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

Learning From Indian River Basins

Mahanadi River Basin

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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.

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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.

www.cmahanadi.org

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

Acknowledgment

This report is a comprehensive outcome of the project jointly executed by NIT Raipur (Lead Institute) and NIT Rourkela (Fellow Institute) under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCD) in 2024. We gratefully acknowledge the individuals who provided information and photographs for this report.

Disclaimer

This report is a preliminary version prepared as part of the ongoing Condition Assessment and Management Plan (CAMP) project. The analyses, interpretations and data presented in the report are subject to further validation and revision. Certain datasets or assessments may contain provisional or incomplete information, which will be updated and refined in the final version of the report after comprehensive review and verification.

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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. We hope that this report will catalyze 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
Management Studies (cMahanadi)
NIT Raipur & NIT Rourkela

ABBREVIATIONS

IWRM	Integrated Water Resources Management
BHIWA	Basin-wide Holistic Integrated Water Assessment Model
CPSP	Country Policy Support Programme
GIS	Geographic Information System
WQI	Water Quality Index
LULC	Land Use / Land Cover
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
WOA	Whale Optimization Algorithm
ANFIS-WOA	Hybrid Adaptive Neuro-Fuzzy Inference System – Whale Optimization Algorithm
DO	Dissolved Oxygen
TDS	Total Dissolved Solids
EC	Electrical Conductivity
SO_4^{2-}	Sulphate ion
Cl^-	Chloride ion
PO_4^{3-}	Phosphate ion
Ca^{2+}	Calcium ion
Mg^{2+}	Magnesium ion
NSE	Nash–Sutcliffe Efficiency
MODIS	Moderate Resolution Imaging Spectroradiometer
SRTM DEM	Shuttle Radar Topography Mission – Digital Elevation Model
WEB-DHM-RRI	Water Energy Budget Distributed Hydrological Model – Rainfall Runoff Inundation

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1. Introduction

The Mahanadi River Basin, one of India's most significant east-flowing river systems, epitomizes both opportunity and challenge in the nation's pursuit of sustainable water resource management. Stretching across the states of Chhattisgarh, Odisha, and parts of Jharkhand, Maharashtra, and Madhya Pradesh, the basin supports millions of people whose livelihoods are closely tied to its waters. From agriculture and industry to domestic use and ecological balance, the Mahanadi forms the lifeline of central and eastern India. However, this lifeline is increasingly under strain due to growing population pressures, industrial expansion, climate variability, and ecological degradation. Understanding, managing, and restoring the health of the Mahanadi is therefore not merely an environmental necessity it is a socio-economic imperative.

The Mahanadi River Basin is characterized by diverse physiographic, climatic, and socio-economic conditions. Originating from the highlands of Chhattisgarh and flowing eastward to meet the Bay of Bengal, the river and its numerous tributaries such as the Seonath, Hasdeo, Mand, Ib, Ong, and Tel, drain an extensive catchment area of nearly 141,600 square kilometers. This vast expanse encompasses forested uplands, agricultural plains, industrial belts, and densely populated urban centers, each exerting unique pressures on the river system. The basin's hydrological regime, dominated by monsoonal rainfall, is marked by pronounced seasonal variability, abundant flows during the wet season followed by lean flows in the dry months. This variability creates challenges for water storage, flood management, irrigation, and environmental flow maintenance.

In recent decades, human interventions have altered the basin's natural flow and ecological equilibrium. The construction of dams and reservoirs has facilitated irrigation, hydropower generation, and flood control, but it has also disrupted sediment transport, aquatic biodiversity, and downstream ecosystems. Industrial clusters and mining belts, particularly in the central and lower reaches, have contributed to water quality deterioration due to untreated effluents and solid waste disposal. Urban expansion has further compounded pollution and encroachment issues. Simultaneously, agricultural intensification and land-use changes have led to soil erosion, siltation, and declining groundwater recharge. These cumulative impacts highlight the urgent need for a basin-wide, integrated management strategy that balances human development with ecological sustainability.

The lessons from other Indian river basins, such as the Baitarani and Brahmani, offer valuable insights for shaping such strategies. In the Baitarani River Basin, for instance, integrated water resource management (IWRM) approaches have demonstrated the effectiveness of data-driven decision-making, stakeholder engagement, and community-based conservation initiatives. Studies conducted under the National River Conservation Directorate (NRCD) and Centres for River Basin Management, like cGanga at IIT Kanpur and cMahanadi at NIT Raipur and NIT Rourkela, underscore the importance of inter-institutional collaboration, long-term monitoring, and policy support in ensuring river system resilience. These approaches provide a guiding framework for the Mahanadi Basin, which faces comparable environmental, social, and hydrological challenges.

Incorporating an integrated river basin approach allows for holistic consideration of all water-related components, surface and groundwater interactions, land use, ecosystem health, and socio-economic development. The adoption of IWRM principles in the Mahanadi Basin could harmonize competing demands between agriculture, industry, domestic needs, and ecological preservation. This approach also encourages multi-sectoral coordination across state and district boundaries, promoting efficient resource allocation and conflict resolution. Furthermore, integrating advanced hydrological modeling tools, GIS-based analysis, and machine learning techniques, as demonstrated in the Baitarani studies, can enhance flood prediction, water allocation planning, and climate change adaptation in the Mahanadi context.

Equally critical is the inclusion of community participation in decision-making processes. The success of initiatives like the Dabur–Baitarani project in Odisha, which focused on community-driven medicinal plant restoration and sustainable livelihoods, demonstrates that environmental conservation and socio-economic development need not be mutually exclusive. In the Mahanadi Basin, involving local stakeholders, including farmers, fisherfolk, women's self-help groups, and tribal communities, can foster ownership and accountability in resource management. Capacity building, awareness programs, and equitable benefit-sharing mechanisms can transform these communities from passive beneficiaries into active custodians of the river system.

Climate change adds another layer of complexity to the Mahanadi Basin's management. Variations in rainfall patterns, increasing frequency of floods and droughts, and shifting temperature regimes threaten water security and ecosystem stability. Integrating climate projections into river basin planning is essential to develop adaptive strategies that enhance resilience. The use of scenario-based modeling and environmental flow assessments can guide sustainable water allocation, ensuring both human and ecological needs are met. Learning from the flood hazard mapping and risk-based embankment management of the Brahmani–Baitarani basin, the Mahanadi Basin could similarly adopt advanced forecasting systems and adaptive reservoir operation models to minimize flood damages and optimize water use.

Another crucial aspect lies in addressing water quality issues. The Baitarani River's experiences with pollution from industrial and agricultural sources highlight the importance of continuous water quality assessment, pollution load apportionment, and enforcement of wastewater treatment norms. For the Mahanadi Basin, particularly in industrial belts such as Raipur, Jharsuguda, and Sambalpur, systematic monitoring and remediation efforts must be prioritized. The introduction of water quality indices (WQIs), coupled with community-based monitoring programs, can enhance transparency and accountability. Sustainable wastewater management, zero-liquiddischarge systems, and green infrastructure solutions such as constructed wetlands and bioremediation can further aid in restoring river health.

Ultimately, the Mahanadi River Basin's management must be grounded in a comprehensive policy framework that integrates environmental, social, and economic objectives. Strengthening institutional mechanisms through the cMahanadi Centre and other basin-level authorities will be vital for coordinating research, data sharing, and governance. Cross-state cooperation between Chhattisgarh and Odisha, supported by central agencies such as NRCD and cGanga, can ensure uniform standards and shared accountability. Policy alignment with national initiatives like the National River Conservation Plan (NRCP) and the Namami Gange model can provide both direction and funding support.

Therefore, the Mahanadi River Basin stands at a critical juncture. It is a river of abundance but also of increasing vulnerability. The convergence of scientific knowledge, community participation, technological innovation, and strong governance offers a pathway toward sustainable river basin management. The insights drawn from the Baitarani and Brahmani experiences demonstrate that integrated, inclusive, and adaptive approaches can transform challenges into opportunities. For the Mahanadi, this means not only conserving a river but also securing the well-being of millions who depend on it a commitment that transcends hydrological boundaries and speaks to the very essence of environmental stewardship and intergenerational equity.

1.1 Objective of the Report

The primary objective of this report is to provide an analysis of international river basin management experiences, with the aim of extracting lessons that can inform and improve water governance practices. In an era marked by rapid urbanization, climate change, and escalating water scarcity, understanding the successes and challenges of well-managed river basins is crucial. By reviewing case studies from some of the world's most iconic rivers, this report seeks to establish a framework for integrated and adaptive river basin management those policymakers, water managers, and stakeholders can apply to local and regional contexts.

1.2 Key highlights and structure of the report

This report is structured to offer a comparative analysis of international river basin management. The key highlights include:

- Case Study Overview: Each case study begins with a background that covers the geographical setting, historical context, and major challenges faced by the river basin. For example, the Thames case study outlines how urban renewal and restoration projects have reversed severe ecological degradation, while the Rhine study discusses cross-border collaboration and the significant reduction in pollutant levels over the decades.

- Problem Statements: For each river basin, the report identifies the core environmental and management challenges, such as pollution, over-extraction, flood risk, and biodiversity loss, and examines the specific factors contributing to these issues. This section not only describes the challenges but also contextualizes them within the broader socio-economic and climatic trends impacting the region.
- Strategies and Interventions: A central part of the report is dedicated to analyzing the approaches adopted to overcome these challenges. This includes legislative reforms, technological innovations, community engagement practices, and restoration initiatives. The report details how integrated water management plans and adaptive governance models have been implemented in each basin, highlighting the importance of continuous monitoring and stakeholder collaboration.
- Outcomes and Impact: The report evaluates the tangible results of the interventions, presenting evidence of environmental recovery, improved water quality, and enhanced socio-economic benefits. Comparative data on water quality, flood management, and biodiversity restoration provide a sense of the progress made over time.
- Lessons Learned and Recommendations: Drawing from the successes and shortcomings observed in each basin, this section synthesizes key lessons for policymakers. It emphasizes the need for long-term commitment, cross-jurisdictional cooperation, and the integration of traditional knowledge with modern management practices. Recommendations are offered to guide future policies and investments in river basin management.

The structure of the report is designed to be wide-ranging and practical. Organizing the content into distinct yet interrelated sections allow readers to gain an understanding of each case study while also appreciating the common themes and divergent approaches across international contexts. The usefulness of learning from these experiences lies in the ability to adapt and tailor proven strategies to local challenges. Policymakers can leverage these insights to formulate context-sensitive policies that enhance the sustainability of their river basins.

2. Baitarani River Basin: A Comprehensive Case Study on Water Resources and Basin Management

2.1 River Basin Planning of Baitarani Sub-Basin, India, Using a River System Approach

1. **Case Study Overview**

a. Project Background and Location

The Baitarani River sub-basin, located in the states of Odisha and Jharkhand, India, faces increasing competition for water resources despite not being classified as a scarcity situation yet (Jain et al., 2017). The 355 km long river has a catchment area of 14,218 sq km. A major portion of the river basin lies within the state of Odisha i.e., 13,482 sq. km (94.83%), and the remaining area of 736 sq. km (5.17%) of its upper reach, lies in Jharkhand state. The basin is surrounded by the Brahmani basin on the South and West, the Subarnarekha basin on the North, the Burhabalang and the Bay of Bengal on the east. The districts falling under the basin are Balasore, Bhadrak, Jajpur, Kendrapada, Angul, Keonjhar, Mayurbhanj and Sundergarh in Odisha and West Singhbhum in Jharkhand. The river basin is situated approximately between East longitudes of 85°10' to 87°03' and between North latitudes of 20°35' to 22°15' (Jain et al., 2017). The major tributaries joining the river include Deo, Kanjhari, Kusei and Salandi.

b. Problem Statement: Management or Environmental Challenge

The Baitarani sub-basin grapples with a complex set of interconnected challenges. Poverty and inequity among tribal communities who practice shifting cultivation in the upper catchments, the threat of floods and droughts impacting economic development, livelihoods, and the ecosystem in its lower rich delta are key issues (Jain et al., 2017). Agriculture remains the largest consumer of water and plays a key role in the sub-basin. The growing pressures of industrialization, urbanization, and population growth on water quality and quantity exacerbate these issues, presenting challenges for future water management. With a population growth gradient of about 14% (2011) to 6% (2051) the expansion of the urban centres, the mining and metallurgic industries, as well as irrigated agriculture, the growing pressure on environment conservation, tremendous challenge lies ahead for the basin planners (Jain et al., 2017). By 2051, with a population increase estimated at 4.74 million, the water availability per capita should fall at around 1635 cum/yr/head.

2. Project Description

a. Goals and Objectives

The primary goals of the river basin planning initiative in the Baitarani sub-basin are: (i) To prepare a long-term perspective plan for the development of the Basin's Water Resources; (ii) To develop a comprehensive and integrated approach to the development of water and other natural resources using water, with due regard to constraints imposed by configuration of water availability (Jain et al., 2017). The study aims to establish a framework to support the goals and targets of basin planning in the context of IWRM.

b. Strategies and Interventions

The study employed the "Source" software developed by eWater, Australia, to simulate various scenarios for the Baitarani sub-basin [1]. The sub-basin was divided into six sub-catchments for modeling purposes: Champua, Kanjhari, Anandpur, Remal, Salandi, and Akhuapada (Jain et al., 2017). Simulations were conducted under three sets of scenarios: baseline scenarios (with and without current infrastructure), scenarios with ongoing projects completed by 2021, and scenarios with proposed projects completed by 2051, both with and without the impacts of climate change (wet and dry spells).

The modeling exercise considered rainfall-runoff patterns, river systems, hydraulic infrastructure, climate change impacts, and various water demands from agriculture, industries, mining, domestic use, livestock, and environmental flow (Jain et al., 2017). Rainfall analysis of 24 years revealed that about 90% runoff generated in monsoon months (June-Oct) and remaining in Non-monsoon (Nov-Feb) and Lean months (March-May). Water regime as an environmental flow (EF) is considered at the rate of 30% (Lean), 25% (Non monsoon), and 20% (Monsoon), within the river to maintain flow requirements for ecosystem.

c. Key Stakeholders and Partnerships

The Basin Planning & Management Organisation, Central Water Commission, New Delhi, conducted the river basin planning study. Key stakeholders include government agencies responsible for water resources management, local communities, industries, and agricultural representatives. Collaboration and partnerships among these stakeholders are crucial for the successful implementation of the basin plan.

3. Outcomes and Impact

a. Environmental Benefits

The study emphasized the importance of maintaining environmental flows (EF) within the Baitarani River to support river health and riverine ecology [1]. The simulation showed average annual water availability in the sub-basin is about 5,642 MCM based on the data range 1988-2012. The proposed EF regime, with rates of 30% (Lean), 25% (non-monsoon), and 20% (Monsoon), aims to balance water resource utilization with the ecological needs of the river system. Climate Change models unveiled water availability as 4,939 MCM and 9,378 MCM for dry and wet spell extremes respectively (Jain et al., 2017).

b. Social Benefits

By addressing water scarcity and promoting equitable distribution, the river basin plan can contribute to improved livelihoods for the communities dependent on the Baitarani River. The plan's focus on IWRM principles emphasizes the importance of community engagement in water resource management, fostering a sense of ownership and responsibility. Further, addressing water scarcity can lead to reduce water related conflicts among various stakeholders. The estimated population of the sub-basin, which was 3.51 million in 2015 is projected to increase to 4.74 million by 2051.

c. Economic Benefits

The river basin plan aims to optimize water resource utilization, leading to potential cost savings in water supply and irrigation (Jain et al., 2017). By promoting sustainable agricultural practices and industrial development, the plan can contribute to job creation and economic growth in the region. The study emphasizes the need for industry planning to develop production functions that relate industrial policies to water availability and wastewater discharge constraints, promoting water use efficiency in the industrial sector (Jain et al., 2017). Agricultural productivity in the sub-basin is quite low, with total yields of 1035 kilotons/year in 2015 against a requirement of 769 kilotons/year. Addressing these issues can improve agricultural productivity and boost the economy.

