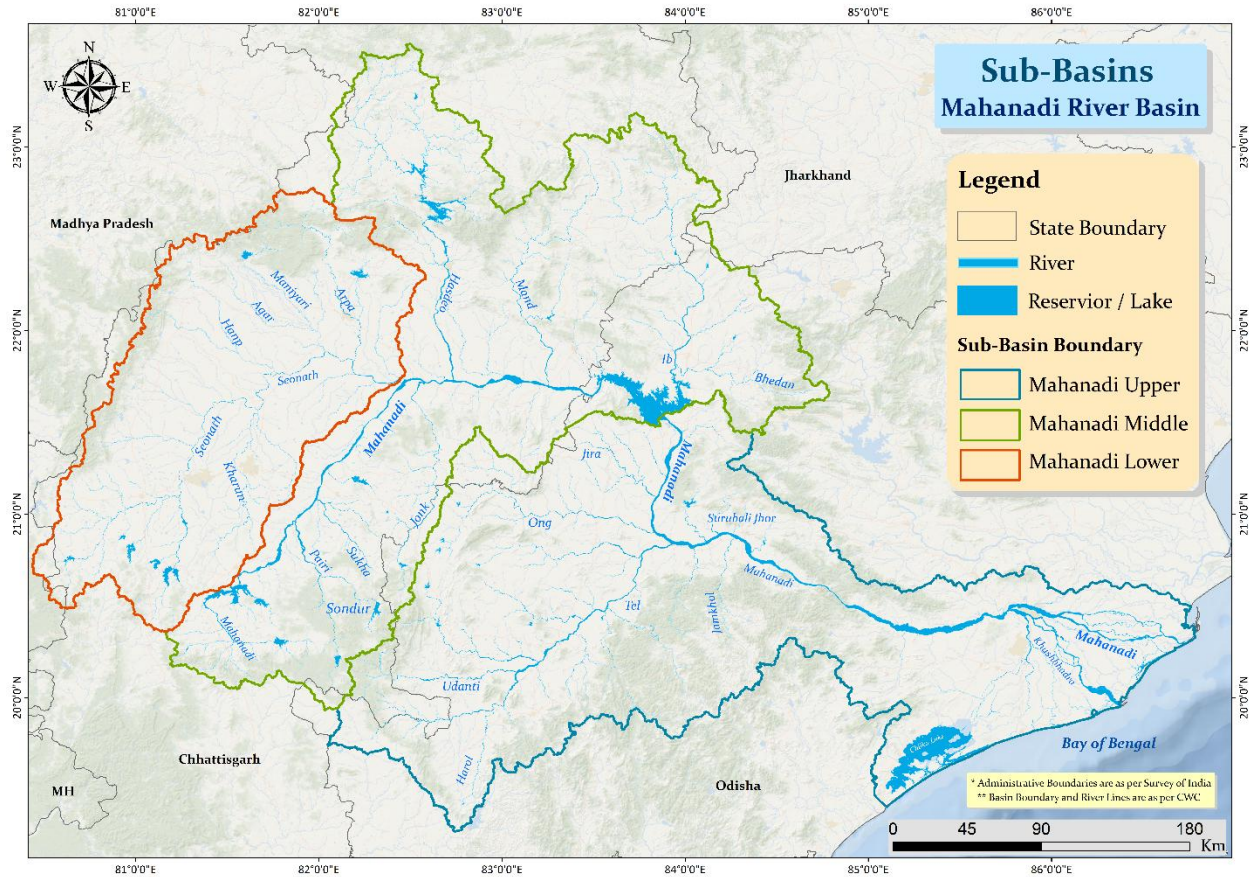


Figure 1. Subbasin MAP of Mahanadi River

1.1.3 Lower Mahanadi Basin and Delta

The lower basin and deltaic region, located primarily in Odisha, is highly fertile but extremely vulnerable to recurrent flooding, cyclones, and storm surges. The flat topography, dense distributary network, and tidal influence exacerbate flood hazards during high monsoon discharge and extreme rainfall events. While the delta supports intensive agriculture and dense population, altered upstream flow regulation and reduced sediment supply have increased coastal erosion, channel instability, and flood risk, highlighting the growing challenges of sustainable river basin management under changing climatic conditions.

Overall, the Mahanadi basin represents a hydrologically diverse and socio-economically critical system, where upstream water scarcity and downstream flood hazards coexist, necessitating an integrated and basin-wide water management approach.

1.2 Historical and Economic Context

Since the 19th century, the Mahanadi River has played a central role in colonial and post-independence water management strategies in India. Under British rule, early hydraulic works and embankments were constructed to reduce the river's frequent flooding in the lower plains. In independent India, the commissioning of the Hirakud Dam in 1957 marked a watershed moment in its history, transforming the Mahanadi from an untamed and flood-prone system famously called the "River of Sorrow" into a regulated multipurpose river valley system for irrigation, hydropower, and flood mitigation. The Hirakud Dam, one of the first and longest earthen dams in the world, was designed to control seasonal floods and facilitate agricultural development, while also supporting electricity generation and industrial water supply.

The river basin facilitates a broad range of economic activities. In Chhattisgarh, the upper basin supports extensive rainfed and irrigated agriculture, bolstered by reservoirs such as Gangrel (Ravishankar Sagar) and Hasdeo Bango, which provide water for crops, drinking purposes, and power generation for local industries. The basin's ample mineral resources and hydropower availability have also encouraged industrial growth, including the Bhilai Iron and Steel Plant, aluminium smelting at Korba, and cement and paper manufacturing units across the region.

Economically, the lower basin and delta in Odisha remain critically important for agricultural productivity. Districts such as Cuttack, Puri, Jagatsinghpur, Kendrapada, and Khordha within the delta constitute the "Rice Bowl of Odisha", sustaining dense rural populations and contributing significantly to regional food security. However, hydrologic extremes — particularly recurrent floods driven by intense monsoon rainfall and cyclonic events — pose persistent threats to agricultural output and rural livelihoods. Research indicates that the basin experienced 14 major flood events in the last 25 years, with each event causing average annual economic losses exceeding USD 200 million (Ghosh et al., 2020)

The Mahanadi basin's extensive network of tributaries — including the Seonath, Hasdeo, Mand, Ib, Jonk, Ong, and Tel rivers — contributes substantially to the river's hydrology and basin economy. The Seonath, as the largest tributary, drains key agricultural districts of Chhattisgarh, while the Tel and Ib rivers enhance agricultural and industrial water availability across western Odisha and eastern Chhattisgarh, respectively. These tributaries support diversified crop systems,

fisheries, and riverine communities, but they also intensify flood risk during extreme monsoon seasons when synchronized high discharge events occur across the basin.

The basin's hydrological regulation infrastructure has boosted irrigation and reduced some flood impacts; yet, this regulation has also altered natural sediment transport and seasonal flow variability, introducing ecological challenges downstream. In both Chhattisgarh and Odisha, debates around equitable water sharing and management have recently intensified, culminating in formation of the Mahanadi Water Disputes Tribunal to address inter-state concerns over upstream infrastructure and downstream water availability

Overall, the Mahanadi basin exemplifies a major Indian river system where historical water management interventions have driven economic growth in agriculture, industry, and energy, while simultaneously confronting challenges of environmental change, flood risk, and inter-regional water equity.

1.3 Problem Statement: The Deltaic Inundation Crisis

Despite the presence of major hydraulic infrastructure within the Mahanadi River basin, flood risk remains spatially uneven and continues to intensify in the downstream reaches. While the Hirakud Dam effectively moderates flood peaks originating from the upper catchment in Chhattisgarh, the lower basin and deltaic plains of Odisha remain highly vulnerable to recurrent inundation. This vulnerability is primarily driven by uncontrolled inflows from the extensive intermediate catchment between Hirakud and the Mundali barrage. This reach receives substantial discharge from major tributaries including the Ib, Ong, Tel, Jonk, Mand, and Hasdeo rivers, draining both eastern Chhattisgarh and western Odisha.

Hydrological analyses indicate that this intermediate reach alone contributes nearly sixty-nine percent of the peak flood volume observed at the Mundali gauging station, significantly reducing the effectiveness of upstream flood moderation (Parhi et al., 2012). The synchronization of peak flows from multiple tributaries during intense monsoon rainfall further amplifies downstream flood severity, transforming the lower Mahanadi basin into a convergence zone for basin-scale flood waves.

