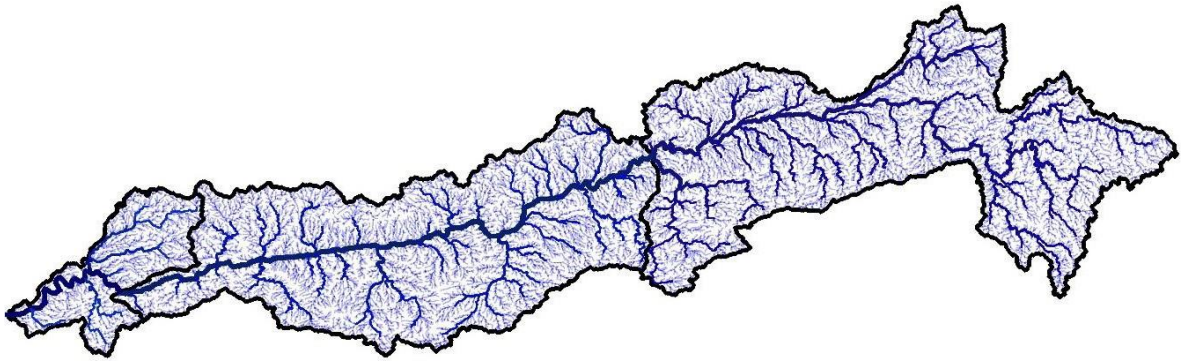




National River Conservation Directorate
Ministry of Jal Shakti, Department of Water
Resources,
River Development & Ganga Rejuvenation
Government of India

Learnings from Other Indian Basins



March 2025



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Learnings from Other Indian Basins



National River Conservation Directorate (NRCDD)

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

www.nrcd.nic.in

Centres for Narmada River Basin Management and Studies (cNarmada)

The Center for Narmada River Basin Management and Studies (cNarmada) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by IIT Gandhinagar and IIT Indore, under the supervision of cGanga at IIT Kanpur, the center serves as a knowledge wing of the National River Conservation Directorate (NRCDD). cNarmada is committed to restoring and conserving the Narmada River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

www.cnarmada.org

Centres 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 IIT Gandhinagar (Lead Institute) along with eleven other participating institutions under the CAMP project, under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCDD) in 2024. We gratefully acknowledge the individuals who provided information and photographs for this report.

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PREFACE

This report synthesizes the experiences and management strategies of various Indian river basins to provide insights for policymakers and practitioners. By examining a range of case studies, the report aims to identify best practices, common challenges, and effective policy interventions that can be adapted and applied to improve river basin management across the country.

In this report, you will find an analysis of several major Indian river basins. Each case study provides an overview of the basin's unique features, including its geographical extent, hydrological characteristics, and socio-economic significance. Furthermore, the report delves into the specific management and environmental challenges confronting each basin, such as pollution in the Ganga, erosion in the Brahmaputra, and water scarcity in the Sabarmati. By examining the strategies and interventions employed to address these issues, the report offers valuable lessons for policymakers.

Learning from the experiences of other Indian basins is of paramount importance for several reasons. Firstly, it allows for the identification of common patterns and challenges that transcend regional specificities, enabling the development of broadly applicable management principles. Secondly, it facilitates the transfer of best practices and innovative solutions, reducing the need to reinvent the wheel in each basin. Finally, it fosters a culture of adaptive learning, where policymakers can continuously refine their approaches based on evidence from both successes and failures in other basins.

The successful compilation of this report would not have been possible without the invaluable contributions of numerous individuals and institutions. We also acknowledge the support and cooperation of the various government agencies, research institutions, and local stakeholders who provided data, information, and insights.

This report is intended to serve as a resource for policymakers, water resource managers, environmentalists, and researchers. By providing an overview of the challenges and opportunities in India's major river basins, it is hoped that this document will inform the development of more sustainable water management policies. Ultimately, the insights presented here can help guide the implementation of new policy prescriptions that balance the need for economic development with the imperative of environmental conservation, ensuring the health and resilience of India's rivers for generations to come.

IIT Gandhinagar, IIT Indore
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Introduction

India is the seventh-largest country in the world by land area, covering 3,287,263 km²—about 2.45% of the world's land resources—and is the second-most populous nation with over 1.4 billion people, accounting for roughly 17–18% of the global population. Despite this, India possesses only about 4% of the world's freshwater resources, making water access a critical driver of development. Every year, the country receives around 4,000 billion cubic meters (BCM) of precipitation, of which approximately 1,869 BCM becomes available as renewable water resources. Of these, about 690 BCM is derived from surface water and 433 BCM from groundwater, summing to roughly 1,123 BCM of utilizable water. According to recent assessments by the Central Water Commission, the average annual per capita water availability was 1,486 cubic meters in 2021 and is projected to decline to around 1,367 cubic meters by 2031—figures that signal increasing water stress as the population grows.

Being an agrarian country, a significant share of this water is withdrawn for irrigation. India has made substantial progress in water management through advanced engineering solutions that have enabled the storage and diversion of large water volumes. For instance, as per data available as of July 2007, the total live storage capacity across Indian river basins was about 282 BCM, supported by 6,138 large dams and more than 1,894 major and medium irrigation projects. This infrastructure, while impressive, underscores the need for integrated, basin-level planning as isolated state projects increasingly interact with one another under rising water demand.

The National Water Policy of India, last revised in 2012, recognizes that the development and management of water resources must be guided by a national perspective. It emphasizes an integrated and environmentally sound approach to harnessing water resources, calling for coordinated basin-level planning that considers the interlinkages between various water projects, demographic pressures, and environmental sustainability initiatives.

Major Indian Basins: Features and Concerns

Rivers in India have profoundly shaped the nation's political, social, and cultural fabric. The country encompasses 25 major river basins, many of which traverse multiple state boundaries, often leading to interstate conflicts over water allocation for agricultural, industrial, and domestic use.

Indian river basins are as diverse as they are vital, each presenting a unique blend of natural endowments and complex challenges. The Ganga Basin, India's largest and most culturally revered river system, spans multiple countries and supports a substantial proportion of the nation's population. It provides critical water resources for agriculture, industry, and domestic use. However, the basin is under severe stress from industrial discharges, untreated sewage, agricultural runoff, and encroachments. These factors not only deteriorate water quality but also threaten aquatic biodiversity and public health, thereby demanding innovative pollution control and comprehensive river management strategies.

In the North-East, the Barak River Basin, with its abundant rainfall and extensive vegetation cover, supports a rich network of tributaries and wetlands that are crucial for maintaining ecological balance. Despite its natural advantages, the Barak Basin is frequently besieged by monsoon-induced floods, which result in riverbank erosion, displacement of communities, and significant socio-economic losses. Additionally, groundwater contamination, particularly with arsenic, and the effects of deforestation compound these issues, highlighting the urgent need for sustainable watershed management and disaster resilience measures.

Moving to the transboundary Brahmaputra Basin, renowned for its colossal discharge and expansive floodplains, the challenges take on a different scale. The Brahmaputra is indispensable for agriculture, fisheries, and hydroelectric power in the region; yet, its highly braided channels and dynamic sediment transport processes lead to recurring floods and severe erosion. These issues, exacerbated by climate change, result in annual economic losses, forced migration, and environmental degradation. Furthermore, the lack of cohesive transboundary governance complicates water sharing and effective resource management across national borders.

Eastern basins, such as the Baitarani and Brahmani, further illustrate the interplay between natural variability and human pressures. These basins support mixed agricultural practices—ranging from rain-fed to irrigated systems—and are experiencing heightened stress due to rapid urbanization, industrial expansion, and mining activities. The increasing demand for water in these regions is outstripping supply, leading to both water scarcity and quality issues. Integrated water resource management approaches that consider both environmental flow requirements and socio-economic development are essential to address these concerns.

In southern India, the Pennaiyar Basin plays a critical role in supporting urban centers and agricultural livelihoods. Despite its importance, the basin is plagued by seasonal water stress, declining groundwater levels, and escalating water pollution from domestic and industrial

sources. The challenge here is compounded by fragmented interstate governance, which complicates coordinated efforts to manage and conserve the basin's water resources.

On the western front, the Sabarmati Basin in Gujarat is emblematic of water-deficit regions where natural flows are limited. Although it is a key source of water for urban, industrial, and agricultural needs in cities like Ahmedabad and Gandhinagar, the basin suffers from heavy groundwater extraction, severe pollution, and a high dependency on interbasin water transfers. Similar challenges are evident in smaller basins such as the Subarnarekha and Tapi, where climate variability, competing water uses, and inadequate infrastructure further stress the system.

Collectively, these diverse river basins underscore a critical need for robust, science-based interventions that balance developmental imperatives with ecological sustainability. Advanced hydrological modeling, integrated policy frameworks, and strong stakeholder engagement are imperative to address issues ranging from pollution control and flood management to groundwater sustainability and transboundary water conflicts. Only through such coordinated strategies can India safeguard these invaluable water resources for current and future generations.



Figure 1: (1) Indus (Up to border); (2a) Ganga; (2b) Brahmaputra; (2c) Barak & others; (3) Godavari; (4) Krishna; (5) Cauvery; (6) Subernarekha; (7) Brahmani and Baitarni; (8) Mahanadi; (9) Pennar; (10) Mahi; (11) Sabarmati; (12) Narmada; (13) Tapi; (14) West flowing rivers South of Tapi; (15) East flowing rivers between Mahanadi and Godavari; (16) East flowing rivers between Godavari and Krishna; (17) East flowing rivers between Krishna and Pennar; (18) East flowing rivers between Pennar and Cauvery; (19) East flowing rivers South of Cauvery; (20) West flowing rivers of Kutch and Saurashtra including Luni; (21) Minor rivers draining into Bangladesh; (22) Minor rivers draining into Myanmar; (23) Area of North Ladakh not draining into Indus; (24) Drainage Area of Andaman & Nicobar Islands; (25) Drainage Area of Lakshadweep Islands.

Overarching Governing and Regulatory Framework

India's legal framework for water is a complex structure that reflects the country's federal character, with a distribution of legislative and executive powers between the Union (central) and State governments. This division of authority, enshrined in the Constitution of India, plays a crucial role in the governance and management of water resources across the nation.

The constitutional basis for water governance is primarily found in the Seventh Schedule of the Constitution, which delineates the subjects under the legislative purview of the Union and the States. Entry 17 of List II (State List) explicitly assigns "Water, that is to say, water supplies, irrigation and canals, drainage and embankments, water storage and water power" to the jurisdiction of the State legislatures. However, this is subject to Entry 56 of List I (Union List), which empowers the Union to legislate on the "regulation and development of inter-State rivers and river valleys" to the extent that such regulation and development is declared by the Parliament to be "expedient in the public interest". This creates a dual framework where States have primary responsibility over water within their boundaries, but the Union can intervene in the case of inter-state rivers.

Article 262 of the Constitution further elaborates on the adjudication of disputes related to inter-state rivers, granting the Parliament the authority to enact laws for the adjudication of such disputes and to bar the jurisdiction of the Supreme Court or any other court in these matters. In exercise of this power, the Parliament enacted the Inter-State River Water Disputes Act, 1956 (ISRWD Act), which provides the primary legal mechanism for addressing disputes between states over water resources.

The ISRWD Act establishes a framework for the constitution of Water Disputes Tribunals to adjudicate specific inter-state water disputes. The process begins with a State government's request to the Central Government, which then assesses the dispute and attempts to resolve it through negotiation. If negotiations fail, the Central Government constitutes a Tribunal to adjudicate the dispute. The Tribunal's decision is final and binding, having the same force as an order or decree of the Supreme Court.

However, the implementation of the ISRWD Act has faced several challenges. These include excessive delays in dispute resolution, weak enforcement mechanisms, and jurisdictional ambiguities. The 2002 amendment to the Act sought to address some of these issues by introducing timelines for tribunal formation and awards, and by giving tribunal decisions the force of a Supreme Court decree. However, challenges persist, including delays in

implementation and the continued ambiguity surrounding the Supreme Court's jurisdiction in inter-state water disputes.

In addition to the constitutional and statutory framework, the judiciary has also played a significant role in shaping the legal landscape for water in India. The Supreme Court of India has, through various judgments, recognized the fundamental right to water as part of the right to life under Article 21 of the Constitution. The Court has also actively intervened in water management issues, sometimes directing the establishment of central authorities and committees, which has led to discussions about the balance of federalism in water governance.

Furthermore, several other legislations contribute to the broader legal framework for water. The River Boards Act, 1956, provides for the establishment of River Boards to advise the Central Government on the regulation and development of inter-state rivers, though no such board has been constituted under this Act. More recently, the Dam Safety Act, 2021, has been enacted to ensure the safety of dams and establish institutional mechanisms for dam safety at both the Central and State levels, adding another layer to the governance structure of inter-state rivers.

In conclusion, the legal framework for water in India is characterized by a mix of constitutional provisions, statutory enactments, and judicial interventions. The federal structure of India necessitates a division of powers between the Union and the States, leading to a complex web of authorities and responsibilities. While this framework aims to ensure the sustainable and equitable management of water resources, it also faces challenges such as delays in dispute resolution, enforcement issues, and jurisdictional ambiguities.

Case Studies of Other Indian Basins

Indus Basin

[NOT YET SUBMITTED, WILL BE UPDATED ONCE RECEIVED]

Ganga River Basin

Case Study Overview

Project background and location

The Ganga Basin spans across four countries—India, Nepal, China, and Bangladesh—covering approximately 1,080,000 km². Around 80% of this basin, known as the National River Ganga Basin (NRGB), lies within India. The NRGB is India's largest river basin, encompassing over 26% of the country's total land area. It contributes 525 km³ per year to India's total renewable water availability of 1,869 km³ per year. As a water-rich basin, it sustains nearly 43% of India's population.

The National River Ganga originates in the Himalayas from multiple headstreams, including Alaknanda, Bhagirathi, Bhilangana, Dhauliganga, Mandakini, Nandakini, and Pindar, which merge at or before Devaprayag. As it descends into the plains, the river flows southeast, receiving water from major tributaries such as Ramganga, Yamuna, Kosi, Gandak, Gomti, Sone, Karamnasa, and Ghaghra, significantly expanding its size downstream of Allahabad (Prayagraj).

Upon reaching the Rajmahal Hills, the Ganga splits into two branches:

- The eastern branch, Padma, flows southeast into Bangladesh, where it joins the Brahmaputra and Meghna before emptying into the sea.
- The southern branch, Hooghly, is fed by the Damodar and Mayurakshi before reaching the sea.

The combined outflow of these branches forms the Sundarbans Delta, the world's largest delta, covering approximately 60,000 km² across Bangladesh and West Bengal. In total, the Ganga River spans over 2,500 km.

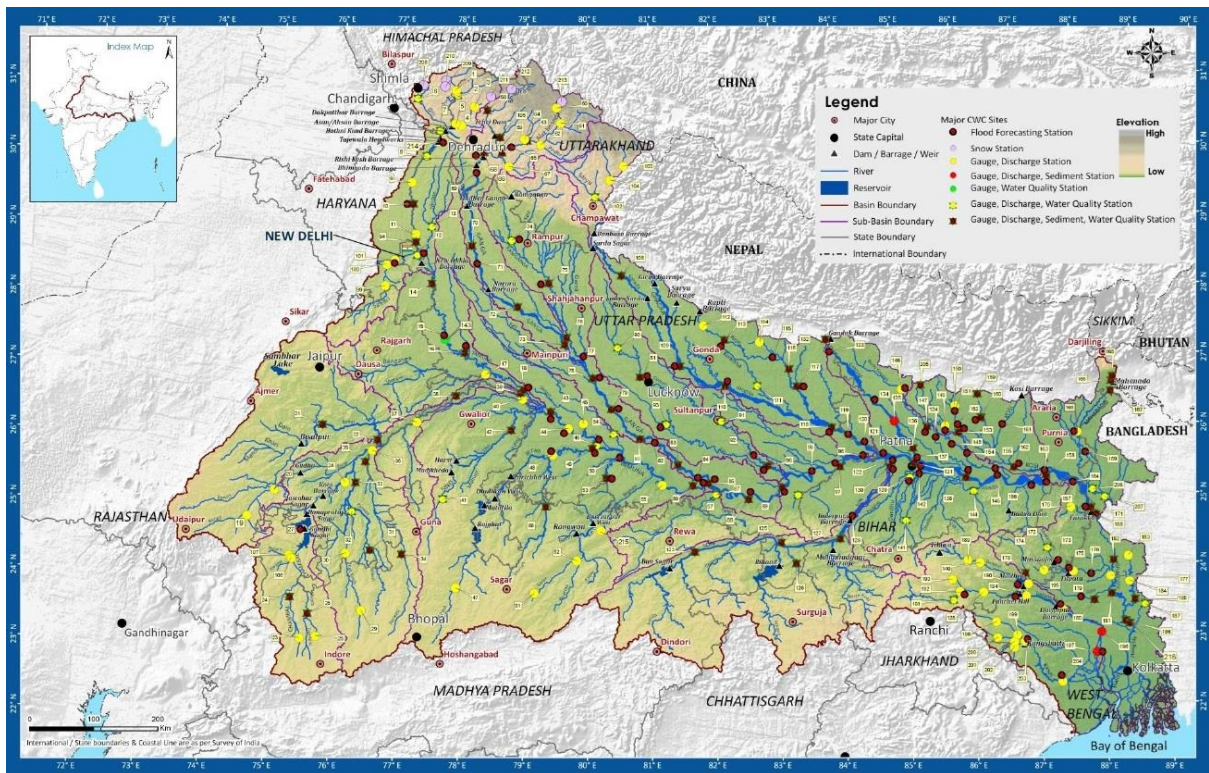


Figure 2: Ganga River Basin map. Source of map:(India-WRIS, 2014, p. 6)

Problem statement: Management and Environmental challenges

The Ganga River, one of India's most significant water bodies, faces multiple challenges, including pollution from industrial discharge, untreated sewage, agricultural runoff, and encroachments. Water quality degradation has severe consequences for public health, aquatic biodiversity, and socio-economic activities dependent on the river. Effective river basin management is critical to mitigating these challenges and ensuring the long-term sustainability of the Ganga ecosystem.

Project Description

The Indian government has implemented several initiatives to manage the Ganga River, starting with the Ganga Action Plan (GAP) in 1985 (Tare et al., 2011), which aimed to reduce pollution but faced significant shortcomings, achieving only 39% of its sewage treatment target (Chaudhary & Walker, 2019). In 2009, the National Ganga River Basin Authority (NGRBA) was established to take a basin-wide approach to river management, but it was later replaced in 2016 by the National Council for Rejuvenation, Protection, and Management of River Ganga. The most ambitious initiative, the Namami Gange Programme, launched in 2015 with a budget of Rs 20,000 for the first five years, focuses on sewage treatment, riverfront development, biodiversity conservation, and industrial pollution control. International agencies, including the World Bank (\$1 billion loan), Japan International Cooperation Agency (JICA), and German International Cooperation (GIC), have provided financial and technical support. The government has also adopted international river management strategies, such as those used for

cleaning the Rhine and Danube rivers.

The Namami Gange Programme covers 3,897 towns and 4,465 villages across 11 states in India, focussing on pollution hotspots in 97 towns in Uttarakhand, Uttar Pradesh, Bihar, West Bengal, and Jharkhand.

Goals and objectives of Namami Gange Programme

Environmental flows must be maintained in all rivers and tributaries of the Ganga River System to support their geological, ecological, socio-economic, and cultural roles.

The water quality of all rivers and tributaries within the system should align with their natural and functional requirements, ensuring ecological balance and sustainability.

The water and aquatic resources of the Ganga River System must be utilized wisely to promote sustainable development across the National River Ganga Basin (NRGB).

All existing, ongoing, and planned human activities within the NRGB should undergo transparent and inclusive review, ensuring the consensus of affected communities and stakeholders for the overall well-being of the basin.

Additionally, the Ganga River Basin Plans also intended to:

Develop a comprehensive water management strategy for the Ganga basin.

Implement pollution control measures to improve water quality.

Promote sustainable water use practices among communities and industries.

Enhance public awareness and stakeholder engagement in river conservation.

Foster international collaborations for knowledge sharing and technology transfer.

Strategies and interventions

Policy and Governance: Development of regulatory frameworks and policies to enforce environmental standards.

Technology Deployment: Adoption of advanced wastewater treatment technologies, real-time water monitoring systems, and bio-remediation techniques.

Community Engagement: Awareness campaigns, training programs, and participatory governance to involve local communities.

Industrial Collaboration: Encouragement of cleaner production techniques and waste management practices in industries along the river.

Scientific Research: Studies on hydrology, pollution dynamics, and ecosystem health to inform decision-making.

The plans are defined by well-defined Missions: (1) Aviral Dhara, (2) Nirmal Dhara, (3) Ecological Restoration, (4) Sustainable Agriculture, (5) Geological Safeguarding, (6) Basin Protection Against Disasters, (7) River Hazards Management, and (8) Environmental

Knowledge-Building and Sensitization.

Key stakeholders and partnerships

Government of India (Ministry of Jal Shakti, National Mission for Clean Ganga)

Research institutions and universities (IIT Kanpur, IIT Delhi, IIT Guwahati, IIT Madras, IIT Roorkee, IIT BHU, IIT Gandhinagar, Central Inland Fisheries Research Institute (CIFRI), National Environmental Engineering Research Institute (NEERI), Jawaharlal National University (JNU), Patna University, NIT Kurukshetra, Delhi University, National Institute of Hydrology (NIH) Roorkee, ISI Kolkata, Allahabad University)

International organizations and funding agencies

Local communities and non-governmental organizations (NGOs) (WWF India)

Private sector industries operating near the river basin

Citizens, and citizen's groups/associations

Outcomes and Impact

The evaluation used OECD-DAC criteria and Logical Framework Approach (LFA) (ASCI, 2020).

Output	Score (1-10)	NGP Thrust Area
Output 1: Wholesomeness of River Achieved	4	Aviral Dhara
Output 2: Clean River Attained	6	Nirmal Dhara
Output 3: River Front Development Completed	8	Protection & beautification of riverfront & development of public amenities
Output 4: Institutional Development Achieved and Capacity Building Institutionalized	5	Inter-ministerial Coordination, State's participation, and Capacity building
Output 5: Research, Monitoring & Learning and Innovative Project Financing Mechanism Established	4	Research and monitoring
Output 6: Aquatic Flora and Fauna Protected and Promoted	5	Conservation of plants and aquatic species
Output 7: Awareness Raised and Behaviour Change Achieved	5	People's Participation and Creating Awareness
Output 8: Social Inclusion, Gender & Equity Integrated	Not Evaluated	Output is not explicitly covered under thrust areas

Source: Table based on Third Party Evaluation of Namami Gange Programme (ASCI, 2020).

Environmental benefits

A total of 200 sewerage infrastructure projects, including one decentralized modular project, have been approved with a combined cost of ₹31,810 crore. Of these, 116 projects have been completed and are operational, while the rest are at different stages of implementation.

A total of 84 projects have been approved for the construction, modernization, and renovation of 286 ghats, crematoria, and ponds.

Restoration of aquatic biodiversity and riverine ecosystems are underway. Evidence shows that various water quality parameters, including dissolved oxygen, pH, and hardness, were generally within the acceptable limits based on drinking water guidelines for humans and the survival of aquatic organisms, with a few exceptions observed at specific locations (Tiwari et al., 2022).

The population of Ganga River Dolphin and the Irrawaddy Dolphin population status remains a concern (Tare & Kapoor, 2021). However, positive results are expected given the associated efforts to improve river health. Project Dolphin was launched in 2020 for conduct focused conservation efforts for the Dolphin.

Social benefits

Reduction in industrial and domestic wastewater discharge into the Ganga.

Improvement in water quality parameters such as dissolved oxygen and biochemical oxygen demand (Tiwari et al., 2022).

Economic benefits

Hilsa and carp fish volumes have been declining in the Ganga River Basin over time, this remains a concern (Tare & Kapoor, Vishal, 2020). In the lower and middle Ganga, major catfish species were found to be over exploited (Ray et al., 2022), needing special attention. Small indigenous fish species are largely being fished sustainably (Ray et al., 2023), barring *morari* (*Cabdio morar*) consumed largely by underprivileged communities. Prayagraj region: Major carp landings declined from 35.82 tons (1981–90) to 5.97 tons (2016–19). Buxar stretch: Hilsa contributed 33.48% (22.35 tons) in the 1960s but declined significantly after the 1980s following the Farakka Barrage construction. Patna: Major carp landings decreased from 23.35 tons (21.48%) in the 1960s to 2.16 tons (7.88%) in 2016–19, while miscellaneous fish species increased. Bhagalpur: Major carp landings declined from 18.66 tons (20.18%) in the 1980s to 1.98 tons (9.90%) in the present study. Catfish and miscellaneous fish species: Increasing trend across all sites, with their share ranging from 29–43% (Das et al., 2023). Overall, there is a declining trend in fish landings, mainly of major carps, and rise in population of small fish. The efforts ongoing should improve fish availability in the river.

Job creation in water management, sanitation, and conservation sectors.

Lessons Learned and Recommendations

Key takeaways from the project

A multi-stakeholder approach is essential for effective river management.

Policy enforcement and monitoring mechanisms need to be strengthened.

Community involvement is critical for long-term sustainability.

Best practices and strategies for replication

The experiences from the NRGB are particularly relevant for the Narmada Basin as well, particularly in terms of institutional practices and the similarity of governance structures.