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

Several key takeaways emerge from the Baitarani sub-basin planning study. First, the integration of climate change considerations into water resource planning is crucial for developing resilient strategies (Jain et al., 2017). The Climate Change models unveiled water availability as 4,939 MCM and 9,378 MCM for dry and wet spell extremes respectively. Second, a comprehensive understanding of water demands across various sectors (agriculture, industry, domestic) is essential for effective water allocation. Third, the implementation of IWRM principles, including stakeholder engagement and equitable distribution, is vital for sustainable water management (Jain et al., 2017). Fourth, the study highlights the need for sound water budgeting for industry and agriculture, and water use efficiency measures to address water stress in specific sub-catchments. Finally, the importance of environmental flows (30% in Lean, 25% in Non-monsoon and 20% in Monsoon) in maintaining river health and ecological integrity cannot be overstated (Jain et al., 2017).

b. Best Practices and Strategies for Replication

The Baitarani sub-basin planning study offers several best practices and strategies that can be replicated in other river basins facing similar challenges. These include:

- **Integrated Modeling Approach:** Utilizing tools like the "Source" software to simulate various scenarios and assess the impacts of climate change and human activities.
- **Sub-Catchment Level Analysis:** Dividing the basin into smaller units for more detailed analysis and targeted interventions.
- **Stakeholder Engagement:** Involving local communities, government agencies, and other stakeholders in the planning process.
- **Environmental Flow Assessment:** Determining and implementing appropriate environmental flow regimes to protect river ecosystems.
- **Water Use Efficiency Measures:** Promoting water conservation and efficiency in agriculture, industry, and domestic sectors.

- **Long-Term Perspective Planning:** Developing long-term plans that consider future water demands and climate change impacts.
- **Data-Driven Decision Making:** Using data and analysis to inform water resource management decisions.
- **Addressing low agricultural productivity:** Promoting use of HYV seeds, chemical fertilizer, organic manure and improving rural infrastructure to meet future food demands.

c. Areas for Further Improvement or Research

While the Baitarani sub-basin planning study provides valuable insights, several areas warrant further improvement or research. These include:

- **Detailed Climate Change Impact Assessment:** Conducting more detailed assessments of climate change impacts on water availability and demand, considering various climate scenarios.
- **Socio-Economic Analysis:** Conducting more in-depth socio-economic analysis to understand the impacts of water resource management on livelihoods and poverty reduction, especially among tribal communities.
- **Land Use Planning Integration:** Integrating land use planning with water resource planning to address the impacts of land use changes on water quality and quantity.
- **Monitoring and Evaluation:** Establishing a robust monitoring and evaluation system to track the implementation of the basin plan and assess its effectiveness.
- **Water Quality Modeling:** Incorporating water quality modeling into the assessment to address pollution issues from industries and urbanization and ensure water quality standards are met.
- **Conflict Resolution Mechanisms:** Developing mechanisms for resolving water-related conflicts among different stakeholders.
- **Capacity Building:** Investing in capacity building for local communities and water resource managers to enhance their ability to manage water resources sustainably.

2.2 Flood Hazard Mapping and Prediction in the Baitarani River Basin, India Using GIS and Machine Learning Techniques

1. Case Study Overview

a. Project Background and Location

The Baitarani River basin, located in East India, predominantly flows through the Keonjhar district of Odisha (India). A small portion of the upper reach lies in Jharkhand. The river basin extends between 21°26'52.92" to 22°11'51.65" N latitude and 85°09'42.66" to 85°44'10.42" E longitude, originating from the Guptaganga hills in Kendujhar (Figure 1). The river travels approximately 360 km before converging into the Bay of Bengal, draining an area of around 14,000 km2. The study focuses on flood hazard mapping and prediction within this basin, aiming to mitigate the increasing economic losses and mortality rates associated with floods in the region (Samantaray et al., 2022).

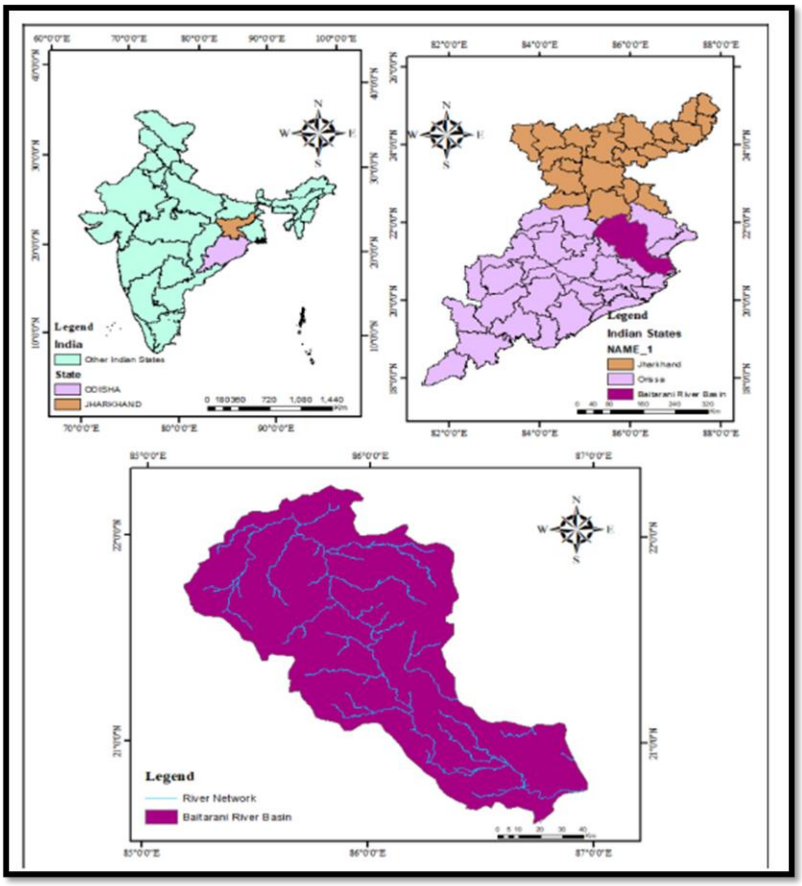

Figure 1: Study area map

b. Problem Statement: Management or Environmental Challenge

The Baitarani River basin is highly susceptible to flooding, mainly due to heavy rainfall concentrated between June and October, accounting for over 80% of the average annual precipitation of 1,534 mm. Floods in the region lead to significant disruptions in urban and rural life, causing damage to infrastructure, agricultural land, and residential areas (Samantaray et al., 2022). The challenge lies in developing effective flood management strategies that can minimize economic losses, protect human lives, and ensure sustainable development in the region. Traditional flood management approaches often lack the accuracy and efficiency required for timely and effective interventions. There is a need for advanced techniques that can provide reliable flood hazard maps and accurate flood predictions to support informed decision-making and proactive disaster management.

2. Project Description

a. Goals and Objectives

The primary goal of this project was to develop a flood hazard map for the Baitarani River basin using a combination of Geographic Information System (GIS) and artificial intelligence models (Samantaray et al., 2022). The specific objectives included:

- Identifying and mapping flood-influencing factors such as slope, elevation, flow length, rainfall, land use/land cover (LULC), and distance from rivers.
- Integrating these factors within a GIS environment to create a flood hazard map.
- Developing and implementing a hybrid Adaptive Neuro-Fuzzy Inference System-Whale Optimization Algorithm (ANFIS-WOA) model for flood prediction.
- Assessing the performance of the hybrid ANFIS-WOA model against standalone ANFIS and Artificial Neural Network (ANN) models.
- Providing a cost-effective solution for flood-related problems in the Baitarani River basin, aiding national and local government plans for future development.

b. Strategies and Interventions

The project employed a multi-faceted approach, integrating GIS techniques with machine learning models to achieve its objectives (Samantaray et al., 2022). The key strategies and interventions were:

- **Data Acquisition and Pre-processing:** Relevant data for the six flood-influencing factors (slope, elevation, flow length, rainfall, LULC, and distance from rivers) were collected from various sources, including the Central Water Commission (CWC), Bhubaneswar. The data were then pre-processed and converted into raster maps with a 30m resolution using ArcGIS 10.2 software.
- **GIS-based Flood Hazard Mapping:** ArcGIS was used to create individual thematic maps for each flood-influencing factor. These maps were then integrated to generate a composite flood hazard map, delineating areas with varying degrees of flood risk. The Analytical Hierarchy Process (AHP) was likely used within the GIS environment to weight and combine the different factors based on their relative importance in causing floods.
- **Flood Prediction Modeling:** The study utilized three different machine learning models for flood prediction: ANN, ANFIS, and a hybrid ANFIS-WOA model. The ANN model was trained using the backpropagation algorithm. The ANFIS model, known for its ability to handle noisy and non-linear data, was implemented with Gaussian membership functions. The hybrid ANFIS-WOA model was developed to enhance the performance of the ANFIS model by using the Whale Optimization Algorithm (WOA) to optimize the membership functions and rule parameters.

- **Model Training and Validation:** The models were trained using historical flood data from the Baitarani River basin. The performance of each model was assessed using statistical criteria such as the coefficient of determination (R2), root mean square error (RMSE), and mean absolute error (MAE). Validation was performed by comparing the model predictions with actual hydrological records.

c. Key Stakeholders and Partnerships

The successful implementation of this project required collaboration among various stakeholders. Key stakeholders included:

- **Researchers:** The research team from the Department of Civil Engineering, CET Bhubaneswar, and the National Institute of Technology, Silchar, were responsible for developing and implementing the methodology.
- **Government Agencies:** The Central Water Commission (CWC), Bhubaneswar, provided essential rainfall and hydrological data. National and local government agencies are the intended beneficiaries of the project's findings, using the flood hazard maps and prediction models for planning and disaster management.
- **Local Communities:** The inhabitants of the Baitarani River basin, who are directly affected by floods, are key stakeholders. The project aims to provide them with better protection and reduce their vulnerability to flood-related disasters.

3. Outcomes and Impact

a. Environmental Benefits

The study assessed flood hazard mapping in the Baitarani River Basin using hybrid data-driven models, specifically ANFIS-WOA, ANFIS, and ANN. The Analytical Hierarchical Process (AHP) was used to assign weights to influencing factors such as elevation, slope, land use/land cover (LULC), rainfall, flow length, and distance from the river. The consistency ratio (CR) was below 0.1, ensuring the validity of weight assignments. The flood hazard map classified the basin into five risk zones: very low, low, moderate, high, and very high hazard areas.

Among the contributing factors, rainfall had the highest impact on flood occurrence ($R^2 = 0.9808$), while flow length had the least influence ($R^2 = 0.9789$). Model performance analysis demonstrated that ANFIS-WOA outperformed standalone ANFIS and ANN, achieving the highest accuracy with an R^2 value of 0.99782 (training) and 0.9849 (testing). The model also had the lowest Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), with values of 0.00268 and 0.1864 during training and 0.00307 and 1.097 during testing, respectively. In comparison, ANFIS exhibited an R^2 of 0.9676 (testing), RMSE of 4.639, and MAE of 0.00508, while ANN had an R^2 of 0.93302, RMSE of 9.9724, and MAE of 0.00721.

The flood hazard map revealed that the southeastern part of the basin is most susceptible to flooding (Figure 2). The study highlights the effectiveness of ANFIS-WOA in improving flood prediction by overcoming limitations of standalone ANFIS through Whale Optimization Algorithm (WOA), which enhances global optimization capabilities. The study recommends integrating flood hazard maps into land-use planning and infrastructure development. Future research should compare these results with flood simulation models and explore the impact of flooding on soil erosion, infrastructure damage, and migration patterns.

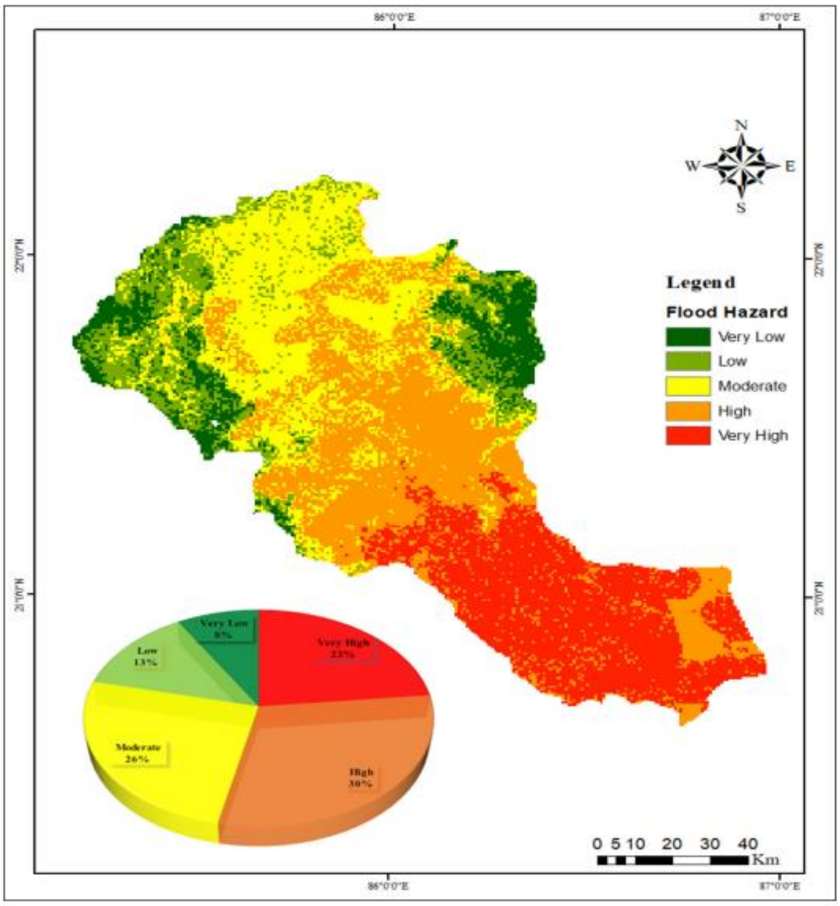

Figure 2: Flood hazard map

b. Social Benefits

The project's outcomes have significant social benefits for the communities living in the Baitarani River basin (Samantaray et al., 2022). These benefits include:

- **Reduced Loss of Life and Property:** Accurate flood predictions and hazard maps enable timely evacuation and preparedness measures, reducing the risk of fatalities and minimizing property damage.
- **Improved Livelihoods:** By protecting agricultural land and infrastructure from floods, the project contributes to the stability and improvement of

livelihoods for farmers and other community members who depend on these resources.

- **Enhanced Community Engagement:** The project's findings can be used to raise awareness among local communities about flood risks and promote their participation in disaster preparedness and mitigation efforts.
- **Increased Resilience:** By providing tools and information for effective flood management, the project enhances the overall resilience of the communities in the Baitarani River basin to climate change and other environmental challenges.

c. Economic Benefits

The project's economic benefits are substantial, stemming from the reduction in flood-related damages and the improvement in resource management (Samantaray et al., 2022). These benefits include:

- **Cost Savings:** By preventing or mitigating flood damage to infrastructure, agriculture, and property, the project leads to significant cost savings for both the government and local communities.
- **Increased Agricultural Productivity:** Protecting agricultural land from floods ensures higher crop yields and increased income for farmers.
- **Job Creation:** The implementation of flood management measures, such as the construction of flood defenses and the development of early warning systems, can create employment opportunities for local communities.
- **Stimulation of Economic Growth:** By reducing the economic disruption caused by floods, the project contributes to a more stable and predictable environment for investment and economic growth.

IV. Lessons Learned and Recommendations

a. Key Takeaways from the Project

The project provided several key takeaways regarding flood hazard mapping and prediction (Samantaray et al., 2022):

- **Integration of GIS and Machine Learning:** The integration of GIS and machine learning techniques offers a powerful approach for flood hazard mapping and prediction, providing more accurate and reliable results than traditional methods.
- **Importance of Hybrid Models:** Hybrid models, such as the ANFIS-WOA model, can significantly improve the accuracy of flood predictions by combining the strengths of different modeling approaches.
- **Data Quality and Availability:** The accuracy of flood hazard maps and prediction models depends heavily on the quality and availability of input data. Efforts should be made to ensure the collection of high-quality data and the establishment of robust data sharing mechanisms.

- **Stakeholder Collaboration:** Effective flood management requires collaboration among researchers, government agencies, and local communities.

b. Best Practices and Strategies for Replication

Based on the project's experience, the following best practices and strategies are recommended for replication in another river basin (Samantaray et al., 2022):

- **Comprehensive Data Collection:** Collect and integrate relevant data on flood-influencing factors, including hydrological data, meteorological data, topographic data, and land use data.
- **Selection of Appropriate Models:** Choose appropriate machine learning models based on the characteristics of the river basin and the availability of data. Hybrid models, such as ANFIS-WOA, should be considered for their potential to improve prediction accuracy.
- **Model Validation and Calibration:** Rigorously validate and calibrate the models using historical flood data to ensure their accuracy and reliability.
- **GIS-based Visualization and Dissemination:** Use GIS to visualize and disseminate the flood hazard maps and prediction results to stakeholders, including government agencies, local communities, and the public.
- **Capacity Building:** Provide training and capacity building to local communities and government agencies on the use of flood hazard maps and prediction models.

c. Areas for Further Improvement or Research

The study identified several areas for further improvement and research (Samantaray et al., 2022):

- **Incorporation of Climate Change Scenarios:** Future research should focus on incorporating climate change scenarios into flood prediction models to assess the potential impacts of climate change on flood risk.
- **Real-time Flood Forecasting:** Develop real-time flood forecasting systems that can provide timely and accurate predictions of flood events, enabling proactive disaster management.
- **Integration of Socio-economic Factors:** Integrate socio-economic factors into flood hazard assessments to better understand the vulnerability of different communities to flood impacts.