1.4 The problem is worsen by:

1.4.1 Channel Conveyance Limitations in the Delta

Flood hazard in the lower Mahanadi basin is strongly influenced by the limited carrying capacity of the deltaic distributary network. The combined safe conveyance capacity of these channels is estimated to be approximately nine hundred thousand to one million cubic feet per second, whereas historical flood peaks have exceeded one and a half million cubic feet per second on multiple occasions. This mismatch leads to widespread overbank flooding across deltaic districts such as Cuttack, Jagatsinghpur, Kendrapada, and Puri. Rapid runoff contributions from tributaries such as the Ib and Tel rivers significantly exacerbate flood magnitude during extreme monsoon events (CWC, 2014).

1.4.2 Sediment Trapping and Delta Degradation

The construction of more than two hundred and fifty large and medium dams across the Mahanadi basin, particularly in the upper and middle reaches of Chhattisgarh and western Odisha, has substantially altered sediment transport dynamics. Studies indicate that sediment delivery to the delta has declined by approximately sixty-seven percent following large-scale river regulation (Gupta et al., 2012). Reduced sediment supply has limited deltaic aggradation, increased relative sea-level rise, and weakened natural levees, thereby increasing flood depth and duration in the lower basin.

1.4.3 Compound Flooding and Backwater Effects

Flood risk in the lower basin is further intensified by compound flooding mechanisms, where high river discharge coincides with elevated tidal levels, cyclonic storm surges, and intense coastal rainfall. These conditions generate pronounced backwater effects at the river mouth, restricting outflow into the Bay of Bengal and forcing floodwaters to spread laterally across the delta. Such compound flood events significantly diminish the effectiveness of upstream flow regulation and represent one of the most critical challenges to flood management in the Mahanadi basin (Parhi et al., 2012; Ghosh et al., 2020).

1.5 Objectives of the Flood Hazard Model

1.5.1 Decision-Support Framework

In view of the interconnected hydrological processes operating across the entire Mahanadi basin, the primary objective of this study is to develop a basin-scale flood hazard modeling framework that can function as a decision-support tool for the Odisha State Disaster Management Authority and the Central Water Commission. The model integrates upstream inflow dynamics from Chhattisgarh, tributary contributions from the middle basin, and compound flooding influences in the deltaic region.

1.5.2 Modeling and Risk Mitigation Goals

The study aims to establish threshold-based early warning indicators for critical control points, particularly the Mundali gauging station, by incorporating cumulative inflows from major tributaries. It further seeks to generate spatially explicit inundation depth and flow velocity maps for twenty-five, fifty, and one-hundred-year return period flood scenarios. The structural integrity and performance of the existing embankment network, extending over approximately six thousand kilometers across the lower basin and delta, are evaluated under extreme and compound flood conditions. Additionally, the study assesses the effectiveness of nature-based solutions, including floodplain reconnection, mangrove restoration, sediment replenishment, and spillway rejuvenation, as complementary measures to conventional structural interventions for enhancing flood resilience.

2. Hydrological Model

2.1 Hydrological Flood Hazard Model

Hydrological models represent the first stage of flood hazard assessment. These models simulate the transformation of rainfall into runoff within a watershed. The primary objective of hydrological modelling is to estimate the volume and timing of runoff generated during rainfall events and to determine the discharge entering the river system. These models analyze watershed characteristics such as rainfall intensity, soil properties, infiltration capacity, vegetation cover, and drainage patterns.

Hydrological modelling plays a crucial role in flood hazard studies because it determines how much water enters the river during extreme rainfall events. During heavy precipitation, excess rainfall that cannot infiltrate the soil becomes surface runoff and eventually reaches the river channel. Hydrological models simulate this process and generate hydrographs that show how river discharge changes over time.

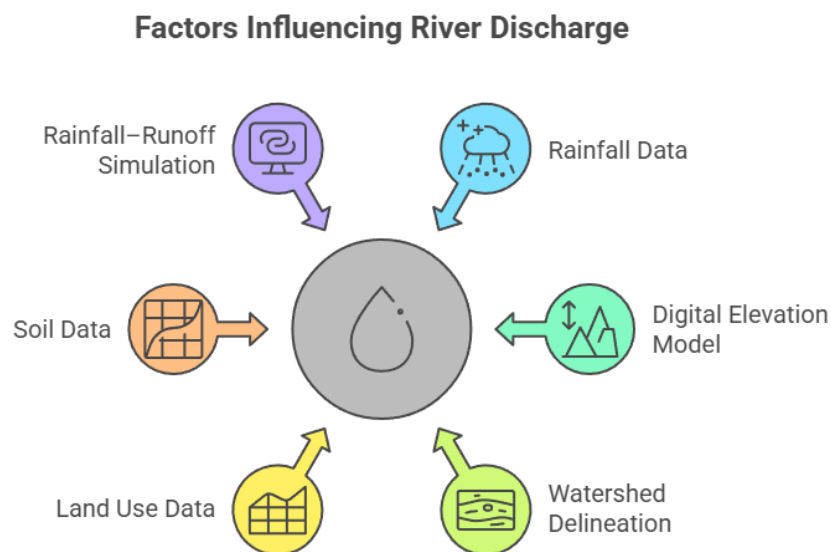


Figure 2. Factor Influencing River Discharge

Another important aspect of hydrological models is watershed representation. Most models divide the catchment area into smaller sub-basins so that rainfall-runoff processes can be simulated more accurately. This approach allows the model to capture spatial variations in rainfall, soil type, and land use, which significantly influence runoff generation.

For large river basins such as the Mahanadi River Basin, hydrological modelling helps estimate peak discharge during monsoon rainfall. These discharge values are later used as inputs in hydraulic models to simulate flood inundation and hazard zones.

2.2 HEC-HMS Flood Hazard Model

HEC-HMS is one of the most widely used hydrological modelling tools for flood hazard studies. It was developed by the U.S. Army Corps of Engineers to simulate rainfall-runoff processes in watershed systems. The model integrates rainfall data, watershed geometry, land use, and soil characteristics to estimate runoff generation and river discharge.

HEC-HMS divides a watershed into multiple sub-basins and calculates runoff from each sub-basin separately. The model includes various hydrological components such as precipitation losses, surface runoff, baseflow, and channel routing. These processes are simulated using mathematical equations that describe how rainfall interacts with the watershed.

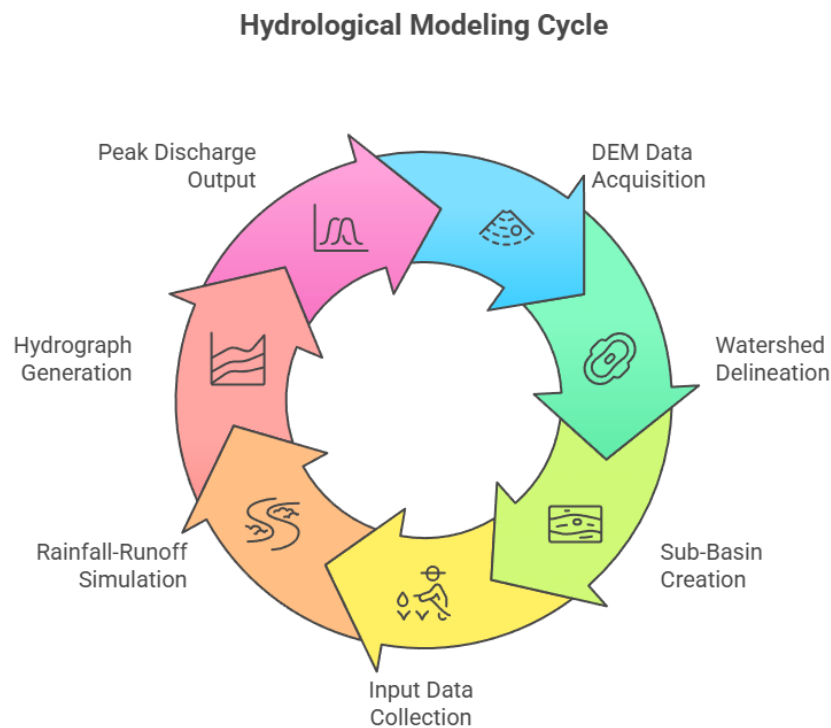


Figure 3. Hydrological Modeling Cycle

One of the main outputs of HEC-HMS is the hydrograph, which represents the variation of river discharge over time. This hydrograph provides critical information about peak discharge, flood

timing, and runoff volume. These outputs are essential inputs for hydraulic models used in flood inundation analysis. In the Mahanadi River Basin, HEC-HMS can be applied using rainfall data from meteorological stations and DEM datasets such as SRTM or ALOS. By delineating the watershed and defining sub-basins, the model can estimate peak discharge during monsoon rainfall events, which helps in flood forecasting and hazard assessment.