However, the Narmada River Basin is distinct from the NRGB. The population residing in the Narmada River Basin is about 1.7% of India's population, as opposed to 43% in the case of the Ganga. Furthermore, a large proportion of the population in the Narmada River basin is Scheduled Tribe, unlike in the Ganga River Basin.

Engaging with local communities to integrate technological innovations with traditional water management practices.

Establishing decentralized wastewater treatment plants (including small-scale sewage treatment plants) at the community level.

Areas for further improvement or research

Conducting regular impact assessments to measure ecological recovery.

Exploring nature-based solutions such as wetland restoration for water purification.

One concern that is likely also prevalent but under-studied and, therefore, not a policy priority is plastic pollution due to river-related economic activity, particularly fisheries. The study in the Ganga highlights the role of plastic gear abandonment as a significant contributor to riverine pollution (Nelms et al., 2021). This is likely an area that needs careful study in the context of the Narmada River.

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Brahmaputra Basin

I. Case Study Overview - Brahmaputra River

a. Project background and location

The Brahmaputra River originates from the Chemayungdung Glacier in the Kailash Range, located in the southern part of the Tibet Autonomous Region, at an altitude of 5,300 meters. It flows through China for 1,625 km, India for 918 km, and Bangladesh for 337 km, where it is known as the Jamuna River. Eventually, it merges with the Ganges (Padma) and then with the Meghna River in Bangladesh before draining into the Bay of Bengal. The Brahmaputra River basin (BRB) is located within China (50.5%), India (33.6%), Bangladesh (8.1%), and Bhutan (7.8%) (Pradhan et al, 2021). The Brahmaputra basin covers an area of 5,80,000 km² and ranks fifth in the world in terms of total flow. The Brahmaputra River is referred to by different names along its course. In Tibet, it is called TsangPo. Upon entering Arunachal Pradesh, India, and curving around Namcha Barwa, it is known as Sihang or Dibang. After flowing into Assam, it is widely recognized by its common name, the Brahmaputra. Along its course, the Brahmaputra River is the lifeline for North East India, supporting agriculture, fisheries, industries, tourism, and hydroelectric power. The Brahmaputra is fed by numerous tributaries like Teesta, Subansiri, Lohit, and Manas, to name a few.

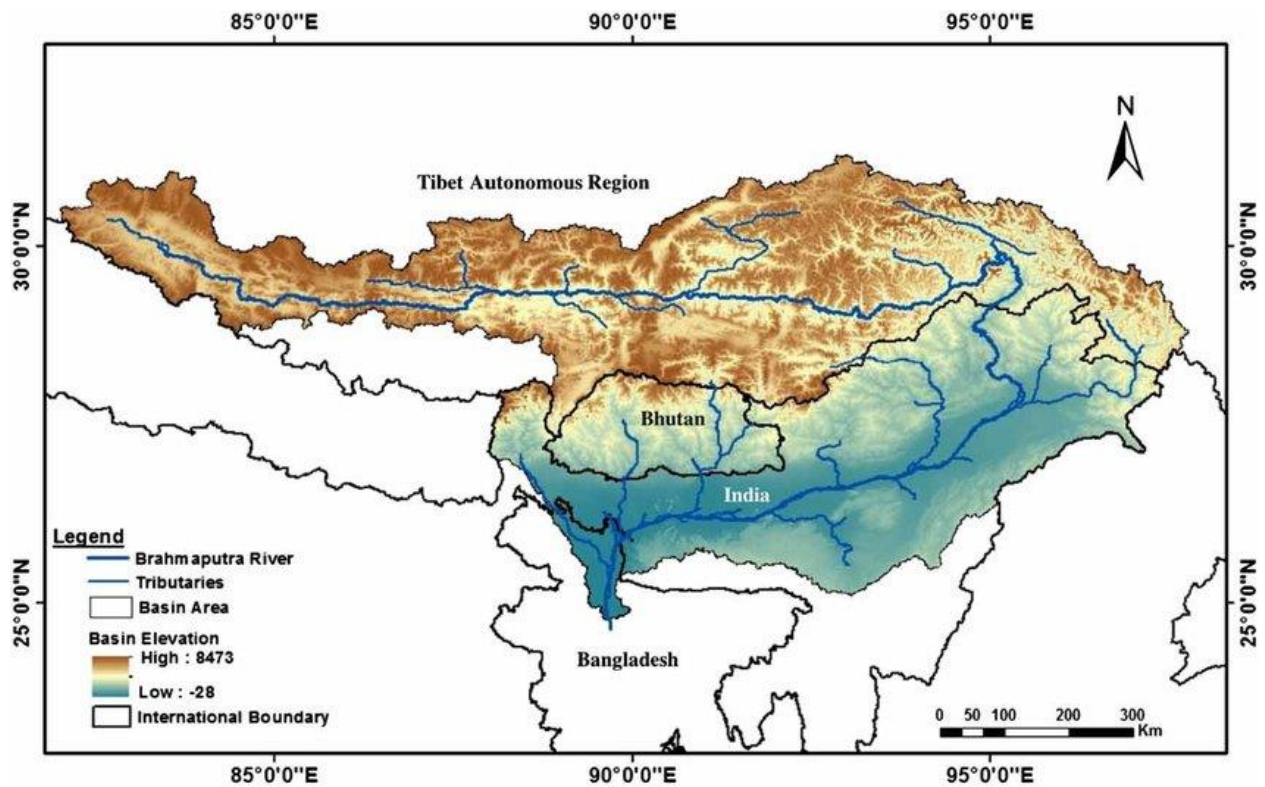


Figure. 1: Brahmaputra Basin (Barua & Vij, 2018)

For instance, in the Tsangpo region of Tibet, meltwater, groundwater, and rainfall contributions are roughly equal (Guan & Chen, 1981). The primary contributor to the discharge of the Brahmaputra is rainfall during the southwest monsoon season (July to September). The monthly discharge pattern at Bahadurabad reflects the monsoon, exhibiting significant temporal variation, ranging from approximately 3300 m³/s in February to around 59000 m³/s in July. February experiences the lowest discharge due to limited rainfall and less meltwater contribution. The Tibetan drainage contributes approximately 10% of the water discharge at the mouth of the Brahmaputra. The floodplains of the Brahmaputra basin are home to many endangered and threatened species of mammals, such as the great One-horned Rhinoceros (*Rhinoceros unicornis*), Wild Water Buffalo (*Bubalus arnee*), Royal Bengal Tiger (*Panthera tigris tigris*), and Indian Elephant (*Elephas maximus indicus*) (Sinha & Bimson, 2021).

b. Problem statement: Management and environmental challenges

1. Flooding and Loss of Biodiversity

The immense discharge of the river poses several challenges, mainly due to climate change and the increased exploitation of natural resources, which have intensified the environmental threats to the region. Due to the highly braided form of the river's lower reaches, with a channel width of up to 10 km, it is prone to flooding and continuous erosion at its banks. On average, around

8,000 hectares of land are lost to erosion each year, reducing the floodplain's productivity and leading to a rise in displacement and loss of livelihood. This results in forced migration to less flood-prone zones and an increasing encroachment of nearby national park areas (Ojha et al., 2023). Flooding along the Brahmaputra causes significant economic losses, with annual damages estimated at approximately \$2 billion. Also, with the creation of dams and reservoirs, the natural movement of various fishes and other aquatic fauna gets disturbed, making it difficult for fauna's survivability. This is more evident in the case of migratory fishes such as the “Mahseer”. The “Golden Mahseer” (*Tor putitora*), for example, is an endangered game fish that has a high value in eco-tourism, mainly among anglers, and is present in several tributaries of the Brahmaputra in India such as the Jia Bharali (known as the Kameng in Arunachal Pradesh), Teesta (Sikkim and West Bengal), Manas (Bhutan and Assam) and Subansiri (Assam) (Pradhan et al, 2021).

2. Transboundary Conflicts and Data Sharing

Brahmaputra River Basin is situated among the regions of intense sensitivity and highly conflicted regions of the world. The heavy conflict of interest among the riparian nations makes it difficult to reach common consciences. There is no basin-scale system of governance or cooperation on water management for the Brahmaputra Basin. None of the Brahmaputra's riparian countries are party to the United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses (UN Watercourses Convention). However, China and India are already exploring the possible transboundary impacts of water diversions. Bhutan is partnering with India to develop its hydropower resources rapidly. Bangladesh is keen not only to secure water for irrigation for agricultural purposes but also to ensure better protection against the ubiquitous seasonal floods of the monsoons (Pradhan et al., 2021). Studying the river basin requires comprehensive data collection, including temperature, precipitation, and biodiversity information, which are essential for accurate analysis and monitoring. Climate monitoring in the region is inadequate, creating many uncertainties, particularly in high-altitude areas (Krishnan et al., 2019). Additionally, the secrecy surrounding hydrological data and limited access to water-related information remain significant constraints (Barua et al., 2019). While China and India established two Memoranda of Understanding (MoUs) in 2002, these agreements focused only on providing seasonal water flow data for the Yarlung Tsangpo during the summer monsoon period. As part of this arrangement, India compensates China for the data. However, no data is shared for the dry season, limiting effective year-round water resource management.

3. Sediment Erosion

The erosion-deposition phenomenon is a typical characteristic feature of the Brahmaputra River, leading to changes in the channel pattern and banking shifts that severely impact the agrarian communities. This also leads to displacement at times, which results in conflict and impoverishment (Borah et al., 2022). The Brahmaputra River's rapid erosion, reaching rates of up to 1 km per year, has led to extensive land loss and frequent displacement of communities (Sarker et al., 2003). This erosion rate is nearly twice that of the Ganga River, posing severe environmental and economic challenges in the region (Galy & France-Lanord, 2001). The agriculture of the Brahmaputra plain is massively dependent on the river for its sustenance; thus, the aggressive nature of erosion and deposition and consequent widening of the river has cascading effects on the livelihood of the dependent. The Majuli Island, the largest riverine island located along the Brahmaputra River in Assam, highlights the severity of the region's environmental challenges. Due to continuous erosion, its original area of 1,250 km² gradually shrank to 584.38 km² by 2011 (Nayak & Panda, 2016).

4. Climate Change and Anthropogenic Stress

The increase in population and urbanization around the river basin puts immense pressure on the river. Among Other stressors are the overexploitation of river resources, pollution of water (at point and nonpoint source), modification of the river flow by blockages and dams, damage to and degradation of riparian habitats, especially of flood plains, posed by the rising demand for land for agricultural and urbanization purposes, and the invasion of exotic fish species (Pradhan et al., 2021). Coupled with Climate change, the effects become catastrophic and cause widespread damage to life and property. Within the Brahmaputra basin, the historic precipitation rate of 1,632 mm/year is projected to increase by 23% and 15% in the dry and wet season, respectively (Climate Resilience & Assessment, 2023). In Upper Brahmaputra, runoff is dominated by rainfall (59%), and meltwater contributes about 25% to total runoff (The Himalayan Climate and Water Atlas, 2015). This increase in precipitation increases the possibility of riverine floods and causes widespread damage to life, property, and biodiversity.

II. Project Description

With countless challenges faced while managing and protecting the river's natural state, numerous steps have been taken in due time to address the damages, prevent further damages, and initiate the dialogue necessary for maintaining the pristine nature of Brahmaputra. The key focus and major stakeholders are now being discussed in detail.

1. Flood Control

Floods have been a major challenge in the region, causing widespread damage and heavily impacting the life and economy of the region. The goal was to implement effective flood management strategies by enhancing river embankments and drainage systems and promoting early warning mechanisms to minimize damage and protect communities.

The key strategies and interventions were:

- Advanced flood detection system by NESAC uses satellite imagery to detect and give warnings before any major floods.
- Flood Inundation mapping was done by NRSC, CWC, Water Resource Department of Assam, and Assam Disaster Management Authority, marking the regions of high risk for better preparedness.
- Community participation and preparedness awareness led by NIDM in the regions for better action during floods and associated hazards.

Major stakeholders, including the state govt of Assam and Arunachal, along with National authorities like The National Institute of Disaster Management (NIDM), The North Eastern Space Applications Centre (NESAC), Central Water Commission (CWC), researchers, academicians and the local community, all have come together.

2. Conservation of Biodiversity

The Brahmaputra basin is a part of the biodiversity hotspot recognized by the International Union for Conservation of Nature (IUCN). Preserving and restoring ecosystems by protecting native species, promoting afforestation, and mitigating the impact of human activities on biodiversity was the objective of this project. Governments and various other organizations have carried out many conservation activities, including the World Wild Fund (WWF) - India and different NGOs. WWF India has mainly focused on protecting Gangetic Dolphins, Horned Rhinoceros and Wetland Conservation, and community action. Measures like anti-poaching and sustainable fishing by fishermen have yielded positive results.

3. Transboundary Cooperation

The Brahmaputra basin is situated in one of the most geopolitically sensitive areas, which makes regional cooperation quite challenging. Among all the challenges, some regional cooperation and MOUs are being signed. The major ones include the hydrological data transfer between India and China during the monsoon period. Establishing the Joint River Commission between India and Bangladesh helps facilitate cooperation, including flood forecasting and signing water-sharing treaties. The most cooperative partner in the region has been Bhutan and the transboundary cooperation has immensely helped Bhutan's economy to flourish. Under the

cooperation, there has been a Joint Expert team to prevent the recurrence of floods on shared rivers. India and Bhutan also run the 'Comprehensive Scheme for Establishment of Hydro-meteorological and Flood Forecasting Network on Rivers Common to India and Bhutan', which consists of 32 hydro-meteorological and meteorological stations in Bhutan that are funded by India (Yasuda et al., 2017). Among others, some key partnerships are Brahmaputra Dialogue initiated by the South Asian Consortium for Interdisciplinary Water Resources Studies (Saci WATERS), in collaboration with the Indian Institute of Technology Guwahati (IITG), and the Institute of Water and Flood Management (IWFM), Bangladesh University for Engineering and Technology (BUET).

4. Sustainable Water Management

Sustainable water management is pivotal for improving resilience against drought and flash floods. Huge steps have been taken concerning sustainable water management in the basin:

- Rainwater harvesting has been promoted in the rural and urban sectors of the region to promote water security, especially during seasonal droughts.
- Initiatives like the Assam Agribusiness and Rural Transformation Project (APART), run by the government of Assam and supported by the World Bank, focus on sustainable agriculture and aquaculture.
- System of Rice Intensification (SRI) methods help reduce water demand for growing paddy and record an increase in production.
- Traditional water conservation methods like *Yetbung Lingang* and *Linkum* are also being promoted.

5. Hydrological Data Collection and Climate Monitoring

Hydrological data plays a crucial role in ensuring accurate water allocation and improving the prediction of floods. The installation of automated weather stations plays a vital role in data collection, supporting climate modelling and aiding in the prediction of Glacial Lake Outburst Floods (GLOFs). The use of satellite imagery for complete monitoring and forecasting of any Major floods by NESAC is a key step in the utilization of data and fostering better preparedness and reducing the impacts of any hazard that comes up in the region.

III. Outcomes and Impact

1. Economic Impact

- The construction of embankments, check dams, and reinforced riverbanks has improved connectivity to the last mile and flourished trade, commerce, and tourism. For example, the

Bogibeel Bridge in Assam, which connects the Dibrugarh and Dhemaji districts across the Brahmaputra, have enhanced trade routes and regional accessibility.

- Bangladesh, which utilizes the Brahmaputra River for inland navigation, has improved bilateral trade significantly.
- Restored wetlands, Kaziranga National Park, and eco-tourism, supported by advanced weather forecasting stations, have helped improve tourism and have been an additional source of income.
- Reduction in Displacements and increased agricultural production.



Figure 2: Bogibel Bridge in Assam (Source: India Infrastructure)

2. Social Impact

- Projects like the Jal Jeevan Mission have ensured access to clean drinking water in flood-affected regions.
- Communities are getting involved in river protection activities, and farmers are getting trained in sustainable agriculture practices like SRI, which reduces water consumption and increases production.



Figure 3: Majuli Islands (Source: Kaziranga National Park Blog)

3. Environmental Impact

- Conservation attempts of endangered and exotic species have been vital in reviving the ecological balance in the region; Projects like Ngok Siang for protection of dolphins makes continuous efforts, due to which it was witnessed by the reduction in the number of poaching activities and the increase in the number of protected species.
- The wetlands act as habitat, natural spawning, and feeding grounds for fish and other aquatic and terrestrial wildlife. Thus, wetland conservation helps rejuvenate natural habitats for various flora and fauna.



Figure 4: Indian rhinoceros (Rhinoceros unicornis) in Kaziranga National Park, Assam, India.

(Source: Britanica)

IV. Lessons Learned and Recommendations

a. Key takeaways from the project

- A comprehensive data collection and processing mechanism for climate monitoring and weather prediction is critical.
- Setting up regional centres for data collection & processing is essential in the river basin management projects.
- Strategic partnerships are key to protecting and preserving the pristine nature of the river. Various key partnerships with different agencies like the World Bank, Asian Development Bank, International Union for Conservation of Nature and different State governments and the Central government work together to achieve the common goal of preserving and conserving Brahmaputra.
- Being a transboundary river, it becomes necessary that all the different countries have a dialogue possible for the various aspects of the river and also foster a mechanism for exchanging climatic data and knowledge with each other for better management of resources.

- Ecological balance is pivotal in river health. Various Indigenous life forms act as indicators of a healthy river, and their protection and conservation play a vital role in the river health assessment.
- Community plays a significant role in preservation and are the first consumers of the river. They use the river, which also plays a crucial role in people's everyday normal life, whether it's for agriculture, domestic use, or industry. Thus, educating them and promoting sustainable measures are the keystones of any project's success.

b. Best practices and strategies for replication

- Establishing Automated Weather Stations in heavily forested and inaccessible regions helps gather data and fill the gaps in data collection.
- Practices like rainwater harvesting and assessing the suitability of the sustainable agriculture method of SRI can be implemented to reduce the water demand and also increase production.
- Community preparedness in river management and also in flood response through training and mock drills led by the Disaster Management Authority.

c. Areas for further improvement or research

- Further research and studies are required for the assessment of climate change and induced impacts.
- Enhanced cooperation between India, China, Tibet, Bhutan and Bangladesh with a complete basin management approach involving better cooperation, Transparency in climate data sharing and forum for clear for active plan to mitigate climate change challenges.

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Barak River Basin

I. Case Study Overview

a. Project background and location

Geographical Extent and Coverage

The Barak River Basin covers parts of India, Bangladesh, and Myanmar. Within India, it is spread over the States of Meghalaya, Manipur, Mizoram, Assam, Tripura, and Nagaland, covering an area of about 45,622.12 sq. km, which corresponds to about 1.38% of the country's total

geographical area. The basin extends from 89° 50' E to 94° 00' E longitudes and from 22° 44' N to 25° 58' N latitudes, its maximum length and width being 460 km and 350 km, respectively. It is bounded in the north by the Barail range, which divides it from the Brahmaputra River Basin, in the east by the Naga and Lushai Hills, and in the south and west by the Mizo Hills and Bangladesh.

The basin comprises 27 Districts covering 10 parliamentary constituencies (as of 2009) - 3 in Assam, 2 each in Tripura and Meghalaya, and 1 each in Mizoram, Manipur, and Nagaland. The State with the maximum area of the basin is Meghalaya, accounting for almost 25.53% of its total geographical area. Manipur State shares 20.42% of its total geographical area, followed by Mizoram, Assam, and Tripura with 20.06%, 16.70%, and 18.31% of its total geographical area respectively. Nagaland has the least area in the river basin - approximately 1.77% of its total geographical area.

River Course and Vegetation

The Barak River originates from the Manipur Hills, to the south of Mao in Senapati District of Manipur at an elevation of about 2,331 m and extends over a length of about 525 km within North-East India (Sengupta et al., 2006). It flows through the hill ranges of Nagaland and Manipur before it enters Assam. Approximately 72.5% of the area of the river basin is vegetated (Deb and Sil, 2019).

Key tributaries

The Barak and its tributaries constitute the second largest river system in the North-Eastern part of India. The main tributaries of the Barak River are Katakhal, Jiri, Chiri, Modhura, Longan, Sonai, Rukni, and Singla (Das 2012). The total length of the river network in the basin is about 5381.19 km.

Hydrological Potential and Seismic Sensitivity

The average annual surface water potential of the Barak River Basin is estimated to be about 48.4 km³ and the groundwater potential of the river basin is put at 1.8 km³ (Jain et al., 2007). The Barak River Basin is particularly susceptible to earthquakes, being located in seismic zone V.

Climate and Population

The region is characterized by high humidity (about 90%) with temperatures ranging from 9.25°C to 30.66°C. It is one of the wettest regions on the planet with an average annual rainfall

of 2,083.50 mm. About 37 lakh people live in the river basin in 2,906 villages (Census 2001). Hydrologically, the river basin is divided into three sub-basins comprising 77 watersheds.

Dams and Hydro-observation points

There are four dams and three barrages in the river basin. The Central Water Commission (CWC) has installed 52 hydro-observation points, of which five are particularly for flood forecasting.

Ecological Significance and Wetland Management

The Barak-Meghna system manages salinity levels in response to increasing sea levels and sustains large wetland ecosystems like Tanguar Haor, Hakaluki Haor, and Hail Haor, which provide the livelihoods of millions of people and essential support for a variety of species (Baten & Titumir, 2015).

Originating from the Manipur Hills, the Barak River flows through diverse terrains and supports a rich network of tributaries. The river basin has very high hydrological potential. With a humid climate and high annual rainfall, the region sustains a large population and extensive vegetation. Its ecological importance is highlighted by crucial wetland ecosystems that regulate salinity and support biodiversity. Additionally, infrastructure like dams, barrages, and hydro-observation points play a vital role in water management and flood forecasting.

b. Problem statement: management and/or environmental challenges

- Flooding and Riverbank Erosion – Frequent monsoon floods submerge large areas, displacing communities, damaging crops, and eroding river banks, leading to loss of land and livelihoods.
- Water Pollution – Industrial effluents, agricultural runoff, and domestic waste contribute to deteriorating water quality, affecting aquatic ecosystems and human health.
- Biodiversity Loss – The significant decline in biodiversity in the region is underscored by the extinction of river dolphins, the decreasing numbers of fish, and the dangers that habitat destruction, unsustainable fishing practices, and water infrastructure developments pose to 38% of the 239 bird species that inhabit the Barak Valley.
- Groundwater Contamination – Arsenic contamination in drinking water poses severe health risks to communities in Assam, Manipur, and Mizoram, requiring urgent mitigation efforts.

- Hydropower and Infrastructure Development – Projects like the Tipaimukh Dam raise concerns over altered water flow, reduced groundwater levels, biodiversity loss, and transboundary disputes.
- Deforestation and Land Use Changes – Urbanization, agriculture, and deforestation have led to river instability, increased sedimentation, and loss of natural floodplain functions.

II. Project Description

a. Goals and objectives

- To assess and mitigate environmental challenges such as flooding, water pollution, and habitat destruction in the Barak River Basin.
- To develop sustainable livelihood solutions for vulnerable communities affected by flooding, pollution, and socioeconomic challenges.
- To promote conservation efforts for endangered species like river dolphins through awareness programs and sustainable fishing practices.
- Conservation efforts in Barak Valley focussing on restoring habitats, protecting trees, and strengthening protection in accordance with the provisions of the Indian Wildlife Protection Act (IWPA) to ensure the safety of endangered bird species.
- To implement water quality improvement measures and mitigate arsenic contamination in groundwater.
- To develop and promote disaster resilience strategies such as flood forecasting, community disaster preparedness, and ecosystem-based flood management.

b. Strategies and Interventions

- **Flood management strategies:** Implementing non-structural flood control measures such as early warning systems, land-use planning, and ecological restoration.
- **Water pollution control:** Monitoring industrial effluents, promoting water treatment solutions, and reducing arsenic contamination through mitigation projects.
- **Biodiversity conservation:** Protecting river dolphin habitats by reducing harmful fishing practices and involving the local community in conservation efforts.
- **Community engagement and awareness:** Conducting educational campaigns, stakeholder meetings, and training programs on disaster preparedness and environmental conservation.
- **Infrastructure and policy interventions:** Advocating improved drinking water supply, sanitation, and electrification in vulnerable villages.

Socioeconomic Challenges and Environmental Pressures in the Barak River Communities

The villages of Borobekra Jatrapur and Bhowmipara, located along the Barak River in Jiribam sub-division, Manipur, have below-average socioeconomic status. The main sources of income of the local people are fishing, bamboo transportation, and daily wage work (Chanu and Singh, 2016). Various factors like small landholdings, insufficient access to drinking water and electrification, and poor sanitation and infrastructure diminish the ability of Dudhpatil, a flood-prone village near the Barak River, to adapt to natural hazards (Das and Dey, 2011). The livelihood challenge is made more critical by the negative effects of water contamination brought on by hydrocarbon extraction. Since 2011, student organizations, civil societies, and village leaders in the potentially impacted area in Manipur have been raising their concerns regarding oil extraction and drilling operations (Laishramcha, 2017).