2.3 Baitarani Initiative - Community-Driven Medicinal Plant and Bark Restoration in Odisha, India

1. Case Study Overview

a. Project Background and Location

The "Dabur - Baitarani Initiative" project in Odisha focuses on the restoration of wild bark species in forest areas by adopting a high-density plantation approach in agricultural fields and promoting fair trading through community involvement around targeted medicinal plant products (Baitarani Initiative, 2019). This initiative aims to ensure alternative income for forest-dependent communities and farmers while simultaneously ensuring the protection and preservation of wild medicinal stock (Baitarani Initiative, 2019). A holistic approach is established by involving different stakeholders like the forest department, PR members, other NGOs, small traders, WSHGs, and forest fringe communities (Baitarani Initiative, 2019). The project operates in eight forest divisions across six districts of Odisha, a state known for its rich biodiversity and significant tribal population (Baitarani Initiative, 2019). The Baitarani Initiative team believes in interfacing knowledge to enhance development impact and blends modern technology with local ecological knowledge to improve the lives and habitats of tribal communities (Figure 3) (Baitarani Initiative, 2019).

Figure 3: Habitats of tribal communities

b. Problem Statement: Management or Environmental Challenge

Forest-dependent communities in Odisha face challenges related to livelihood security and forest degradation. Over-harvesting of medicinal plants and bark for commercial purposes threatens biodiversity and ecosystem health. The project addresses the need for sustainable resource management by promoting the cultivation of medicinal plants and bark, thereby reducing pressure on wild populations. It seeks to establish a community-driven model that balances economic benefits with environmental conservation. This sustainable approach is crucial for long-term ecological and economic resilience.

2. Project Description

a. Goals and Objectives

The primary goals of the Dabur-Baitarani Initiative are:

- **Restoration of Wild Bark Species:** Promoting high-density plantations of targeted bark species in agricultural fields to reduce dependence on wild harvesting.
- **Fair Trading of Medicinal Plant Products:** Ensuring fair prices and market access for communities involved in harvesting and processing medicinal plants.
- **Alternative Income Generation:** Providing sustainable livelihood options for forest-dependent communities through cultivation and sustainable harvesting practices.
- **Community Empowerment:** Building the capacity of local communities to manage and conserve natural resources.
- **Biodiversity Conservation:** Protecting and preserving wild medicinal plant stocks through sustainable harvesting and regeneration practices.

b. Strategies and Interventions

The Baitarani team developed a "T-5 approach" (Targeting, Terms and Condition, Training, Trading, and Transparency) to effectively achieve its objectives in a sustainable and practical manner, particularly in the field of forest-based livelihoods (Baitarani Initiative, 2019). The operational process is well-defined to carry out the entire activity systematically and meaningfully (Baitarani Initiative, 2019).

- **Targeting:** One of the key aspects of the project's success is the proper and scientific targeting of the product, geographic area, and community to work with (Baitarani Initiative, 2019). Identification and revival of village-level institutions like Vana Samrakhyan Samiti (VSS), Women Self Help Groups (WSHG), and business clusters are also part of the targeting process (Baitarani Initiative, 2019). During the reported year, around 4000 households were covered in 400 villages across 6 districts (8 forest divisions), 22 forest ranges, 8 business clusters, and 22 aggregation points (Baitarani Initiative, 2019). Out of the 400 villages, 219 are VSS and 30 are SHGs actively involved in this process. Seven medicinal plant products targeted for harvesting are Terminalia chebula (Harda), Terminalia bellirica (Baheda), Emblica officinalis (Anola), Woodfordia fruticosa (Dhatki flower), Asparagus racemosus (Shatavri), Pueraria tuberosa (Vidharikand), and Curculigo orchioides (Talmuli) (Baitarani Initiative, 2019). Four bark species targeted for high-density plantation (HDP) are Premna integrifolia (Premna), Aegle marmelos (Beal), Stereospermum suaveolens (Padal), and Oroxylum indicum (Shyonaka) (Baitarani Initiative, 2019). A Computer Assisted Personal Interviewing (CAPI) based Socio-Economic survey of target households ensures proper community targeting (Baitarani Initiative, 2019) (Table 1).

- **Terms and Condition:** The terms and conditions for harvesting, aggregation, and marketing of medicinal plants are clearly defined to ensure fairness and transparency (Baitarani Initiative, 2019).

Table 1: Summary of the T5 Approach Framework and Its Key Components

Targeting	Terms & Conditions	Training	Trading	Transparency
• Village / Community• Product• Geographic area for wild harvesting and farming in Agri-field.	• MAT – Mutually Agreed Terms• PIC – Prior Informed Consent	• Coordination• Quality Parameter/Addition• MF & MFE in Field Nursery & Plantation (only for targeted species)• Awareness (Dos & Don'ts)	• Focus on Business Sustainability – Long run• Forest Gathering & High-density Plantation• Focus on primary value addition• Packaging – storing and labeling• Transport• Value chain development• Purchase order (FPCs, Forest Dept., GP, Stock Card, loading etc.)	• Community-based demand driven• Financial transparency• Payment through bank only• Aadhar linkage• Common price sheet for entire Odisha state

- **Training:** Skill up-gradation is a continuous process (Baitarani Initiative, 2019). To ensure a systematic micro-enterprise model around medicinal plant products, properly capacitating different stakeholders is extremely important (Baitarani Initiative, 2019). During the reported year, 283 training programs were conducted in 247 days, covering all 6 districts, with a total of 5634 persons trained. Four major types of training were conducted at five different levels (village, aggregation, district, state, and exposure visit) (Baitarani Initiative, 2019).
- **Trading:** Fair trading practices are promoted by establishing direct market linkages with reputable Ayurvedic companies (Baitarani Initiative, 2019).

- **Transparency:** Transparency is maintained in all transactions related to harvesting, aggregation, and marketing of medicinal plants (Baitarani Initiative, 2019).
- **High-Density Plantation (HDP):** Promoting the cultivation of targeted bark species in farmers' fields using a high-density plantation model reduces the need to harvest bark from wild trees. In the reported year, 70,000 plants were planted in farmers' fields (Baitarani Initiative, 2019). This activity can be taken up both in a block plantation approach or through an agro-forestry model. Instead of harvesting barks from wild trees for medicinal purposes, after long research, it was decided to harvest the young roots of the same bark species. Over a period of 6-24 months, those plants will be uprooted, and their roots are to be used for medicinal purposes, providing an alternative additional source of income for villagers (Baitarani Initiative, 2019).
- **Sustainable Harvesting and Aggregation:** During the year 18-19, around 290 MT of raw material was aggregated (Baitarani Initiative, 2019). Facilitation has been made to process the stock at the primary level, and after 100% processing, around 82 MT of processed stock is marketed.
- **Market Linkages:** Stocks were lifted by a third-party lifting agent to the factory point. A direct market linkage is established with a reputed Ayurvedic company like Dabur. All payments against the lifted stock are directly deposited in the business cluster account. For the above stock, around Rs 35 lakh was deposited, which is further shared with different stakeholders and primary collectors in a proportionate ratio (Baitarani Initiative, 2019).
- **Geospatial Platform Development:** A Geo platform was developed for 8 clusters, 22 aggregation points, and 343 villages for better planning and coordination (Baitarani Initiative, 2019).
- **Handbook on Medicinal Plant Harvesting:** A handbook (in English) on seven targeted medicinal plant product harvesting and processing was prepared and released (Baitarani Initiative, 2019).
- **Partnerships:** The Baitarani Initiative works closely with several partner organizations, including TDH-DISHA-PECUC, IFPRI, CYSD, and NRMC, to implement its various programs and activities (Baitarani Initiative, 2019).

c. Key Stakeholders and Partnerships

The Dabur-Baitarani Initiative involves a diverse range of stakeholders:

- **Forest-dependent Communities:** The primary beneficiaries of the project, involved in cultivation, harvesting, and processing of medicinal plants and bark.
- **Baitarani Initiative:** The implementing organization, providing technical expertise, training, and market linkages. The Baitarani Initiative team comprises personnel with diverse expertise working at village, district, and state levels (Baitarani Initiative, 2019).
- **Dabur:** The corporate partner, providing market access and financial support.

- **Forest Department:** Government agency providing regulatory support and guidance.
- **Village Level Institutions:** VSS and WSHGs, playing a crucial role in community mobilization and resource management.
- **Other NGOs:** Partnering in specific project activities and providing additional support.

3. Outcomes and Impact

a. Environmental Benefits

The Dabur-Baitarani Initiative has yielded several environmental benefits:

- **Reduced Pressure on Wild Resources:** By promoting the cultivation of medicinal plants and bark, the project reduces the need to harvest these resources from wild populations, thereby contributing to biodiversity conservation.
- **Habitat Restoration:** High-density plantations of native bark species contribute to habitat restoration and carbon sequestration.
- **Sustainable Harvesting Practices:** Training and awareness programs promote sustainable harvesting practices, ensuring the long-term availability of medicinal plants and bark.
- **Protection of Endangered Species:** The project focuses on protecting and regenerating populations of threatened medicinal plant species.
- **Increased Awareness:** The initiative raises awareness among local communities about the importance of biodiversity conservation and sustainable resource management.
- **Inventorization of Targeted Products:** The initiative also undertakes scientific inventorization to understand the stock availability, its presence, density, growth, regeneration status, and other relevant aspects through a scientific process (Baitarani Initiative, 2019).

b. Social Benefits

The project has also generated significant social benefits:

- **Improved Livelihoods:** Alternative income opportunities from cultivation and sustainable harvesting have improved the livelihoods of forest-dependent communities. In the reported year, Rs 35 lakh was deposited directly into business cluster accounts for the harvested stock, which was then distributed among stakeholders (Baitarani Initiative, 2019).
- **Community Empowerment:** The project has empowered local communities to manage and conserve their natural resources, enhancing their self-reliance and decision-making power.
- **Skill Development:** Training programs have equipped community members with valuable skills in sustainable harvesting, processing, and marketing.

- **Strengthened Social Capital:** The project has strengthened village-level institutions like VSS and WSHGs, promoting collective action and social cohesion.
- **Gender Equity:** The project has focused on empowering women by involving them in income-generating activities and decision-making processes.
- **Socioeconomic Survey of Targeted Households:** The initiative also undertakes socioeconomic surveys of targeted households using Computer Assisted Personal Interviewing (CAPI) to access the present socioeconomic condition of targeted villages (Baitarani Initiative, 2019). During the reported year, data was collected from 1575 households in 262 targeted villages. Data compilation and analysis have been completed, and a report is going to be prepared that will be helpful for future planning (Baitarani Initiative, 2019).
- **Awareness Programs:** The project conducts awareness programs, such as Banamahoschhab, to educate communities on the protection, conservation, and stock augmentation of medicinal plants (Baitarani Initiative, 2019). During the reported year, 3000 seedlings of 15 different species were planted, and seed dibbling programs were organized at educational institutions and VSS sites.

c. Economic Benefits

The economic benefits of the project include:

- **Increased Income:** Alternative income opportunities from cultivation and sustainable harvesting have increased the income of forest-dependent communities.
- **Cost Savings:** By promoting local cultivation and processing, the project reduces the cost of procuring medicinal plants and bark from distant sources.
- **Job Creation:** The project has created job opportunities in cultivation, harvesting, processing, and marketing.
- **Market Access:** The project facilitates direct market linkages between community producers and reputable Ayurvedic companies, ensuring fair prices and market access.

IV. Lessons Learned and Recommendations

a. Key Takeaways from the Project

Several key takeaways from the Dabur-Baitarani Initiative can inform similar projects:

- **Community Participation is Crucial:** The success of the project hinges on the active participation and ownership of local communities.
- **Capacity Building is Essential:** Providing training and technical support to community members is critical for ensuring sustainable practices.
- **Market Linkages are Vital:** Facilitating direct market linkages between community producers and buyers is essential for ensuring fair prices and market access.

- **A Holistic Approach is Necessary:** Addressing both environmental and socio-economic needs is crucial for achieving sustainable development.
- **Monitoring and Evaluation are Important:** Regular monitoring and evaluation are necessary to track progress and identify areas for improvement.

b. Best Practices and Strategies for Replication

The following best practices and strategies can be replicated in similar contexts:

- **Adopt a Community-Driven Approach:** Involve local communities in all stages of project planning and implementation.
- **Provide Comprehensive Training:** Offer training programs on sustainable harvesting, processing, and marketing techniques.
- **Establish Strong Market Linkages:** Facilitate direct market linkages between community producers and buyers.
- **Promote Diversification of Livelihoods:** Support a range of income-generating activities to reduce dependence on any single resource.
- **Foster Collaboration:** Build partnerships between government agencies, NGOs, and private sector companies.

c. Areas for Further Improvement or Research

Areas for further improvement and research include:

- **Value Addition:** Exploring opportunities for value addition through local processing and product development.
- **Certification:** Obtaining organic or fair-trade certifications to enhance market access and prices.
- **Impact Assessment:** Conducting a comprehensive impact assessment to quantify the environmental, social, and economic benefits of the project.
- **Scaling Up:** Expanding the project to other regions with similar ecological and socio-economic conditions.
- **Policy Advocacy:** Advocating for policies that support sustainable harvesting and trade of medicinal plants and bark.

2.4 Water Quality Assessment and Management Strategies for the Baitarani River Basin, Odisha

1. Case Study Overview

a. Project Background and Location

The Baitarani River in Odisha, India, faces serious deterioration due to massive human intervention, making it particularly susceptible to degradation because it receives industrial and wastewater emissions from surrounding organizations and municipal bodies (Das, 2025). This river is a crucial water resource for the region, supporting agriculture, drinking water, and sanitation for local communities, as well as sustaining aquatic ecosystems. However, industrial discharges, untreated sewage, and agricultural runoff have significantly polluted the river, posing serious health risks and ecological damage. This study assesses the water quality of the Baitarani River basin using Water Quality Indices (WQIs) and multivariate statistical techniques to identify pollution sources and suggest management strategies (Figure 4). The analyses conducted include Weighted Arithmetic (WA), Canadian Council of Ministers of the Environment (CCME), Integrated (I) Weight methods, Cluster Analysis (CA), and Principal Component Analysis (PCA).

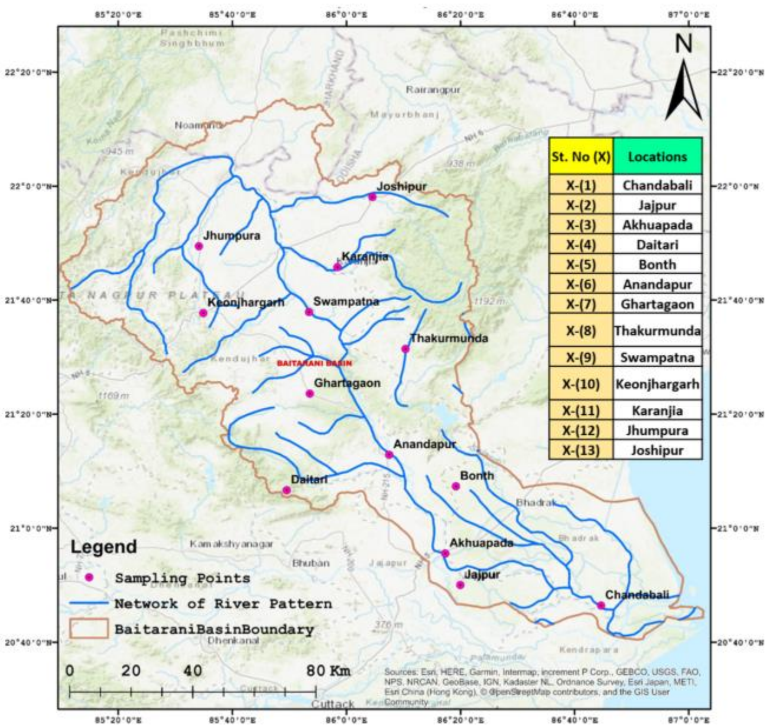

Figure 4: Study area map

b. Problem Statement: Management or Environmental Challenge

The primary environmental challenge is the deteriorating water quality of the Baitarani River, rendering it unsuitable for drinking and impacting aquatic life. The management challenge lies in identifying the key pollution sources and implementing effective strategies to mitigate pollution and restore the river's ecological health. The river receives pollutants from point and non-point sources, including industrial effluents, municipal waste, and agricultural runoff. The lack of comprehensive water quality assessments and management plans hinders effective intervention and sustainable development in the region. The study aims to provide baseline information that would serve as an effective plan for the management of the river basin (Das, 2025).