2.3 SWAT Hydrological Model

SWAT is a physically based distributed hydrological model widely used for large river basins. It was developed to predict the impact of land management practices on water resources, sediment transport, and agricultural pollution. SWAT integrates climate data, soil characteristics, land use, and topography to simulate watershed processes. A key feature of the SWAT model is the concept of Hydrological Response Units (HRUs). HRUs represent unique combinations of soil type, land use, and slope within a watershed. By dividing the basin into HRUs, the model can simulate spatial variations in hydrological processes more accurately.

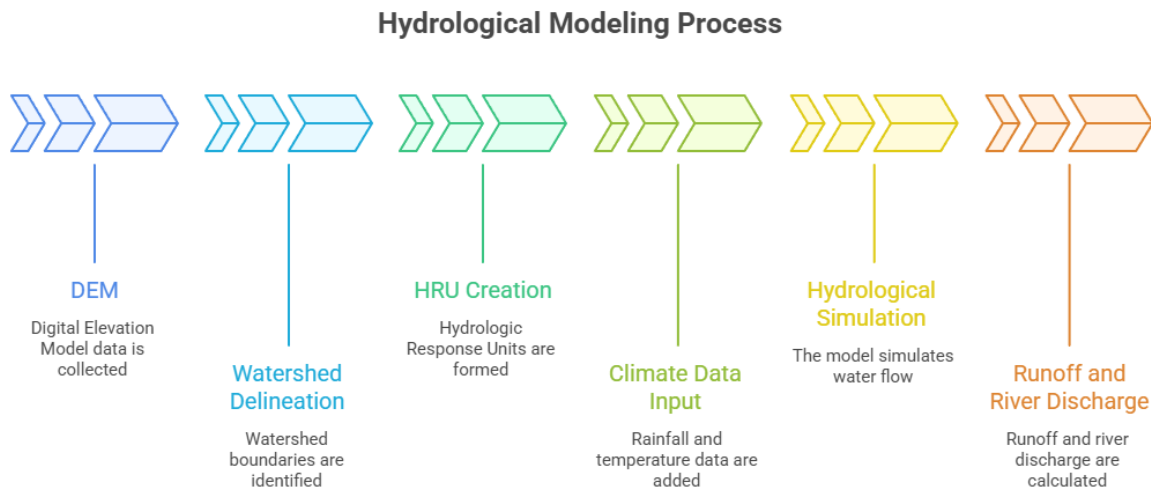


Figure 4. Hydrological Modelling Process

SWAT is particularly useful for long-term hydrological simulations and climate change studies. It can simulate surface runoff, groundwater flow, evapotranspiration, and sediment transport over extended periods. Because of its distributed modelling approach, SWAT is well suited for large basins with diverse land use and climatic conditions. In the Mahanadi River Basin, SWAT can be used to simulate rainfall-runoff processes across the entire basin. By integrating climate data, DEM, soil maps, and land use information, the model can estimate river discharge and runoff

patterns. These results are valuable for flood risk assessment and watershed management planning.

2.4 Hydraulic Flood Hazard Models

Hydraulic models simulate the movement of water through river channels and floodplains once the discharge from hydrological models is known. These models use hydraulic equations to estimate water surface elevation, flow velocity, and flood depth during flood events.

Hydraulic modelling is essential for flood hazard mapping because it determines how floodwaters spread across floodplains. These models require inputs such as river cross-sections, channel geometry, terrain elevation, and discharge values. Most hydraulic models are based on the Saint-Venant equations, which describe the conservation of mass and momentum in open channel flow. These equations allow the model to simulate water flow in rivers under different conditions.

Hydraulic modelling is particularly important in flood-prone regions where floodplain dynamics play a significant role in flood hazards. In the Mahanadi River Basin, hydraulic models help identify flood-prone areas and estimate flood depth during extreme rainfall events.

2.5 HEC-RAS Flood Hazard Model

flow conditions and calculates water surface profiles along river channels. The model supports both one-dimensional (1D) and two-dimensional (2D) hydraulic simulations. HEC-RAS requires several input datasets, including river cross-section geometry, discharge values, terrain elevation, and channel roughness coefficients. Using these inputs, the model calculates water levels along the river and identifies areas that may be inundated during flood events. The outputs of HEC-RAS include water surface elevation, flood depth, and inundation extent. These outputs can be integrated with GIS software to produce flood hazard maps. These maps help planners and disaster management authorities identify flood-prone areas and develop mitigation strategies.

Hydrological Model Output Process

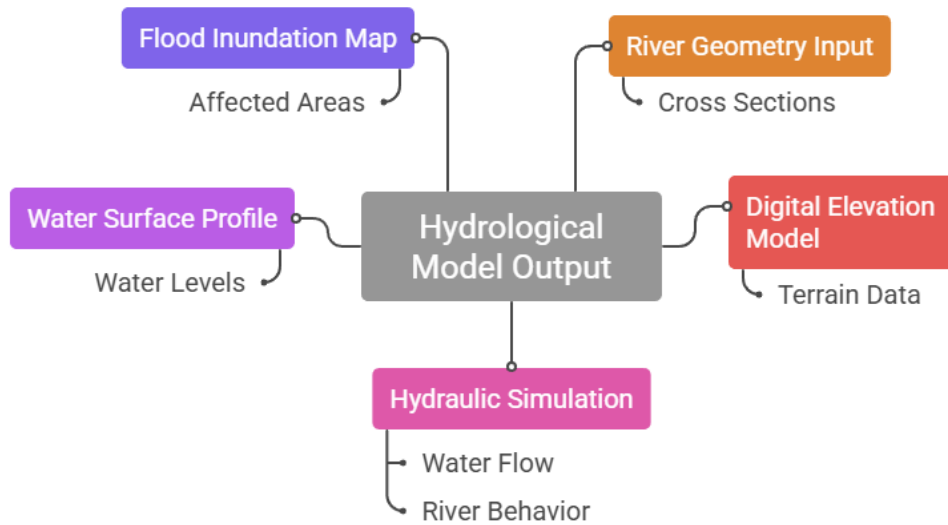


Figure 5. HEC-RAS Modelling methodologies

In the Mahanadi River Basin, HEC-RAS can be used with DEM data and river cross-section information to simulate flood propagation along the river channel. The model can generate flood inundation maps that show the spatial extent of flooding during extreme rainfall events.

3. Methodology and Assessment Framework

3.1 The Challenge of Flood Risk Assessment in the Mahanadi Basin

Flood risk assessment in the Mahanadi River basin presents significant methodological challenges due to the basin's large spatial extent, physiographic diversity, and strong hydrological connectivity between its upper, middle, and lower reaches. The basin spans the states of Chhattisgarh and Odisha and encompasses a wide range of hydro-climatic regimes, from forested uplands and plateau regions in the upper catchment to highly dynamic alluvial and deltaic environments near the coast. Major tributaries such as the Seonath, Hasdeo, Mand, Ib, Ong, Tel, and Jonk contribute substantially to the basin's hydrological response, often with asynchronous peak flows during extreme monsoon events.

One of the primary challenges arises from the mismatch between structural flood control measures and basin-scale hydrological processes. While large reservoirs such as the Hirakud Dam provide partial regulation of upstream flows, flood peaks generated from the uncontrolled middle catchment often dominate downstream flood behavior. This spatial decoupling complicates flood attribution and limits the effectiveness of single-structure-based flood management strategies (Parhi et al., 2012; CWC, 2014).

Additionally, flood risk in the lower Mahanadi basin is increasingly influenced by compound drivers, including high river discharge, tidal backwater effects, cyclonic storm surges, and sea-level rise. These interacting processes challenge conventional flood frequency analysis methods, which typically assume stationarity and independence of drivers. As a result, flood hazard assessment in the Mahanadi basin requires an integrated and multi-source methodological framework capable of capturing both upstream hydrological controls and downstream coastal influences (Ghosh et al., 2020).

3.2 Review of Methodological Approaches in Mahanadi Flood Studies

Previous flood-related studies in the Mahanadi basin have employed a range of methodological approaches, broadly categorized into statistical, hydrological, hydraulic, and geospatial techniques. Early studies primarily relied on statistical flood frequency analysis using gauge-based discharge records to estimate design floods at key locations such as Hirakud and Mundali. While

these approaches provided baseline estimates, they were limited in their ability to represent spatial inundation patterns and tributary interactions (Parhi et al., 2012).

Subsequent research incorporated hydrological modeling to simulate rainfall–runoff processes across sub-basins, often using lumped or semi-distributed models. These studies improved understanding of tributary contributions but were constrained by data availability, particularly in the upper catchment of Chhattisgarh where gauge density remains low (Rath et al., 2019). Hydraulic modeling efforts, focused mainly on the deltaic reach, have been used to simulate water levels and inundation extents under extreme discharge scenarios; however, many of these models rely on simplified boundary conditions and do not fully integrate upstream basin dynamics.