Deforestation and Land Use Changes

The instability of the river can be attributed to significant land use and land cover (LULC) changes that have taken place in the Barak River Basin over the last three decades, which include a decline in vegetation (3.48%), an increase in built-up regions (73.76%), expansion of cultivated land (8.08%), and accumulation of sediment in the riverbed (53.37%) (Annayat et al., 2024). As stated by Gupta (2009), the loss of forests has worsened soil erosion, reduced the number of lakes within floodplain areas, and caused an increase in silt accumulation. Conservation initiatives aim to address this issue by promoting wildlife-friendly practices, minimizing human-animal conflicts, cultivating food plants for wildlife, and supporting alternative income sources (Talukdar & Choudhury, 2018). Of the 239 identified bird species in the Barak Valley, 38% face endangerment due to loss of habitat and the degradation of wetlands. To preserve the diversity of birdlife, conservation efforts focus on restoring habitats, protecting crucial tree species such as *Artocarpus chaplasha* and *Ficus* spp., and enhancing the Indian Wildlife Protection Act (IWPA) to shield vulnerable species, including Baer's Pochard, Black-necked Stork, and Greater Spotted Eagle (Dev, 2015).

Flooding in the Barak River Basin

Impacts

Though the Barak River supports the livelihood of residents of the river basin through agriculture, fisheries, transportation etc., frequent flooding results in widespread socio-economic and ecological consequences. Of the 13,747.50 ha of wetlands, 10,016 ha (72.9%) are seasonally inundated floodplains. The majority of floodplains in the Valley are low-lying regions that are flooded during the south-west monsoon season between June and September (Gupta, 2009).

Recurrent flooding in the cultivable area of the river basin significantly affects agricultural production, resulting in the migration of farmers to other cities (Das and Das, 2022).

Hydropower and Infrastructure Development

The Tipaimukh Dam project, launched in 1972 for flood control, has raised environmental and hydrological concerns in Bangladesh. The project, located in a seismically active area, has raised numerous concerns, including changes in water flow, sedimentation, reduced groundwater levels, biodiversity loss, lower agricultural yields, deteriorating water quality, flooding, fragmented ecosystems, and increased seismic risk (Baten and Titumir, 2015; Toufique, 2015). There are also claims that it violates the Joint River Commission Agreement between India and Bangladesh, which could interfere with Boro cultivation, an important agricultural activity in the Barak River Basin, especially in the floodplain regions of Assam (Asaduzzaman & Rahman, 2015).

Outcomes/ Conservation Efforts

Flood control methods, such as embankments, have negatively impacted natural flood pulse dynamics, causing decline in fisheries and agriculture. Therefore, an integrated ecological approach is needed to manage floods and floodplains, focusing on non-structural measures like improved flood warning, relief, and cropping changes (Gupta, 2003). The establishment of Village Disaster Management Committees (VDMCs), along with strategic planning and advanced technologies would improve disaster resilience and promote sustainable development (Sharma, 2015). Some researchers have attempted to predict floods using models which have proven to be effective in giving better forecasts (Sahoo et al., 2021).

Threats to River Dolphins

Impacts

In the 1970s and 1980s, the Ganges River Dolphin (*Platanista gangetica*), which was once seen widely in the Barak River system, went extinct due to habitat degradation, by-catch (accidental capturing of a non-target species), over-fishing, poaching, and fragmentation brought on by dredging, construction, and water extraction (Choudhury et al., 2019). Accidental entanglement of dolphins in plastic gillnets, and the usage of Dolphin oil and body parts as fish baits highlighted the need for sustainable fishing practices (Smith et al., 1998).

Outcomes/ Conservation Efforts

To address this issue, a project was initiated involving major stakeholders in conservation efforts.

Regional "Dolphin Conservation Training Camps" for communities and a central "Dolphin Conservation Workshop" for managers, researchers, and conservationists have been organised. 42 awareness campaigns were conducted in 30 Districts, and 70 community youths were trained for dolphin monitoring in 2006. Recommendations for long-term conservation of Dolphins have been proposed (Wakid, 2007). Implementing environmental flows and conducting robust environmental assessments and monitoring processes are crucial for maintaining river habitats for aquatic species and river dolphins (Braulik et al., 2021). Conservation of Dolphins requires the elimination or management of threats. Restoration in their traditional habitats can enhance ecotourism in the region (Biswas, 2023).

Groundwater Contamination and Public Health Risks

Impacts

Most of the groundwater in the Barak Valley, covering the north-eastern States of Assam, Manipur, and Mizoram, is arsenic (As) contaminated, mostly from geogenic sources (Thambidurai et al., 2013). Arsenic in groundwater is primarily sourced from apatite minerals in Charnockite rocks, Red Mudstone/ Siltstones, and Grey Shale in sedimentary areas; its presence can also be influenced by agricultural activities (Barhai et al., 2023). The presence of Arsenic in groundwater is observed, particularly in regions where Arsenic mobilization occurs due to microbial reductive breakdown of organic materials (Gupta et al., 2015). Though the main mechanism of Arsenic discharge appears to be the reductive hydrolysis of iron hydroxides, its actual origin seems to be in the sediments in the Barak River, mainly from the Barail Hills (Das et al., 2015).

Although the reductive hydrolysis of iron hydroxides is the primary process of arsenic (As) mobilization in the Barak Valley Plain, the actual source of As appears to be the sediments deposited by the mountainous Barak River, which originates from the Barail Hills (Das et al., 2015).

Outcomes/ Conservation Efforts

Analysis of rice plants in Bashkandi, Assam, has revealed significant Arsenic content in the grains, husks, straw, and roots, surpassing WHO limits, primarily due to organic matter and amorphous Fe-oxides, posing risks to the human food chain (Ponnugounder and Singh, 2020). Though the potential of removal technologies like co-precipitation, adsorption, aeration, and sedimentation reveals Arsenic reduction of up to 67%–99%, their full adoption has not been fully evaluated (Kanungo, 2015). State Government Departments in the region have reported that out of 2571 arsenic-contaminated habitations, 2212 have been mitigated in Assam, with piped water

supply schemes and dug-wells constructed in 2097 habitations. For the remaining 359 habitations, 50 Piped Water Supply Scheme (PWSS) and 18 dug-wells are planned. However, no action has been initiated for Arsenic mitigation in groundwater in Manipur (Bhattacharya and Lodh, 2018).

Fish Diversity

Impacts

The Barak River Basin in Assam, India, hosts a rich variety of fish species, with Sone Beel having 70 species, Chatla Haor 57 species, and Baskandi Anua 13 species (Kar, 2019). Although Chandubi Tectonic Lake serves as an essential breeding ground for 63 species, it faces threats such as overfishing, festival fishing, agricultural practices, pollution, siltation, and poor enforcement of fishery regulations (Nath & Deka, 2012). A research conducted by Kar & Khynriam (2023) identified 45 species within five Anuas, predominantly belonging to Cypriniformes, including key species like *Neolissochilus hexagonolepis*, *Labeo pangusia*, and *Ompok bimaculatus*, which are categorized as "Near Threatened." These fish are crucial for supporting local fisheries, maintaining food chain stability, and facilitating nutrient cycling. To safeguard these habitats, conservation efforts have to focus on pollution control, sustainable fishing practices, and the restoration of wetlands (Kar, 2019; Kar & Khynriam, 2023).

Outcomes/ Conservation Efforts

Improving water quality, preventing habitat degradation, and restoring connectivity between the Anuas and Barak Rivers are some strategies proposed/ employed in conservation efforts for the Barak River Basin and Chandubi Lake to protect vital fish species and their ecosystems. Constructing check dams to manage siltation, planting trees to reduce erosion, monitoring pollutants, and adopting sustainable fishing practices such as aquaculture and seasonal restrictions in "Bundh" zones. These initiatives have led to a stable fish population, enhanced aquaculture production, and increased community awareness (Kar, 2014; Kar & Khynriam, 2023). In an effort to mitigate harmful fishing practices and preserve biodiversity, ecotourism has been promoted as an alternative source of income in the Chandubi Lake (Nath & Deka, 2012).

Algal Diversity

Impacts

The rise in pollution in the Barak River near the Cachar Paper Mill has led to a decline in algal diversity, with the highest diversity recorded 0.5 km upstream from the discharge point and the lowest found at sites affected by pollution. Important algal species such as *Gyrosigma*

maharastrensis, *Oscillatoria tenuis*, *Oscillatoria ornata*, *Surirella robusta*, *Spirogyra crassa*, and *Nitzschia* sp. act as indicators of water quality. While Bacillariophyceae flourish in cleaner environments, pollution-tolerant groups like Cyanophyceae and Chlorophyceae prevail in contaminated regions, aiding in nutrient cycling and maintaining ecological balance (Rout & Sarma, 2010). The microbial diversity within the Barak River is crucial for upholding water quality, with bacteria such as *Pseudomonas*, *Staphylococcus*, and *Enterobacter* facilitating nutrient cycling and the breakdown of organic matter. However, the detection of harmful bacteria like *Shigella*, *Klebsiella*, and *E. coli* indicates pollution risks, highlighting the urgent need for better water quality management to safeguard public health and the environment (Alam & Pandey, 2014).

Outcomes/ Conservation Efforts

Conservation initiatives along the Barak River aim to improve industrial waste management, encourage environmentally friendly practices, and monitor water quality to safeguard aquatic organisms. Pollution from the Cachar Paper Mill has led to a decline in algal diversity, an increase in alkalinity and carbon dioxide levels, and a decrease in dissolved oxygen, creating conditions that favour pollution-tolerant species such as *Oscillatoria tenuis* and *Spirogyra crassa*, reflecting a deterioration in water quality (Rout & Sarma, 2010). Furthermore, the presence of sewage, industrial discharges, and agricultural runoff has elevated coliform levels, heightening the risk of waterborne illnesses. To tackle these issues, conservation measures focus on promoting sustainable farming, bolstering sanitation, improving waste management, updating water treatment facilities, and encouraging responsible fishing practices to restore water quality and protect biodiversity (Alam & Pandey, 2014). Pollution from industrial waste, sewage, and runoff has further degraded water quality, leading to a rise in pollution-resistant algal species like *Oscillatoria* and *Microcystis*, which indicates stress on the ecosystem due to decreasing dissolved oxygen levels and increasing turbidity that threaten aquatic biodiversity (Laskar & Gupta, 2009).

IV. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- **Community involvement is crucial** – Engaging local communities through awareness campaigns and training programs has been effective in conservation efforts.
- **Interdisciplinary collaboration strengthens conservation** – The involvement of researchers, conservationists, and policymakers has led to more comprehensive solutions.

- **Sustainable fishing practices must be prioritized** – Addressing by-catch and harmful fishing techniques is essential for reducing dolphin mortality.
- **Monitoring and data collection are essential** – Long-term conservation success depends on continuous monitoring and scientific assessments.

b. Best Practices and Strategies for Replication

- **Community-based conservation models** – Expanding training programs for local youth and fisherfolk to create more "citizen scientists" for aquatic life monitoring.
- **Adoption of environmental flow assessments** – Ensuring water extraction projects consider aquatic biodiversity before approval.
- **Public-private partnerships** – Encouraging collaboration between government bodies, NGOs, and local businesses to fund and sustain conservation efforts.

c. Areas for Further Improvement or Research

- **Impact assessment of conservation measures** – Conducting long-term studies to evaluate the success of conservation interventions.
- **Climate change impacts on river dolphins** – Studying how changes in water temperature, flow, and pollution affect dolphin population.
- **Alternative livelihood options for fisherfolk** – Developing sustainable income sources for fishing communities to reduce dependence on harmful fishing practices.

In order to manage the Barak River Basin sustainably, a multifaceted and integrated approach is necessary that takes into account the large number of environmental and socioeconomic constraints. The river basin may be efficiently managed to strike a balance between ecological conservation and development by putting adaptive techniques into place, strengthening governance systems, and encouraging community involvement.

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Subarnarekha Basin

About the basin

The Subarnarekha River Basin is located in eastern India, spanning parts of Jharkhand, West Bengal, and Odisha, with a total basin area of approximately 19,296 square kilometres.

Geographically, it lies between 21°15'N to 23°30'N latitude and 85°00'E to 87°30'E longitude.

The river originates from the Chhotanagpur Plateau near Nagri village in Ranchi district, Jharkhand, India, at an elevation of around 600 meters above sea level. Flowing for about 395 kilometers, it traverses diverse terrains before draining into the Bay of Bengal near Kirtania in Balasore district, Odisha, India. The basin is contributed by several significant tributaries, including the Kharkai, Kanchi, Karkari, and Gurma Rivers, which contribute to its hydrological and ecological significance.

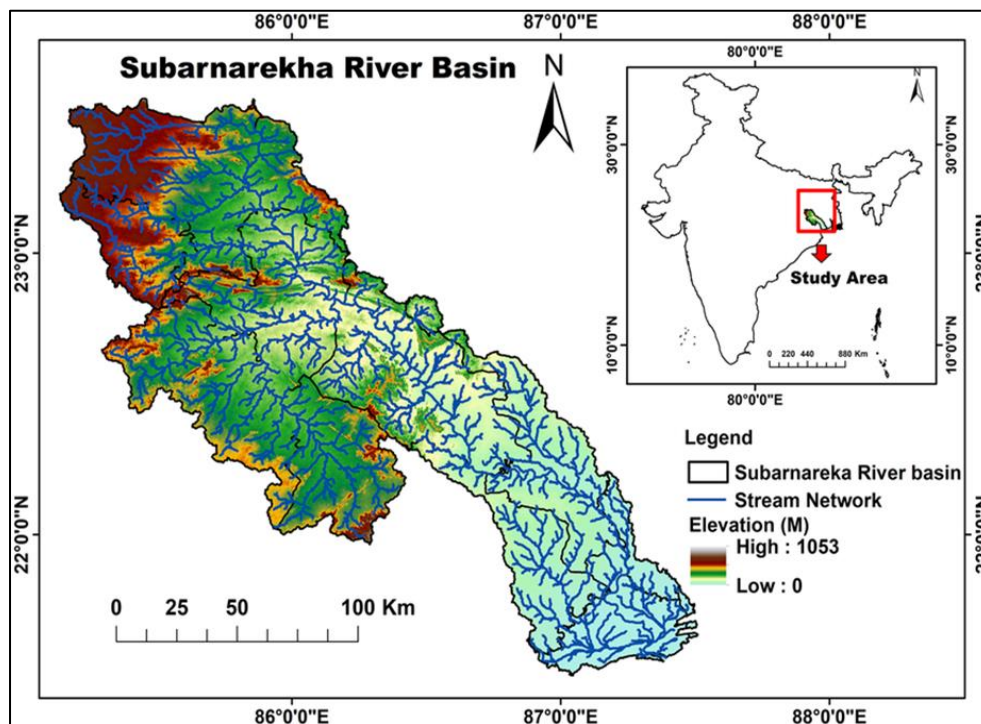


Figure 3. Index Map of Subarnarekha River (Image Source: <https://link.springer.com/article/10.1007/s10661-022-10547-1/figures/1>)

Climate Change

Swain et al. (2023) developed a framework using the elasticity-based Budyko approach to evaluate the hydrologic sensitivity and resilience of the Brahmani, Baitarani, and Subarnarekha catchments under historical and projected climate conditions. Their analysis revealed that the Subarnarekha catchment is highly sensitive to anthropogenic influences, whereas the Brahmani and Baitarani catchments are predominantly affected by climate variability. Future projections under CMIP6 SSP scenarios indicate that the latter two catchments are expected to exhibit greater resilience and higher water yields. This study underscores the importance of sustainable water resource management to mitigate climate and human-induced hydrological changes in the region.

Yaduvanshi et al. (2019) assessed the risk of extreme rainfall events in the Subarnarekha River Basin using hydro-meteorological trend analysis and extreme value theory. Their findings highlighted significant short-term fluctuations in rainfall patterns, with a 20-year return level indicating 163 mm of daily rainfall. Additionally, the study observed a rising trend in actual evapotranspiration (AE) over the past two decades, raising concerns about agricultural water availability. In the lower basin, frequent floods and heavy siltation pose significant challenges, while the upper basin faces threats from deforestation and soil erosion. These findings emphasize the need for proactive water management and conservation strategies.

Shree et al. (2020) analyzed the spatial and temporal variations of the diurnal temperature range (DTR) in the Subarnarekha River Basin over a 35-year period (1983–2017). Their findings

revealed a significant decreasing trend of -0.31°C per decade, with the most pronounced decline occurring during the pre-monsoon season (-0.49°C per decade). This reduction was primarily attributed to the minimum temperature ($T_{\min}$) rising at a faster rate than the maximum temperature ($T_{\max}$). Additionally, the study identified a strong negative correlation (-0.77) between DTR and rainfall, highlighting potential climate-induced changes in regional hydrology and ecology. These results underscore the need for further research to understand the long-term implications of climate change on water availability and ecosystem stability in the basin.

Climate change and LULC change impact on hydrology

Gaur et al. (2021) conducted a comprehensive study to assess the combined effects of climate change (CC) and land use/land cover (LULC) changes on hydro-climatic extremes, water balance components, and hydrometeorological conditions in the Subarnarekha River Basin (SRB) and Baitarani River Basin. Utilizing an integrated modeling framework, the study incorporated a spatially explicit LULC model, the MIKE SHE/MIKE HYDRO RIVER hydrological model, and an ensemble of regional climate models (RCMs) to evaluate future flood risks. In the flood-prone SRB, findings projected a substantial increase in extreme flow events, ranging from 20% to 85%, particularly in the 2050s and 2080s. These results suggest a heightened vulnerability to flooding, emphasizing the need for proactive water resource management, improved flood mitigation strategies, and resilient infrastructure planning to safeguard communities and ecosystems in the region.

In addition, Kumar et al. (2024) conducted an uncertainty analysis on streamflow projections in the Subarnarekha River Basin (SRB) using ANOVA and quantile regression, revealing that regional climate models (RCMs) contribute significantly—between 40% and 62%—to overall projection uncertainties. These findings underscore the critical need for enhanced flood mitigation strategies to improve predictive accuracy. Additionally, the study evaluated water balance components using the Soil and Water Assessment Tool (SWAT). Results showed that multi-site calibration (MSC) captured spatial heterogeneity more effectively than single-site calibration (SSC), emphasizing the importance of advanced hydrological modeling techniques for better water resource management in the SRB.

Tabassum & Krishna et al. (2024) projected land use and land cover (LULC) changes for 2033 in the Subarnarekha River Basin (SRB) using the CA-Markov model, predicting continued forest decline alongside expanding settlements and agricultural land. Climate projections under RCP4.5 and RCP8.5 scenarios indicated increased rainfall in the upper (Muri) and lower (Ghatshila) regions, while the middle region (Jamshedpur) is expected to experience reduced precipitation. These changes could significantly impact the hydrological cycle, reducing

groundwater recharge by 29-30% and water yield by 46-47%, while evapotranspiration is expected to increase by 5-7%. The study found that the combined effects of climate change (CC) and LULC shifts closely resemble those of CC alone, emphasizing climate's dominant role in influencing streamflow variations, agricultural water scarcity, and flood risks.

Furthermore, an analysis of the upper SRB integrating CHIRPS precipitation data, FLDAS temperature records, and groundwater fluctuations, assessed via Theil-Sen's Median Trend and Mann-Kendall tests, showed rising temperatures and a statistically insignificant but increasing rainfall trend (9.83 mm/year). This pattern correlated with groundwater depletion, attributed to reduced soil water retention and increased runoff. The findings emphasize the urgent need for sustainable water and land management strategies to mitigate the compounded effects of climate change and LULC alterations.

Kumari et al. (2024) utilized the SWAT model to evaluate the impacts of land use/land cover (LULC) changes and climate change (under RCP8.5) on streamflow dynamics in the Subarnarekha River Basin, India. Their findings revealed a significant increase in surface runoff (+98.85 mm) and a decline in total water yield (-13.33 mm) between 2013 and 2020. Future projections indicated an even steeper rise in surface flow (+142.85 mm) and a substantial reduction in groundwater flow (-68.37%), emphasizing the critical need for enhanced surface water storage strategies. SWAT demonstrated high performance in model calibration and validation (NSE: 0.72–0.85, R²: 0.82–0.83), reinforcing its reliability. The study highlighted the declining winter water availability, urging policymakers to implement improved irrigation techniques and sustainable groundwater management strategies to mitigate seasonal water shortages and ensure long-term water security.

Hydrological model for climate change and stream flow prediction:

Kumar and Joshi (2019) analyzed the impact of climate change on the hydrological dynamics of the upper Subarnarekha watershed in Jharkhand, India, using the SWAT model coupled with the SUFI-2 algorithm. The study incorporated IPCC SRES A1B climate projections, revealing a 1.4% decline in precipitation by the 2020s, followed by increases of 6.2% and 9.1% in the 2050s and 2080s, respectively. Surface runoff showed an initial decrease of 18.4% but was projected to rise by 11.8% and 38.2% in the later decades, heightening flood risks. These findings highlight the urgent need for proactive water management, including reservoir construction, infiltration enhancement, and flood control measures, to mitigate climate-induced hydrological fluctuations and safeguard regional water resources.

Gaur et al. (2021) employed the SWAT model with regional climate models (RCMs) under RCP4.5 and RCP8.5 emission scenarios to project future streamflow changes in the Subarnarekha River Basin. Their findings revealed significant increases in streamflow, with

flood volumes expected to surge by 342.4% at Jamshedpur and 224.6% at Ghatshila between 2025 and 2049. These results emphasized the urgent need for adaptive flood management strategies.

In another hydrological study, Yaduvanshi (2017) divided the basin into 32 sub-basins, calibrating (1982–1997) and validating (1998–2011) streamflow data using SWAT-CUP. The highest model performance was recorded at Ghatshila (NSE: 0.68 during calibration, 0.62 during validation). Extreme rainfall events were simulated with high accuracy (NSE: 0.89–0.96), highlighting SWAT's reliability in hydrological assessments and reinforcing the necessity of improved flood mitigation measures in response to increasing climate variability.

Extreme Events

Farhin and Akhouri (2022) conducted an in-depth analysis of drought occurrences in the upper Subarnarekha Basin using multiple hydrometeorological indices, including the Rainfall Anomaly Index (RAI) and Standardized Precipitation Index (SPI). They integrated these indices with Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) remote sensing data to enhance drought detection accuracy. Their findings classified the region as highly drought-prone, with eight major drought events recorded over a 40-year period. The longest drought spanned 49 months (2002–2006), significantly impacting water availability and agricultural productivity. A Mann-Kendall trend test revealed an increase in pre-monsoon rainfall, indicating rising precipitation levels. However, short-term SPI trends pointed to worsening meteorological droughts driven by persistent soil moisture deficits. These results highlight CHIRPS as a valuable tool for remote drought monitoring and stress the necessity for sustainable water management, early warning systems, and adaptive agricultural practices to mitigate future drought risks.

In flood risk assessment, Das and Gupta (2021) analyzed the flood hydrology of the Subarnarekha River Basin and developed a GIS-based flood susceptibility map using the Analytical Hierarchy Process (AHP) and an optimized AHP-VIP method. This approach provided a cost-effective flood risk assessment tool for disaster management. The study found that monsoon peak flows often exceeded five times the mean streamflow, with 38% of the basin classified as highly susceptible to flooding, especially in low-lying areas. Key flood-conditioning factors included elevation, slope, topographic wetness index (TWI), and drainage density. The flood maps demonstrated high accuracy (AHP: 0.917, AHP-VIP: 0.934), validating their reliability in flood preparedness and infrastructure planning.

Similarly, Bera and Bhandari (2016) utilized GIS-based flood hazard mapping techniques to identify risk zones within the Subarnarekha Basin. By analyzing satellite imagery, Digital Elevation Model (DEM) data, river basin maps, geology, soil data, and rainfall records through

weighted overlay analysis in ArcGIS, they categorized flood risk into five levels: Very High, High, Moderate, Low, and Very Low. Their study identified the downstream regions, particularly Baleswar (Odisha), East and West Singhbhum (Jharkhand), and West Medinipur (West Bengal), as the most vulnerable flood-prone areas. These findings underscore GIS as an effective and low-cost tool for flood risk assessment, mitigation, and land-use planning.

Flood Risk Assessment and Mapping

To improve urban flood management in the Subarnarekha River catchment, Samanta et al. (2018) applied a Geographic Information System (GIS)-based Frequency Ratio (FR) model to develop a flood susceptibility map. A comprehensive flood inventory was created using field surveys and historical reports, incorporating data from 32 flood locations (70%) for model training and 14 locations (30%) for validation. The study analyzed eight key flood-conditioning factors—elevation, slope, geomorphology, soil type, drainage network, rainfall distribution, and land use/land cover (LULC)—at a high spatial resolution of 20×20 meters. The resulting flood susceptibility map classified areas into different risk categories, offering crucial insights for flood preparedness. Model validation through the Area Under Curve (AUC) method demonstrated an 84.80% success rate and 81.20% prediction accuracy, confirming the model's reliability. However, the study acknowledged certain limitations, such as the exclusion of hydrological parameters like river proximity and overall water budget. These findings provide valuable tools for urban planners, yet future research should integrate finer-resolution datasets and dynamic hydrological modeling to enhance predictive accuracy.