2. Project Description

a. Goals and Objectives

The main goal of this project was to evaluate the surface water quality of the Baitarani River basin in Odisha, India, to understand the extent of pollution and identify its sources. The specific objectives included:

- Analyzing seasonal (post-monsoon) and temporal variations in hydro-chemical variables throughout the river channel from 2021-2024.
- Calculating Water Quality Indices (WQIs) using Weighted Arithmetic (WA), Canadian Council of Ministers of the Environment (CCME), and Integrated (I) Weight methods to assess water quality.
- Applying multivariate statistical analysis techniques, such as Cluster Analysis (CA) and Principal Component Analysis (PCA), to identify pollution sources and patterns.
- Providing baseline data for developing effective strategies for river basin management and pollution control.

b. Strategies and Interventions

The study employed a comprehensive approach involving water sampling, laboratory analysis, and statistical modeling. Water samples were collected from thirteen sampling sites along the Baitarani River during the post-monsoon season from 2021 to 2024. Fifteen physicochemical parameters were analyzed. Environ-metric techniques, such as principal component analysis (PCA), and hierarchical (H) cluster analysis (CA), were used to assess the hydro-chemical variables (Das, 2025). PCA was used to reduce the dimensionality of the data and identify the key factors influencing water quality. CA was used to group the sampling sites into clusters based on their pollution levels. The results were used to identify the major pollution sources and provide recommendations for improving river water quality.

c. Key Stakeholders and Partnerships

The key stakeholders in this project include:

- **Researchers:** Involved in data collection, analysis, and interpretation.
- **Local Communities:** Dependent on the river for water and sanitation.
- **Government Agencies:** Responsible for environmental monitoring and regulation.
- **Industrial Units:** Potential sources of pollution.
- **Agricultural Sector:** Contributes to non-point source pollution through runoff.

Effective partnerships among these stakeholders are crucial for implementing sustainable management practices and ensuring the long-term health of the Baitarani River basin. Collaboration can facilitate the implementation of pollution control measures, promote sustainable agricultural practices, and improve community engagement in river conservation efforts.

3. Outcomes and Impact

a. Environmental Benefits

The study revealed significant environmental benefits that could be achieved through targeted interventions. The water quality assessment using WAWQI showed that almost 61.54% of sampling sites have poor to unsuitable quality of water (Das, 2025). On the contrary, the computed CCMEWQI value varied between 23 and 97, indicating water quality ranging from excellent to very poor water quality (Das, 2025). Spanning a spectrum, the values of Integrated Weight (I)-WQI oscillated between 14 and 97, indicating 76.92% of samples renders poor water and thus, significant contamination of the research zone by elements like turbidity, EC, and TDS indicates that the water quality in these areas is below drinkable limits and requires purification before use (Das, 2025). Furthermore, in all sites, the indicator Turbidity did not meet the drinking water quality limits (< 5NTU) (Das, 2025).

The PCA resulted into 4 components namely PC-1 (51.31 %), PC-2 (16.044 %), PC-3 (11.799 %) and PC-4 (9.04 %) and indicated that particularly PC-1 contributes parameters such as turbidity, EC, TDS, Na^+, K^+, Ca^{2+}, and Mg^{2+}, were mostly influenced by mineralization, ions dissolution, and rock weathering (Das, 2025). The CA grouped four zones into three clusters, i.e., relatively low-polluted, medium-polluted, and high polluted (Das, 2025). The current condition of the river is deplorable, leaving behind only minimal economic and ecological values, reducing sewage outflow, blocking direct stormwater discharge, and avoiding continuous solid garbage disposal by neighbouring populations are ways to improve river water quality (Das, 2025). By addressing the identified pollution sources, such as natural phenomena, along with agricultural, municipal, and industrial discharges, which are the major polluting sources in the river basin. The key environmental benefits are:

- **Improved Water Quality:** Reducing pollutants like turbidity and TDS can enhance water clarity and reduce health risks.
- **Enhanced Aquatic Ecosystems:** Lowering pollutant concentrations can improve habitat conditions for aquatic life.
- **Reduced Waterborne Diseases:** Treating sewage and preventing direct discharge can minimize the spread of waterborne diseases.
- **Restoration of Ecological Values:** Addressing the deplorable condition caused by industrial and wastewater emissions can restore the river's economic and ecological values. This involves reversing the current trend of minimal economic and ecological value due to pollution, ultimately leading to a healthier and more vibrant river ecosystem.

b. Social Benefits

The project's outcomes have significant social benefits for the communities dependent on the Baitarani River:

- **Improved Public Health:** Access to cleaner water reduces the risk of waterborne diseases, improving overall public health.
- **Enhanced Livelihoods:** Healthier River ecosystems support fisheries and agriculture, boosting local livelihoods.
- **Increased Awareness:** Community engagement in water quality monitoring and conservation efforts increases awareness of environmental issues.
- **Equitable Access to Resources:** Sustainable water management ensures equitable access to clean water for all community members.

By involving local communities in the management of the river basin, the project can empower them to protect their water resources and improve their quality of life.

c. Economic Benefits

The economic benefits of the project include:

- **Reduced Healthcare Costs:** Improved water quality leads to fewer waterborne diseases, reducing healthcare costs for individuals and the government.
- **Increased Agricultural Productivity:** Healthier water resources support irrigation and agriculture, increasing crop yields and farmer incomes.
- **Sustainable Tourism:** A cleaner river can attract tourists, boosting the local economy and creating jobs in the tourism sector.
- **Cost Savings on Water Treatment:** Reducing pollution at the source lowers the costs associated with water treatment and purification.

Moreover, investments in wastewater treatment plants and sustainable agricultural practices can create new job opportunities in the environmental sector, further contributing to economic growth.

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

The key takeaways from the project include:

- The Baitarani River is significantly polluted, with a large percentage of sampling sites showing poor to unsuitable water quality, as indicated by WAWQI, CCMEWQI and IWQI.
- Turbidity, EC, and TDS are major pollutants affecting water quality in the river basin.
- Natural phenomena, agricultural activities, municipal waste, and industrial discharges are the primary pollution sources, identified through CA and PCA.
- Water Quality Indices (WQIs) and multivariate statistical techniques (PCA and CA) are effective tools for assessing water quality and identifying pollution sources.

- Community involvement and stakeholder collaboration are essential for successful river basin management.

b. Best Practices and Strategies for Replication

The following best practices and strategies can be replicated in similar river basins:

- **Regular Water Quality Monitoring:** Establish a routine water quality monitoring program to track changes and identify emerging pollution issues.
- **Integrated Water Resource Management:** Adopt an integrated approach that considers all aspects of the river basin, including water quality, quantity, and ecosystem health.
- **Stakeholder Engagement:** Involve local communities, government agencies, and industrial units in decision-making processes.
- **Pollution Control Measures:** Implement strict regulations on industrial discharges and promote sustainable agricultural practices.
- **Wastewater Treatment:** Invest in wastewater treatment plants to reduce sewage outflow into the river.
- **Public Awareness Campaigns:** Conduct public awareness campaigns to educate communities about the importance of water conservation and pollution prevention.

c. Areas for Further Improvement or Research

Further research is needed in the following areas:

- **Long-Term Monitoring:** Conduct long-term monitoring to assess the effectiveness of implemented management strategies.
- **Source Tracking:** Use advanced techniques to identify and track specific pollution sources.
- **Ecosystem Health Assessment:** Assess the impact of pollution on aquatic ecosystems and biodiversity.
- **Climate Change Impacts:** Evaluate the effects of climate change on water quality and availability in the river basin.
- **Socio-Economic Studies:** Conduct socio-economic studies to understand the impacts of water quality on local communities and livelihoods.

2.5 Flood Protection by Embankments in the Brahmani-Baitarani River Basin, India: A Risk-Based Approach

1. Case Study Overview

a. Project Background and Location

The Brahmani-Baitarani River basin, located in eastern India across the states of Chhattisgarh, Jharkhand, and Odisha, is a region frequently affected by floods

(Government of Odisha, 2011). This poses significant challenges to the predominantly agricultural communities in the area. The basin was selected due to the frequent occurrence of floods in the delta and the significance of state water resources controlled by the Rengali reservoir (Marchand et al., 2022). The area is an inter-state river basin, spreading across Chhattisgarh, Jharkhand, and Odisha, with elevations ranging from over 750m in the north-western part to approximately 10m in the delta (Marchand et al., 2022). Given the recurring flood events and their impact on livelihoods, an assessment of existing flood protection measures, specifically embankments, was deemed necessary.

b. Problem Statement: Management or Environmental Challenge

India faces significant challenges related to flood management due to its monsoon climate and high spatial-temporal rainfall variability (Guhathakurta et al., 2015). While embankments are a common structural flood protection measure (Gupta et al., 2003; Viglione et al., 2014), determining optimal safety levels for their design is complex, especially in data-scarce environments typical of developing countries. The current Indian standards for embankment design, set in 1980, may no longer be adequate due to population growth and increased economic activity (World Bank, 2017). This case study addresses the need for a risk-based approach to evaluate and optimize flood protection levels provided by embankments in the Brahmani-Baitarani River basin, considering the limitations of data availability and the need for cost-effective solutions. This study aims to develop a risk-modelling approach to calculate current flood risks and analyze the economic efficiency of different embankment safety levels in this predominantly agricultural area (Marchand et al., 2022).

2. Project Description

a. Goals and Objectives

The primary goal of this project was to develop and apply a comprehensive, yet relatively simple, method to determine optimal flood protection levels for pre-feasibility analysis in data-poor environments. Specifically, the project aimed to review the flood protection safety levels for overtopping of embankments in the Brahmani-Baitarani River basin in India.

a. Key objectives

- Developing a combined hydrological-hydraulic model for the river basin.
- Creating a damage model to assess the economic impact of floods.
- Analyzing the economic efficiency of different embankment safety levels using a risk-based approach.
- Identifying the optimal safety level that maximizes the benefit-cost ratio for embankment construction.
- Providing recommendations for updating flood protection standards based on the study findings.

- Integrating GIS-based tools for flood extent and depth mapping to optimize dam operations and reduce inundation.

b. Strategies and Interventions:

The project employed a risk-based approach, assessing the probability of flooding (hazard), the assets exposed to flooding (exposure), and the vulnerability of those assets to flood damage (Klijn et al., 2015; Ward et al., 2011). The following strategies and interventions were implemented:

- **Hydrological-Hydraulic Modelling:** A combined model was developed to simulate flood events in the Brahmani-Baitarani River basin (Marchand et al., 2022). The WEB-DHM-RRI model was deployed to simulate river discharge, achieving Nash-Sutcliffe Efficiency (NSE) values of 0.86–0.89 at Jenapur and 0.74 at Anandapur, validating its predictive reliability (Marchand et al., 2022).
- **Flood Inundation Mapping:** The MGBM method and FwDET v2.0 tools were applied to estimate flood extents and depths using MODIS satellite imagery and SRTM DEM data (Marchand et al., 2022).
- **Damage Modelling:** A damage model was created to estimate the economic losses resulting from flooding. This model considered factors such as agricultural land use, crop types, infrastructure, and population density to quantify the potential damage for different flood depths and durations.
- **Risk Analysis:** The hydrological-hydraulic model and the damage model were integrated to perform a risk analysis. This involved calculating the expected annual damage for different embankment safety levels, considering the probability of embankment failure and the resulting flood damage.
- **Cost-Benefit Analysis:** A cost-benefit analysis (CBA) was conducted to evaluate the economic efficiency of different embankment safety levels. The costs of embankment construction and maintenance were compared to the benefits of reduced flood damage to determine the optimal safety level that maximizes the benefit-cost ratio.
- **Optimized Dam Operations:** The Rengali dam's operations were revised using a three-day rainfall forecast to enable controlled early water releases (Marchand et al., 2022). This strategy aimed to reduce peak outflow to below the critical flood damage threshold.

c. Key Stakeholders and Partnerships:

The success of this project relied on the collaboration of various stakeholders and partnerships. Key stakeholders included:

- **Deltares:** Provided technical expertise in hydrological modelling, flood risk assessment, and cost-benefit analysis.

- **Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore:** Provided expertise in water resource management and policy.
- **RMSI, India:** Contributed local knowledge and data on flood events, infrastructure, and socio-economic conditions in the Brahmani-Baitarani River basin.
- **C. J. Sprengers Consultancy:** Provided consulting services in the field of water management.
- **Government of Odisha:** Provided access to data and facilitated stakeholder engagement.
- **Local Communities:** Participated in data collection, provided feedback on flood impacts, and contributed to the development of mitigation strategies.

3. Outcomes and Impact

a. Environmental Benefits

The study demonstrates the application of GIS-based tools for flood extent and depth mapping, integrated with hydrological modeling to optimize dam operations and reduce inundation in the Brahmani-Baitarani River basin. The project's integrated approach yielded measurable environmental improvements:

- **Flood Inundation Mapping**: The MGBM method and FwDET v2.0 tools effectively estimated flood extent and depth in the coastal delta region using MODIS satellite data and SRTM DEM data. The estimated flood depths (1.0 to 2.5 m) closely matched real-world observations from the National Water Mission, confirming the reliability of GIS-based methods.
- **Comparison with Numerical Modeling**: Results from GIS-based approaches were comparable to those from the WEB-DHM-RRI hydrological model, demonstrating the effectiveness of both methodologies despite their respective advantages and limitations.
- **Dam Operation and Flood Mitigation**: The Rengali dam's conventional operation led to excessive water discharge (>12,000 Cumecs) during extreme rainfall events in September 2011, causing devastating floods. A revised approach, assuming a three-day rainfall forecast, enabled controlled early water releases, reducing peak outflow to 7,000 Cumecs, which is below the critical flood damage threshold of 8,000 Cumecs.
- **Hydrological Model Performance**: The WEB-DHM model demonstrated strong predictive accuracy, with Nash-Sutcliffe Efficiency (NSE) values of 0.86–0.89 at Jenapur and 0.74 at Anandapur.
- **Impact of Optimized Dam Operations**: The modified dam operation strategy led to a significant reduction in flood extent and depth, as validated by simulation results. This highlights the necessity of integrating hydrological forecasting and adaptive reservoir management to mitigate flood risks in deltaic regions.

These findings emphasize the effectiveness of GIS-based flood mapping and integrated hydrological modeling for flood risk management, demonstrating the potential for improved decision-making in dam operations to prevent extreme flooding.

b. Social Benefits

The project has significant social benefits for the communities in the Brahmani-Baitarani River basin:

1. **Improved Livelihoods:** Reduced flooding protects agricultural lands and crops, ensuring food security and income stability for farmers and rural communities.
2. **Reduced Displacement:** Embankments prevent the displacement of people from their homes and villages due to flooding, minimizing social disruption and trauma.
3. **Enhanced Community Engagement:** The project involved local communities in data collection, consultation, and decision-making, fostering a sense of ownership and promoting community-based flood management.
4. **Health Benefits:** Reducing flood events minimizes the risk of waterborne diseases and other health hazards associated with flooding, improving public health outcomes.

c. Economic Benefits

The project's focus was on achieving economic efficiency in flood protection. The key economic benefits include:

- **Reduced Flood Damage:** Embankments significantly reduce the economic losses resulting from flooding, including damage to crops, infrastructure, and property. The study demonstrated that embankments providing a protection level of once in 25 years could control more than 90% of the total flood risk (Marchand et al., 2022).
- **Cost Savings:** By optimizing embankment design, the project helps to minimize the costs of construction and maintenance while maximizing the benefits of flood protection.
- **Increased Agricultural Productivity:** Protecting agricultural lands from flooding leads to increased crop yields and higher incomes for farmers.
- **Infrastructure Protection:** Embankments protect vital infrastructure, such as roads, bridges, and power plants, from flood damage, ensuring the smooth functioning of the economy.
- **Stimulated Economic Growth:** By reducing the risk of flooding, the project creates a more stable and predictable environment for economic development, attracting investment and promoting economic growth in the region.