More recent studies have increasingly utilized remote sensing and GIS-based techniques to map flood extents, land-use exposure, and historical inundation footprints. Satellite-derived flood maps have proven valuable for capturing large-scale flood events in the delta but are often limited by cloud cover, revisit time, and lack of flow velocity information (Surwase et al., 2018). Overall, the literature reflects a fragmented methodological landscape, with limited integration across spatial scales and disciplinary boundaries.

3.3 Rationale for a Consolidated Assessment Framework

Given the limitations of isolated methodological approaches, there is a strong need for a consolidated assessment framework that synthesizes hydrological, hydraulic, historical, and geospatial evidence. Flood risk in the Mahanadi basin is inherently cumulative, shaped by upstream rainfall and reservoir operations, middle-basin tributary inflows, and downstream channel capacity and coastal boundary conditions. Addressing these interconnected drivers requires a framework that moves beyond single-model dependency and instead emphasizes cross-validation using multiple data sources.

A consolidated framework allows for the reconciliation of model outputs with observed flood behavior documented in historical archives, government reports, and satellite imagery. Such an approach enhances the robustness of flood hazard estimates and supports more reliable identification of risk hotspots across the basin. Similar basin-wide assessment strategies have been successfully applied in large Indian river systems, including the Narmada and Godavari

basins, where integrated frameworks improved flood preparedness and decision-making (CWC, 2018; Jain et al., 2020).

3.4 The Adopted Framework for This Report

The present study adopts a literature-driven, basin-scale flood hazard assessment framework designed to integrate diverse data sources and analytical perspectives. Rather than relying on a single numerical model, the framework emphasizes synthesis, triangulation, and consistency across hydrological observations, historical flood records, and geospatial evidence. This approach is particularly suited to data-scarce environments and supports transparent decision-making for flood risk management agencies.

3.4.1 Data Sources for This Assessment

3.4.1.1 Hydrological and Meteorological Data

Hydrological and meteorological data form the foundation of the flood hazard assessment. Daily and sub-daily rainfall records, river discharge data, and water level observations were obtained from the India Meteorological Department and the Central Water Commission for key stations across the Mahanadi basin, including upstream locations in Chhattisgarh and downstream control points such as Mundali. These datasets were used to characterize historical flood magnitudes, seasonal variability, and extreme event behavior (CWC, 2014).

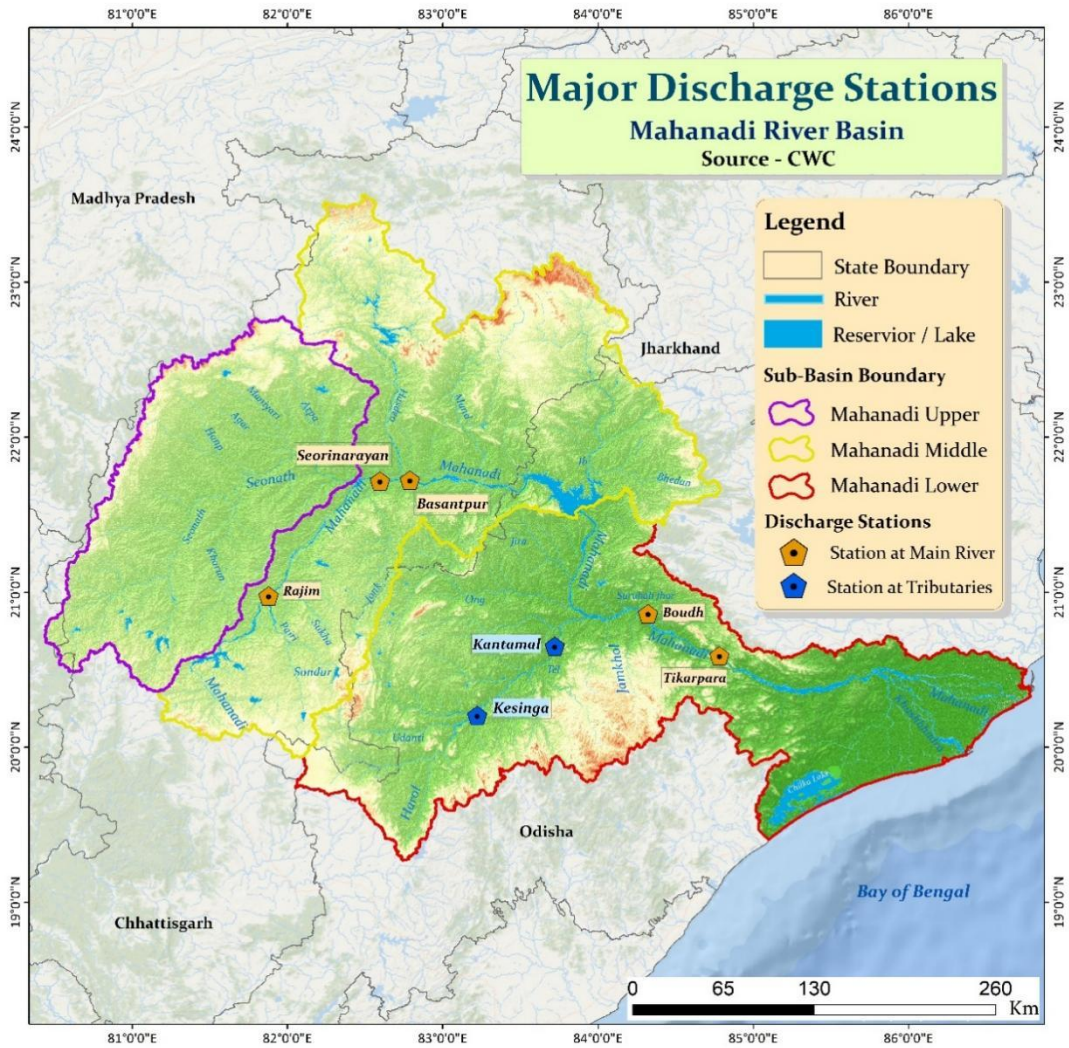


Figure 6. Major Discharge Station [CWC]

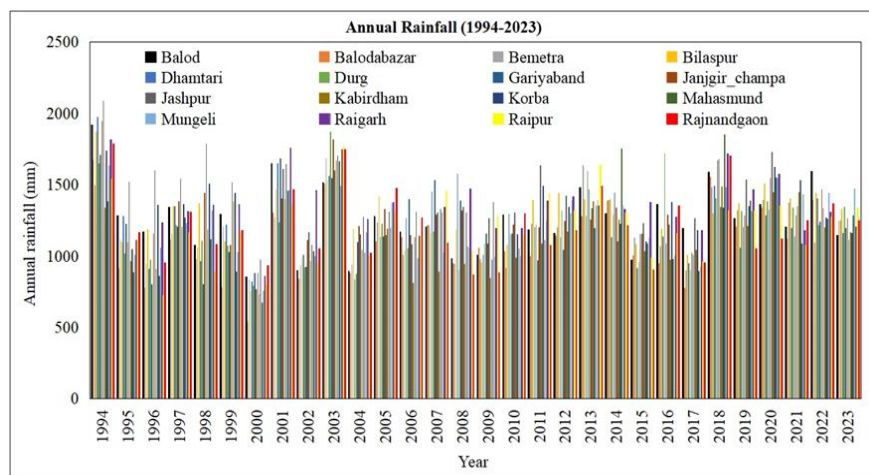


Figure 7. Annual Rainfall (1994-2023)

3.4.1.2 Historical Archives and Reports

Historical flood chronicles, government flood enquiry reports, dam operation records, and disaster loss assessments were reviewed to contextualize observed flood events. These archival sources provide critical insights into flood impacts, embankment failures, and socio-economic consequences that are not captured by instrumental records alone. Such qualitative evidence is particularly valuable for validating modeled flood extents and identifying recurrent vulnerability zones in the delta (Ghosh et al., 2020).

3.4.1.3 Geospatial Datasets

Geospatial datasets, including digital elevation models, river network layers, land-use and land-cover maps, and satellite-derived flood inundation products, were used to support spatial analysis of flood hazards. These datasets enabled the identification of low-lying flood-prone areas, channel confinement zones, and floodplain connectivity across the basin. Remote sensing products were particularly useful for assessing historical flood footprints in the deltaic region (Surwase et al., 2018).

3.4.1.4 Published Scientific Literature

Peer-reviewed journal articles, technical reports, and basin studies related to the Mahanadi River system were systematically reviewed to inform methodological choices and parameter selection. Literature covering tributary hydrology, sediment dynamics, reservoir impacts, and compound flooding processes was prioritized to ensure basin-wide relevance (Parhi et al., 2012; Gupta et al., 2012).