Similarly, Chatterjee (2014) utilized GIS, Remote Sensing (RS), and the NRCS-Curve Number (CN) method to estimate runoff variations in the Subarnarekha catchment. This study integrated Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM), Tropical Rainfall Measuring Mission (TRMM) precipitation data (2001–2011), and Landsat ETM+ LULC datasets to build a rainfall-runoff model. HEC-Geo-HMS software was employed to determine CN values, while ArcGIS 10 enabled pixel-wise runoff estimation. The analysis revealed an increase in average runoff depth from 2.25 mm to 2.48 mm and a rise in total runoff volume from 61.24 to 68.47 million cubic meters. These changes were attributed to declining agricultural land, expansion of open land, and reductions in vegetation cover. The findings serve as a crucial tool for watershed management, soil erosion control, and groundwater conservation. However, the study did not account for climate variability or LULC-induced changes in soil moisture and groundwater recharge, highlighting the need for further hydrological assessments integrating climate change projections and groundwater dynamics.

Impact of LULC Changes on hydrological components

Shree and Kumar (2023) examined the impact of land use and land cover (LULC) changes on hydrological components in the upper Subarnarekha River Basin, Jharkhand, using the SWAT model. They assessed three LULC scenarios from 2000, 2012, and 2020, identifying RCHRG_DP (deep aquifer percolation fraction) and ALPHA_BF (baseflow recession constant) as the most sensitive parameters. The findings indicated a decline in evapotranspiration and groundwater recharge, accompanied by an increase in surface runoff due to urban expansion, which surged from 2.52% to 12.27%. Consequently, water yield rose from 7.86% to 14.96%, driven primarily by increased runoff, which outpaced the decline in baseflow and lateral flow. This surge in surface runoff poses erosion risks and disrupts watershed equilibrium. However, the study acknowledged that climate change effects and model uncertainties remain underexplored, underscoring the necessity for further research to refine hydrological simulations and inform effective water resource management strategies

River Morphology

The geomorphological dynamics of the Subarnarekha River and its surrounding landscape have been extensively studied using various methodological approaches, offering critical insights into tectonic activity, riverbank shifting, and coastal hazards. Guha and Patel (2017) examined the tectonic influences on the Subarnarekha River Basin by analyzing morphometric parameters and stream profiles. Their study employed DEM-based extraction techniques and chi plots to identify knickpoints aligned with fault zones, revealing ongoing slow uplift in the Precambrian cratonic landscape. Their findings suggested that the region undergoes piecemeal deformation due to localized thresholds, impacting river channel morphology and sediment transport.

Expanding on river dynamics, Jana (2021) analyzed riverbank shifting in the middle-lower course of the Subarnarekha River, primarily driven by monsoonal hydrodynamics and intensive sand mining. The study utilized a Digital Shoreline Analysis System (DSAS) with six multi-temporal banklines to quantify shifting rates. Results indicated that meandering bends experienced the highest displacement, with a mean model error of 0.02 m. The study validated short-term predictions for 2020, confirming model accuracy, but acknowledged uncertainties in long-term forecasts due to sediment variability and human interventions.

Further complementing these findings, Nath et al. (2020) assessed coastal hazards along the Subarnarekha–Rasulpur estuary stretch, focusing on vulnerabilities to cyclones and erosion. Using a Multi-Criteria Evaluation (MCE) approach, the study integrated GIS-based weighted overlay analysis with factors such as coastal slope, shoreline change, and land use patterns to develop a Coastal Hazard Zone (CHZ) map. The classification identified five levels of vulnerability, emphasizing the need for sustainable coastal management.

Additionally, Acharyya et al. (2021) employed SWAT modeling to simulate daily, monthly,

and annual runoff responses and soil loss in the Subarnarekha Basin. Their analysis revealed significant seasonal variations in discharge, ranging from 8.85 m³/s during pre-monsoon to 5016 m³/s in the monsoon season. Sub-basin analysis identified the Delta sub-basin as the largest contributor to river flow, followed by Adityapur, Jamshedpur, and Ghatshila, while Muri exhibited the lowest discharge. These findings underscore the interconnectedness of tectonic activity, riverbank shifts, and hydrological variations, necessitating integrated river basin management strategies.

Groundwater Potential Zone

Groundwater potential zones (GPZ) in various regions of India have been identified using integrated approaches that incorporate the Analytical Hierarchical Process (AHP), remote sensing, and GIS-based spatial analysis. These techniques provide a systematic framework for assessing groundwater availability by considering multiple influencing factors, making them valuable tools for sustainable water resource management.

In the Jhargram district, Guria et al. (2023) conducted a detailed study analyzing twelve environmental parameters, including geology, geomorphology, soil texture, and rainfall, to assess groundwater availability. After multicollinearity testing, a weighted sum overlay method in ArcGIS was applied to classify the study area into five GPZ categories. The model's accuracy was validated using receiver operating characteristics (ROC) and borewell yield data, yielding high prediction accuracies of 78.4% and 84%, respectively. Findings indicated that 46.25% of the area fell within poor to very poor groundwater zones, with the highest groundwater potential observed near riverbanks, emphasizing the importance of surface water interaction in groundwater recharge.

Similarly, Mandal et al. (2016) assessed groundwater potential in a coastal groundwater basin in eastern India, integrating twelve thematic layers such as land use/land cover (LU/LC), soil, geomorphology, hydrogeology, recharge rate, and drainage density. Recharge rate values were estimated using a hydrological water balance model, while the overlay weighted sum method was used to generate a groundwater potential zone (GWPZ) map, classifying the basin into four categories. Validation using well yield data and Google Earth imagery showed strong agreement with the GWPZ map. Sensitivity analysis revealed that excluding rainfall and lineament density increased the poor GWPZ area, whereas omitting hydrogeology, soil, surface geology, and NDVI expanded the extent of good GWPZ.

Additionally, Bhunia and Sankar (2020) assessed groundwater recharge potential in the Gopiballavpur block, Paschim Medinipur, using remote sensing and GIS. Thematic maps were developed using Landsat 8-OLI, SRTM, and field data, with a weighted linear combination approach applied to classify recharge zones. Results indicated that the highest recharge

potential was in the central and northwest areas, where artificial recharge structures were recommended to enhance groundwater sustainability.

These studies collectively demonstrate the effectiveness of remote sensing, GIS, and AHP in groundwater resource assessment. They highlight the importance of incorporating additional parameters such as pre- and post-monsoon groundwater depth, water draft, and vegetation indices to improve prediction accuracy. Future research should integrate high-resolution satellite data, machine learning techniques, and long-term groundwater monitoring to enhance groundwater management strategies and ensure sustainable water resource utilization.

Groundwater quality

Groundwater contamination due to heavy metals has been widely studied to assess pollution levels and associated health risks, particularly in regions affected by industrial and agricultural activities. Various models have been employed to analyze contamination sources, hazard indices, and potential mitigation strategies.

A study conducted by Chaturvedi et al. (2018) developed a multivariate non-linear regression (MVNLR) model to establish a correlation between the Hazard Index (HI) and the heavy metal pollution index (m-HPI). This model was optimized by adjusting weightage factors (W_i) to improve accuracy, with the USEPA reference dose (RfD) yielding the most reliable results. Validation of the model was conducted using 305 groundwater samples across seven datasets, demonstrating strong predictive capability and global applicability. The findings confirmed that the optimized MVNLR model effectively predicts HI, making it a valuable tool for assessing water quality and associated health risks. Furthermore, Chaturvedi et al. (2021) expanded on this research by analyzing the role of metal interactions, including synergistic and antagonistic effects, in influencing m-HPI and HI. Site-specific variations in pollution levels were identified using groundwater samples from ten different locations. This study proposed a secondary guideline value for iron (Fe) in regions with limited drinking water sources, underscoring the importance of localized water quality assessments.

In the middle Subarnarekha River Basin, Jharkhand, hydrochemical analysis revealed varying degrees of contamination from mining, agricultural runoff, and natural processes. A study by Gautam et al. (2015) classified groundwater into different types and found elevated levels of TDS, NO_3 , Cd, Pb, and Ni in several locations, particularly in Govindpur, where concentrations exceeded BIS and WHO limits. Despite these contaminants, groundwater was still considered suitable for irrigation, though the study emphasized the need for continuous monitoring.

To further investigate heavy metal contamination, Giri & Singh (2015) analyzed groundwater samples from 30 sites within the Subarnarekha River Basin. Using inductively coupled plasma-mass spectrometry (ICP-MS), they measured the concentrations of 14 heavy metals, including

arsenic (As), manganese (Mn), iron (Fe), copper (Cu), and selenium (Se). Principal Component Analysis (PCA) was employed to identify pollution sources, distinguishing between geological and anthropogenic contributions. The hazard quotients (HQ) and hazard index (HI) assessments indicated that Mn, Co, and As posed significant non-carcinogenic and chronic health risks, with certain locations exceeding safe drinking water limits established by WHO, India, and USEPA. This study highlighted the urgent need for improved water management practices, particularly in industrial and mining-affected areas.

A separate study conducted by Gautam et al. (2021) focused on the spatial and seasonal variations of nitrate pollution in groundwater along the Subarnarekha River in Jharkhand, India. Groundwater samples collected from hand pumps revealed nitrate concentrations ranging from 0.2 to 264.6 mg/L, with higher levels recorded in Hatia Bridge, Tatanagar, Govindpur, Mushabani, Kandra, and Saraikela. In these locations, nitrate levels exceeded WHO safety limits, posing potential health risks, particularly to marginalized communities. The study attributed contamination to agricultural runoff, industrial waste discharge, and poor sanitation infrastructure. ANOVA analysis confirmed significant seasonal variability, while PCA identified anthropogenic sources as the dominant contributors to nitrate pollution. With 44% of the study area classified as unsafe, researchers recommended implementing groundwater treatment measures, expanding regular water quality monitoring programs, and promoting rainwater harvesting initiatives to mitigate contamination risks and enhance long-term water security.

River Water Quality

Mishra et al. (2019) reported that the Subarnarekha River at Ghatsila, Jharkhand, faces severe eutrophication due to excessive organic and inorganic pollution from industrial discharge, agricultural runoff, and human activities. High phosphate (0.85–1.50 ppm) and nitrate (0.95–1.25 ppm) levels have fueled algal blooms, while low dissolved oxygen (5.0–5.2 ppm), high temperature (34.5°C), and slight acidity (pH 4.5–5.8) indicate deteriorating water quality. The study emphasizes the urgent need for wastewater treatment and stricter environmental regulations to mitigate pollution.

Similarly, Deo & Ahmad (2021) highlighted the impact of industrial and mining activities on oxygen depletion in the river, essential for aquatic life. Their study predicted that if pollution continues at 0.06 kg/m/day, oxygen levels will eventually reach zero, rendering the river ecologically dead. However, some ecological functionality persists within the first 325 km of the river.

In addition, Pradhan et al. (2024) assessed water quality in the lower Subarnarekha River, classifying it as “moderate to very poor” in the pre-monsoon season and “moderate to poor” in

the post-monsoon season. Heavy metal contamination, including Pb, Cu, Ni, Cd, Fe, and Cr, poses significant long-term health risks, particularly for children. Monte Carlo Simulation (MCS) further predicts ongoing contamination risks.

Furthermore, Kadave & Kumari (2023) linked seasonal variations in water quality to extensive urbanization, which has led to reduced forest cover and wetland depletion, exacerbating groundwater depletion and pollution. Their study calls for afforestation, wetland conservation, and sustainable land management strategies.

Singh et al. (2018) conducted hydrochemical analyses that revealed the river fluctuates between mild acidity and alkalinity, with seasonal ionic concentration variations primarily driven by rock weathering. The study estimated that the river delivers approximately 1.477×10^6 tons of dissolved loads annually into the Bay of Bengal and remains suitable for irrigation.

Similarly, Gautam et al. (2018) identified Pb, Ni, NO₃, Mn, and fluoride (F) as critical pollutants in the middle Subarnarekha Basin, necessitating targeted remediation strategies.

Similarly, Banerjee et al. (2015) confirmed heavy metal contamination in water and sediments due to industrial and mining discharge, with Pb, Ni, and Cd exceeding Indian drinking water standards. Pollution indices indicated progressive site deterioration, underscoring the need for long-term monitoring, advanced treatment technologies, bioremediation strategies, and sustainable sediment management.

Fluvial Abrasion and Sediment Transport

Dhali (2019) analyzed potholes on the granite and quartzite riverbed of the Subarnarekha River, highlighting their formation through monsoon-driven abrasion and fluvial turbulence. A study across 17 sites (n=1707 potholes) demonstrated that joint length positively correlated ($R^2=0.71$) with pothole expansion, while sediment load hindered further growth.

Similarly, Dhali & Biswas (2017) used Multi-Criteria Analysis (MCA), ArcGIS, and SPSS to study pothole evolution, identifying larger potholes (>10 m²) in high-energy zones like Subarnarekha-Apurpoth and Kharsoti. Their findings emphasized the geomorphic significance of pothole formation in sediment transport and channel evolution.

In addition, Purkait & Majumdar (2024) validated grain sorting and channel bar migration in the Subarnarekha River through flume experiments, revealing that sediment transport disruptions at bar edges lead to aperiodic sorting changes. Cross-stratifications in bars indicated migration patterns similar to asymmetric mega-ripples, highlighting the dynamic nature of sediment deposition.

Expanding on sediment transport, Acharyya et al. (2023) assessed shoreline changes in the Subarnarekha deltaic estuary using a coupled SWAT-DSAS model with remote sensing data. Their findings revealed a significant rise in sediment loss, from 28,737 tons in 2017 to 83,749

tons in 2021, causing erosion on the right bank and deposition on the left bank.

Furthermore, Giri & Singh (2015) analyzed spatial and seasonal variations of metal concentrations in bed sediments using ICP-MS, identifying Pb and Cu contamination at higher levels than Ni, Zn, Co, and Ba, necessitating urgent mitigation strategies.

Similarly, Dhali & Sahana (2017) examined fluvial hydraulics in the Subarnarekha-Kharsoti River Basin using mathematical models and GIS, identifying the middle section as highly erosive, with post-monsoon hydraulic activity as the primary driver of erosion dynamics.

Panda et al. (2021) applied SWAT to estimate soil loss in the Upper Subarnarekha catchment, calibrating (1996–2008) and validating (2009–2013) the model using the SUFI-2 algorithm in SWAT-CUP. Their findings showed an average annual soil loss of 4.84 Mg ha^{-1} , with SW18 experiencing the highest erosion ($10\text{--}15 \text{ Mg ha}^{-1} \text{ year}^{-1}$). Sub-watershed prioritization identified SW17, SW18, and SW19 as highly vulnerable, requiring immediate soil conservation measures.

Das & Banerjee (2021) conducted a 40-year analysis (1972–2013) of streamflow and sediment load trends, revealing significant seasonal shifts. Upstream discharge declined, while downstream discharge increased post-monsoon, influenced by anthropogenic activities.

Similarly, Chatterjee et al. (2013) mapped soil erosion vulnerability in the Upper Subarnarekha River Basin using the Universal Soil Loss Equation (USLE) model and remote sensing. Their findings showed an increase in erosion severity between 2001 and 2011 due to vegetation loss and expanding impervious surfaces, with annual soil erosion rates classified into five severity levels.

Samanta et al. (2016) used the GIS-based Revised Universal Soil Loss Equation (RUSLE) model to classify 40% of the basin under severe to very severe erosion and 38.9% under low to very low erosion risk. The highest erosion rates were recorded in Keshiary, Dantan-I, Jaleswar, and Sankrail blocks, necessitating immediate conservation interventions.

Lastly, Das (2019) analyzed four decades of discharge and sediment load data, identifying a statistically significant decline in sediment load ($p < 0.05$) due to dam construction in 1998 and 2010. These findings urge policy interventions to ensure environmental flow protection and sustainable sediment management.

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Brahmani and Baitarni Basin

Brahmani River Basin

Case Study -I

Water Resources Assessment of Brahmani River Basin, India

Case Study Overview

The Brahmani Basin, an east-flowing river system in India, spans 39,268 km² 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) [1]. 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 [1].

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 [1]. 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 [1].

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 [1].

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 [1][2].

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 [3]. 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 [3][4]. Spanning 39,268 km², the Brahmani Basin covers parts of Odisha (22,516 km²), Jharkhand (15,405 km²), and Chhattisgarh (1,347 km²), supporting a population of 8.5 million with agriculture and industrial activities [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 [5].



Figure 1. Brahmani River Basin (Source: International Commission on Irrigation and Drainage (ICID) New Delhi, 2005).

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 [1][2]. 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 [3][4]. Legal regulations must be enforced to prevent untreated effluent discharge, replacing dilution methods with effective treatment solutions [5]. Over-extraction and poor water management threaten ecosystems, necessitating a shift towards sustainable water resource practices, emphasizing precipitation as the primary renewable resource [6]. 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.

Pollution Control in Angul-Talcher Region

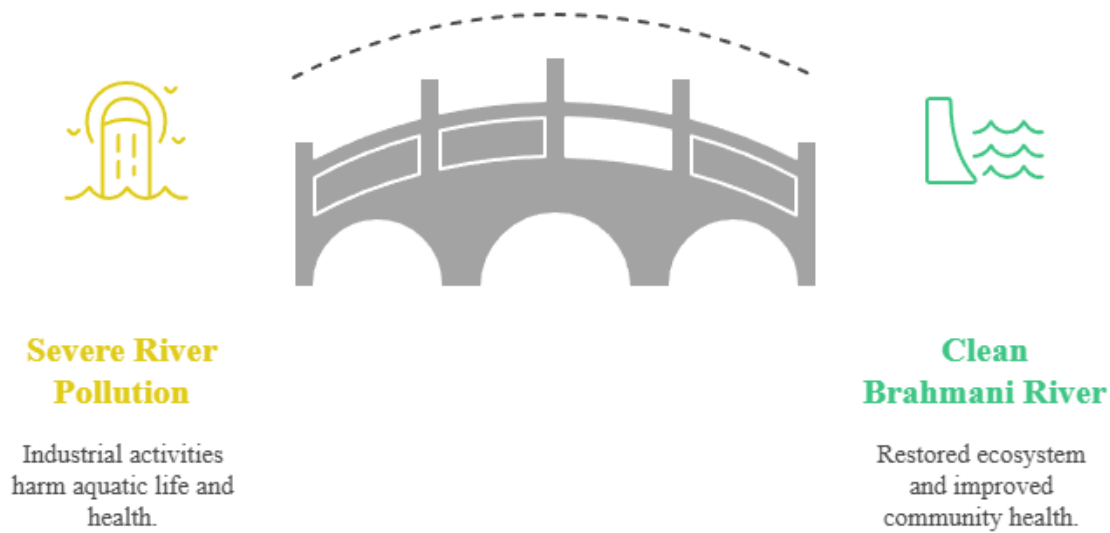


Figure 2. Pollution control in Angul-Talchar region in Brahmani River stretch.

Project Description

Goals and objectives

Emphasizes water-related challenges in the Brahmani basin to evaluate policy effectiveness for similar basins.

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.

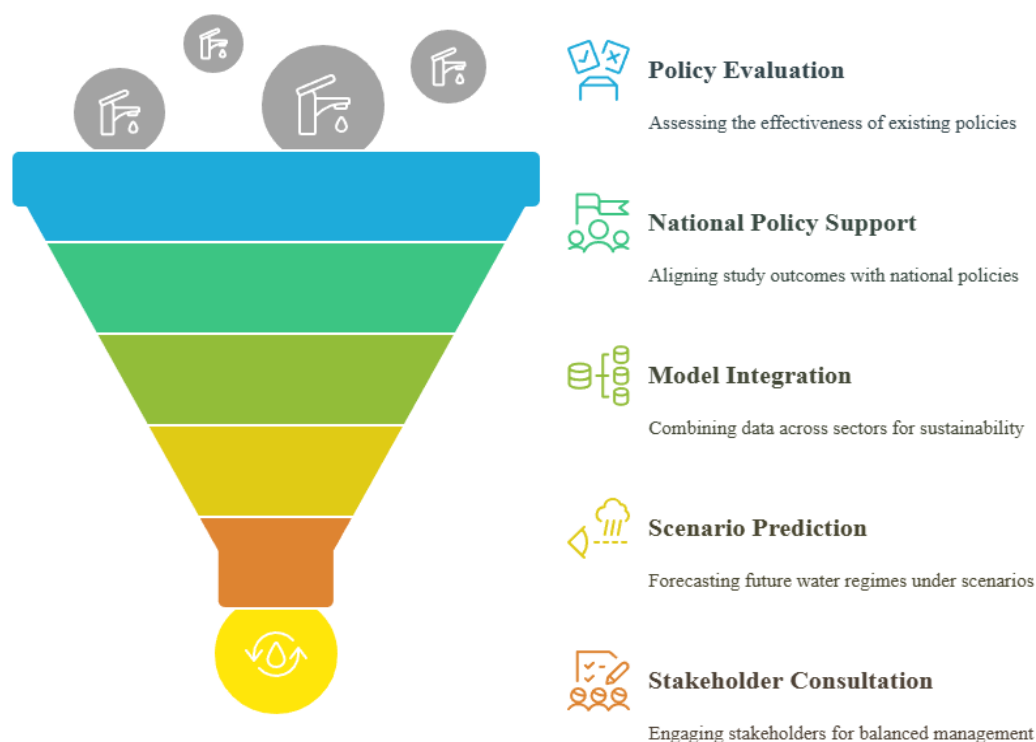


Figure 3. Goals and objectives

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 [1].

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 [2]. 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 [3][4].

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 [5][6]. Flood Mitigation Strategies are discussed with an emphasis on stakeholder consultation to assess limitations and make informed decisions on flood control and drainage measures [3][4]. 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 [6].

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 [1]. 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 [2]. 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 [2]. 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 [1]. Community involvement was emphasized as essential for identifying local water-related challenges and creating culturally appropriate management strategies [2]. 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 [3].

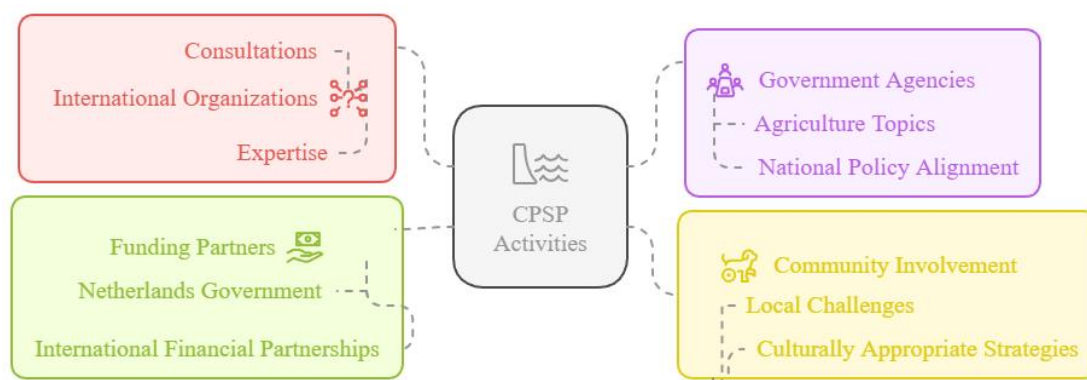


Figure 4. Key stakeholders and partnership.

Outcomes and Impact

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 [1], [2]. Recognizing EFRs as valid requirements in water-rich basins supports riverine ecosystems and the diverse species that depend on them, enhancing regional biodiversity [3]. 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 [3]. Additionally, proper irrigation and drainage practices help mitigate environmental pollution, particularly in estuary areas where river currents interact with tidal waters, preventing contamination [4], [5]. Sustainable agricultural practices further optimize water use, reducing over-extraction and preserving water quality while improving productivity [6]. Lastly, engaging local

communities in water management fosters stewardship and responsibility, leading to better conservation practices and greater awareness of ecosystem health [6].

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 [1][2]. 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 [3][4]. Community engagement is essential in effective water management, as involving local populations in decision-making fosters ownership, responsibility, and sustainable conservation practices [5]. 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 [3][6]. Socioeconomic models aid in setting water management targets aligned with community needs by considering water and land constraints, thereby promoting sustainable rural development [7][8]. 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 [5].

Lessons Learned and Recommendations

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 [1]. Multi-stakeholder engagement played a crucial role, as consultations at both basin and national levels provided valuable insights that refined the analysis and outcomes [2]. The findings led to key policy recommendations, emphasizing the need for integrated and sustainable water resource management [3]. Basin-specific results were extrapolated to similar basins, ensuring that local insights contributed to broader national strategies [4]. 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 [2]. Future projections included estimates for water use, irrigated and rain-fed lands, and reservoir operations, which are vital for long-term planning [5]. The project also acknowledged the contributions of international organizations and stakeholders, highlighting the collaborative nature of the initiative [2].

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.

Areas for further improvement or research

Future research should focus on sustainable groundwater management to prevent over-extraction [1][2], effective land use planning to expand cultivation while minimizing environmental impacts [3][4] and refining the BHIWA model for broader water assessments [5]. Stakeholder collaboration is essential for inclusive decision-making [5]. Climate change adaptation strategies should enhance water security [5], while integrated policies should address water supply, food security, and rural development [5]. Establishing monitoring frameworks with indicators is crucial for evaluating management strategies [5]. 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 [1]. 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 [2]. 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 [3]. 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 [4]. 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 [5]. Stakeholder engagement remains crucial, and research should explore improved strategies for involving local communities and industries in water management discussions [6]. 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 [7].