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- A risk-based approach is feasible and valuable for determining optimal flood protection levels, even in data-poor environments.
- Embankments can be an effective flood protection measure, but their design and safety levels need to be optimized based on a comprehensive risk assessment.
- The current Indian standards for embankment design may need to be updated to reflect changes in population, economic activity, and climate change.
- GIS-based flood mapping and hydrological models (e.g., WEB-DHM-RRI) are critical for accurate risk assessments in data-scarce regions.
- Proactive dam operations using rainfall forecasts can reduce peak discharges and mitigate flood risks (Marchand et al., 2022).
- Stakeholder engagement and community participation are crucial for the success of flood management projects.

b. Best Practices and Strategies for Replication

- **Adopt a Risk-Based Approach:** Use a risk-based approach to assess flood risk and determine optimal flood protection levels, considering hazard, exposure, and vulnerability.
- **Develop Integrated Models:** Integrate hydrological-hydraulic models with damage models to comprehensively assess the economic impacts of flooding.
- **Integrate GIS Tools:** Utilize GIS tools like FwDET v2.0 for rapid flood mapping in deltaic regions with limited ground data (Marchand et al., 2022).
- **Engage Stakeholders:** Involve local communities, government agencies, and other stakeholders in data collection, consultation, and decision-making.
- **Optimize Dam Operations:** Integrate real-time rainfall forecasts with reservoir management to enable early water releases (Marchand et al., 2022).
- **Use Local Materials:** Utilize locally available materials for embankment construction to reduce costs and promote local employment.
- **Monitor and Evaluate:** Continuously monitor and evaluate the performance of embankments and other flood protection measures to identify areas for improvement.
- **Capacity Building:** Invest in capacity building and training for local communities and government agencies to enhance their ability to manage flood risk.

c. Areas for Further Improvement or Research

- **Climate Change Impacts:** Further research is needed to assess the impacts of climate change on flood frequency and intensity and to incorporate these impacts into flood protection planning.

- **Non-Structural Measures:** More emphasis should be placed on integrating non-structural measures, such as flood forecasting, early warning systems, and land-use planning, into flood management strategies.
- **Data Collection and Sharing:** Efforts should be made to improve data collection and sharing on flood events, hydrology, and socio-economic conditions to enhance the accuracy of flood risk assessments.
- **Economic Valuation of Ecosystem Services:** Further research is needed to quantify the economic value of ecosystem services provided by wetlands and other natural areas in reducing flood risk.
- **Social Equity:** Flood management strategies should be designed to ensure that the benefits of flood protection are equitably distributed across all communities, particularly vulnerable populations.

This case study demonstrates the feasibility of using a risk-based approach to optimize flood protection levels in data-poor environments. By adopting the lessons learned and implementing the recommendations, policymakers and practitioners can improve the effectiveness and efficiency of flood management strategies, protecting lives, livelihoods, and the environment. The study illustrates the feasibility of a relatively basic flood-risk analysis that can be applied at pre-feasibility level in a data-poor environment (Marchand et al., 2022).

3. Integrated Water Resource Management in the Brahmani River Basin: A Case Study

3.1 Water Resources Assessment of Brahmani River Basin, India

1. Case Study Overview

The Brahmani Basin, an east-flowing river system in India, spans 39,268 km^2 across Odisha, Jharkhand, and Chhattisgarh. It has two main tributaries, the Sankh and Koel, and experiences a sub-humid tropical climate with an average annual rainfall of 1305 mm, mostly during the southwest monsoon season (June–October) (CWC, 1995). Agriculture in the basin is primarily rain-fed in the upper regions, while irrigation supports farming in the lower deltaic areas. Of the total cropped area of 1.57 million hectares, around 1.23 million hectares are irrigated, demonstrating a reliance on both methods (CWC, 1995).

Water availability remains relatively high, with per capita water availability at 2,590 cubic meters per year in 2001, well above the 1,000 cubic meter water stress threshold. Industrial development, driven by rich mineral resources such as iron ore, coal, and limestone, has led to significant industrial activities, including the Rourkela Steel Plant and multiple thermal power plants. This has contributed to water usage and pollution concerns in the basin (CWC, 1995).

Environmental issues include industrial effluent pollution, particularly downstream of the Rengali dam, and frequent flooding in the delta region, which impacts both populations and agriculture [1]. To address water management challenges, the International Commission on Irrigation and Drainage (ICID) launched the Country Policy Support Programme (CPSP), focusing on integrated water resource management, food security, and rural development, with international support mobilization.

Project background and location

The Country Policy Support Programme (CPSP), launched by the International Commission on Irrigation and Drainage (ICID) in 2002, aims to enhance water resources management for food security and sustainable rural development. It operates in China, India, Egypt, Mexico, and Pakistan, with funding from the Government of the Netherlands (CWC, 1993). As part of CPSP, the Basin-wide Holistic Integrated Water Assessment (BHIWA) model was developed to analyze water resources in selected river basins, including the Brahmani Basin in India. This basin, located on India's east coast, is water-rich compared to the water-deficient Sabarmati Basin on the west coast (CWC, 1988a). The program conducted detailed water assessments of the Brahmani Basin, examining past and present conditions to guide policy decisions. Basin-level consultations in January 2003 helped refine the model for better accuracy (CWC, 1988a; CWC, 1993). Spanning 39,268 km^2, the Brahmani Basin covers parts of Odisha (22,516 km^2), Jharkhand (15,405 km^2), and Chhattisgarh (1,347 km^2), supporting a population of 8.5 million with agriculture and industrial activities (CWC, 1988b) (Figure 5). Rich in iron ore and coal, the basin hosts major industries like the Rourkela Steel Plant, raising concerns over water pollution and environmental sustainability. Balancing industrial growth with ecological conservation remains a key challenge.

Figure 5: Brahmani River Basin

Problem statement: management and/or environmental challenge(s)

The industrial and mining activities in the Angul-Talcher region have severely polluted the Brahmani River, particularly through the river Nandira, endangering aquatic life and community health. Immediate wastewater treatment is needed to achieve zero industrial effluent discharge (CWC, 1993). Industries must adopt better wastewater management practices, including recycling and adequate treatment, while violators should be penalized under the "polluter pays" principle to ensure compliance (CWC, 1988a; CWC, 1993). Legal regulations must be enforced to prevent untreated effluent discharge, replacing dilution methods with effective treatment solutions (CWC, 1988b). Over-extraction and poor water management threaten ecosystems, necessitating a shift towards sustainable water resource practices, emphasizing precipitation as the primary renewable resource (Directorate of statistics and Economics, 1995a). An integrated water management approach is essential, incorporating land use impact assessments and effective policies, with the BHIWA model providing a framework for informed decision-making (Figure 6).

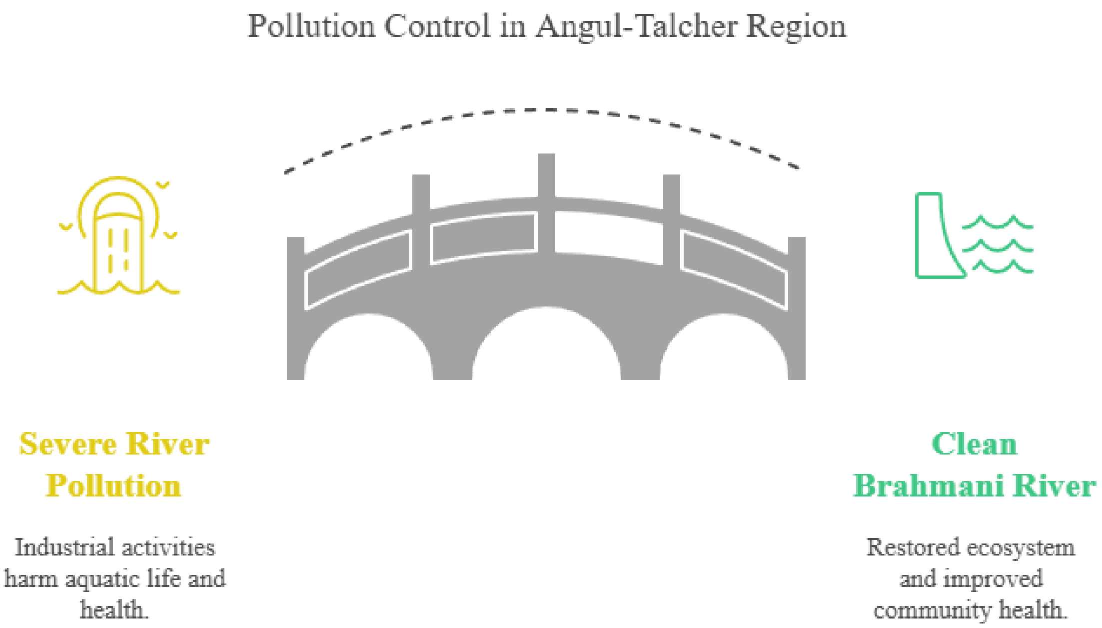

Figure 6: Pollution control in Angul-Talchar region in Brahmani River stretch

2. Project Description

a. Goals and objectives

- Emphasizes water-related challenges in the Brahmani basin to evaluate policy effectiveness for similar basins (Figure 7).
- Extends study outcomes to support national water policies using key water indicators applicable to other river basins.
- Uses the BHIWA model to integrate water supply and demand across agriculture, domestic, and industrial sectors for sustainable management.
- Calibrates the BHIWA model with hydrologic and land use data to predict future water regimes under different scenarios.
- Analyzes alternative water policy scenarios for 2025 to achieve balanced and integrated water management through stakeholder consultations.
- Uses the BHIWA model to quantify human impacts on water resources, including land use changes and water withdrawals.

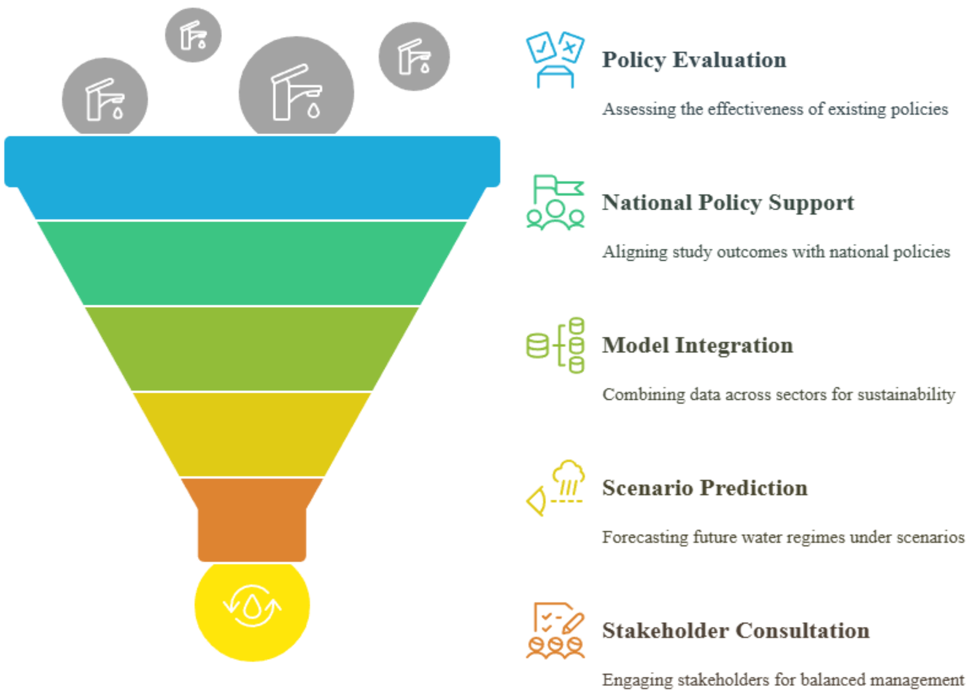

Figure 7: Integrated framework linking policy analysis, modelling, scenarios, and stakeholder input

b. Strategies and interventions

The report underscores the importance of Integrated Water Resource Management (IWRM) by emphasizing a holistic approach to water resource management, considering supply, demand, and sectoral interdependencies. The BHIWA model is highlighted as a crucial tool for assessing water resources comprehensively (CWC, 1995).

Policy Interventions in Chapter 3 focus on addressing challenges in the Brahmani basin while aligning with the National Water Policy, making these strategies applicable to similar basins (CWC, 1993). Stakeholder Engagement is a key strategy, particularly in flood mitigation, ensuring that decision-making processes incorporate stakeholder input to create well-informed and widely accepted solutions (CWC, 1988a).

Watershed Management is identified as essential for enhancing water availability and quality, contributing to poverty alleviation among tribal populations. However, caution is advised against local practices that could negatively impact downstream water resources (Directorate of statistics and Economics, 1995a). Flood Mitigation Strategies are discussed with an emphasis on stakeholder consultation to assess limitations and make informed decisions on flood control and drainage measures. The Country Policy Support Programme (CPSP), initiated by ICID, aims to analyze supply and demand across food, people, and nature sectors. It seeks international support for water policies that enhance food security and reduce poverty in developing countries (Directorate of statistics and Economics, 1995a).

c. Key stakeholders and partnerships

The report highlights the crucial role of various stakeholders in the success of the Country Policy Support Programme (CPSP) activities. International organizations provided significant support through consultations and dialogues, contributing valuable expertise for effective water management strategies (Figure 8). At both basin and national levels, multi-stakeholder consultations engaged over 55 professionals, including NGOs, consultancy firms, and organizations like IWMI, FAO, and IPTRID, to address integrated water resources development and management (IWRDM) issues (CWC, 1993). Government agencies played a key role in basin-level consultations, presenting on topics such as rain-fed and irrigated agriculture, wastewater treatment, and forestry water needs, ensuring alignment with national policies. The Indian Association of Hydrologists (IAH) contributed by conducting water assessments and developing the Basin-wide Holistic Integrated Water Assessment (BHIWA) model to analyze policy issues in India and China. Community involvement was emphasized as essential for identifying local water-related challenges and creating culturally appropriate management strategies. Additionally, funding from the Government of The Netherlands played a crucial role in supporting CPSP initiatives, underscoring the importance of international financial partnerships in achieving food security and poverty reduction in developing countries (CWC, 1988a).

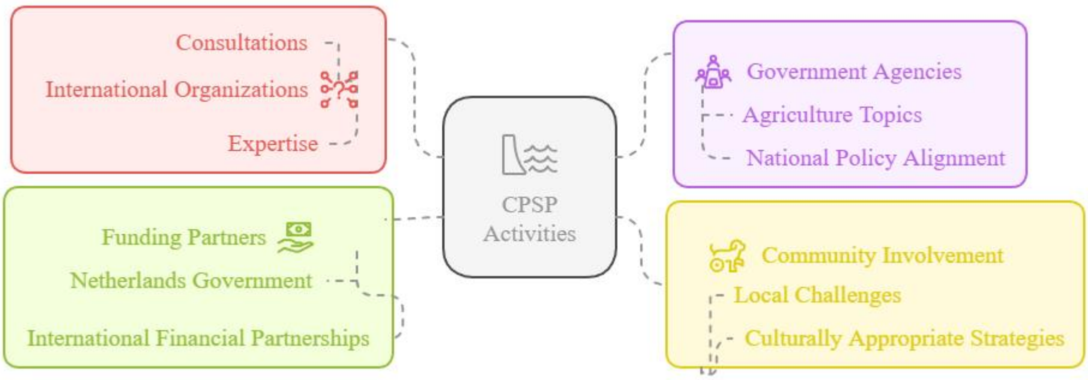

Figure 8: Key stakeholders and partnership

3. Outcomes and Impact

a. Environmental benefits

Effective water management is essential for maintaining both aquatic and terrestrial ecosystems, with the Environmental Flow Requirement (EFR) ensuring adequate water flow to sustain biodiversity and environmental health. Recognizing EFRs as valid requirements in water-rich basins supports riverine ecosystems and the diverse species that depend on them, enhancing regional biodiversity. Case studies, such as the Brahmani basin, highlight the importance of balancing various water needs, including fisheries, mangroves, and irrigation, to protect fragile ecosystems vital for coastal protection and biodiversity. Additionally, proper irrigation and drainage practices help mitigate environmental pollution, particularly in estuary areas where river currents interact with tidal waters, preventing contamination. Sustainable agricultural practices further optimize water use, reducing over-extraction and preserving water quality while improving productivity (Directorate of statistics and Economics, 1995a). Lastly, engaging local communities in water management fosters stewardship and responsibility, leading to better conservation practices and greater awareness of ecosystem health.

b. Social benefits (e.g., improved livelihoods, enhanced community engagement)

Water management initiatives play a crucial role in enhancing rural livelihoods by expanding irrigation coverage, which increases agricultural productivity and provides farmers with a more stable income source, contributing to poverty alleviation. These initiatives also support food security by ensuring a reliable water supply for crops, particularly in regions with unpredictable rainfall, reducing the risk of crop failure due to droughts or floods. Community engagement is essential in effective water management, as involving local populations in decision-making fosters ownership, responsibility, and sustainable conservation practices. Additionally, sustainable water management helps preserve forest resources that many rural communities depend on for their livelihoods, ensuring continued access to forest produce as an income source. Socioeconomic models aid in setting water management targets aligned with community needs by considering water and land constraints, thereby promoting sustainable rural development (Directorate of statistics and Economics, 1995b; Directorate of statistics and Economics, 1996). Furthermore, capacity-building programs within these initiatives equip individuals with essential skills and knowledge to manage water resources efficiently, improving agricultural practices and strengthening community resilience.