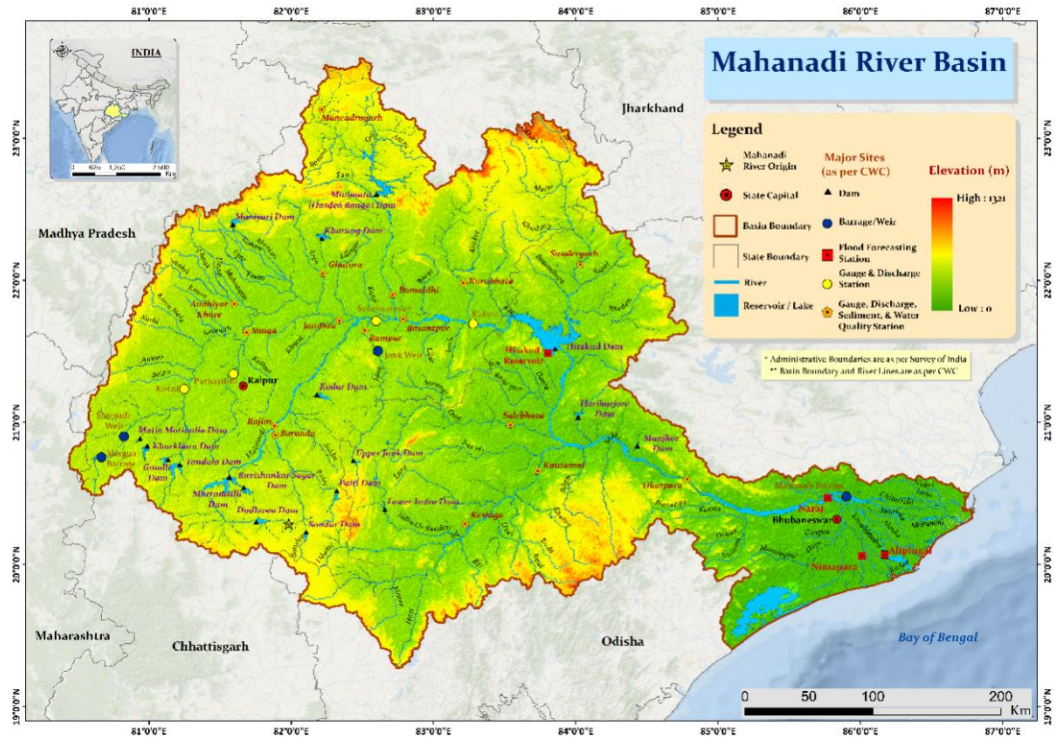


Figure 8. Elevation MAP of Mahanadi River Basin

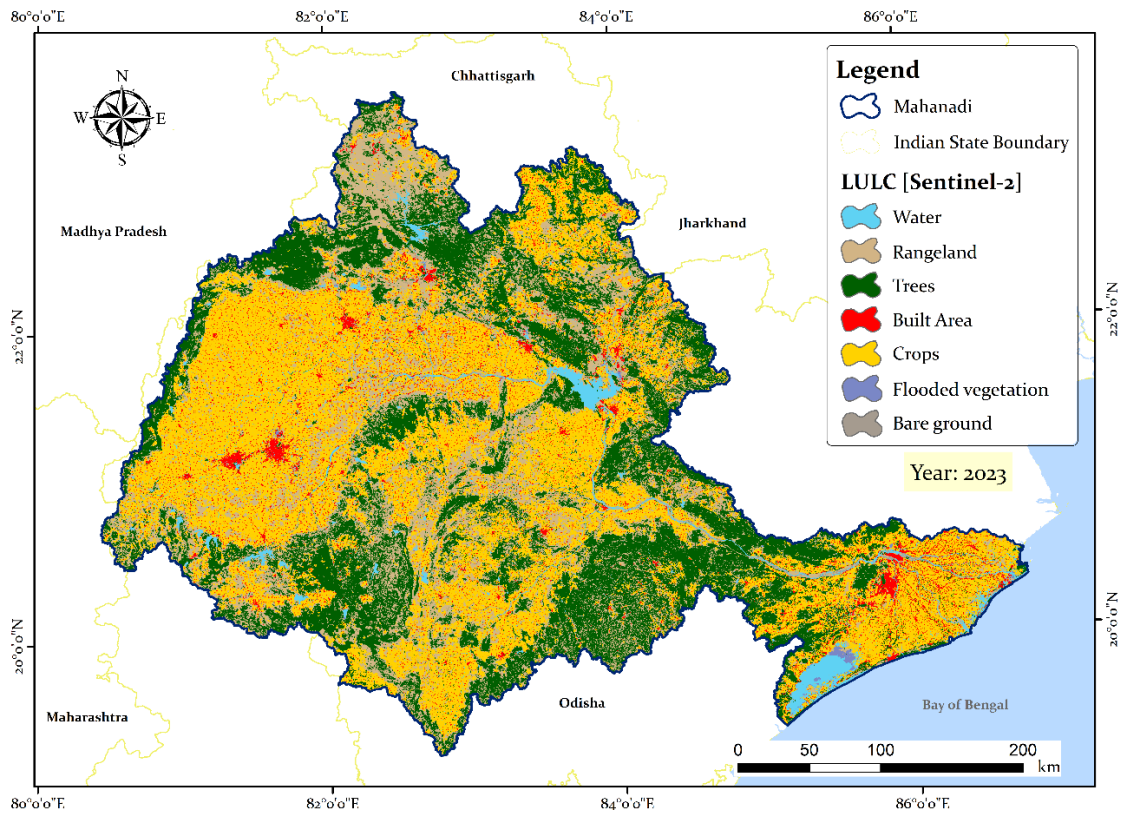


Figure 9. LULC MAP of Mahanadi River Basin

3.4.2 Framework for Synthesis and Risk Identification

The final stage of the framework involves synthesizing evidence from all data sources to identify dominant flood drivers and spatial patterns of hazard. Hydrological thresholds derived from gauge records are interpreted alongside historical flood narratives and satellite observations to validate flood-prone zones. Emphasis is placed on identifying locations where multiple risk drivers converge, including high tributary inflows, limited channel capacity, embankment confinement, and coastal backwater effects. This synthesis-based approach supports the development of a realistic and policy-relevant flood hazard model for the Mahanadi basin.

4. Analysis of Historical Flood Events

4.1 Chronology of Major Recorded Floods in the Mahanadi Basin

The Mahanadi River basin has a long history of recurring floods, driven by intense monsoonal rainfall, synchronized tributary inflows, and limited downstream conveyance capacity. Historical flood records indicate that major flood events have occurred at irregular intervals since the early twentieth century, with particularly severe floods recorded in 1957, 1970, 1982, 1994, 2006, 2011, 2013, 2020, and 2023. These events affected extensive areas across both Chhattisgarh and Odisha, highlighting the basin-wide nature of flood generation and propagation.

In the upper basin, floods are primarily triggered by widespread rainfall over the Seonath, Hasdeo, Mand, and Ib sub-basins, while in the lower basin, flood severity is amplified by high inflows from the Ong, Tel, and Jonk rivers combined with tidal and backwater effects near the delta. The Mundali gauging station has consistently served as the critical control point for assessing flood severity in the lower Mahanadi basin (CWC, 2014).

4.2 Case Study 1: The Benchmark Flood of 1970

4.2.1 Hydro-meteorological Context and Drivers

The 1970 flood is widely regarded as the benchmark flood of the Mahanadi basin. The event was triggered by a sequence of intense monsoon depressions over central and eastern India during August 1970, resulting in sustained high rainfall across both Chhattisgarh and western Odisha. Catchments of the Seonath, Hasdeo, Mand, and Ib rivers experienced near-saturation conditions, leading to rapid runoff generation and exceptionally high tributary inflows.

At the time, flood moderation infrastructure was limited, and reservoir regulation capabilities were still evolving. The cumulative effect of synchronized tributary peaks resulted in unprecedented flood volumes entering the middle and lower basin.

4.2.2 Recorded Peak Discharge and Regional Impact

At Mundali, the peak discharge during the 1970 flood exceeded 1.4 million cusecs, inundating large parts of the deltaic plain. Extensive flooding was reported in Cuttack, Puri, and Kendrapada districts, while upstream areas in Chhattisgarh experienced prolonged submergence of

agricultural land. The event established a reference benchmark for subsequent flood frequency and hazard assessments in the basin (CWC, 2014).

4.3 Case Study: The 1994 Flood – An Event of Extreme Discharge

4.3.1 Hydro-meteorological Context and Hydrological Response

The 1994 flood resulted from exceptionally heavy rainfall concentrated over the middle Mahanadi basin, particularly the Tel and Ong sub-basins. Unlike earlier events, rainfall intensity during this period was highly localized but persistent, leading to sharp and rapid rises in river stage across tributaries. The hydrological response was characterized by steep rising limbs and limited lag time between rainfall and peak discharge, overwhelming downstream channels.