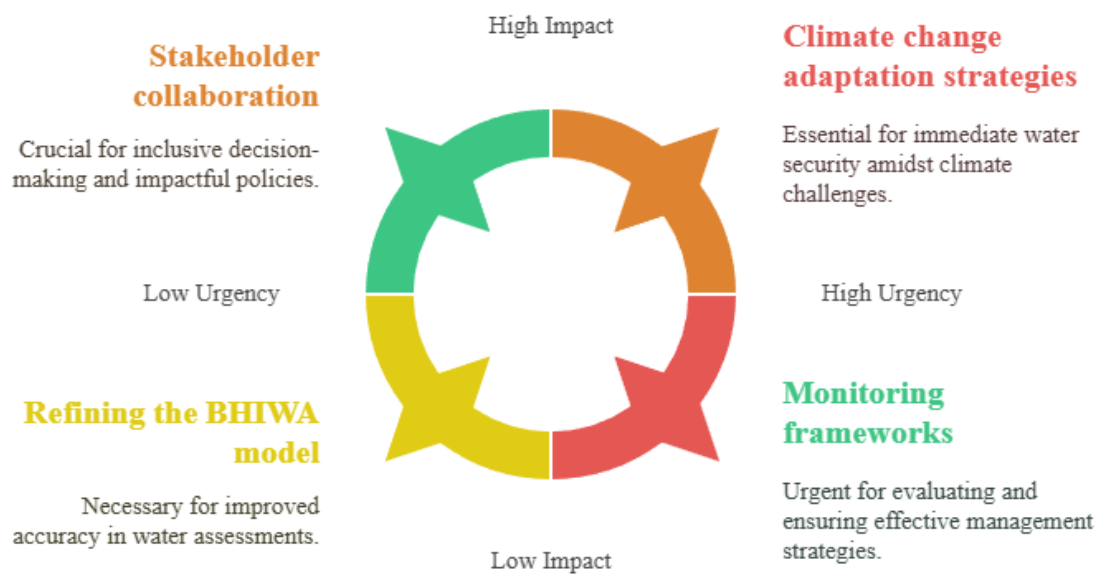


Figure 5. Areas for further improvement or research.

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BRAHMANI RIVER BASIN

Case Study -II

Influence of physico chemical parameters on surface water quality: a case study of the Brahmani River, India
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-} [1][2]. 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 [1]. 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 [2]. 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 [3][2]. 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 [4][2]. Future research could integrate these findings with Geographic Information System (GIS) techniques to develop a WQI map of the river [5][6].

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 [1] [2] [3].

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 [1][2].

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 [3][4]. 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 [5].

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 [1].

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.

Project Description**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.

Outcomes and Impact**Environmental benefits**

Enhanced Biodiversity: Improving Brahmani River's water quality supports diverse aquatic life,

promoting healthy ecosystems and sustaining fish and plant species [1].

Sustainable Water Use: Clean water ensures safe usage for drinking, irrigation, and industry, benefiting communities reliant on the river [2].

Reduction of Pollution: Controlling industrial discharges and agricultural runoff minimizes contaminants, protecting water quality and the environment [3].

Improved Public Health: Cleaner water lowers the risk of waterborne diseases, ensuring safety for consumption and recreation [1].

Ecosystem Services: Healthy rivers provide flood regulation, water purification, and carbon sequestration, benefiting both nature and people [4].

Climate Resilience: Good water quality helps ecosystems withstand climate change effects like floods and droughts [4].

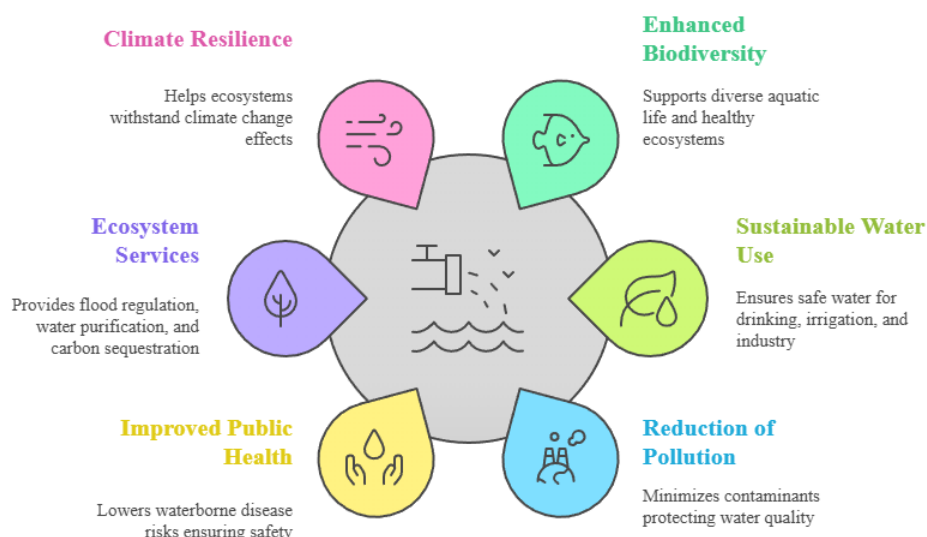


Figure 1. Environmental benefits of the study.

Lessons Learned and Recommendations

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 [1][2]. The river's slightly alkaline nature was found to promote phytoplankton growth, which is essential for maintaining aquatic ecosystems [1][2].

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 [3]. 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 [4][5].

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 [1].

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 [2].

Aquatic Habitat Preservation: The river supports aquatic life, benefiting biodiversity, local fisheries, and recreational activities, emphasizing the need for water quality protection [1].

Pollution Management: Untreated wastewater and agricultural runoff impact water quality, necessitating strict regulations on industrial and agricultural waste discharges to improve water conditions [2].

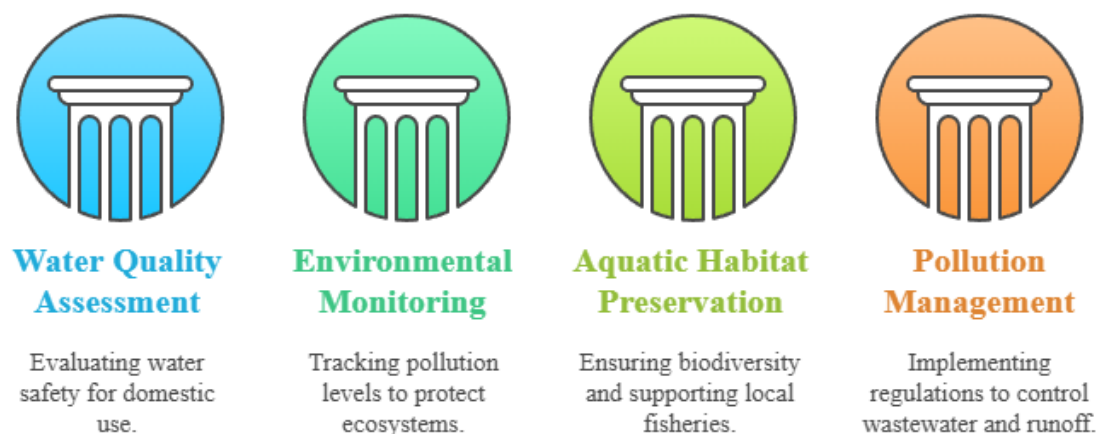


Figure 2. Practical implications of the study.

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. 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 [1]. 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 [1]. 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 [2]. 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 [3]. 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 [4]. 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 [3].

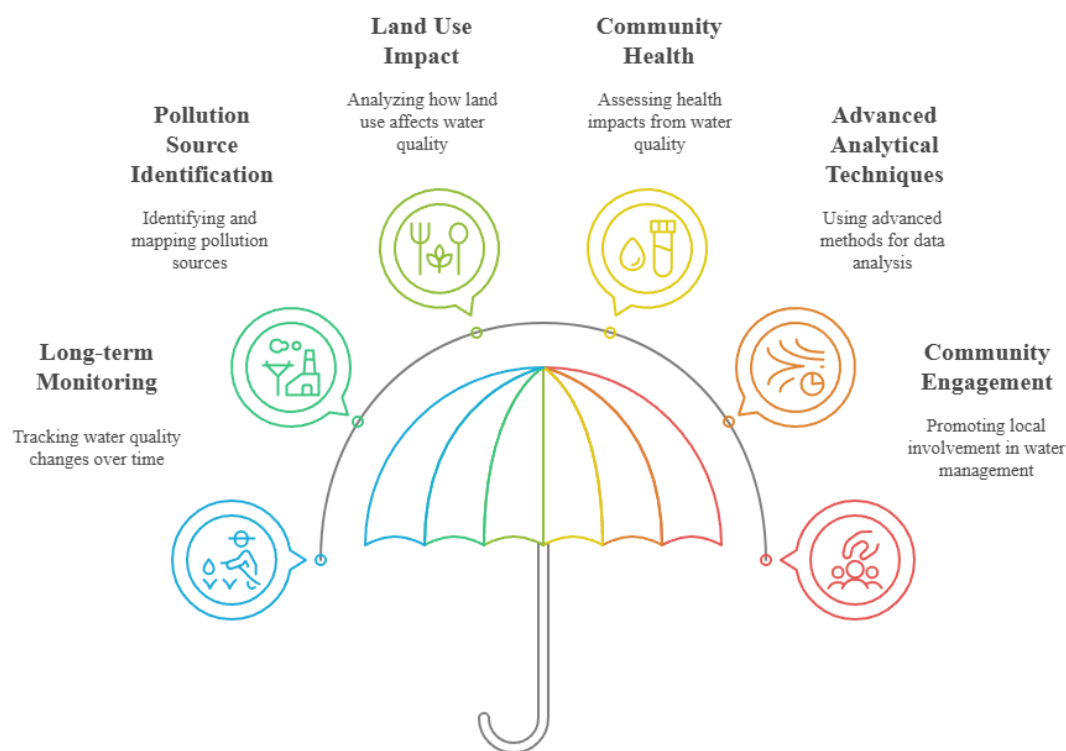


Figure 3. Shows the areas for further improvement or research.

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BRAHMANI RIVER BASIN

Case Study -III

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

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. The findings aim to support water management adaptation strategies in the region.

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.

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.

Threat to Mangrove Ecosystems: The Bhitarkanika mangrove ecosystem in the delta is under threat from environmental changes.

Project Description

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.

Strategies and interventions

Water Storage Structures: Build reservoirs to store monsoon water for irrigation and flood control.

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.

Irrigation Planning: Adjust irrigation practices to align with changing streamflow patterns, particularly in winter.

Outcomes and Impact

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.

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.

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.

Lessons Learned and Recommendations

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. 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.

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.

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.

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BRAHMANI RIVER BASIN

Case Study -IV

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 [1].

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 km², with a total river length of 799 km [2]. 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 [1]. 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 [1] [2]. 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 [3].

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 [4].

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

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BRAHMANI RIVER BASIN

Case Study –V

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 [1] [5]. 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 [2].

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:

Predict flood discharges for return periods of 2, 5, 10, 20, 50, 100, and 200 years.

Apply and compare probability distribution models (GEV, Gumbel Max, Log-Pearson III, Lognormal) to estimate peak flood discharges [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 [4].

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.

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BRAHMANI RIVER BASIN

Case Study –VI

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) [1] [2]. 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 [3]. 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 [4][5]. This includes mapping pollution hotspots and guiding corrective measures for water conservation [6].

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.

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BRAHMANI RIVER BASIN

Case Study –VII

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 [1] [2]. The primary objective is to identify pollution sources and their impacts on water quality through methods like the CRITIC mechanism and the MOORA model [5].

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 [6].

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 [7].

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 [4].

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.

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BRAHMANI RIVER BASIN

Case Study –VIII

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 [1][2]. 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 [3].

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. 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 [3]. 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.

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Baitarani River Basin

Case Study – I: 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 [1]. 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 [1]. 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 [1]. 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 [1]. 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 [1].

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 [1]. 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 [1].

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 [1]. 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 [1].

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.

References

[1] Jain, R.K., Sankhua, R.N., Shikha, D., & Bisht, S. (2017). River Basin Planning of Baitarani Sub-Basin Using River System Approach. *NDC-WWC Journal*, 6(1), 26-29.

BAITARANI RIVER BASIN

Case Study - II

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. 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 ([1]).

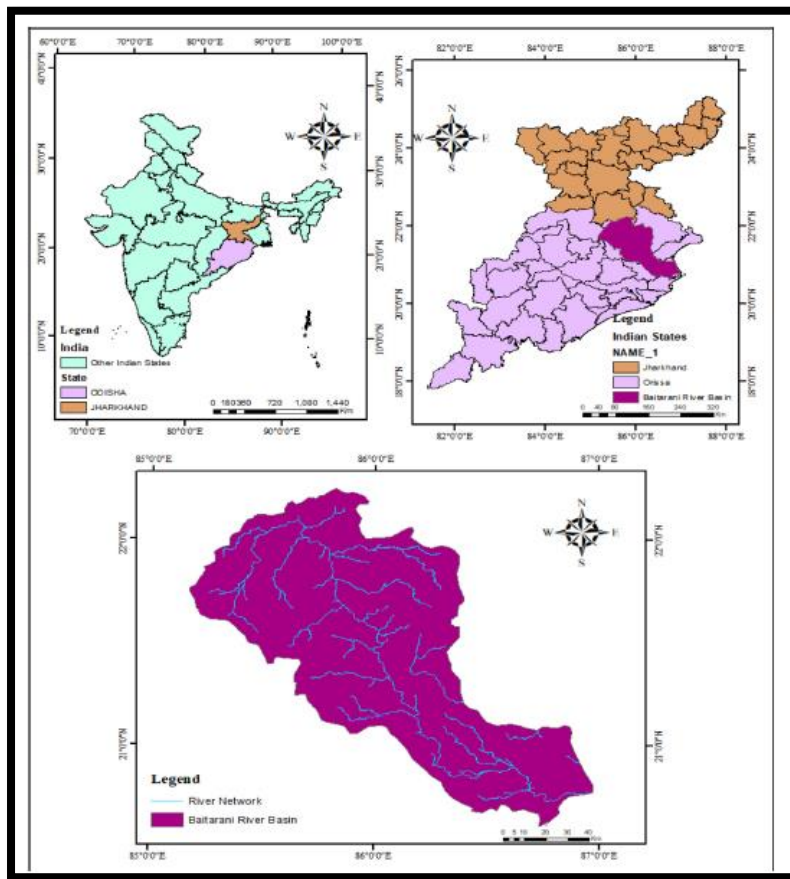


Figure 4 Study Area Map [1].

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 [1]. 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 [1]. 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 [1]. 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 (R^2), 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 [1]. 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 (fig. 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.

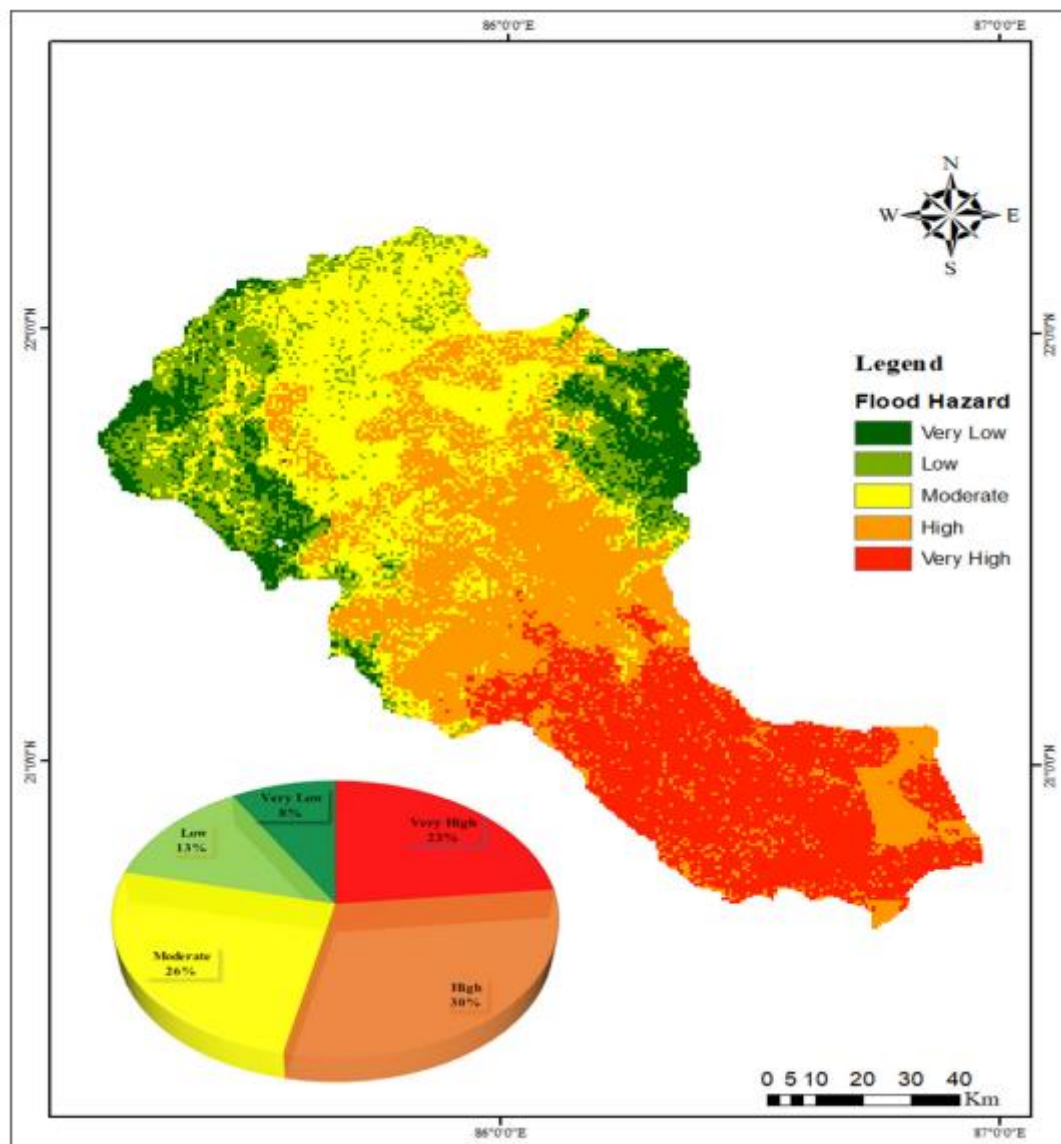


Figure 5 Flood Hazard Map [1].

b. Social Benefits

The project's outcomes have significant social benefits for the communities living in the Baitarani River basin [1]. 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 [1]. 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 [1]:

- **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 other river basins (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 [1]:

- **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.

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BAITARANI RIVER BASIN

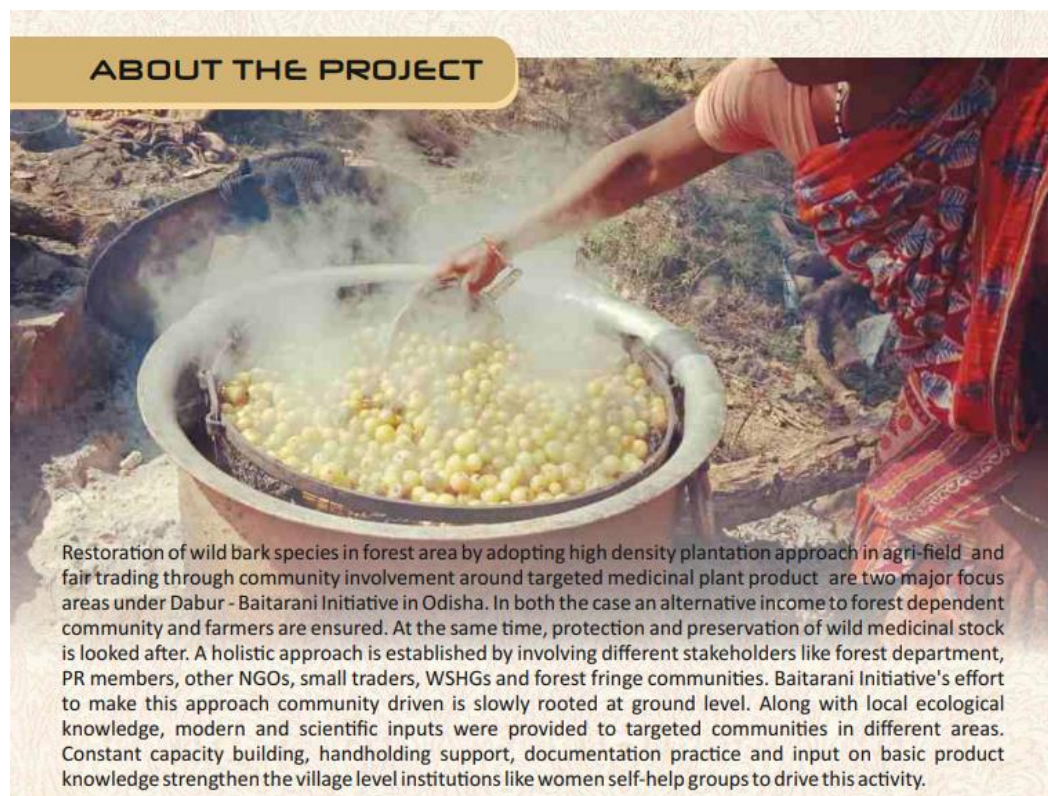
Case Study – III

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 (Baitarani Initiative, 2019).



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 orchioidea* (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).

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).

APPROACH

Baitarani team developed a T-5 approach to roll on the activity in such a manner so that the targeted objectives can be fulfilled. This T-5 approach is not only sustainable but also a practical action oriented model in the field of forest base livelihood.

T5 APPROACH

TARGETING	TERMS & CONDITIONS	TRAINING	TRADING	TRANSPERANCY
- Village / Community - Product - Geographic area for wild harvesting and Farming in Agri-field.	- MAT - Mutually Agreed Terms - PIC- Prior Informed Consent	- Coordination - Quality Parameter/ Value addition - MF & ME - In field Nursery & Plantation (only for targeted bark species) - Awareness (Dos & Don'ts)	- Focus on business Sustainability- Long run Approach – Forest Gathering & High Density Plantation - Focus on primary value addition - Packaging- Storing and leveling - Expose to basic lifting process (Purchase Order, Clearance from GP, Forest Dept., Use of Stack Card, loading etc..)	- Community base demand driven - Financial transparency payment through bank only - Product source mapping - Common price structure 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 assess 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.

References

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BAITARANI RIVER BASIN

Case Study – IV

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 [1]. 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. 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).

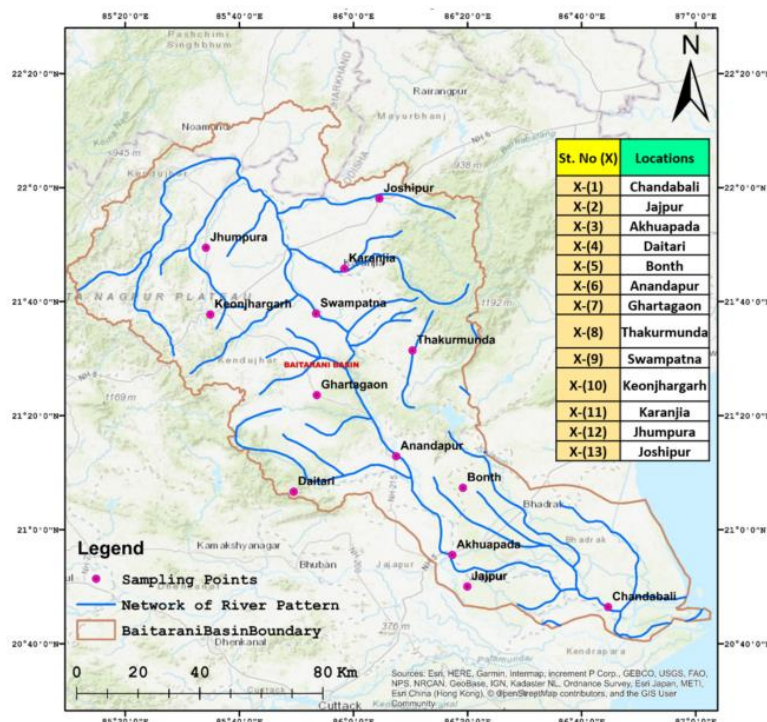


Figure 1 Study Area Map [1].

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 [1].

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 ($< 5\text{NTU}$) (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.

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BAITARANI RIVER BASIN

Case Study – V

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

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:

Improved Livelihoods: Reduced flooding protects agricultural lands and crops, ensuring food security and income stability for farmers and rural communities.

Reduced Displacement: Embankments prevent the displacement of people from their homes and villages due to flooding, minimizing social disruption and trauma.

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.

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).

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Pennaiyar River Basin

I. Case Study Overview

a. Project background and location

The Pennaiyar River basin (Latitude 11°38'30" N & 12°54'00" N and Longitude 77°39'30" E & 79°54'15" E) is the second largest interstate east-flowing river basin between the Pennar and Cauvery basins. It covers parts of Tamil Nadu, Karnataka, and Andhra Pradesh, with the majority of the basin lying in Tamil Nadu (11,375 sq. km) and a small portion (90 sq.km) in Puducherry (Figures 1). The basin is crucial for agriculture, drinking water supply, and industrial usage across multiple districts, including Krishnagiri, Dharmapuri, Vellore, Thiruvannamalai, Villupuram, and Cuddalore.