4. Lessons Learned and Recommendations

a. Key takeaways from the project

The project conducted comprehensive water assessments in major basins of populous countries like China and India, analyzing water demands driven by population growth and urbanization to inform policy decisions. Multi-stakeholder engagement played a crucial role, as consultations at both basin and national levels provided valuable insights that refined the analysis and outcomes. The findings led to key policy recommendations, emphasizing the need for integrated and sustainable water resource management. Basin-specific results were extrapolated to similar basins, ensuring that local insights contributed to broader national strategies. Additionally, the project developed the Basin-wide Holistic and Integrated Water Assessment (BHIWA) model, a critical analytical tool for evaluating sub-basin dynamics and policy issues. Future projections included estimates for water use, irrigated and rain-fed lands, and reservoir operations, which are vital for long-term planning. The project also acknowledged the contributions of international organizations and stakeholders, highlighting the collaborative nature of the initiative.

a. Practical implications

The paper highlights the need for integrated water resource management in the Brahmani Basin to balance supply and demand across sectors. Stakeholder engagement is crucial for effective decision-making, while the BHIWA model aids water assessment and planning. It addresses flood management, ecological flow requirements, and sustainable agricultural and industrial water use. Future projections guide long-term planning for infrastructure and climate adaptation. The study emphasizes policy development based on comprehensive assessments and consultations to ensure sustainable, equitable water management.

b. Areas for further improvement or research

Future research should focus on sustainable groundwater management to prevent over-extraction, effective land use planning to expand cultivation while minimizing environmental impacts and refining the BHIWA model for broader water assessments. Stakeholder collaboration is essential for inclusive decision-making. Climate change adaptation strategies should enhance water security (CWC, 1988a), while integrated policies should address water supply, food security, and rural development. Establishing monitoring frameworks with indicators is crucial for evaluating management strategies. These efforts will ensure efficient and responsible water resource utilization in the face of growing agricultural demands.

A comprehensive study on overall water use and wastewater treatment across industries, particularly in regions like Angul-Talcher, is essential for understanding water availability and ensuring optimal utilization for environmental protection. The impact of industrial and mining effluents on water quality, such as in the Brahmani River, demands urgent attention, with research needed on effective wastewater treatment and zero effluent discharge strategies. Integrating findings with the BHIWA model could enhance sub-basin-level assessments, and future research should focus on incorporating diverse data sources for improved accuracy. Additionally, while policy recommendations have been made, further research is necessary to evaluate their real-world effectiveness by monitoring implementation and outcomes in similar basins. Future projections of water use and cultivated land could also be refined by incorporating climate change scenarios and their effects on water resources and agriculture. Stakeholder engagement remains crucial, and research should explore improved strategies for involving local communities and industries in water management discussions (Figure 9) Finally, the findings highlight the need for basin-specific policy interventions, necessitating further research to identify and test tailored, context-sensitive solutions for different basins (Directorate of statistics and Economics, 1995b).

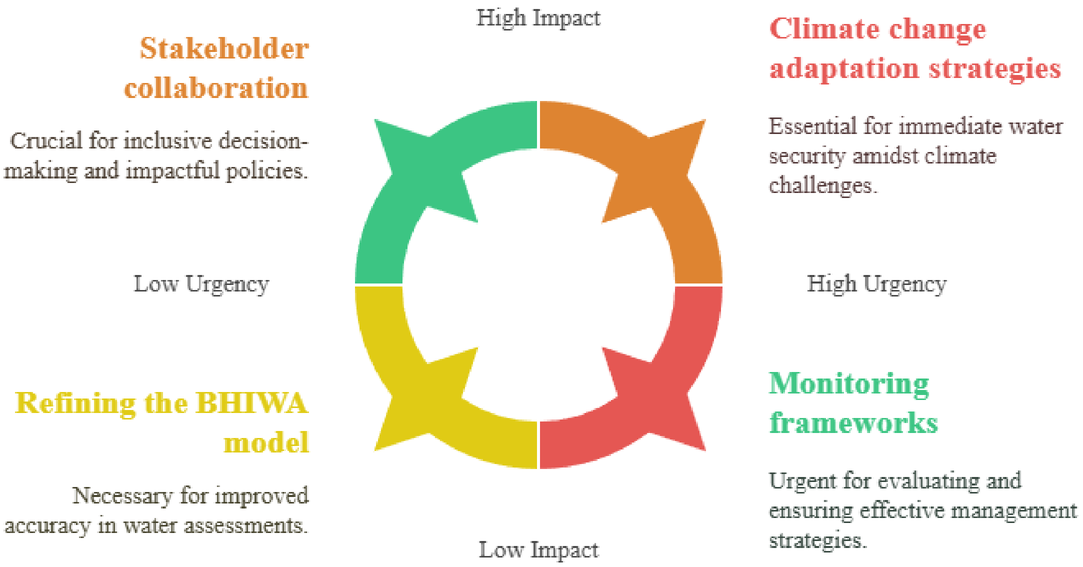

Figure 9: Areas for further improvement or research

3.2 Influence of physico chemical parameters on surface water quality: a case study of the Brahmani River, India

1. Case Study Overview

The study evaluates the surface water quality of the Brahmani River in India to determine its suitability for various uses. Water samples were collected monthly from February 2014 to July 2015, analyzing fifteen physicochemical parameters, including pH, temperature, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and major cations and anions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, SO_4^{2-}, NO_3^-, and PO_4^{3-} (Agarwal and Saxena, 2011; Ahipathy and Puttaiah, 2006; CPCB, 2006). Seven strategic sampling stations were selected along the river, including Panposh Down Stream, Rourkela Down Stream, Rengali, Talcher Up Stream, Kamalanga Down Stream, Bhuban, and Pattamundai. The Water Quality Index (WQI) was used to assess the overall water quality, with values ranging from 37.87 to 62.36, indicating a quality range from good to poor (Ahipathy and Puttaiah, 2006; CPCB, 2009). Most water quality parameters were within desirable limits, except for elevated levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), and phosphate (PO_4^{3-}) at certain stations. The river was slightly alkaline, promoting phytoplankton growth, though declining water quality at some locations was attributed to untreated wastewater from industrial, domestic, and agricultural sources (Ayoko et al., 2007). The study concluded that the river water could be used for domestic purposes and, with proper disinfection, could be suitable for drinking, while also serving as a good habitat for aquatic organisms (Bhadra et al., 2014; Ahipathy and Puttaiah, 2006). Future research could integrate these findings with Geographic Information System (GIS) techniques to develop a WQI map of the river (Bordalo et al., 2001; BIS, 2012).

a. Project background and location

The Brahmani River, a significant waterway in eastern India, is the focal point of this study, which aims to evaluate its surface water quality. The river is formed by the confluence of the Sankh and South Koel rivers and flows through several districts in Odisha, including Sundergarh, Kendujhar, Dhenkanal, Cuttack, and Jajpur. This region is characterized by a semi-arid to arid climate, with an average annual precipitation of approximately 1,400 mm and a mean annual temperature of 25.7°C. The river traverses a predominantly agricultural landscape interspersed with various industrial units before ultimately joining the Bay of Bengal.

For the study, seven strategic sampling stations were selected along the river's stretch, including Panposh Down Stream, Rourkela Down Stream, Rengali, Talcher Up Stream, Kamalanga Down Stream, Bhuban, and Pattamundai. These locations were chosen to provide a comprehensive assessment of water quality across different sections of the river. Monthly data on fifteen physicochemical parameters, such as pH, temperature, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and major cations and anions, were collected from February 2014 to July 2015. The findings from this investigation are crucial for understanding the river's water quality and its implications for various uses, including domestic and agricultural applications, as well as its ecological health. The study also highlights the impact of anthropogenic activities, such as industrial discharges and agricultural runoff, on the river's water quality, emphasizing the need for effective management strategies to protect this vital resource (Agarwal and Saxena, 2011; Ahipathy and Puttaiah, 2006; Ayoko et al., 2007; CPCB, 2009).

b. Problem statement: management and/or environmental challenge(s)

The Brahmani River faces significant management and environmental challenges that threaten its water quality and overall ecosystem health. One of the primary issues is the impact of anthropogenic activities, including urbanization, industrial discharges, and agricultural practices, which have led to the deterioration of water quality in various sections of the river. The study highlights that untreated wastewater and effluents from industries, along with agricultural runoff containing fertilizers, contribute to the declining water quality, particularly at certain sampling stations where parameters such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and phosphate (PO_4^{3-}) exceed permissible limits (Agarwal and Saxena, 2011).

Additionally, the presence of high concentrations of sulfate (SO_4^{2-}) and chloride (Cl^-) ions at various locations indicates the influence of industrial activities and municipal waste, further exacerbating pollution levels in the river (Ayoko et al., 2007). The river's Water Quality Index (WQI) ranged from good to poor, suggesting that while some areas may still support aquatic life, others are severely impacted and may pose risks to human health and the environment (Bordalo et al., 2001).

These challenges necessitate effective management strategies to mitigate pollution sources, enhance water quality monitoring, and promote sustainable practices among local industries and the agricultural sector. The integration of Geographic Information System (GIS) techniques to create a WQI map of the river is suggested as a future step to better visualize and address these environmental challenges. Overall, the study underscores the urgent need for coordinated efforts to protect the Brahmani River, ensuring it remains a viable resource for both ecological and human needs.

2. Project Description

a. Goals and objectives

- Assess physicochemical parameters of the Brahmani River for domestic, agricultural, and industrial suitability.
- Investigate the impact of untreated wastewater, industrial discharges, agricultural runoff, and urban waste.
- Measure pH, electrical conductivity, dissolved oxygen, total dissolved solids, and major cations/anions.
- Calculate WQI at various sampling stations to classify water quality and identify areas of concern.
- Advocate for pollution mitigation strategies to improve and sustain river water quality.
- Use GIS to develop a WQI map for better visualization and management of water quality issues.
- Evaluate the river's ability to sustain aquatic biodiversity.
- Educate local communities on water quality importance and pollution impacts on health and the environment.

3. Outcomes and Impact

a. Environmental benefits

- **Enhanced Biodiversity:** Improving Brahmani River's water quality supports diverse aquatic life, promoting healthy ecosystems and sustaining fish and plant species (Agarwal and Saxena, 2011).
- **Sustainable Water Use:** Clean water ensures safe usage for drinking, irrigation, and industry, benefiting communities reliant on the river (Ahipathy and Puttaiah, 2006) (Figure 10).
- **Reduction of Pollution:** Controlling industrial discharges and agricultural runoff minimizes contaminants, protecting water quality and the environment (Ayoko et al., 2007).
- **Improved Public Health:** Cleaner water lowers the risk of waterborne diseases, ensuring safety for consumption and recreation (Agarwal and Saxena, 2011).
- **Ecosystem Services:** Healthy rivers provide flood regulation, water purification, and carbon sequestration, benefiting both nature and people (Bhadra et al., 2014).

➢ **Climate Resilience:** Good water quality helps ecosystems withstand climate change effects like floods and droughts (Bhadra et al., 2014).

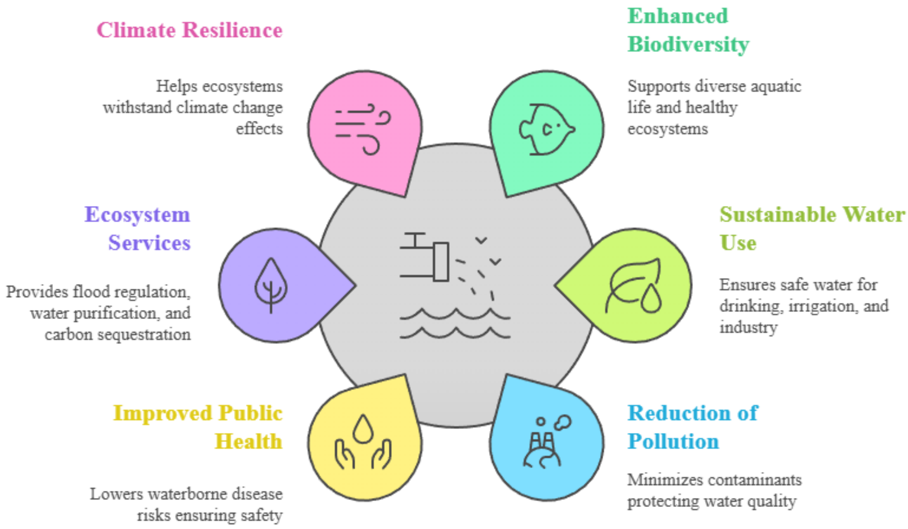

Figure 10: Environmental benefits of the study

4. Lessons Learned and Recommendations

a. Key takeaways from the project

The project investigating the surface water quality of the Brahmani River has yielded several important insights into its physicochemical parameters and overall water quality. The study revealed that most water quality parameters were within desirable limits, except for calcium (Ca^{2+}), magnesium (Mg^{2+}), and phosphate (PO_4^{3-}) at certain sampling stations, indicating localized pollution issues (Ahipathy and Puttaiah, 2006). The river's slightly alkaline nature was found to promote phytoplankton growth, which is essential for maintaining aquatic ecosystems (Agarwal and Saxena, 2011; Ahipathy and Puttaiah, 2006).

The Water Quality Index (WQI) calculated for the river ranged from 37.87 to 62.36, categorizing the water quality from good to poor. This index serves as a valuable tool for assessing the river's suitability for various uses, including domestic and agricultural purposes (Ayoko et al., 2007). The project also highlighted the impact of anthropogenic activities, such as industrial discharges and agricultural runoff, on water quality, particularly the elevated levels of phosphates and sulfates in certain areas (Bhadra et al., 2014; Bordalo et al., 2001).

b. Practical implications

➢ **Water Quality Assessment**: River water quality is generally acceptable for domestic use, with safe drinking possible after proper disinfection, benefiting communities with limited water supply systems (Agarwal and Saxena, 2011) (Figure 11).

- **Environmental Monitoring**: Elevated levels of calcium, magnesium, and phosphates at certain stations highlight the need for continuous water quality monitoring to identify pollution sources and implement timely interventions (Ahipathy and Puttaiah, 2006).
- **Aquatic Habitat Preservation**: The river supports aquatic life, benefiting biodiversity, local fisheries, and recreational activities, emphasizing the need for water quality protection (Agarwal and Saxena, 2011).
- **Pollution Management**: Untreated wastewater and agricultural runoff impact water quality, necessitating strict regulations on industrial and agricultural waste discharges to improve water conditions (Ahipathy and Puttaiah, 2006).

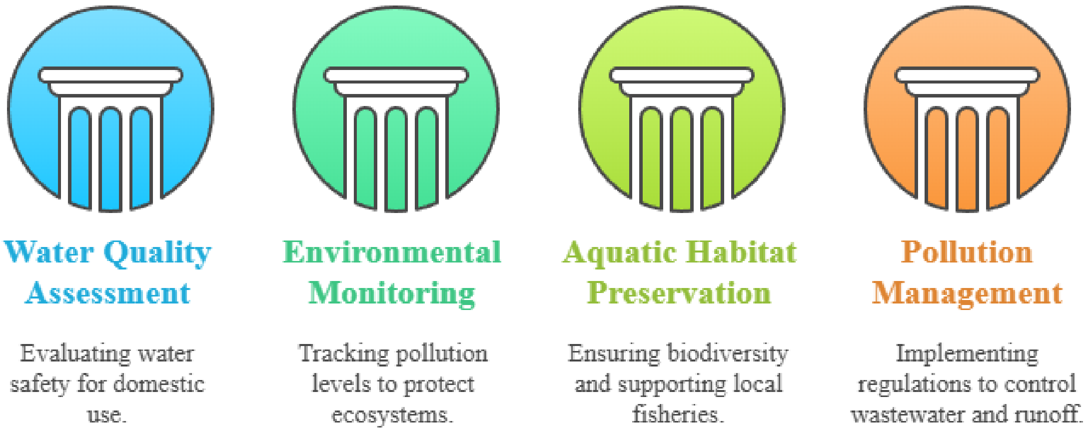

Figure 11: Practical implications of the study

c. Areas for further improvement or research

The study on the Brahmani River's water quality has established a strong foundation, but further research is needed to enhance understanding and management of the river's ecosystem (Figure 12). Conducting long-term monitoring of water quality parameters across different seasons would provide deeper insights into temporal variations and trends, helping to assess the effects of seasonal changes and climate change on the river system (Agarwal and Saxena, 2011). Additionally, while some pollutants have been identified, more detailed studies are required to pinpoint specific sources of contamination from industrial and agricultural activities, including analyses of land use patterns and their correlation with water quality degradation (Agarwal and Saxena, 2011). Investigating how changes in land use within the river basin affect water quality could offer valuable information for land management, particularly in understanding the impacts of urbanization and agriculture (Ahipathy and Puttaiah, 2006). Further research should also explore the health implications for communities relying on the river, including epidemiological studies assessing the incidence of waterborne diseases in relation to water quality parameters (Ayoko et al., 2007). Advanced analytical techniques, such as machine learning algorithms alongside PCA and PFA, could enhance the analysis of complex datasets, improving the prediction of water quality changes and identification of critical influencing parameters (Bhadra et al., 2014). Lastly, researching effective methods for engaging local communities in water quality monitoring and management can empower residents and promote sustainable practices, while educational programs can raise awareness about pollution prevention and the importance of maintaining water quality (Ayoko et al., 2007).