4.3.2 Regional Impacts and Early Backwater Effects

The 1994 flood marked one of the earliest documented instances of pronounced backwater effects in the delta. Elevated sea levels and tidal influence coincided with high river discharge, restricting outflow and prolonging inundation in coastal districts. This event highlighted the growing role of compound flooding processes in the lower Mahanadi basin (Parhi et al., 2012).

4.4 Case Study: The 2006 Flood and Upstream Submergence

The 2006 flood was notable for extensive upstream submergence in Chhattisgarh, particularly in the Hasdeo and Seonath sub-basins. Prolonged monsoon rainfall led to high reservoir inflows, resulting in widespread inundation of agricultural land and rural settlements. Downstream impacts were relatively moderated due to controlled reservoir releases; however, the event underscored the vulnerability of upper basin communities to prolonged flooding and reservoir backwater effects.

4.5 Case Study 2: The 2013 Flood – A Multi-State Cascade of Disaster

4.5.1 Hydro-meteorological Context and Drivers

The 2013 flood was driven by a sequence of monsoon systems producing intense rainfall across both Chhattisgarh and Odisha. The simultaneous activation of the Seonath, Hasdeo, Ib, Ong, and Tel tributaries resulted in a cascading flood wave moving downstream.

4.5.2 Recorded Peak Discharge and Regional Impact

High inflows forced substantial releases from Hirakud Dam, coinciding with peak tributary flows downstream. This synchronization significantly amplified flood magnitude in the lower basin, affecting millions across coastal Odisha. The event demonstrated the critical importance of coordinated reservoir operation and basin-wide flood forecasting (Ghosh et al., 2020).

4.6 Case Study: The 2020 Flood and the Role of Dam Operations

4.6.1 Hydro-meteorological Context and Upstream Impact

The 2020 flood occurred during an above-normal monsoon season, with persistent rainfall over the upper and middle Mahanadi basin. Reservoirs in Chhattisgarh and Odisha approached full capacity early in the season, reducing flood buffering potential.

4.6.2 Dam Operations and Downstream Impact

Emergency releases from Hirakud Dam, combined with high inflows from uncontrolled tributaries, led to severe downstream flooding. The event reignited debate on dam operation protocols and highlighted the need for dynamic, forecast-based reservoir management (CWC, 2020).

4.7 Case Study: The 2023 Flood – Unprecedented Hydrological Extremes

4.7.1 Hydro-meteorological Context and Hydrological Impact

The 2023 flood was characterized by extreme short-duration rainfall events over multiple sub-basins, attributed to intensified monsoon variability. Several tributaries recorded near-record discharge levels, overwhelming local drainage systems.

4.7.2 Dam Operations and Regional Impacts

Despite regulated releases, downstream flood impacts were severe due to limited channel capacity and strong backwater effects. Large areas of the delta experienced prolonged inundation, reaffirming the increasing influence of compound flood drivers under changing climatic conditions.

4.8 Synthesis of Flood Characteristics and Patterns

Analysis of historical flood events in the Mahanadi basin reveals consistent patterns of flood generation and propagation. Extreme floods are typically associated with synchronized tributary inflows rather than solely upstream releases. The middle basin between Hirakud and Mundali emerges as the dominant contributor to peak flood volumes, while the lower basin remains highly sensitive to backwater and coastal processes. These findings underscore the necessity of basin-wide flood hazard modeling that integrates tributary dynamics, reservoir operations, and deltaic constraints.

5. Synthesis of Scientific Knowledge on Flood Risk in the Mahanadi Basin

5.1 The Mahanadi Flood Regime: Natural Versus Human-Modulated Controls

The flood regime of the Mahanadi River basin is governed by a combination of natural hydro-climatic processes and extensive human intervention through river regulation and flood control infrastructure. Naturally, the basin is characterized by a monsoon-dominated rainfall regime, with intense precipitation events occurring between June and September. The spatial variability of rainfall across the upper plateau regions of Chhattisgarh and the lower alluvial plains of Odisha results in uneven runoff generation and tributary synchronization during extreme events (Kumar & Bassi, 2021).

Human interventions, particularly the construction of large reservoirs such as the Hirakud Dam and multiple medium and minor dams across tributaries including the Seonath, Hasdeo, Mand, and Ib rivers, have significantly altered the natural flow regime. While these structures have reduced the frequency of moderate floods, they have not eliminated extreme flood events. Instead, regulation has shifted flood timing, modified peak characteristics, and increased downstream dependence on operational decisions, particularly during high inflow periods (CWC, 2014; Parhi et al., 2012).

5.2 Insights from Palaeo flood and Geological Archives

Although palaeo flood studies in the Mahanadi basin are limited compared to some other Indian river systems, available geological and geomorphological evidence suggests that extreme floods have been an intrinsic component of the basin's long-term evolution. Floodplain stratigraphy, abandoned channels, and sedimentary deposits in the middle and lower basin indicate the occurrence of large-magnitude floods well before the construction of major dams.

Deltaic sediment records along the Odisha coast reveal alternating phases of aggradation and erosion, reflecting long-term variability in sediment supply and flood energy. Recent reductions in sediment delivery due to upstream damming have altered these natural processes, increasing the vulnerability of the delta to prolonged inundation and coastal backwater effects (Gupta et al., 2012). These geological insights reinforce the need to interpret modern flood events within a broader temporal context rather than as isolated anomalies.

5.3 Review of Flood Hazard Modeling and Mapping Studies

5.3.1 Summary of Methodologies and Models Used

Scientific studies on flood hazard assessment in the Mahanadi basin have employed a range of methodological approaches, including statistical flood frequency analysis, hydrological rainfall-runoff modeling, hydraulic flow routing, and GIS-based inundation mapping. Early modeling efforts focused on estimating design discharges at key gauging stations such as Hirakud and Mundali, primarily using historical discharge records.

More recent studies have adopted two-dimensional hydraulic models to simulate flood depths and extents in the deltaic region, often integrating digital elevation models and satellite-derived flood footprints. However, most modeling efforts remain spatially fragmented, with limited integration of upstream tributary inflows and reservoir operation dynamics (Ghosh et al., 2020; Surwase et al., 2018).

5.3.2 Compilation of Findings and Published Hazard Maps

Published flood hazard maps for the Mahanadi basin consistently identify the lower basin and delta as the most flood-prone regions, particularly districts such as Cuttack, Jagatsinghpur, Kendrapada, and Puri. Hazard maps also highlight recurrent inundation zones along major tributaries, including the Tel and Ong rivers, which contribute disproportionately to downstream flood peaks.

Despite these advances, existing hazard maps often differ in extent and severity classification due to variations in input data, model assumptions, and boundary conditions. This inconsistency underscores the need for a consolidated hazard assessment framework that harmonizes modeling outputs with historical flood evidence and observed inundation patterns.

5.4 The Critical Role of Dam Operations in Modern Floods

5.4.1 The Dam Management Paradox: Conflicting Objectives of Storage and Safety

Modern flood behavior in the Mahanadi basin is increasingly influenced by reservoir operation strategies. Large reservoirs are expected to simultaneously meet competing objectives, including irrigation supply, hydropower generation, and flood moderation. During extreme monsoon

seasons, these objectives often conflict, as reservoirs approach full capacity early in the season, reducing their ability to buffer subsequent flood inflows.

This operational paradox is particularly evident at the Hirakud Dam, where decisions on pre-monsoon drawdown and emergency releases directly influence downstream flood severity. Similar challenges are observed in reservoirs across Chhattisgarh, where upstream storage decisions cumulatively affect basin-scale flood response (CWC, 2020).

5.4.2 Analysis of Avoidable Disasters and Operational Lapses

Post-flood analyses indicate that several recent flood events could have been partially mitigated through improved reservoir coordination and real-time forecasting. Sudden high-volume releases during peak downstream inflow periods have exacerbated flooding in the lower basin, raising concerns regarding operational transparency and institutional coordination. These findings emphasize the importance of adaptive, forecast-informed dam operation protocols to reduce avoidable flood impacts (Ghosh et al., 2020).

5.5 Synthesis of Flood Vulnerability Studies

5.5.1 Identification of Vulnerable Districts and Populations

Flood vulnerability studies consistently identify the lower Mahanadi basin as the most exposed region, with high population density, intensive agriculture, and extensive embankment confinement increasing risk. Districts such as Kendrapada, Jagatsinghpur, Cuttack, and Puri experience repeated flood impacts, while upstream districts in Chhattisgarh face prolonged waterlogging and reservoir-induced submergence.