The Pennaiyar River basin lies within the tropical monsoon zone. Based on the hydro-meteorological features of the basin, year is divided into two periods, i.e., 1) Monsoon period spanning from June to December and 2) Non-monsoon period spanning from January to May. The monsoon period is further sub-divided into Southwest monsoon period spanning from June to September (4 months) and Northeast monsoon period spanning from October to December (3 months). Similarly, the non-monsoon period is further sub-divided into winter period spanning from January & February (2 months) and summer period spanning from March to May (3 months). The monsoon period is hydrological significant for water resources analysis. The South Pennar River (also known as Dakshina Painakini in Kannada and Thenpennai or Ponnaiyar or Pennaiyar in Tamil) is a river in India. It is the second longest river in Tamil

Nadu, with a length of 497 km, after the Cauveri River. The river rises near Hongashenhalli village at an elevation of about 900 m above MSL at North latitude 13° 25' and East longitude 77° 58' (near Nandidurg) in the Kolar district of Karnataka state. From its origin, the river Pennaiyar generally flows in the Southern direction for a length of 79 km through Kolar and Bangalore districts of Karnataka before entering the Krishnagiri district of Tamil Nadu. The river flows another 247 km generally in the South-Easterly direction in the districts of Krishnagiri, Vellore, Tiruvannamalai, Cuddalore and Villupuram. The river then flows in Easterly direction below the Tirukoyilur anicut for another 70 km before finding its way into Bay of Bengal. The river Pennaiyar branches into two rivers viz., the Gadilam and the Pennaiyar, below the Tirukoyilur anicut. The Gadilam joins the Bay of Bengal near Cuddalore and the Pennaiyar near the Union Territory of Pondicherry. The Pennaiyar river is having 14 tributaries, namely, Chinnar West, Chinnar East, Markandanadhi, Kambainallur, Pambar, Vaniyar, Kottaipatti, Kallar, Valayar Odai, Ramakkal, Pambanar, Aliyar, Musukundanadhi and Thuringalar. There are also 7 major Anicuts namely Nedungal Anicut, Kumarapatti Anicut, Ichembadi Anicut, Sathanur pick up Anicut, Tirukkoilur Anicut, Ellis Choultry Anicut and Sornavur Anicut. In addition to this, there are 152 Minor Anicuts and about 66 open offtake channels in this river basin. A pickup anicut is located below 7 km from the Sathanur reservoir to divert water to canals and river. Tirukovilur, Ellis Choultry, Sornavuranicuts are the major anicuts located below the Sathanur reservoir. There are 19 open off takes to feed the tanks above Tirukovilur Anicut and 47 open off takes to feed the tanks below Tirukovilur Anicut.

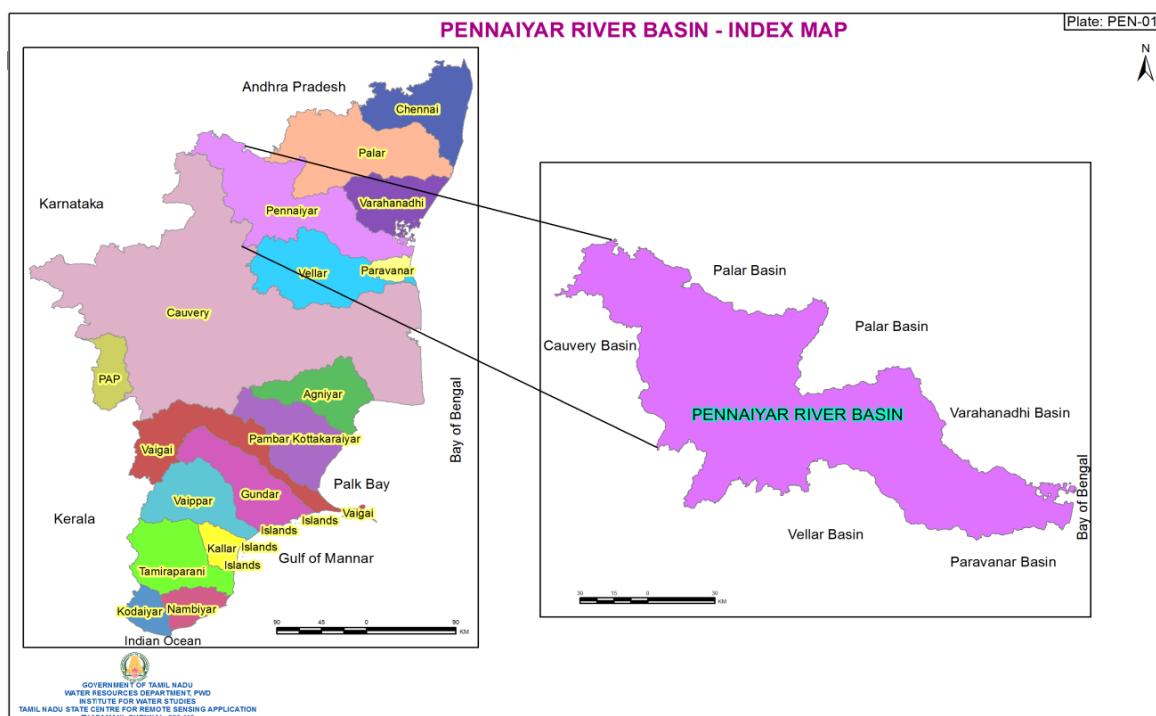


Figure 1. Index Map of Pennaiyar River Basin

(Source: https://nwm.gov.in/sites/default/files/Pennaiyar_Basin_14.07.17.pdf)

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

The Pennaiyar River basin faces several chronic environmental and management challenges, including:

Water scarcity and seasonal water stress due to irregular rainfall, over-extraction, and poor groundwater recharge.

Declining groundwater levels from unsustainable irrigation practices.

Water pollution from untreated sewage, industrial effluents, and agricultural runoff.

Fragmented governance between Tamil Nadu, Karnataka, and Andhra Pradesh, leading to interstate water conflicts.

Frequent drought conditions (semi-arid to dry-humid climate).

Soil erosion and land degradation in the uplands and foothills.

Limited water storage infrastructure and aging irrigation systems.

II. Project Description

a. Goals and objectives

Ensure sustainable water resource management for agricultural, domestic, and industrial needs.

Improve groundwater recharge through better watershed management.

Strengthen resilience to droughts through multi-source water supply strategies.

Prevent and control pollution in surface and groundwater.

Enhance cross-border water governance to reduce interstate disputes.

Promote sustainable agriculture through improved irrigation efficiency.

b. Strategies and interventions

Watershed development projects: Check dams, percolation ponds, and contour bunding to enhance groundwater recharge.

Reservoir optimization: Improve storage and conveyance efficiency in major reservoirs like Sathanur, Krishnagiri, and Kelavarapalli.

Community-led water management: Village-level water committees to monitor usage, especially during drought years.

Reuse and recycling: Promote industrial water recycling and treat sewage reuse for non-potable purposes.

Pollution control: Enforce stricter effluent treatment standards for industries along the river.

Rainwater harvesting: Mandatory rooftop rainwater harvesting for urban settlements.

Agricultural best practices: Introduce drip irrigation, crop diversification, and drought-resistant crops.

Real-time monitoring: Use remote sensing and GIS tools to monitor land use, groundwater levels, and surface water quality.

A summarised flowchart of river basin planning is shown in Figure 2.

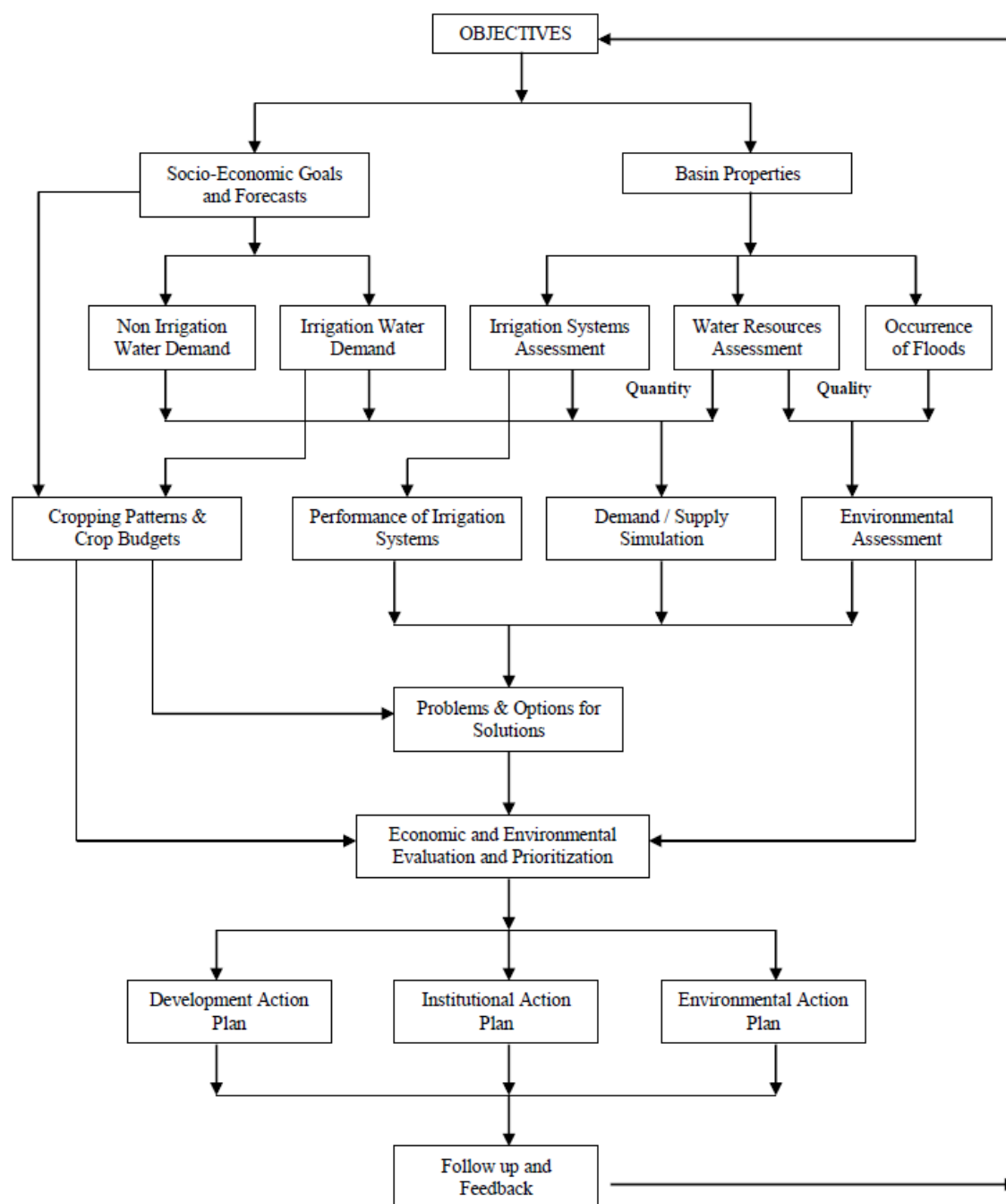


Figure 2. Summary flowchart of river basin planning

(Source: <https://wrd.tn.gov.in/wp-content/uploads/2024/09/Pennaiyar-VOL-I.pdf>)

Table 1. Strategic objectives, issues and action plan

(Source: <https://wrd.tn.gov.in/wp-content/uploads/2024/09/Pennaiyar-VOL-I.pdf>)

Sl. No.	Strategic objective	Issues	Strategies recommended
1.	Strengthening The Rain Gauge Stations	Non availability of Rain Gauge Station.	Install Rain Gauge Station in sub basins.

2.	Augmentation of Groundwater	Pennaiyar basin is assessed as “Critical” in groundwater development.	To improve the groundwater potential Artificial Recharge Structure Viz. Vertical Shaft, Percolation Pond, Check Dam and Anicut are proposed.
		Groundwater extraction is rampant in Musukundanadhi, Gadium and Pamber to Thirukovilur sub-basins.	Groundwater development is to be maintained at present level in Musukundanadhi, Gadium and Pamber to Thirukovilur sub-basins
3.	Storing the Surplus Water	The surplus flow assessed at 50% dependability rainfall at the tail end storage structure, Sornavur Anicut in Pennaiyar river is being let into the sea.	Construct an off-take channel for a length of 23.55 Km and then a feeder canal for a length of 38.720 Km at LS 12.88 Km from the main canal, to divert the surplus water of Pennaiyar Basin from Sathanur to Palar River through Cheyyar and augmenting the supply to Nandan Canal in Thiruvannamalai District.
4.	Modernisation of Irrigation & Agriculture	Low Irrigation Efficiency.	Apply drip irrigation for the cultivation of Vegetables to save 29% (13.46MCM) of water. Apply micro irrigation method for the cultivation of Groundnut to save 49.40% (28.29MCM) water. Apply drip irrigation for the cultivation of Banana and Sugarcane to save 33.33% (7.23MCM) and 40% (131.238MCM) water respectively.
		Water wastage in conventional cultivation method	Change the old paddy cultivation to SRI cultivation to save 40% (330.56 MCM)
5.	Sustainability of Environment	In Pennaiyar river basin, domestic sewage pollution is more severe than the industrial pollution.	Treat the sewage and reuse the treated water for firefighting, toilet flushing etc in a phased manner to meet the growing demand. Completely stop open discharge of domestic effluents into the river. Sanitary facilities have to be provided at public places.

		Excessive use of fertilizer	Encourage crop residue management, green manure, organic manure and composting method. Promote Organic farming.
		Increase in number of Water Borne disease case and death.	Domestic and industrial effluents have to be treated before letting into any sources after ascertaining the permissible limits.
		Reduction in storage capacity of reservoir due to sedimentation in Krishnagiri and Sathanur reservoirs.	Construction of dykes, check dams and detention basins may be formed in the main river and tributaries Gullies control measures and stream bank protection measures may be adopted.
		Sea water intrusion into the aquifer.	The land ward movement of sea water has to be checked or prevented by maintaining the water level. There should not be any over exploitation of ground water within 10 km, from the coastal line.

c. Key stakeholders and partnerships

State Governments of Tamil Nadu, Karnataka, and Andhra Pradesh.

Central Water Commission (CWC).

Tamil Nadu Water Resources Department.

District Administrations across Krishnagiri, Dharmapuri, Thiruvannamalai, Villupuram, Vellore, and Cuddalore.

Local Panchayats and Water User Associations.

Industries (especially in Krishnagiri and Hosur industrial belts).

NGOs focused on watershed management and environmental conservation.

Academic and research institutions for hydrogeological studies.

III. Outcomes and Impact

a. Environmental benefits

Improved groundwater recharge in semi-arid areas through check dams and percolation ponds.

Reduced pollution load in the Pennaiyar River by promoting better industrial effluent management and municipal sewage treatment.

Reduced soil erosion in the uplands through afforestation and vegetative bunds.

Increased biodiversity in and around riverine areas through habitat restoration.

b. Social benefits

Improved drinking water access in rural areas through rainwater harvesting and restored tanks.

Enhanced drought resilience in farming communities through diversification into low-water-use

crops.

Community engagement through village-level water governance institutions.

Improved health outcomes from cleaner water sources and better sanitation infrastructure.

c. Economic benefits

Increased agricultural productivity from assured irrigation and adoption of water-efficient techniques.

Cost savings for industries through water recycling and efficient water use technologies.

Job creation through watershed works (check dams, reforestation, desilting) and eco-tourism development around restored water bodies.

Stabilized livelihoods for marginal farmers through resilient farming systems and alternative income sources.

IV. Lessons Learned and Recommendations

a. Key takeaways from the project

Integrated water resource management (IWRM) is critical in basins with multiple water users.

Groundwater and surface water management must be combined to ensure water security.

Data-driven decision-making using remote sensing, GIS, and real-time data enhances project effectiveness.

Interstate collaboration mechanisms should be institutionalized to avoid conflicts.

b. Best practices and strategies for replication

Micro-watershed planning tailored to sub-basin characteristics.

Participatory water budgeting with community involvement.

Scaling up drip irrigation, System of Rice Intensification (SRI), and agroforestry.

Incentives for industries achieving zero liquid discharge (ZLD).

Payment for Ecosystem Services (PES) schemes to reward upstream watershed protection.

c. Areas for further improvement or research

Climate change adaptation plans for future hydrological changes.

Strengthening groundwater governance and extraction controls.

Enhancing urban water efficiency in rapidly growing towns.

Developing integrated flood management plans for extreme weather events.

Sediment management programs for reservoir sustainability.

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Sabarmati River Basin Management: A Case Study

I. Case Study Overview

a. Project Background and Location

River Sabarmati is one of the biggest and major river of Gujarat that runs through two major cities of Gujarat, Gandhinagar and Ahmedabad and finally meets the Gulf of Khambhat (GoK) in the Arabian Sea. It originates from the Aravalli Hills in Rajasthan and flows for about 371 km. This water deficit basin lies on the west coast of India between latitudes 22° N to 25° N and longitudes 71° E to 73° 30' E. It is one of the major west-flowing rivers in India and serves as a critical water source for urban areas, industries, and agriculture. The river basin covers 21,674 sq. km. Location map of the Sabarmati basin is shown in Figure 1. The basin is characterized by seasonal flow variability, heavy reliance on groundwater, and dependence on interbasin water transfers, particularly through the Narmada canal system. Rapid urbanization, industrial expansion, and agricultural demands contribute to persistent groundwater depletion, pollution, and competing stakeholder interests. Addressing these challenges requires a comprehensive understanding of hydrological dynamics, governance structures, and technical interventions suited to the region's complex socio-environmental context (Halдар et al. 2014). Several studies have analyzed water resource management in the Sabarmati basin from different perspectives. Research utilizing hydrological modeling has provided insights into surface and groundwater interactions, recharge processes, and climate change impacts. Studies employing SWAT-MODFLOW modeling (Sinan and Mishra (2020), Loukika et al. 2025) have demonstrated that groundwater recharge is highly sensitive to climatic extremes and intensified anthropogenic extraction, emphasizing the need for integrated management approaches. Tritium tagging and hydrogeochemical analyses have further refined the understanding of

recharge variability and groundwater evolution in fractured basement aquifers (Gupta and Sharma(1984), Pradhan et al. 2022). Additionally, urbanization has been identified as a significant stressor, increasing the risk of flash flooding in Ahmedabad, with hydrodynamic models illustrating the role of infrastructure modifications in exacerbating floodplain vulnerability (Chandel and Shah 2021).

Reservoir and interbasin water transfer operations play a critical role in mitigating the basin's water scarcity, yet their long-term effectiveness remains uncertain. Studies on reservoir operation and flood regulation (Jain et al. 1998) along with assessments of canal automation and controlled water distribution through the Sardar Sarovar conveyance system (Joshi 2001), highlight the technical strategies employed to maximize water availability. However, concerns over water quality deterioration persist, particularly in relation to salinity management, as studied in the context of the Gulf of Khambhat freshwater reservoir project [8].

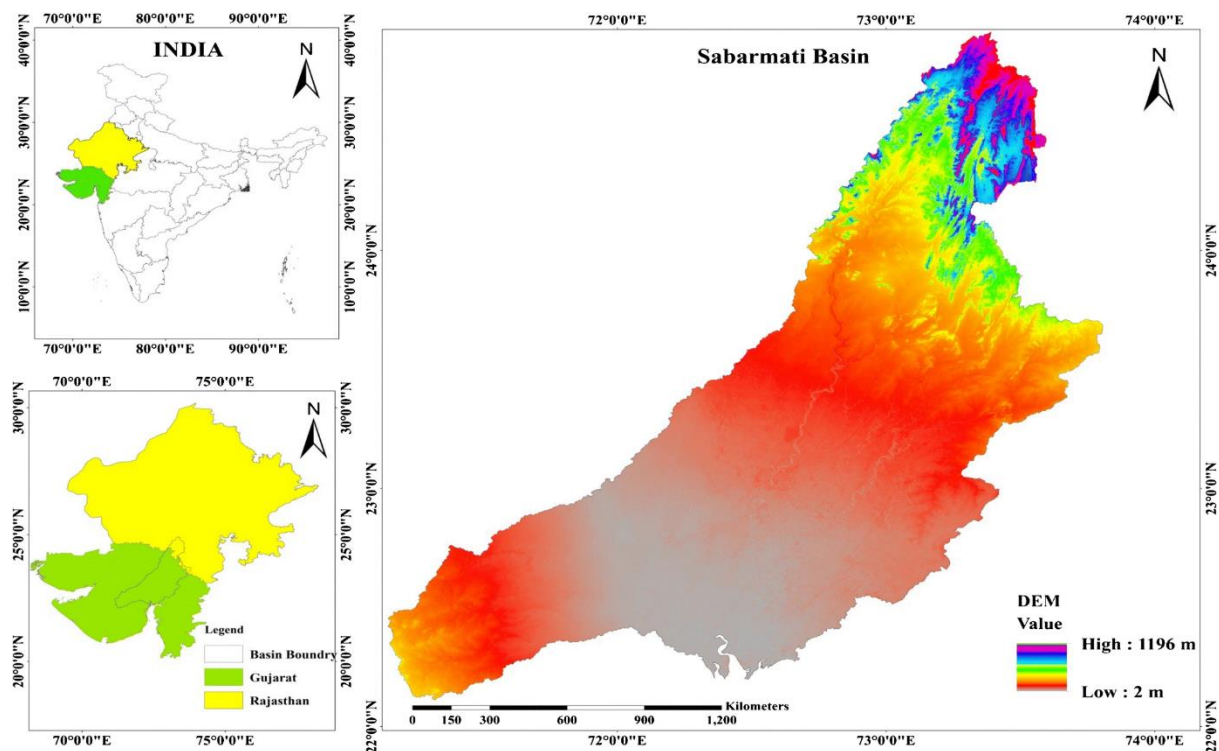


Figure 1. Location map of the Sabarmati River Basin (Kumari et al. 2021)

Governance and policy issues contribute to systemic inefficiencies, with inadequate groundwater regulation, weak enforcement mechanisms, and the absence of effective economic instruments to incentivize sustainable water use. Policy analyses indicate that existing regulatory frameworks fail to equitably balance agricultural, industrial, and municipal demands, and suggest the adoption of market-based strategies such as groundwater pricing, subsidies, and tradable rights to improve resource allocation (Bala 2015). Meanwhile, managed aquifer recharge (MAR) strategies, including check dams and percolation tanks, have gained traction for groundwater replenishment, though implementation challenges such as clogging and unintended downstream impacts remain unresolved (Ganguly and Ganguly 2021).

Taken together, these studies underscore the Sabarmati basin's urgent need for a more integrated approach that blends technical expertise, hydrological modeling, infrastructure optimization, and governance reforms. While significant advancements have been made in characterizing water availability and system vulnerabilities, critical gaps persist in implementing long-term climate resilience strategies, improving stakeholder coordination, and ensuring equitable water distribution. Future research must address these challenges through interdisciplinary frameworks that align hydrological sustainability with social and economic priorities.

b. Problem Statement: Management or Environmental Challenge

The Sabarmati River is under severe environmental stress due to a combination of natural and human-induced factors. To ensure its long-term sustainability, an integrated approach involving better water management policies, pollution control measures, sustainable groundwater use, and ecosystem restoration efforts is urgently needed. The Sabarmati River faces multiple challenges, including:

Water Scarcity and Over-Extraction:

- The river has limited natural flow due to low rainfall in its catchment area.
- Heavy dependence on Narmada Canal water to sustain the river.

Pollution and Industrial Waste:

- Untreated sewage and industrial effluents have significantly degraded water quality.
- High levels of heavy metals and chemical pollutants impact aquatic ecosystems.

Groundwater Depletion:

- Excessive groundwater extraction for irrigation and urban use has led to declining water tables.
- Salinity intrusion in some areas due to overuse.

Encroachment and Habitat Loss:

- Unregulated urban expansion has led to shrinking floodplains.
- Loss of natural wetlands that supported biodiversity.

Seasonal Flow Issues:

- The river remains dry for most of the year, except during the monsoon.
- Heavy dependence on inter-basin water transfers from the Narmada River.

Climate Change and Unpredictable Weather Patterns

- Rising temperatures increase evaporation rates, reducing water availability.

- Changing rainfall patterns lead to shorter, intense monsoons, causing flash floods and waterlogging in some areas, while prolonged dry spells worsen water scarcity.
- Reduction in groundwater recharge due to irregular rainfall further worsens seasonal water shortages.

Decline in Aquatic Biodiversity

- Loss of natural riparian habitats has led to a decline in fish populations and other aquatic species.
- Toxic pollutants and reduced oxygen levels from industrial discharge have caused fish kills.
- Decreased flow velocity in the river limits the ability of fish and migratory species to survive and reproduce.
- Disappearance of native vegetation along riverbanks has increased soil erosion, degrading habitat quality.

Contamination of Drinking Water Sources

- Mixing of untreated sewage with river water poses severe health risks to communities relying on the river for drinking water.
- Presence of pesticides, nitrates, and heavy metals in water sources leads to long-term health issues such as cancer, neurological disorders, and gastrointestinal diseases.
- Industrial waste dumping near water intakes increases the cost and complexity of water purification for urban areas like Ahmedabad and Gandhinagar.

Socio-Economic Conflicts and Water Inequality

- Displacement of local communities due to riverfront development and urbanization.
- Water shortages for farmers due to excessive diversion for urban and industrial purposes.
- Marginalized communities and informal settlements often receive the lowest priority in water distribution, leading to inequalities in access to clean water

Inefficient Water Management and Policy Gaps

- Unequal water allocation prioritizes urban and industrial needs over rural and agricultural demands.
- Lack of proper enforcement of pollution control measures allows industries to discharge untreated wastewater.