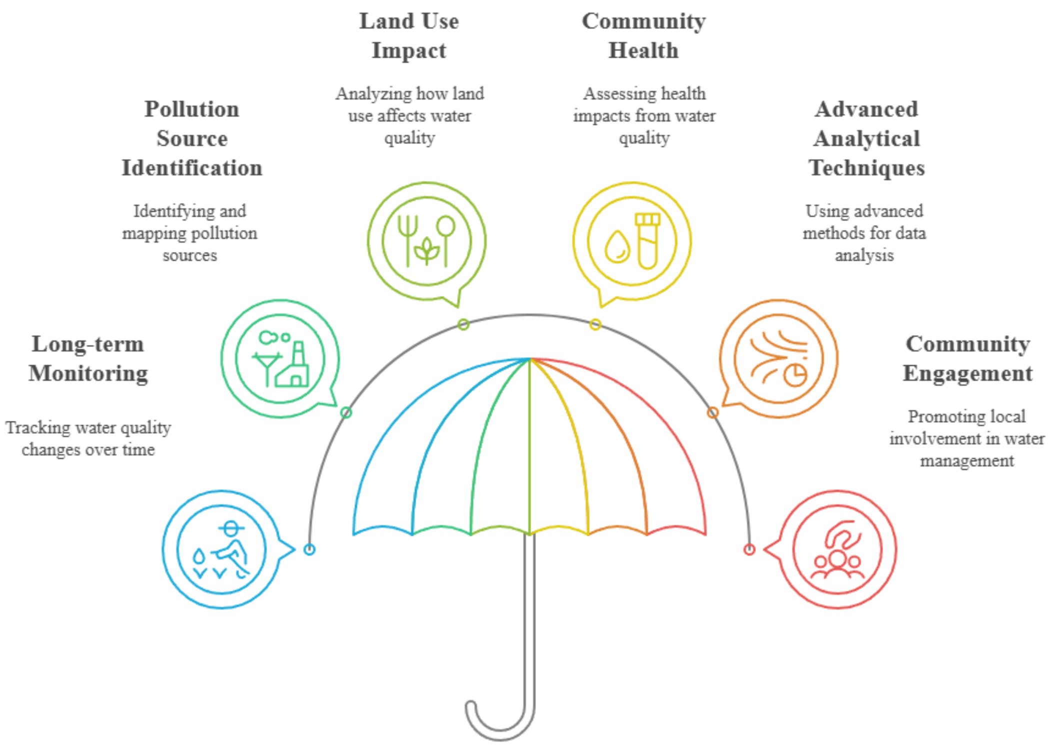

Figure 12: Areas for further improvement or research

3.3 Assessment of potential impact of climate change on stream flow: a case study of the Brahmani River Basin, India

1. Case Study Overview

The study evaluates the impact of future climate change on streamflow in the Brahmani River basin, India. It employs a distributed parameter hydrological model, the Precipitation Runoff Modelling System (PRMS), and multi-model ensemble climate change scenarios to assess changes in streamflow (Adam and Lettenmaier, 2003; Andersen et al., 2001). The findings aim to support water management adaptation strategies in the region.

a. Project background and location

The Brahmani River basin is in eastern India, covering a catchment area of 39,313 km². It comprises four sub-basins: Tilga, Jaraikela, Gomlai, and Jenapur. The region receives an average annual rainfall of 1305 mm, mostly during the southwest monsoon season (June–October). The basin is a critical water source for towns, industries, and agriculture in Odisha (Boorman and Sefton, 1997; Christensen and Lettenmaier, 2007).

b. Problem statement: management and/or environmental challenge(s)

The basin faces significant water management challenges, including:

- Flooding: Recurring floods in the delta region.
- Water Scarcity: Low flows during non-monsoon periods.
- Climate Change Impacts: Projected changes in streamflow, with increased high flows and reduced low flows, intensifying both flood and drought risks.
- Water Quality Deterioration: Due to agricultural runoff, fertilizer application, and industrial discharges (Croke et al., 2011).
- Threat to Mangrove Ecosystems: The Bhitarkanika mangrove ecosystem in the delta is under threat from environmental changes.

2. Project Description

a. Goals and objectives

- Assess climate change impacts on hydrological conditions of the Brahmani River basin.
- Use PRMS modeling to simulate future streamflow variations under different climate scenarios.
- Develop insights for water management and climate adaptation strategies.

a. Strategies and interventions

- Water Storage Structures: Build reservoirs to store monsoon water for irrigation and flood control (Dickerson-Lange and Mitchell, 2014).
- Water Management Adaptation Plans: Develop plans to manage increased high flows and reduced low flows, addressing flood risks and water scarcity.
- Environmental Flow Management: Ensure sufficient water flow to sustain ecosystems, especially in the deltaic region.
- Drought Management: Implement strategies to manage water scarcity during dry periods (Elshamy et al., 2009).
- Irrigation Planning: Adjust irrigation practices to align with changing streamflow patterns, particularly in winter.

3. Outcomes and Impact

a. Environmental benefits

- Better Flood Management: Understanding streamflow changes helps design flood control measures.
- Sustainable Water Use: Insights aid in developing efficient water storage and irrigation plans.

- Ecosystem Protection: Addressing water quality and flow variations supports the conservation of the Bhitarkanika mangrove ecosystem (Ficklin et al., 2016).

b. Significant findings

The study assesses the future impact of climate change on streamflow in the Brahmani River basin, India, using the PRMS hydrological model and multi-model ensemble climate scenarios. Projections indicate rising temperatures (0.8–3.3°C) and variable rainfall changes (−1.6% to 8.1%) across the 2020s, 2050s, and 2080s. Annual streamflow is expected to increase (−2.5% to 12.6%), with higher peak flows and reduced low flows, leading to more frequent extreme events. These findings are crucial for water management and adaptation planning in the region.

c. Social benefits (e.g., improved livelihoods, enhanced community engagement)

- Improved Livelihoods: Enhanced agricultural productivity and water availability can boost farmers' incomes.
- Community Engagement: Involving locals in water management fosters ownership and collaboration.
- Flood Risk Reduction: Water storage structures can lower flood risks, protecting lives and property.
- Sustainable Development: Protecting ecosystems ensures long-term water resource sustainability.
- Climate Resilience: Adaptation strategies increase community resilience to climate change impacts.

4. Lessons Learned and Recommendations

a. Key takeaways from the project

Climate change is projected to significantly alter the hydrology of the Brahmani River basin, leading to increased high flows and reduced low flows. As a result, the frequency of both flood and drought events is expected to rise, posing significant challenges for water resource management (Gain et al., 2011). To adapt to these changing hydrological patterns, the development and enhancement of water storage infrastructure, including reservoirs and floodplain management strategies, will be crucial. These measures will help regulate water availability, mitigate extreme weather impacts, and ensure sustainable water management in the region.

b. Practical implications

- **Irrigation Strategies:** Adjusting crop planning to accommodate changing water availability.
- **Flood Control Measures:** Designing reservoirs and flood defenses to mitigate extreme flow events.

- **Water Policy Adjustments:** Incorporating climate projections into long-term water management planning.

c. Areas for further improvement or research

Further research is needed to refine climate models to enhance the accuracy of future hydrological predictions, ensuring more reliable assessments of streamflow variations under changing climate conditions. Additionally, improved water quality monitoring is essential to address the impact of pollutants and industrial waste on the river system, helping to mitigate environmental degradation and protect aquatic ecosystems. Moreover, developing region-specific adaptation strategies is crucial for sustainable water management, as tailored policies can help communities effectively respond to the unique challenges posed by climate change in the Brahmani River basin (Gain et al., 2011).

3.4 Effect of LULC changes on surface runoff in Brahmani River basin using Soil and Water Assessment Tool (SWAT)

1. Case Study Overview

The study examines the impact of Land Use Land Cover Changes (LULCC) on surface runoff in the Brahmani River Basin using the Soil and Water Assessment Tool (SWAT). The primary objective is to understand how changes in land cover over time influence hydrological processes, particularly runoff generation, in the region. By utilizing the SWAT model and Geographic Information System (GIS) techniques, the study analyzes historical LULCC data from 1983 to 2019 and assesses its effects on runoff at multiple observation stations across the basin (Srinavasan and Wiliams, 2009).

a. Project Background and Location

The Brahmani River Basin spans across the states of Chhattisgarh, Jharkhand, and Odisha in northeast India. It is characterized by diverse landforms, including the northern plateau, the eastern ghats, the central tablelands, and the coastal lowlands. The river is formed by the confluence of the South Koel and Sankh Rivers and extends over 34,614 km^2, with a total river length of 799 km (Joh et al., 2011). The study focuses on understanding hydrological changes within this basin, considering its climatic conditions, topographical variations, and increasing urbanization.

b. Problem Statement: Management and/or Environmental Challenges

The Brahmani River Basin has experienced significant land cover changes due to deforestation, urban expansion, and agricultural intensification. These changes have led to a decrease in infiltration rates, contributing to an increase in surface runoff by 6.06% over the study period (Srinavasan and Wiliams, 2009). The primary environmental challenges include increased flood risk, soil erosion, and water quality deterioration due to sediment transport. Additionally, unplanned urbanization has exacerbated the Urban Heat Island (UHI) effect, further influencing hydrological processes in the region.

2. Project description

a. Goals and Objectives

The study aims to:

- Analyze historical LULCC patterns in the Brahmani River Basin.
- Quantify the impact of LULCC on surface runoff using the SWAT model.
- Compare different hydrological models, including the Green-Ampt (GA) and the Soil Conservation Service Curve Number (SCS-CN) models, to determine their effectiveness in simulating runoff.
- Provide recommendations for sustainable land and water resource management to mitigate adverse hydrological impacts.

b. Strategies and Interventions

The research employs a combination of remote sensing, GIS-based analysis, and hydrological modeling to assess runoff variations. It integrates various datasets, including elevation, drainage, slope, land use, and soil maps, to generate accurate hydrological predictions. The SWAT model is calibrated and validated using SWAT-CUP and the Sequential Uncertainty Fitting (SUFI-2) technique, ensuring robust simulation results (Srinavasan and Wiliams, 2009; Joh et al., 2011). The study also compares different runoff estimation models to evaluate their performance and reliability.

3. Outcomes and Impact

a. Environmental Benefits

The findings highlight the critical role of vegetation in mitigating surface runoff. Increasing green cover in strategic locations can help reduce flood risks, enhance groundwater recharge, and improve overall water balance in the basin. Sustainable land management practices, such as afforestation and soil conservation, can further mitigate erosion and enhance water retention capacity (Kabir et al., 2013).

b. Significant Findings

- Surface runoff has increased by 6.06% due to reduced infiltration rates over time.
- The SCS-CN model demonstrated better performance in simulating runoff compared to the Green-Ampt model, with an R^2 value of 0.89 and a Nash-Sutcliffe Efficiency (NSE) of 0.86.

- The basin has experienced significant land cover changes, with forest cover declining by 21.19% and urban land expanding by 41.76% from 1983 to 2019.
- Monthly rainfall trends indicate a slight increase, but the rise in impervious surfaces has led to higher runoff volumes.

c. Social Benefits

The study underscores the importance of sustainable land-use planning for improving community resilience against flooding and water scarcity. Enhanced vegetation cover can improve livelihoods by supporting agriculture and reducing soil degradation. Additionally, strategic green infrastructure interventions, such as urban green spaces and afforestation programs, can enhance community engagement and promote environmental awareness (Kale and Sahoo, 2011).

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- Land use changes have a direct impact on hydrological processes, particularly surface runoff and infiltration.
- The SWAT model is a valuable tool for assessing hydrological impacts and guiding sustainable watershed management.
- Increased urbanization necessitates the integration of green infrastructure to balance development with environmental sustainability.
- Data-driven decision-making using remote sensing and hydrological modeling can improve water resource management strategies.

b. Practical Implications

The study provides essential insights for policymakers and urban planners to design climate-resilient cities and sustainable water management strategies. The integration of hydrological modeling with GIS can support informed decision-making in land-use planning, flood control measures, and watershed management initiatives.

c. Areas for Further Improvement or Research

Future research can focus on:

- Exploring the impact of climate change on runoff patterns in the basin.
- Investigating the effectiveness of nature-based solutions in mitigating runoff.
- Integrating socio-economic factors into hydrological models for a holistic approach to land and water management.
- Conducting high-resolution studies on micro-watersheds within the basin for localized water resource planning

3.5 Significance of different probability distributions in flood frequency analysis of Brahmani-Baitarani River Basin, India

1. Case Study Overview

The study focuses on the Brahmani-Baitarani River Basin in India, analyzing hydrological changes due to land use and land cover (LULC) modifications (Ul Hassan et al., 2019; Kundzewicz et al., 2018). The research primarily aims to estimate peak flood discharges by applying probability distribution models to observed discharge data at various gauges.

a. Project Background and Location

- The Brahmani-Baitarani Basin spans 83°55″E to 87°30″E longitudes and 20°28″N to 23°38″N latitudes (Singh and Rawat,, 2024).
- It covers a total area of 51,907.45 km², with 39,116 km² belonging to the Brahmani sub-basin and 14,351 km² to the Baitarani sub-basin.
- The basin is encircled by the Bay of Bengal on the east, Chota Nagpur Plateau on the north, and a ridge separating it from the Mahanadi watershed on the west and south.
- The Rengali Dam controls flood protection over 25,100 km², while the remaining part of the basin remains uncontrolled.

b. Problem Statement: Management and/or Environmental Challenge(s)

The Brahmani-Baitarani Basin faces increasing flood vulnerability due to:

- Population growth and urban expansion.
- LULC changes, such as deforestation and agricultural encroachment.
- Increased flood frequency and intensity, driven by climate change and anthropogenic activities.

2. Project description

a. Goals and Objectives

The study aims to:

1. Predict flood discharges for return periods of 2, 5, 10, 20, 50, 100, and 200 years.
2. Apply and compare probability distribution models (GEV, Gumbel Max, Log-Pearson III, Lognormal) to estimate peak flood discharges **(Murtaza et al., 2022).**
3. Assess flood risk and improve hydrological infrastructure planning.

b. Strategies and Interventions

- Application of probability distribution models for flood discharge prediction.
- Use of GIS and Remote Sensing to analyze hydrological patterns.
- Implementation of hydrological modeling tools for flood vulnerability assessment.
- Integration of LULC data to evaluate land cover changes affecting runoff dynamics (Brakenridge, 2024).

3. Outcomes and Impact

a. Environmental Benefits

- Improved flood prediction accuracy aids in mitigating disaster impacts.
- Better land use planning contributes to sustainable water resource management.
- Helps preserve natural floodplains, reducing downstream flooding.

b. Significant Findings

- The study confirms that extreme flood events in the Brahmani-Baitarani Basin are intensifying.
- The Gumbel Maximum and GEV models provided the best estimates for peak flood discharges.
- The most flood-prone areas are in the lower floodplain regions, such as Anandapur and Jenapur.

c. Social Benefits

- **Improved flood risk assessments** help communities prepare for disasters.
- **Better-informed decision-making** for policymakers and urban planners.
- **Enhanced engagement of local stakeholders** in flood mitigation strategies.

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- A combination of **probability models** enhances **flood prediction accuracy**.
- **LULC changes significantly influence flood magnitudes**, necessitating **integrated land and water management**.
- The **integration of GIS-based hydrological modeling** provides valuable insights for **sustainable river basin management**.

b. Practical Implications

- The study supports flood vulnerability mapping and hydraulic structure design.
- It offers a scientific basis for infrastructure planning, particularly for dam construction and water storage management.

- Findings can be used for disaster preparedness policies at the state and national levels.

c. Areas for Further Improvement or Research

- Incorporating climate change projections into flood prediction models.
- Exploring additional hydrological models for enhanced simulation accuracy.
- Examining socio-economic impacts of flood events on affected communities.
- Assessing groundwater interactions with surface water to refine hydrological analysis.

3.6 Surface water potential zones delineation and spatiotemporal variation characteristics of water pollution and the cause of pollution formation in Brahmani River Basin, Odisha

1. Case Study Overview

The study aims to delineate surface water potential zones in the Brahmani River Basin, Odisha, using Geographical Information Systems (GIS), Cluster Analysis (CA), and Multi-Criteria Decision-Making (MCDM) methods like Simple Additive Weighting (SAW) (Abdel-Monem et al., 2023; Acharya et al., 2020). The research evaluates water quality across multiple locations to identify pollution sources and their impacts.

a. Project Background and Location

The Brahmani River Basin, located in Odisha, spans approximately 39,268 km² across Odisha, Jharkhand, and Chhattisgarh (Achu et al., 2020). The study focuses on surface water potential zones within this basin, where water contamination is prevalent due to industrial waste and urban discharge.