Tributary floodplains along the Ib, Tel, and Ong rivers also exhibit high vulnerability due to limited channel capacity and rapid runoff response. These areas often receive less attention in basin-scale planning despite their significant contribution to downstream flood risk.

5.5.2 Socio-Economic Impacts and Livelihood Disruption

Flood events in the Mahanadi basin result in substantial socio-economic losses, including damage to crops, housing, infrastructure, and livelihoods. The deltaic region, often referred to as the rice bowl of Odisha, experiences repeated crop losses due to prolonged inundation. In the upper

basin, floods disrupt mining, power generation, and industrial operations, highlighting the basin-wide economic consequences of extreme events (Ghosh et al., 2020).

5.6 Consolidated Gaps in Knowledge and Future Research Directions

Despite extensive research, significant gaps remain in understanding and managing flood risk in the Mahanadi basin. Limited availability of high-resolution hydrological data, insufficient integration of tributary dynamics, and inadequate representation of compound flooding processes constrain existing models. Furthermore, palaeoflood evidence and sediment dynamics remain underutilized in flood hazard assessments.

Future research should focus on basin-wide integrated modeling frameworks that combine hydrological forecasting, reservoir operation simulation, and coastal boundary processes. Strengthening data sharing between states, enhancing real-time monitoring, and incorporating nature-based solutions are essential for improving long-term flood resilience in the basin.

6. Identification of Flood Risk and Vulnerability

6.1 Delineation of Flood-Prone Zones Based on Consolidated Evidence

Flood-prone zones within the Mahanadi River basin were identified through consolidation of historical flood records, hydrological observations, published flood hazard maps, and documented impact assessments. Evidence consistently indicates that flood risk is spatially concentrated in the lower basin and deltaic plains of Odisha, while significant localized flood hazards also exist along major tributaries in both Chhattisgarh and western Odisha.

The most flood-prone zones include the downstream reaches between the Mundali barrage and the Bay of Bengal, where limited channel capacity, embankment confinement, and backwater effects result in frequent overbank flooding. Tributary floodplains along the Ib, Tel, Ong, and Jonk rivers exhibit recurrent inundation due to rapid runoff response and restricted drainage. In the upper basin, flood-prone areas are primarily associated with reservoir backwater zones and low-lying agricultural lands along the Seonath and Hasdeo rivers. The spatial consistency of these zones across multiple flood events confirms their classification as high-risk areas (CWC, 2014; Ghosh et al., 2020).

Singh and Mohanty (2023) investigated basin-scale flood hazard modelling for the Mahanadi River Basin using a combination of global hydrological and hydrodynamic datasets. The study utilized ERA5 atmospheric reanalysis data to derive discharge inputs and employed the LISFLOOD-FP two-dimensional hydrodynamic model to simulate flood inundation across the basin using the MERIT digital elevation model and global river geometry datasets. Flood simulations were conducted for multiple historical flood events (2006, 2008, 2011, and 2014), and the simulated flood extents were validated using MODIS satellite-derived flood observations. The model performance was evaluated using statistical metrics, including the correlation coefficient, Nash–Sutcliffe efficiency, and Kling–Gupta efficiency, indicating strong agreement between ERA5-derived and observed flows, particularly during extreme events. Flood hazard maps were generated using flood depth and depth-velocity relationships to classify hazard intensity into multiple categories ranging from very low to very high. The study further applied extreme value analysis to estimate design discharges for return periods such as 50- and 100-year floods,

demonstrating that reanalysis datasets combined with large-scale hydrodynamic modelling can provide reliable flood hazard assessments in data-scarce basins like the Mahanadi.

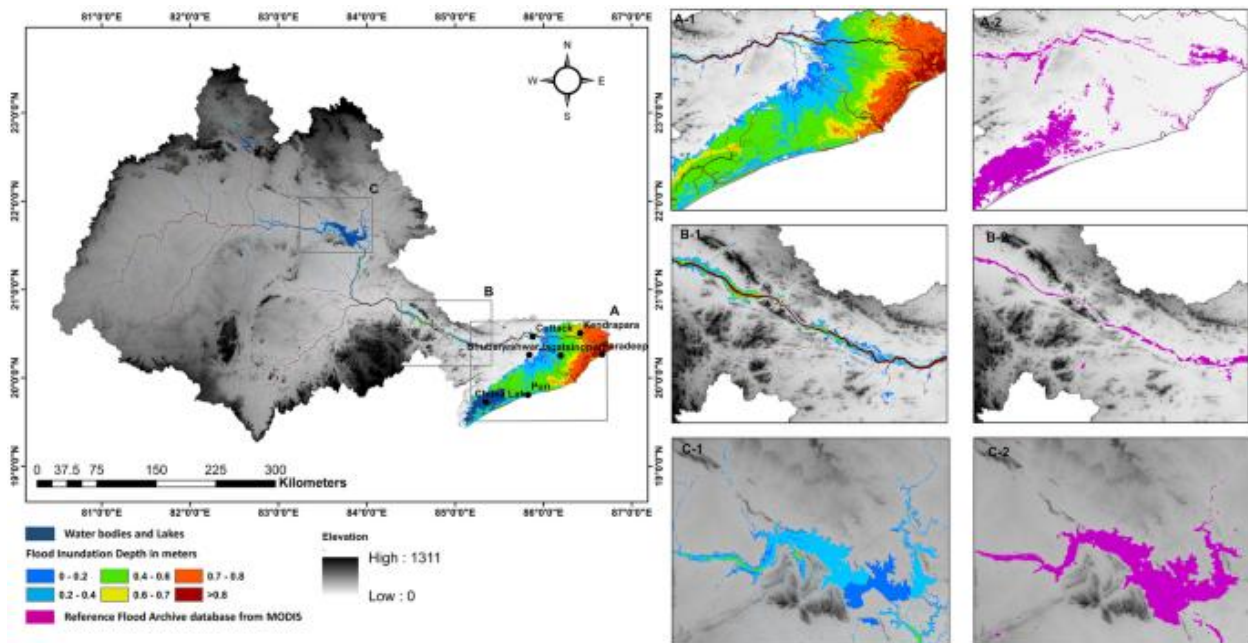


Figure 10 . Simulated flood inundation map for the 2003 flooding event over MRB. (Singh & Mohanty, 2023)

The Figure 10 illustrates the spatial distribution of simulated flood inundation across the Mahanadi River Basin (MRB) covering both Chhattisgarh (upstream region) and Odisha (downstream deltaic region). The main panel shows the basin-wide flood depth simulated using the LISFLOOD-FP hydrodynamic model, where flood depth is categorized into multiple classes ranging from shallow inundation (0–0.2 m) to deep flooding (>0.8 m). The results indicate that the highest flood depths occur in the lower Mahanadi delta in Odisha, particularly downstream of the Hirakud Dam toward the coastal plains, where the terrain is relatively flat and highly susceptible to widespread inundation. In contrast, the upper basin in Chhattisgarh exhibits comparatively limited flood spread, primarily confined along the main river channels and tributaries due to steeper topography and better drainage.

6.1.1 Evolution of the "Tri-Delta" Complex

The geomorphological architecture of the Mahanadi Delta is not merely a collection of river channels but a complex, multi-stage evolutionary product of fluvial-marine interactions spanning the Holocene epoch. This chapter provides a deep technical analysis of the delta's formation, its

tectonic underpinnings, and the administrative-hydrological classification of the "Doabs"—the inter-stream areas that define the risk profile of the region. The Mahanadi Delta is situated on the east coast of Peninsular India, occupying a tectonic depression known as the Mahanadi Graben. Geologically, the basin is contiguous with the Gondwana landmass, and its basement is characterized by two major lineaments: the Dhamra Offshore Lineament (DOL) and the Chilika Offshore Lineament (COL) (Das, 2020). The deltaic plain itself is divisible into two distinct sectors: 1. The Fluvial Sector (Upper Delta), comprising more than the western half of the delta, this region is dominated by terrestrial sediments. The marine influence is negligible here, and the landforms are primarily levees, backswamps, and abandoned meander loops. 2. The Marine-Marginal Sector (Lower Delta), a belt running parallel to the present-day shoreline where fluvial, marine, and aeolian processes (wind-driven) converge. This zone is characterized by beach ridges, tidal flats, and mangrove swamps.

Scholars such as Hazra et al. (2019) and Dash et al. (2020) classify this region as a Tri-Delta. This is because the Mahanadi Delta does not exist in isolation; it is a composite feature formed by the coalescence of three major river systems: the Mahanadi, the Brahmani, and the Baitarani. The evolution of the modern Mahanadi Delta is believed to have begun in the Mid-Holocene period (approx. 10,800 years BP), following a stabilization of the mean sea level. Research by Somanna et al. (2016) indicates a progradation rate (the rate at which the land grows into the sea) of approximately 9.1 km per 1,000 years. This progradation, however, has been significantly altered in the Anthropocene, experiencing reduced sediment supply and coastal retreat due to anthropogenic interventions (Hazra et al., 2019).