- Weak monitoring of groundwater extraction contributes to unsustainable water use.
- Failure to implement decentralized water management strategies, such as rainwater harvesting and localized wastewater treatment, leads to inefficient resource utilization.

II. Project Description

a. Goals and Objectives

The Sabarmati River Basin Management focuses on:

- Improving water availability through sustainable river management.
- Enhancing water quality by controlling pollution and sewage discharge.
- Restoring aquatic and riparian ecosystems through conservation projects.
- Promoting climate resilience by adopting sustainable water practices.
- Encouraging community participation in river conservation.

b. Strategies and Interventions

□ Sabarmati Riverfront Development Project (SRDP):

- Aimed at **revitalizing the river** by channelizing water from the **Narmada Canal**.
- Development of **urban infrastructure, public spaces, and green zones** along the river.

□ Industrial Effluent Treatment and Wastewater Management:

- Establishment of **Common Effluent Treatment Plants (CETPs)** for industries.
- Strict **pollution control measures** under the Gujarat Pollution Control Board (GPCB).

□ Inter-Basin Water Transfers from the Narmada River:

- Dependence on **Sardar Sarovar Dam** releases to maintain river flow.
- Narmada water is used for **drinking, industrial, and irrigation purposes**.

□ Riparian Restoration and Wetland Conservation:

- Development of **riverbanks with green cover** to reduce erosion.
- Protection of **existing wetlands** that serve as natural water filters.

□ Groundwater Recharge and Sustainable Water Use:

- Promotion of **rainwater harvesting structures** in urban and rural areas.
- Implementation of **drip irrigation** to reduce agricultural water demand.

□ Public Awareness and Community Engagement:

- **Clean Sabarmati Campaigns** to educate the public on pollution control.
- Involvement of **NGOs and research institutions** in conservation projects.

c. Key Stakeholders and Partnerships

- **Government Agencies:**

- Gujarat Water Resources Development Corporation (**GWRDC**) – Oversees water distribution and irrigation projects.
- Ahmedabad Municipal Corporation (**AMC**) – Manages urban wastewater treatment and riverfront development.
- Gujarat Pollution Control Board (**GPCB**) – Enforces environmental regulations.

- **Local Communities and NGOs:**

- Sabarmati Riverfront Development Corporation (**SRDC**) – Responsible for urban river restoration projects.
- Centre for Environment Education (**CEE**), Ahmedabad – Conducts water quality monitoring and public awareness programs.

- **Research and Scientific Institutions:**

- Indian Institute of Technology (IIT) Gandhinagar – Provides research on water quality and climate resilience.
- Gujarat Ecological Education and Research Foundation (**GEER**) – Works on ecological restoration.

III. Outcomes and Impact

a. Environmental Benefits

- **Improved Water Flow and Quality:**

- Inter-basin transfer has ensured a steady water supply in the Sabarmati River.
- Reduction in industrial and sewage pollution in key river sections.

- **Ecosystem Restoration:**

- Revival of riparian vegetation and aquatic biodiversity.
- Protection of wetlands and urban lakes linked to the river system.

b. Social Benefits

- **Improved Public Spaces and Livelihood Opportunities:**

- Sabarmati Riverfront has become a major recreational and tourism hub.

- Enhanced employment in urban development, tourism, and river conservation projects.
- **Better Water Security for Urban Areas:**
 - Ahmedabad and Gandhinagar have gained reliable drinking water sources.
 - Increase in awareness and community participation in water conservation.

c. Economic Benefits

- **Growth in Eco-Tourism and Urban Development:**
 - Riverfront development has attracted real estate investments and commercial growth.
- **Enhanced Agricultural Productivity:**
 - Improved water availability has benefited farmers along the basin.
- **Cost Savings in Water Treatment:**
 - Pollution control measures have led to lower water purification costs.

IV. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- Integrated river basin management is essential for sustainable water resources.
- Effective policy enforcement and monitoring play a crucial role in pollution control.
- Community participation enhances project sustainability.
- Inter-basin water transfers can help sustain rivers with limited local water sources.
- Strict pollution control measures are necessary to maintain river health.
- Urban planning must balance development and ecological conservation.
- Groundwater recharge strategies need to be prioritized to reduce dependence on external water sources.

b. Best Practices and Strategies for Replication

- Developing riverfronts as eco-friendly public spaces
- Encouraging industries to adopt zero liquid discharge systems
- Strengthening wastewater treatment infrastructure in urban areas
- Implementing continuous water quality monitoring systems

c. Areas for Further Improvement or Research

- Assessing long-term ecological impacts of riverfront development
- Enhancing flood management strategies
- Exploring advanced water treatment technologies
- Strengthening transboundary water governance with Rajasthan
- Reducing dependency on Narmada water by increasing local rainwater harvesting
- Enhancing sewage treatment capacity to ensure 100% wastewater recycling
- Restoring lost wetlands to enhance natural flood control and biodiversity conservation
- Expanding climate change resilience in river management planning

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Mahi Basin

[NOT YET SUBMITTED, WILL BE UPDATED ONCE RECEIVED]

Sabarmati Basin

I. Case Study Overview

a. Project Background and Location

River Sabarmati is one of the biggest and major river of Gujarat that runs through two major cities of Gujarat, Gandhinagar and Ahmedabad and finally meets the Gulf of Khambhat (GoK) in the Arabian Sea. It originates from the Aravalli Hills in Rajasthan and flows for about 371 km. This water deficit basin lies on the west coast of India between latitudes 22° N to 25° N and longitudes 71° E to 73° 30' E. It is one of the major west-flowing rivers in India and serves as a critical water source for urban areas, industries, and agriculture. The river basin covers 21,674 sq. km. Location map of the Sabarmati basin is shown in Figure 1. The basin is characterized by seasonal flow variability, heavy reliance on groundwater, and dependence on interbasin water transfers, particularly through the Narmada canal system. Rapid urbanization, industrial expansion, and agricultural demands contribute to persistent groundwater depletion, pollution, and competing stakeholder interests. Addressing these challenges requires a comprehensive understanding of hydrological dynamics, governance structures, and technical interventions suited to the region's complex socio-environmental context (Halder et al. 2014). Several studies have analyzed water resource management in the Sabarmati basin from different perspectives. Research utilizing hydrological modeling has provided insights into surface and groundwater interactions, recharge processes, and climate change impacts. Studies employing SWAT-MODFLOW modeling (Sinan and Mishra (2020), Loukika et al. 2025) have demonstrated that groundwater recharge is highly sensitive to climatic extremes and intensified anthropogenic extraction, emphasizing the need for integrated management approaches. Tritium tagging and hydrogeochemical analyses have further refined the understanding of recharge variability and groundwater evolution in fractured basement aquifers (Gupta and Sharma(1984), Pradhan et al. 2022). Additionally, urbanization has been identified as a significant stressor, increasing the risk of flash flooding in Ahmedabad, with hydrodynamic models illustrating the role of infrastructure modifications in exacerbating floodplain vulnerability (Chandel and Shah 2021).

Reservoir and interbasin water transfer operations play a critical role in mitigating the basin's water scarcity, yet their long-term effectiveness remains uncertain. Studies on reservoir operation and flood regulation (Jain et al. 1998) along with assessments of canal automation

and controlled water distribution through the Sardar Sarovar conveyance system (Joshi 2001), highlight the technical strategies employed to maximize water availability. However, concerns over water quality deterioration persist, particularly in relation to salinity management, as studied in the context of the Gulf of Khambhat freshwater reservoir project [8].

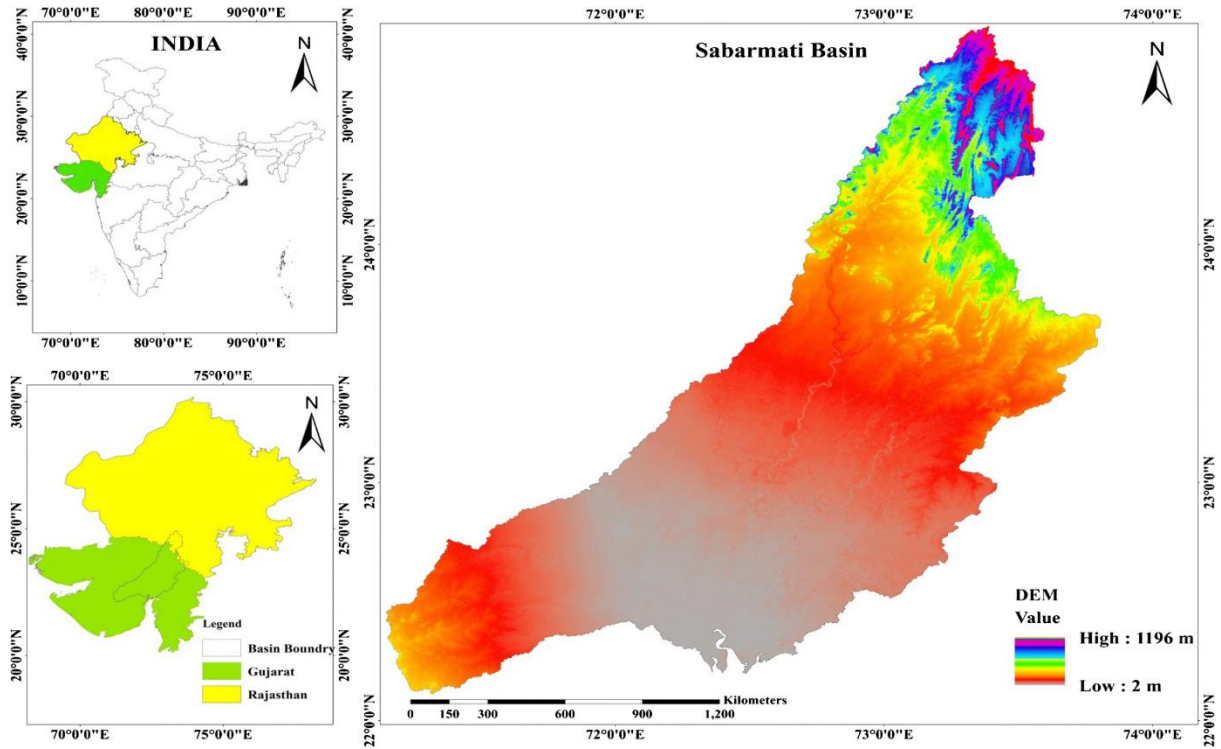


Figure 1. Location map of the Sabarmati River Basin (Kumari et al. 2021)

Governance and policy issues contribute to systemic inefficiencies, with inadequate groundwater regulation, weak enforcement mechanisms, and the absence of effective economic instruments to incentivize sustainable water use. Policy analyses indicate that existing regulatory frameworks fail to equitably balance agricultural, industrial, and municipal demands, and suggest the adoption of market-based strategies such as groundwater pricing, subsidies, and tradable rights to improve resource allocation (Bala 2015). Meanwhile, managed aquifer recharge (MAR) strategies, including check dams and percolation tanks, have gained traction for groundwater replenishment, though implementation challenges such as clogging and unintended downstream impacts remain unresolved (Ganguly and Ganguly 2021).

Taken together, these studies underscore the Sabarmati basin's urgent need for a more integrated approach that blends technical expertise, hydrological modeling, infrastructure optimization, and governance reforms. While significant advancements have been made in characterizing water availability and system vulnerabilities, critical gaps persist in implementing long-term climate resilience strategies, improving stakeholder coordination,

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b. Problem Statement: Management or Environmental Challenge

The Sabarmati River is under severe environmental stress due to a combination of natural and human-induced factors. To ensure its long-term sustainability, an integrated approach involving better water management policies, pollution control measures, sustainable groundwater use, and ecosystem restoration efforts is urgently needed. The Sabarmati River faces multiple challenges, including:

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- High levels of heavy metals and chemical pollutants impact aquatic ecosystems.

Groundwater Depletion:

- Excessive groundwater extraction for irrigation and urban use has led to declining water tables.
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- Unregulated urban expansion has led to shrinking floodplains.
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- Toxic pollutants and reduced oxygen levels from industrial discharge have caused fish kills.
- Decreased flow velocity in the river limits the ability of fish and migratory species to survive and reproduce.
- Disappearance of native vegetation along riverbanks has increased soil erosion, degrading habitat quality.

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- Presence of pesticides, nitrates, and heavy metals in water sources leads to long-term health issues such as cancer, neurological disorders, and gastrointestinal diseases.
- Industrial waste dumping near water intakes increases the cost and complexity of water purification for urban areas like Ahmedabad and Gandhinagar.

Socio-Economic Conflicts and Water Inequality

- Displacement of local communities due to riverfront development and urbanization.
- Water shortages for farmers due to excessive diversion for urban and industrial purposes.
- Marginalized communities and informal settlements often receive the lowest priority in water distribution, leading to inequalities in access to clean water

Inefficient Water Management and Policy Gaps

- Unequal water allocation prioritizes urban and industrial needs over rural and agricultural demands.
- Lack of proper enforcement of pollution control measures allows industries to discharge untreated wastewater.
- Weak monitoring of groundwater extraction contributes to unsustainable water use.
- Failure to implement decentralized water management strategies, such as rainwater harvesting and localized wastewater treatment, leads to inefficient resource utilization.

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- Development of **urban infrastructure, public spaces, and green zones** along the river.

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- Implementation of **drip irrigation** to reduce agricultural water demand.

□ Public Awareness and Community Engagement:

- **Clean Sabarmati Campaigns** to educate the public on pollution control.
- Involvement of **NGOs and research institutions** in conservation projects.

c. Key Stakeholders and Partnerships

- **Government Agencies:**

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- **Research and Scientific Institutions:**
 - Indian Institute of Technology (IIT) Gandhinagar – Provides research on water quality and climate resilience.
 - Gujarat Ecological Education and Research Foundation (GEER) – Works on ecological restoration.

III. Outcomes and Impact

a. Environmental Benefits

- **Improved Water Flow and Quality:**
 - Inter-basin transfer has ensured a steady water supply in the Sabarmati River.
 - Reduction in industrial and sewage pollution in key river sections.
- **Ecosystem Restoration:**
 - Revival of riparian vegetation and aquatic biodiversity.
 - Protection of wetlands and urban lakes linked to the river system.

b. Social Benefits

- **Improved Public Spaces and Livelihood Opportunities:**
 - Sabarmati Riverfront has become a major recreational and tourism hub.
 - Enhanced employment in urban development, tourism, and river conservation projects.

- **Better Water Security for Urban Areas:**

- Ahmedabad and Gandhinagar have gained reliable drinking water sources.
- Increase in awareness and community participation in water conservation.

c. Economic Benefits

- **Growth in Eco-Tourism and Urban Development:**

- Riverfront development has attracted real estate investments and commercial growth.

- **Enhanced Agricultural Productivity:**

- Improved water availability has benefited farmers along the basin.

- **Cost Savings in Water Treatment:**

- Pollution control measures have led to lower water purification costs.

IV. Lessons Learned and Recommendations

a. Key Takeaways from the Project

- Integrated river basin management is essential for sustainable water resources.
- Effective policy enforcement and monitoring play a crucial role in pollution control.
- Community participation enhances project sustainability.
- Inter-basin water transfers can help sustain rivers with limited local water sources.
- Strict pollution control measures are necessary to maintain river health.
- Urban planning must balance development and ecological conservation.
- Groundwater recharge strategies need to be prioritized to reduce dependence on external water sources.

b. Best Practices and Strategies for Replication

- Developing riverfronts as eco-friendly public spaces
- Encouraging industries to adopt zero liquid discharge systems
- Strengthening wastewater treatment infrastructure in urban areas
- Implementing continuous water quality monitoring systems

c. Areas for Further Improvement or Research

- Assessing long-term ecological impacts of riverfront development
- Enhancing flood management strategies
- Exploring advanced water treatment technologies
- Strengthening transboundary water governance with Rajasthan
- Reducing dependency on Narmada water by increasing local rainwater harvesting
- Enhancing sewage treatment capacity to ensure 100% wastewater recycling
- Restoring lost wetlands to enhance natural flood control and biodiversity conservation
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Tapi River Basin

Case Study Overview

Basin Overview

The Tapi River also known as Tapi is one of the leading rivers of Central India. Though geographically and historically important, a river like this remains less renowned than some other famous rivers in the region, such as the Narmada or Godavari; hence, it has been named the “Forgotten River.” Consequently, passing through the states of Madhya Pradesh, Maharashtra, and Gujarat, the Tapi River has maintained communities and industries along its banks for centuries. Many of its waters feed into agriculture, irrigation, and hydropower as a source of regional economies and biodiversity. The Tapi River is the second largest westward draining interstate river of the Peninsula. It originates near Multai reserve forest in Betul district of Madhya Pradesh at an elevation of 752 m. The total length of the river from origin to outfall into the Arabian Sea is 724 km. For the first 282 km the river flows in Madhya Pradesh, out of which 54 km forms the Common boundary with Maharashtra State. It flows for 228 km in Maharashtra before entering Gujarat. Traversing the length of 214 km in Gujarat, the Tapi River joins Arabian Sea in the Gulf of Cambay after flowing past the Surat city. The river receives tidal influence for a length of about 25 km upstream from the mouth and its important tributaries are the Suki, the Gomai, the Arunavati and the Aner which joins it from right and those joining from left are the Vaghur, the Amravati, the Buray, the Panjhra, the Bori, the Girna, the Purna, the Mona and the Sipna. The Purna and the Girna, the two important left bank tributaries together account for nearly 45 percent of the total catchment area of the Tapi River.

It covers a large area in the State of Maharashtra besides areas in the states of Madhya Pradesh and Gujarat. The Tapi Basin is the northern-most basin of the Deccan plateau and is situated between latitudes 20° N to 22° N approximately. The basin extends over states of Madhya Pradesh, Maharashtra and Gujarat having an area of 65,145 Sq.km out of which nearly 80 percent area lies in Maharashtra state. It lies between 72°33' to 78°17' east longitudes and 20°9' to 21°50' north latitudes. Situated in the Deccan plateau the Satpura range forms its northern boundary whereas the Ajanta and Satmala hills form its southern extremity. Mahadeo hills form its eastern boundary. The basin finds its outlet in the Arabian Sea in the west. The entire Tapi basin can be divided in three sub-basins: Upper Tapi Basin up to Hatnur confluence of Purna with the main Tapi (29,430 sq. km)], Middle Tapi Basin from Hatnur up to the Gidhade gauging

site (25,320 Sq. km), and Lower Tapi Basin from the Gidhade gauging site up to the sea (10,395 Sq. km). The annual rainfall for the upper, middle, and lower Tapi basins for an average year is 935.55 mm, 631.5 mm, and 1,042.33 mm respectively.

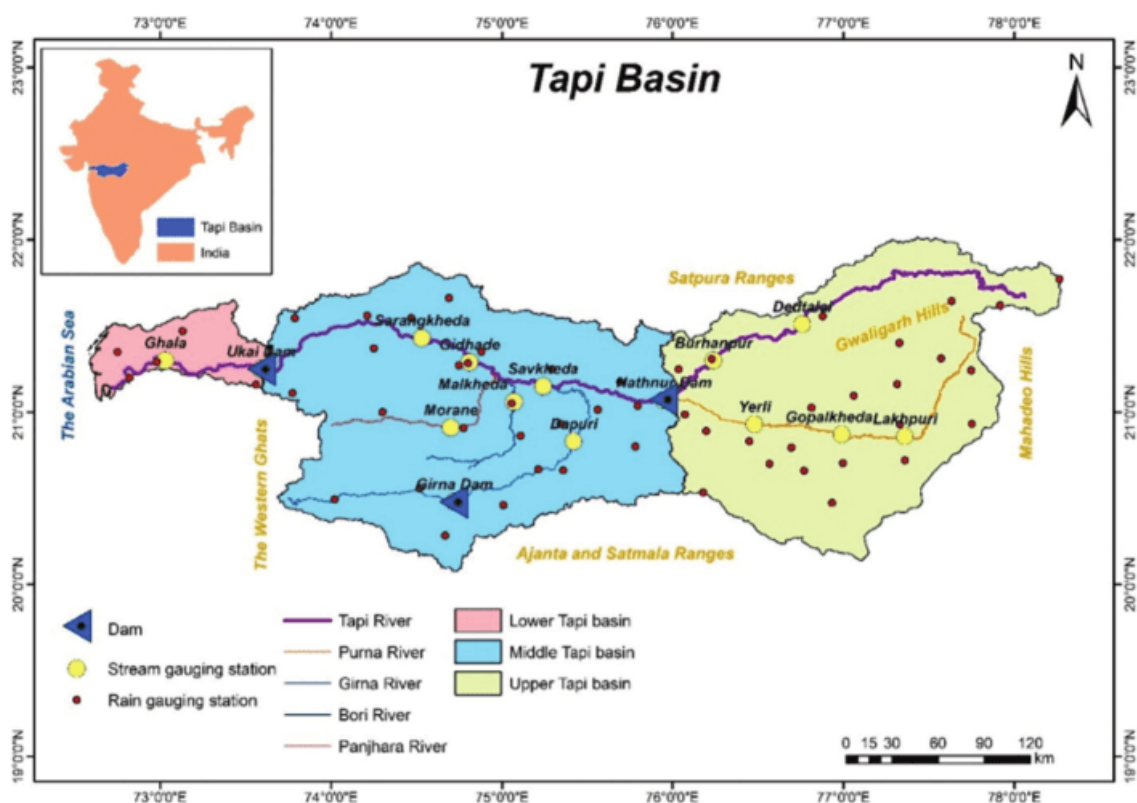


Figure 1. Index Map of Tapi river Basin

Source: [*Climate Change-Sensitive Water Resources Management*](#)

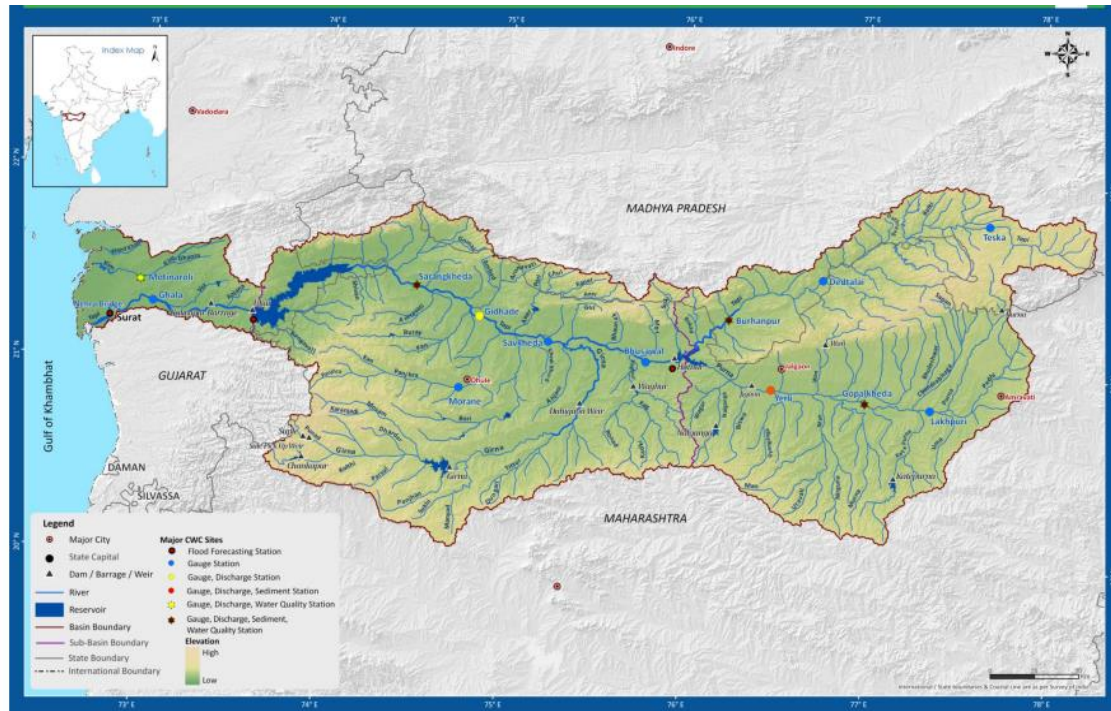


Figure 2. Drainage and Sub basin Map of Tapi Basin

Source: <https://indiawris.gov.in/downloads/Tapi%20Basin.pdf>

Problem Statement

The **Tapi River Basin** faces multiple management and environmental challenges due to rapid urbanization, industrial expansion, and agricultural activities. Issues such as water pollution, declining groundwater levels, habitat degradation, and seasonal water scarcity have significantly impacted the basin's ecological health and water security. Effective management strategies are essential to address these challenges and ensure the sustainable use of water resources in the region.