2. Project description

a. Goal and Objectives

The primary objective is to utilize GIS, CA, and SAW to locate and define surface water potential zones, assess water quality, and aid in the sustainable management of surface water resources (Akdogan and Guven, 2023; Anbarasu et al., 2020). This includes mapping pollution hotspots and guiding corrective measures for water conservation (Anh et al., 2023).

b. Strategies and Interventions

- **GIS and Remote Sensing**: Used for mapping and analyzing surface water zones.
- **Cluster Analysis (CA)**: Helps identify pollution clusters based on water quality data.

- **Simple Additive Weighting (SAW)**: Prioritizes locations based on pollution severity.
- **Water Quality Monitoring**: Spatial and temporal data collection at multiple sampling points.

3. Outcomes and Impact

a. Environmental Benefits

- Identification of water pollution sources aids in targeted intervention strategies.
- Supports sustainable surface water management to prevent contamination.
- Contributes to ecological preservation by mapping critical water quality zones.

b. Significant Findings

- Approximately 42.85% of the study locations were found suitable for consumption.
- Industrial and household waste were major contributors to poor water quality.
- Four locations exhibited significantly high pollution levels, making water unsafe without treatment.

c. Social Benefits

- Improved water quality assessment supports better public health initiatives.
- Helps policymakers implement targeted pollution control measures.
- Enhances water availability for drinking and irrigation by guiding conservation efforts.

4. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- GIS and MCDM techniques offer a robust framework for water resource management.
- Industrial and urban wastewater contribute significantly to water pollution.
- The study highlights the urgent need for wastewater treatment facilities.

b. Practical Implications

- Policymakers can use the study's findings to enforce stricter regulations on industrial discharge.
- Local authorities can implement targeted interventions in pollution hotspots.
- Advanced water treatment technologies should be prioritized in high-risk areas.

c. Areas for Further Improvement or Research

- Inclusion of seasonal variations in water quality assessment.

- Implementation of machine learning models for more precise pollution prediction.
- Expansion of study scope to include groundwater interactions with surface water.

3.7 Evaluation of water quality in the Brahmani River basin, Odisha: A multicriteria decision-making approach for sustainable management

1. Case Study Overview

The study presents an in-depth evaluation of water quality in the Brahmani River Basin (BRB) in Odisha, India, using an integrated approach combining Geographic Information System (GIS) and Multi-Criteria Decision-Making (MCDM) techniques. The study spans three years (2020-2023) and assesses water quality at seven key locations (Abbas and Ali, 2020; Agarwal, 2022). The primary objective is to identify pollution sources and their impacts on water quality through methods like the CRITIC mechanism and the MOORA model (Brauers and Zavadskas, 2006).

a. Project Background and Location

The Brahmani River Basin, a crucial water resource in Odisha, spans 39,268 km² and supports agricultural, industrial, and domestic needs. However, rapid urbanization, industrial expansion, and wastewater discharge have significantly degraded its water quality. The study monitors seven strategic locations along the river to analyze contamination patterns and the extent of pollution (Bruce and Limin, 2021; Agarwal et al., 2020).

b. Problem Statement: Management and/or Environmental Challenge(s)

The Brahmani River faces severe pollution challenges primarily due to:

- Industrial Waste Discharge: Factories and power plants release untreated effluents into the river.
- Domestic Sewage: Unregulated discharge of wastewater contributes to bacterial contamination.
- Agricultural Runoff: Excess fertilizers and pesticides enter the river, increasing nitrate and phosphate levels.
- Climate Variability: Seasonal fluctuations affect pollutant concentrations, exacerbating contamination.

2. Project description

a. Goal and Objectives

- To evaluate the water quality of the Brahmani River at multiple locations.

- To identify pollution hotspots and determine primary sources of contamination.
- To employ GIS and MCDM techniques for a comprehensive water quality assessment.
- To propose sustainable management strategies to mitigate pollution.

b. Strategies and Interventions

The study adopts a multi-pronged approach for water quality assessment and management:

- Water Quality Monitoring: Collection and analysis of water samples using 15 physicochemical parameters, including pH, dissolved oxygen (DO), nitrate, phosphate, and heavy metals.
- GIS-Based Spatial Analysis: Mapping pollution sources using the CRITIC method to visualize water quality variations.
- MCDM Techniques (MOORA and CRITIC): These models help prioritize pollution control efforts by categorizing locations based on water quality levels.
- Identification of Point and Non-Point Sources: Differentiating industrial discharge from agricultural runoff to guide regulatory actions.

3. Outcomes and Impact

a. Environmental Benefits

- Identification of high-risk pollution zones to enable targeted interventions.
- Support for improved wastewater treatment and pollution control strategies.
- Enhancement of river ecosystem health by reducing contaminant levels.
- Promotion of sustainable freshwater conservation efforts.

b. Significant Findings

- Water Quality Classification: Approximately 57% of the sampled locations exhibited poor water quality.
- High-Pollution Zones: Industrial areas, especially near Rourkela and Talcher, showed extreme contamination.
- Spatial Variability: Seasonal changes significantly impacted pollutant concentrations, requiring year-round monitoring.
- Effectiveness of MCDM Methods: The MOORA method successfully categorized locations based on pollution severity, aiding decision-making for water management (Azhdarpoor et al., 2019).

c. Social Benefits

- Improved understanding of water contamination risks for local communities.
- Enhanced policy development for better drinking water management.

- Reduction in health hazards by addressing contamination sources.
- Increased public awareness of water conservation practices.

4. Lessons Learned and Recommendation

a. Key Takeaways from the Project

- GIS and MCDM provide a robust framework for water quality assessment: The integration of spatial and decision-making techniques enhances pollution analysis (Azhdarpoor et al., 2019).
- Industrialization and population growth are major pollution drivers: Stringent regulatory measures are essential.
- Targeted wastewater management is crucial: High-pollution areas need immediate intervention, including treatment plants and stricter regulations.

b. Practical Implications

- Policy Recommendations: Policymakers can utilize GIS maps to enforce regulations on industrial effluents.
- Infrastructure Development: Installing wastewater treatment plants in critical pollution zones.
- Community Engagement: Educating residents on pollution reduction strategies.
- Agricultural Best Practices: Encouraging sustainable farming methods to limit chemical runoff.

c. Areas for Further Improvement or Research

- Integration of AI and Machine Learning: Automating real-time water quality monitoring for more accurate predictions.
- Seasonal Water Quality Variations: Conducting longitudinal studies to assess year-round pollution trends.
- Community-Driven Water Conservation Initiatives: Engaging local populations in sustainable water management.
- Advanced Treatment Technologies: Exploring innovative filtration and bioremediation techniques for pollutant removal.

3.8 Development of a Functional Water Quality Index: a case study in Brahmani River Basin, India

1. Case Study Overview

The study focuses on developing a Functional Water Quality Index (FWQI) to assess and manage water quality effectively across diverse environmental conditions. Unlike conventional water quality indices that rely on specific parameters, the FWQI incorporates a broad range of indicators, making it adaptable to different water bodies and environmental concerns. The study applies this index to the Brahmani River Basin in India, evaluating its effectiveness in characterizing overall water quality status and identifying trends over time (Abtahi et al., 2016; Mohan et al., 1996). The approach is designed to be a versatile and accessible tool for decision-makers, scientists, and the general public.

a. Project Background and Location

The research is conducted in the Brahmani River Basin (BRB), a crucial water resource in eastern India that spans Odisha, Jharkhand, and Chhattisgarh. The river supports a variety of uses, including drinking water supply, irrigation, industrial operations, and ecological balance. However, increasing anthropogenic pressures, including industrial waste discharge, agricultural runoff, and urban expansion, have led to significant water quality degradation. The study uses data from nine gauging stations across the basin, covering a period from January 2002 to December 2016, to evaluate long-term water quality trends and assess the feasibility of implementing the FWQI for better resource management (Taylor and Hiscock, 2016).

b. Problem Statement: Management and/or Environmental Challenge(s)

Water quality assessment is a complex and challenging task due to the variability of pollutants, seasonal changes, and differences in monitoring approaches. Traditional water quality indices (WQIs) often have limitations, including dependence on a fixed set of parameters and subjective weight assignments (Sahoo et al., 2016). The Brahmani River faces serious pollution challenges from industrial effluents, domestic sewage, and agricultural chemicals, making it imperative to develop a more comprehensive and adaptable assessment tool (Taylor and Hiscock, 2016). The lack of standardized monitoring systems further complicates decision-making, resulting in inadequate water management strategies. This study seeks to address these issues by introducing the FWQI, which offers a more inclusive and flexible method for water quality assessment.

2. Project description

a. Goal and Objectives

- To develop a Functional Water Quality Index (FWQI) that integrates multiple parameters for a comprehensive water quality assessment.
- To evaluate the effectiveness of FWQI in characterizing water quality status in the Brahmani River Basin.
- To analyze spatiotemporal variations in water quality based on long-term data from nine gauging stations.
- To provide a decision-support tool that is adaptable across different environmental conditions and can aid policymakers in sustainable water resource management.

b. Strategies and Interventions

The development of the Functional Water Quality Index (FWQI) introduces an innovative approach that allows for the inclusion of multiple water quality indicators without being restricted to a predefined set of parameters. This flexibility makes it a more comprehensive and adaptable tool for water quality assessment. To achieve this, extensive data collection and analysis were conducted, utilizing water quality data from nine gauging stations over a period of 14 years (2002-2016). This long-term dataset enables the identification of significant trends and variations in water quality across different locations.

A crucial aspect of the FWQI methodology is the parameter weighting process, where a fuzzy entropy weight method is employed to assign weights to various water quality parameters. This ensures objectivity in the assessment by preventing subjective bias in parameter selection and evaluation. Furthermore, the concept of the Quality Contributing Factor (QCF) is incorporated to categorize water quality based on the contribution of each parameter, providing a more detailed and precise classification system.

To enhance the practical applicability of the FWQI, GIS-based visualization techniques are utilized. These spatial analysis tools help in mapping water quality distribution and identifying critical pollution zones. By integrating GIS, the study facilitates better decision-making by offering visual insights into pollution sources and trends, ultimately aiding policymakers, researchers, and environmental managers in implementing targeted water quality improvement strategies.

3. Outcomes and Impact

a. Environmental Benefits

The Functional Water Quality Index (FWQI) enables a more accurate and dynamic assessment of water quality, allowing for the early detection of pollution sources. By integrating multiple parameters and using a flexible weighting system, it ensures a comprehensive evaluation of water quality conditions. Additionally, the FWQI provides a standardized method for comparing water quality across different regions and time periods, making it a valuable tool for large-scale environmental assessments. The study also highlights how the FWQI supports sustainable water resource management by identifying high-risk pollution areas and recommending targeted interventions to mitigate contamination. Furthermore, by offering an adaptable framework, the FWQI enhances environmental planning and policy formulation, enabling decision-makers to implement more effective water conservation and pollution control strategies.

b. Significant Findings

- The analysis reveals considerable spatiotemporal variations in water quality across the Brahmani River Basin.

- Industrial zones show consistently poor water quality, primarily due to high levels of heavy metals and chemical pollutants.
- Agricultural runoff significantly contributes to elevated nitrate and phosphate levels, particularly during the monsoon season.
- The FWQI successfully categorizes water quality in a more detailed manner compared to conventional indices, making it a valuable tool for water resource management.

c. Social Benefits

The improved water quality assessment provided by the Functional Water Quality Index (FWQI) plays a crucial role in supporting public health initiatives by reducing the prevalence of waterborne diseases. By offering a more comprehensive evaluation of water quality, the study provides actionable insights that policymakers can use to enhance drinking water safety and sanitation measures, ensuring cleaner and safer water sources for communities. Additionally, the adaptability of the FWQI makes it an effective tool for engaging local communities in water conservation efforts, fostering a sense of responsibility toward sustainable water management. Furthermore, the index helps industries and local governments collaborate on pollution control strategies, promoting environmentally friendly practices and ensuring compliance with regulatory standards to protect water resources for future generations.

4. Lessons Learned and Recommendation

a. Key Takeaways from the Project

- The FWQI represents a significant advancement in water quality assessment by incorporating a flexible and inclusive approach.
- The study highlights the urgent need for stricter regulations on industrial and agricultural pollution in the Brahmani River Basin.
- GIS-based spatial analysis enhances decision-making by providing visual insights into pollution distribution.
- The FWQI framework can be replicated in other river basins for more effective water management.

b. Practical Implications

The Functional Water Quality Index (FWQI) serves as a crucial tool for various stakeholders in water resource management. For policymakers, it provides a scientifically robust framework to design effective water quality regulations and monitoring programs, ensuring sustainable management and conservation efforts. Industries can leverage the FWQI to assess their environmental impact, allowing them to adopt more sustainable waste disposal practices and mitigate pollution risks. Researchers benefit from the study as it establishes a methodological foundation for further advancements in water quality assessment, fostering innovation in monitoring and remediation techniques. Additionally, communities can utilize FWQI data in public awareness campaigns to promote responsible water usage and conservation, empowering local populations to play an active role in preserving water resources.

c. Areas for Further Improvement or Research

- **Integration with AI and Machine Learning:** Future studies could explore automated systems for real-time water quality monitoring.
- **Expansion of FWQI Application:** Testing the index in different geographic locations and water bodies would enhance its reliability.
- **Long-Term Monitoring Strategies:** Developing standardized protocols for continuous water quality assessment.
- **Climate Change Impact Studies:** Examining how climate variations affect water quality and refining FWQI to incorporate these factors.

4. Conclusions

The study and comparative insights from the Baitarani and Brahmani basins provide invaluable lessons for the sustainable management of the Mahanadi River Basin. As one of India's most vital river systems, the Mahanadi embodies the intricate interplay between water, people, and ecosystems. Ensuring its long-term health requires moving beyond fragmented interventions toward a unified, science-based, and community-centered river management framework. The basin's future hinges on how effectively it integrates environmental restoration with socio-economic development, guided by data, innovation, and inclusivity.

The Mahanadi Basin must be envisioned as a dynamic, living system rather than merely a resource to be exploited. Protecting its hydrological integrity demands that ecological flow requirements are recognized and maintained to sustain aquatic habitats and biodiversity. Industrial and agricultural growth must align with stringent water quality standards, supported by continuous monitoring and enforcement. Investments in wastewater treatment, solid waste management, and green infrastructure can significantly reduce pollution loads while improving water availability for downstream users.

A critical outcome from the Baitarani experience is the recognition that community participation is the cornerstone of successful river basin management. Empowering local communities through capacity building, livelihood diversification, and environmental education ensures that conservation becomes a shared responsibility. Initiatives such as high-density plantations, sustainable harvesting of forest produce, and fair-trade models can be replicated across the Mahanadi's riparian zones to simultaneously enhance livelihoods and biodiversity. Similarly, promoting gender-inclusive and youth-focused participation can strengthen the social fabric of river stewardship.

From an institutional perspective, coordination among states and agencies is essential. The establishment of the Centre for Mahanadi River Basin Management and Studies (cMahanadi) under NIT Raipur and NIT Rourkela provides a robust platform for interdisciplinary collaboration. Strengthening its linkages with research institutions, policymakers, and local bodies will facilitate data-driven decisions and integrated planning. The basin can further benefit from adopting adaptive management frameworks that respond to emerging challenges such as climate change, population growth, and land-use transitions.

Technological innovations, including GIS-based flood mapping, hydrological modelling, and machine learning-driven water prediction tools, can revolutionize basin management. These tools, already proven effective in the Baitarani and Brahmani studies, should be institutionalized within the Mahanadi's monitoring and planning systems. Risk-based flood management, early warning systems, and optimized dam operations can minimize disaster impacts while improving water storage efficiency. At the same time, policy instruments should incentivize water use efficiency across sectors agriculture, industry, and domestic supply through demand management and pricing mechanisms.

Ultimately, the Mahanadi's conservation journey must embody a balance between utilization and preservation. River basin management should not only aim to restore physical and chemical parameters but also revive the cultural and ecological identity of the river. Public engagement campaigns, eco-tourism initiatives, and school-based river education programs can foster emotional and civic connections to the Mahanadi, ensuring that conservation becomes an enduring societal value. Therefore, the path forward for the Mahanadi River Basin lies in embracing a holistic, inclusive, and forward-looking vision. By learning from the experiences of the Baitarani and Brahmani basins and adapting them to its unique context, the Mahanadi can become a model of sustainable river basin governance in India. Integrating science, policy, and people anchored in shared responsibility will not only rejuvenate the river but also secure water, food, and ecological security for generations to come.

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