According to the seminal work of N.K. Mahalik (Mahalik, 1994; Mahalik et al., 1996; Mahalik, 2006), the delta's growth occurred in four distinct hydrological stages:

Stage I: The formation of the proto-Mahanadi and old Kathajodi systems near Cuttack.

Stage II: The evolution of the Sukhabhadra and Burdha systems towards the northern delta.

Stage III: The emergence of the Prachi, Alaka, and Ratnachira systems. During this stage, the Ratnachira river carved its path from the old Kathajodi.

Stage IV (Present): The current growth phase, characterized by the New Kathajodi-Kuakhai-Birupa systems, which feed the Daya and Bhargavi rivers.

6.1.2 The 8-Doab Framework: Origin and Classification

The division of the Mahanadi Delta into 8 distinct Doabs (land between two rivers) is the standard hydrological and administrative framework used for irrigation and flood management. This classification was formalized by the Department of Water Resources (DoWR), Government of Odisha, specifically detailed in the Orissa State Water Plan (2004) and subsequent updates. This division allows engineers to manage the "Mahanadi Delta Command Area Stage-I and Stage-II" as independent hydrological units.

Table 1 : The Doabs and their characteristics

Doab No.	Name/ Boundaries	Characteristics & Vulnerabilities
Doab I	Mahanadi-Khajuri-Devi	The most populous doab. It includes the city of Cuttack. Vulnerable to high-velocity floods from the Khajuri and the backwater effect of the Devi estuary.
Doab II	Mahanadi-Birupa-Luna	Also known as the "Central Delta." Characterized by heavy siltation and the presence of the Birupa-Genguti system.
Doab III	Luna-Chitrotpala	A narrow, highly fertile strip. This doab is prone to "blind end" flooding where local drainage cannot exit due to high river stages.
Doab IV	Area East of HLC Range-I	Defined by the High-Level Canal (HLC). This doab relies heavily on canal irrigation but faces severe waterlogging in its tail-end reaches.
Doab V	Mahanadi-Paika	A relatively smaller doab formed by the bifurcation of the main

		Mahanadi and the Paika distributary near Paradip.
Doab VI	Kushabhadra-Bhargavi	A critical zone for the Puri district. This doab manages the spill of the Kuakhai system.
Doab VII	Daya-Bhargavi (Chilika)	The southernmost part of the delta. This doab drains directly into the Chilika Lagoon. It is the most sensitive to "compound flooding" from the lake's rising levels.
Doab VIII	Coastal Strip (Puri-Konark)	The marine-marginal zone, characterized by sand dunes and tidal inlets. It acts as the "deltaic lip" protecting the inner doabs from the sea.

6.2 Key Factors Contributing to Flood Risk

Flood risk in the Mahanadi basin arises from the interaction of natural basin characteristics and human-induced alterations to the river system. These factors collectively determine the magnitude, duration, and spatial extent of flood impacts.

6.2.1 Natural Factors

Natural flood risk drivers include basin topography, drainage density, soil characteristics, and monsoonal rainfall variability. The upper basin in Chhattisgarh is characterized by undulating terrain and relatively shallow soils, which promote rapid runoff generation during intense rainfall events. The middle and lower basin transition into low-gradient alluvial plains, where reduced flow velocities increase flood residence time.

The deltaic region of Odisha is particularly vulnerable due to its extremely low elevation, dense distributary network, and tidal influence. During high discharge events, these natural conditions limit the river's ability to convey floodwaters efficiently to the sea, resulting in widespread inundation (Parhi et al., 2012).

6.2.2 Anthropogenic Factors

Human activities have significantly amplified flood risk across the basin. Encroachment onto floodplains, expansion of urban areas, and construction of embankments have reduced natural flood storage and constrained river channels. Urban centers such as Cuttack, Sambalpur, and parts of Raipur have experienced increased flood exposure due to impervious surface expansion and inadequate drainage infrastructure.

In the delta, embankment networks have altered natural floodplain connectivity, often transferring risk downstream or across administrative boundaries. Sand mining, deforestation, and land-use change in tributary catchments have further increased runoff intensity and sediment imbalance, exacerbating flood hazards (CWC, 2018).

6.2.3 Influence of Dam Operations on Downstream Flooding

Reservoir operations play a critical role in shaping flood risk in the modern Mahanadi basin. While dams such as Hirakud provide partial flood moderation, operational constraints related to storage targets, hydropower generation, and safety requirements often limit their buffering capacity during extreme events. Sudden or high-volume releases during peak inflow periods have, in several instances, coincided with high tributary discharge downstream, amplifying flood impacts in the lower basin (Ghosh et al., 2020).

6.3 Assessment of Vulnerability

6.3.1 Vulnerable Population Centers and Communities

Flood vulnerability assessments consistently identify the lower Mahanadi basin as hosting the most exposed populations, with dense rural settlements and limited evacuation options. Districts such as Kendrapada, Jagatsinghpur, Cuttack, and Puri experience repeated flood impacts, particularly affecting low-income and agrarian communities.

In the upper basin, vulnerable populations include communities residing near reservoir backwater zones and along tributaries such as the Hasdeo and Seonath, where prolonged inundation disrupts livelihoods and access to essential services.

6.3.2 Critical Infrastructure at Risk

Floods in the Mahanadi basin pose significant risks to critical infrastructure, including road and rail networks, bridges, embankments, and irrigation structures. Repeated overtopping and breaching of embankments in the delta undermine long-term flood protection efforts. Transportation corridors connecting coastal Odisha with inland regions are frequently disrupted during major flood events, hampering relief and recovery operations (CWC, 2020).

6.3.3 Impact on Agriculture and Livelihoods

Agriculture remains one of the most flood-affected sectors in the basin. The deltaic region, often referred to as the rice bowl of Odisha, suffers extensive crop losses during prolonged inundation, particularly during the kharif season. In Chhattisgarh, floods affect paddy cultivation, fisheries, and forest-based livelihoods, while also disrupting mining and industrial activities in selected areas. Recurrent flood damage contributes to long-term livelihood insecurity and economic vulnerability across the basin (Ghosh et al., 2020).

7. Conclusions and Recommendations

7.1 Summary of Key Findings

This report synthesizes historical records, scientific literature, and institutional knowledge to assess flood risk in the Mahanadi River basin. The analysis demonstrates that flood hazards are basin-wide phenomena driven primarily by synchronized tributary inflows, limited downstream conveyance capacity, and compound flooding processes in the delta. Structural flood control measures have reduced moderate floods but remain insufficient for managing extreme events, particularly under changing climatic conditions.

7.2 Recommendations for Integrated Flood Risk Management

Effective flood risk management in the Mahanadi basin requires a shift from isolated structural interventions to integrated, basin-scale strategies. Priority should be given to coordinated reservoir operation protocols based on real-time hydrological forecasting. Strengthening floodplain zoning regulations, improving embankment maintenance, and restoring natural flood buffers such as wetlands and mangroves can significantly reduce flood impacts. Enhanced inter-state coordination between Chhattisgarh and Odisha is essential for equitable and effective flood management.

7.3 Intended Applications and Uses of This Report

The findings of this report are intended to support decision-making by agencies such as the Odisha State Disaster Management Authority and the Central Water Commission. The report provides a scientific basis for flood preparedness planning, early warning system development, infrastructure design, and long-term resilience-building initiatives. It may also serve as a reference framework for future basin-scale flood hazard assessments in India.

7.4 Directions for Future Research and Detailed Studies

Future research should focus on developing fully integrated hydrological–hydraulic–coastal models that capture tributary dynamics, reservoir operations, and sea-level interactions. Improved use of palaeoflood evidence, high-resolution topographic data, and climate change projections will enhance understanding of extreme flood behavior. Strengthening long-term monitoring networks and data-sharing mechanisms will be critical for advancing flood risk science and management in the Mahanadi basin.

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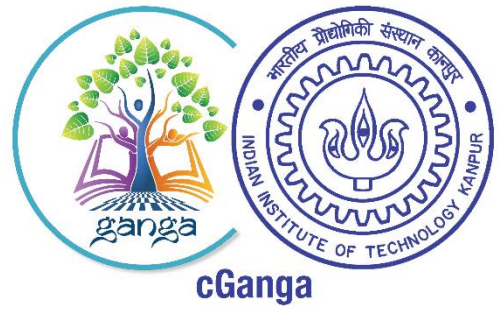
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