- **Pollution:**

Tapi River in Gujarat faces moderate pollution due to industrial waste, domestic sewage, and agricultural runoff. Key water quality parameters such as high turbidity, elevated pH, low DO, and increased BOD & COD exceed permissible limits, posing environmental and health risks. *(Monika Dubey and N.C. Ujjania, 2013).*

- **Religious Activities:**

Idol immersion during Ganesh Chaturthi affects the water quality of the Tapi River, leading to significant changes in key physico-chemical parameters such as pH, DO, BOD, COD, and total solids. While these changes remain within BIS standard limits, they indicate potential environmental stress. Public awareness campaigns have helped mitigate the impact, but continued efforts are necessary to further reduce pollution and protect the river's ecological balance. *(Kinjal Sangani and Kapila Manoj, 2017)*

- **Flooding:**

The Lower Tapi River Basin (LTRB) is increasingly vulnerable to flood risk due to rapid urbanization and climate change. Identifying key contributing factors such as topography, rainfall, land use, and population density is essential for understanding and assessing flood hazards and vulnerabilities in the region. *(Vishal Chandole, 2024)*

- **Environmental Flow requirements:**

The Lower Tapi Basin faces challenges in maintaining environmental flows, which are crucial for preserving the river's ecological integrity. Ensuring adequate water flow in the river is essential to prevent ecosystem degradation and balance competing water demands. *(Jaini Umrigar, 2023)*

- **Socio-Economic Conflicts and Water Inequality:**

The Tapi River Basin faces significant socio-economic and environmental challenges, including water resource disparity, unplanned irrigation leading to groundwater stress, industrial pollution, and soil and bank erosion. While some rivers experience excess runoff, others suffer from severe

water scarcity, exacerbating regional inequalities in water availability. Unregulated industrial discharge further deteriorates water quality, impacting agriculture and livelihoods. A lack of scientific evaluation and planned management hampers sustainable socio-economic development in the region. *(Alpa Sridar, 2018)*

- **Seasonal Flow issues:**

The Tapi River, spanning approximately 724 kilometers through the Indian states of Madhya Pradesh, Maharashtra, and Gujarat, exhibits significant seasonal flow variations. During the monsoon season, the river experiences substantial flow, often leading to flooding. However, for the majority of the year, especially during the dry seasons, the river's flow diminishes considerably, sometimes resulting in sections of the river running dry. *(Saubhagya Kulavi, 2024)*

Project Description

Goals and Objectives

The Tapi River Basin Management focuses on:

- ✓ Assess and mitigate pollution from industrial waste, domestic sewage, and agricultural runoff.
- ✓ Identify flood-prone areas and implement effective flood management strategies.
- ✓ Ensure adequate environmental flow to sustain river ecosystems and biodiversity.
- ✓ Study seasonal flow variations and implement measures for year-round water availability.
- ✓ Enhance public awareness and stakeholder participation in river conservation efforts.

Strategies and Interventions

Tapi River Flont Development Project:

The primary focus of TRDRP is to strengthen the river edge against flood risk through a combination of riparian banks and engineered banks for a total length of 65.81 km (includes both sides). Additionally, the project aims to clean the river water through aeration systems, fulfil the water requirement for which people would otherwise depend on ground-water, provide universally accessible open spaces, and strengthen the road network.

Key stakeholders and Partnerships

Several government and community-led initiatives have been implemented in response to the need to protect the river's environment:

River Clean-Up Drives: Local authorities have begun preparing measures to reduce pollution and raise awareness among businesses and residents about the importance of sustainable water use.

Ukai Dam Management: Enhanced control practices at the Ukai Dam aim to optimise water releases, minimise the impact of floods, and ensure a steady water supply for agriculture and enterprise.

Afforestation Programs: Planting trees alongside the riverbanks reduces soil erosion and promotes groundwater recharge, thereby mitigating floods.

Community Participation: NGOs and local communities actively monitor water quality and promote conservation through education programmes.

Government Agencies

[Surat Municipal Corporation, Tapi River Front Development Corporation Limited.](#)

Objective: To enhance urban flood resilience along the Tapi River in Surat and strengthen the institutional and financial capacity of Surat Municipal Corporation.

[Surat Municipal Corporation, India.](#)

Objective: Ensure long-term water security, prevent pollution and salinity ingress, improve groundwater quality, and mitigate flooding in Surat. Enhance urban mobility, develop recreational facilities, promote wastewater recycling, and reduce pollution while generating revenue.

[India- EU Water Partnerships.](#)

Objective: To develop Tapi River Basin Management Plan which is adopted by the Tapi River Basin Committee.

Research and Scientific Institutions

[National Institute of Hydrology \(NIH\)](#)

Objective: Conducts hydrological and environmental flow assessments in the Tapi Basin.

[Central Water and Power Research Station \(CWPRS\)](#)

Objective: Studies river hydraulics, sediment transport, and flood control in the Tapi river.

[Gujarat Ecological Education and Research \(GEER\) Foundation](#)

Objective: Focuses on ecological and biodiversity studies in the Tapi Basin.

Outcomes and Impact

The successful implementation of strategic interventions in the Tapi River Basin will lead to transformative environmental, social, and economic benefits. By improving water management, reducing pollution, and enhancing infrastructure, the basin will witness a revitalized ecosystem, improved quality of life for local communities, and sustainable economic growth. The key outcomes and impacts can be categorized into three major areas: environmental, social, and economic benefits.

Environmental benefits

Enhanced Water Quality: Initiatives to reduce industrial pollution and manage sewage have led to

improved water quality, benefiting aquatic ecosystems.

Biodiversity Conservation: Efforts to address environmental challenges, such as pollution and habitat degradation, have contributed to the preservation of the river's ecological health.

Social Benefits

Improved Public Health: Cleaner water sources have reduced waterborne diseases, enhancing the health and well-being of communities along the river.

Recreational Opportunities: Development projects have created public spaces along the river, providing areas for leisure and community activities.

Economic Benefits

Agricultural Productivity: The fertile plains along the Tapi River support agriculture, shaping the economic landscape of the areas it flows through.

Urban Development: Projects like the Tapi Riverfront Development have revitalized urban areas, attracted tourism and boosted local economies.

Lessons Learned and Recommendations

Key Takeaways

Pollution Control Measures – Strengthening industrial and sewage treatment to maintain river water quality.

Flood and Drought Resilience – Implementing adaptive strategies to mitigate seasonal flow variations and climate change impacts.

Community Participation – Encouraging local involvement in conservation efforts through awareness and public engagement.

Sustainable Agriculture – Promoting efficient irrigation methods to reduce water stress in agricultural regions.

Policy and Governance Strengthening – Enforcing regulations to prevent illegal water extraction and ensure equitable water distribution.

Best Practices and Strategies for Replication

Riverfront Development and Urban Planning – Expanding sustainable riverfront projects to improve water quality and urban aesthetics.

Community-Led River Conservation – Encouraging local participation in pollution control and watershed management programs.

Water Resource Optimization – Implementing efficient irrigation techniques like drip and sprinkler systems to reduce water wastage.

c. Areas for Further Research and Improvement

Climate-Resilient Water Management – Studying the impact of changing rainfall patterns on water availability and floods.

Strengthening Transboundary Water Governance – Enhancing coordination between Madhya Pradesh, Maharashtra, and Gujarat for equitable water sharing.

Advanced Monitoring and AI-Based Forecasting – Expanding real-time water quality and flow monitoring using IoT and AI technologies.

Controlling Emerging Contaminants – Investigating microplastics, heavy metals, and pharmaceutical residues in the river ecosystem.

Conclusion

Though overlooked or overshadowed by the glittering plumes of more famous rivers, the Tapi River is an integral part of the rich history and culture of Central India. The geographical and historical landscape of India has seen various roles played by it, from ancient trade routes to Mughal period settlements and modern agriculture. The river is now, however, still under increasing environmental challenges such as pollution, water scarcity, and loss of biodiversity pointing to the urgency of preservation efforts.

Among the initiatives developed to restore its ecological balance are the construction of the Ukai Dam and several cleanup programs. However, restoring the Tapi would require a two-way approach from the governments, industries, and local communities in handling the issues confronting it. The river evolved from a historically important waterway to a modern-day lifeline for agriculture and industry as the priorities of the places it passed through changed.

The story of the Tapi reminds humankind of this fragile relationship between the development of humanity and nature. The motivation to sustain such practices would continue the lifelines of millions while preserving cultural and ecological significance for future generations. With constant effort and community participation, the Tapi will regain its importance as something more than an ignored river-it will be rediscovered as a veritable lifeline for the development of Central India as a whole.

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Vaigai Basin

I. VAIGAI BASIN - OVERVIEW

a. BACKGROUND AND LOCATION

The Vaigai river rises on the Eastern slopes of the Varushanadu hills at an elevation of 1200 m above mean sea level near Kottaimalai in Madurai district at North latitude 9° 32' and East longitude 77° 23'. It flows in the Northerly and North-Easterly directions up to its confluence with the Varahanadhi and then takes a turn towards the East and South-East to flow through Madurai, Sivagangai and Ramanathapuram districts. After traversing for about 258 km, the river Vaigai discharges into Ramnad big tank and some other tanks. The surplus water from the tanks finally discharges into the Palk Bay near Mandapam (India WRIS). The Location of the Vaigai basin is mentioned in figure 1. Geographically, the Vaigai river basin stretches between 9° 15' to 10° - 20' North latitude and 77° 10' to 79° 15 East longitude. The average rainfall is about 850 mm. The basin covers an area of about 7009.13 sq.km and is surrounded by Cauvery and Pambar Kottakaraiyar basins in the north, Gundar basin in the south, west by Periyar basin and east by Bay of Bengal. The length of the basin is about 289.59 km and the width varies from 15 to 55 km. Since the basin is situated in the rain shadow area of the Western Ghats, it receives very little rainfall during the South-West monsoon in the hilly region.

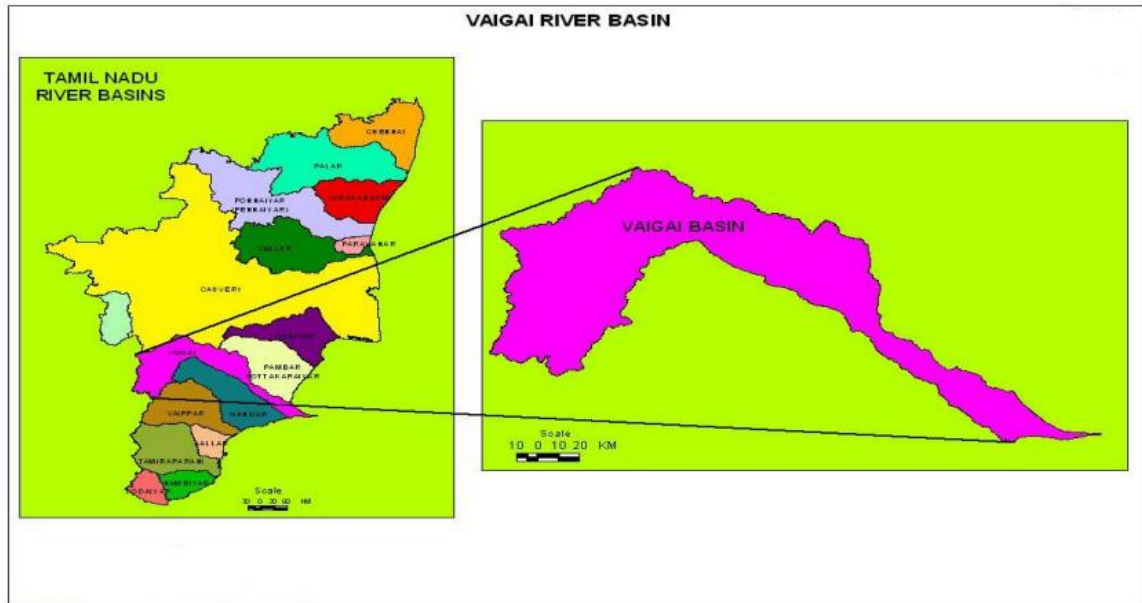


Figure 1 Location of Vaigai Basin
(Source : National Water Mission)

This basin is divided into 10 sub basins as Upper Vaigai Sub basin, Suruliyar, Theniar, Varattar-Nagalar, Varahanadhi, Manjalar-Marudhanadhi, Surumalaiyar, Sathiyar, Uppar and Lower Vaigai. The major Water resources projects in Vaigai river include Parthibanur Regulator, Vaigai Dam and Virahanur Regulator. The drainage map of the Vaigai basin is given in figure 2.

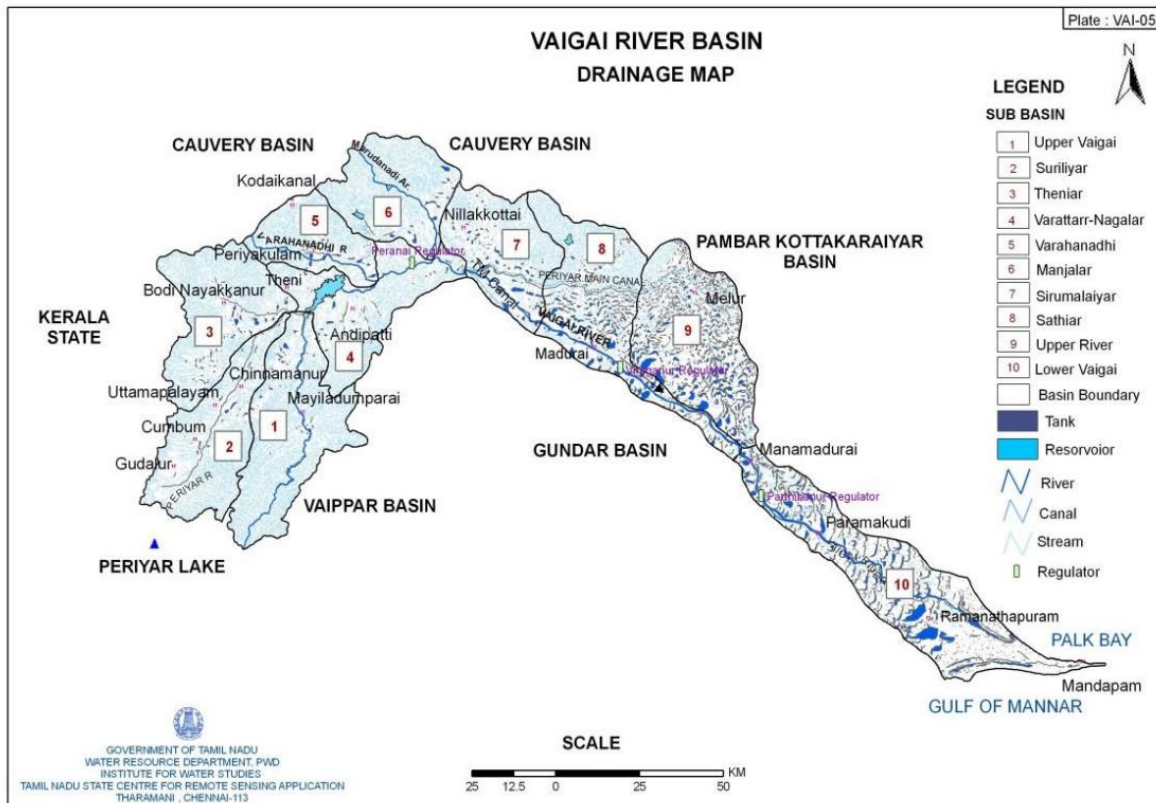


Figure 2 Drainage map of Vaigai Basin

(Source : National Water Mission)

b. MANAGEMENT AND ENVIRONMENT CHALLENGES

Since the basin contains approximately 60% agricultural land (Venkatraman, V., Selvan, E.P. and Chandran, S., 2014) the major source of pollution is due to domestic waste and improper waste management practices.

1. WATER POLLUTION

A study was carried out to evaluate the extent of pollution of groundwater in and around the Vaigai River and to analyze the toxic effect of sewage water and solid wastes in drinking water. The physico-chemical analysis of water in the river as well as the groundwater sources around the river revealed that the turbidity and TDS was high, which indicated that the water cannot be used for drinking purposes. The electrical conductivity, the total hardness, and the high chloride value in the groundwater sources revealed that the water cannot be used for human consumption (Jesu, A., Prabudoss Kumar, L., Kandasamy, K. and Dheenadayalan, M.S., 2013).

Waste from 5 districts found polluting Vaigai (THE TIMES OF INDIA 13 November

2024)

The Madurai Nature and Cultural Forum (MNCF) had conducted a study on Vaigai river and found out that the higher levels of pollution in Vaigai river is due to improper discharge of domestic and industrial waste at 177 locations across five districts. 197 pipes and canals connecting to the river were identified and water samples were tested which indicated alarming contamination, with all samples classified below D-grade water quality, recommended only for agricultural and industrial purposes. Some of the samples were also ranked as E-grade indicating its suitability only for industrial use. Unchecked domestic, industrial and medical waste that were being directly dumped into the river due to inadequate sewage systems were the major reasons for the pollution.

2. INDUSTRIAL EFFLUENT

A study was carried out on physicochemical and biological characteristics of Vaigai river water and its suitability for drinking and irrigation purposes was found out from water samples collected from five sampling sites. The result indicated that most of the parameters in Vaigai Dam and Kunnur lie within the permissible limits, whereas in Anaipatti sampling point parameters such as temperature, electrical conductivity, suspended solids, total solids and magnesium were found to be higher than the World Health Organisation and Bureau of Indian Standards permissible limit (Karuppaiah, K.P. and Ramesh, U., 2016).

As Vaigai gets dirtier, civic body takes a relook at its waste disposal setup (THE HINDU 30 August 2018)

About 600 tonnes of waste that were generated in Madurai was dumped at a 110-acre landfill in Vellakkal. It was observed that the garbage was hardly ever segregated into biodegradable and non-biodegradable. The disposal of waste in the North Bank of Vaigai river is shown in figure 3. 250 new waste collection vehicles were introduced and a total of 23 new micro composting centres had been identified by the local body to promote the concept of decentralised waste management.



Figure 3 North Bank of Vaigai River

(Source: The Hindu)

3. UNTREATED SEWAGE

An analysis of Vaigai River water quality in seven locations was carried out to determine the physical and chemical characteristics of water. Seven sampling sites were selected. The results indicated that the high conductivity in some of the samples was due to the prolonged and extensive agricultural practices. Total dissolved solids and Electrical conductivity were found moderate in all sites except Teppakulam. Teppakulam recorded maximum in total dissolved solids, Electrical conductivity, hardness, alkalinity, Calcium, Magnesium and Iron. The surface running water was contaminated at Arapalayam, Goripalayam and Teppakulam due to anthropogenic activity (Mallika, S., Umamaheswari, R. and Krishnamoorthy, S., 2015).

Quiet flows sewage into Vaigai (THE HINDU 18 January 2018)

All kinds of wastes such as garlands, plastic bottles, leftover food and used clothes were seen dumped on the river bank. According to a reliable source in the Pollution Control Board, the Government Rajaji Hospital did not treat the medical waste and pumped them into the river. Water (five lakh litres) was allegedly pumped from the State-run hospital into the river. Animal wastes were seen everywhere near Sellur. The pollution of the river due to improper waste disposal is shown in figure 4. Dumping of Untreated sewage causes several risks including threats to public health, water contamination and soil degradation.



Figure 4 Vaigai River pollution near Ismailpuram

(Source: The Hindu)

II. PROJECT DESCRIPTION

a. GOALS AND OBJECTIVES

Based on the current Environmental Challenges, the following goals and objectives can be cited:

1. Restoration of river water quality by significantly reducing the discharge of industrial effluents and untreated sewage.
2. Implementation of proper waste management practices thereby improving sanitation and environment health.
3. Promoting sustainable land use practices along the riverbank to protect the ecological balance.
4. Implementation of proper water management practices to maintain reliable and clean water supply for agricultural, domestic, and industrial use.

b. STRATEGIES AND INTERVENTIONS

1. Vaigai Reservoir Medium Irrigation Project

The Vaigai Reservoir Medium Irrigation project was carried out to provide an irrigation facility to a large area of agricultural land, ensuring year-round water supply for farming, especially during the dry season. Vaigai dam as shown in figure 5, was constructed under this project.



Figure 5 Vaigai Dam

(Source: The Hindu)

2. TN IAMWARM Project in Theniar Sub basin

The World Bank Supported TN IAM (Tamil Nadu Irrigated Agriculture Modernisation) Project was a follow up of IAMWARM (Irrigated Agriculture Modernisation and Water-Bodies Restoration and Management) Project and it focused on improving water use efficiency, enhancing yields and productivity of agriculture. The main objective of TNIAMP was to improve irrigation and water management, covering both supply and demand aspects, increase market opportunities for farmers and agro-entrepreneurs in the sub basin. Rehabilitation and Modernisation of canals and tanks, Bund strengthening was carried out in the sub basin (TN IAM - PROJECT).

c. KEY STAKEHOLDERS AND PARTNERSHIPS

1. DHAN Foundation
2. Tamil Nadu River Retrieval Movement (TNRM)
3. Madurai Corporation
4. Public Works Department (PWD)
5. Kadai Madai Farmers Association (KAFA)

III. OUTCOMES AND IMPACT

a. ENVIRONMENTAL BENEFITS:

1. DHAN Foundation:

Development of Humane Action (DHAN) Foundation, an NGO and nonprofit organization in Madurai, has a separate institution namely the 'DHAN Vayalagam (Tank) Foundation

(DVTf)'for carrying out the restoration works in Vaigai river. The main objective of the program was to clean the Vaigai river, carry out the study of water quality, increase the public awareness and to develop community participation. The Foundation aimed to restore water quality and access water through tank-based watershed development supporting agriculture needs. DHAN was also engaged in programs to clean the Vaigai River as shown in figure 6, from waste dumping and contaminants. They also worked on enhanced water management, tank-based watershed development and created access to drinking water (Earth Celebrations).



Figure 6 Vaigai River Restoration

(Source: The Hindu)

b. SOCIAL BENEFITS:

1. Vaigai River Restoration Pageant & Project:

The Vaigai River Restoration Pageant Project was launched on October 2, 2014 in Madurai to engage the local community, raise public environmental awareness as shown in figure 7, and to mobilize direct action and restore the water quality, species, habitats and health of the River. The project applied Felicia Young's methodology (Earth Celebrations). The main objectives of the project include :

1. Mobilize public support to effect policy change to restore the Vaigai river and mitigate pollution, waste dumping and drying effects of climate change.
2. Build a coalition effort engaging government officials, cultural organizations, academic institutions and community people to work together to implement solutions.
3. Incentivize the community to keep the river clean and not to dump waste through education, workshops and awareness campaigns.
4. Inspire action on these issues through creative strategy utilizing local arts and cultural heritage to effect environmental, political, cultural and social transformation.



Figure 7 Members of Vaigai River Restoration Project taking out a rally
(Source: The Hindu)

2. Environmental & Art Workshops: January — April 2015:

An educational workshop series was built for community engagement and awareness of the Vaigai River for 3 months leading up to the culminating Vaigai River Restoration Pageant. Community participants work with artists-in-residence to create giant mobile sculptures, puppets, costumes, visual artwork, and performances. A total of 20 workshops were led by local artists to engage community participants and students (Earth Celebrations).

3. Asia Initiatives:

Asia Initiatives, a non-profit organization, was involved in a project to restore the Vaigai River and primarily focused on raising awareness about the river's environmental crisis through a "Vaigai River Restoration Pageant Project" (Earth Celebrations). The Project raised awareness to mitigate the severe environmental crisis of pollution and contamination of a major natural water resource and to counter the effects of climate change including:

- Household waste and sewage dumping.
- Industrial and chemical pollutants flowing into the river.
- Sand mining the riverbed.
- Issues of dam control and water releases.
- Lack of drainage and sanitation infrastructure.
- Restoration and expansion of water storage tanks for agricultural irrigation and drinking water.
- Improvement of the water quality from contaminants for healthy drinking water which the community depends on for survival.

- Building environmental awareness and community engagement in river restoration efforts.

c. ECONOMIC BENEFITS:

National River Conservation Plan:

Under National River Conservation Plan (NRCP), the sewage outfall from the towns into the rivers Cauvery, Vaigai and Tamiraparani was intercepted, collected and treated in Sewage Treatment Plants and the treated water was let into the river. The core works in Madurai was taken up at an overall project cost of Rs.165.00 crore during the year 2007. Interception & Diversion works and Pumping stations (Phase I & II) were done by Chennai Metro Water Supply and Sewerage Board and the works were completed (NRCP, Government of Tamil Nadu). Construction of the Sewage Treatment Plant was completed by Madurai Corporation with Jawaharlal Nehru National Urban Renewal Mission (JNNURM) funding (Department of Environment and Climate Change, Government of Tamil Nadu).

IV. LESSONS LEARNED/ RECOMMENDATIONS

a. KEY TAKEAWAYS FROM THE PROJECT:

Regular river cleanup: River cleaning programs should be organized for volunteers, government officials and local communities to work together regularly to remove waste from the river.

b. BEST PRACTICES AND STRATEGIES FOR REPLICATION:

Collaboration with Educational Institutions: Schools and colleges students are involved in awareness efforts thereby educating their families and neighbors about the importance of keeping the river clean.

Awareness Campaign: Raising Awareness and Community engagement to tackle the river pollution

c. AREAS FOR FURTHER IMPROVEMENT:

Industrial effluent monitoring: Regularly monitor industrial effluents to ensure compliance with discharge standards.

Improvement in Collection and Segregation of waste- Proper collection of waste from

door to door has to be done on a regular basis.

Enforcement of pollution control laws- Enforcing strict penalties and fines for industries and individuals that are found polluting the river by dumping waste, untreated sewage, or industrial effluents.

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Conclusions

Summary and Major Takeaways

Across India's diverse river basins—from the massive Ganga–Brahmaputra–Meghna system and the ecologically and culturally significant Narmada to the dynamic Brahmaputra, Barak, and Pennaiyar basins—the overarching challenge is to balance rapid economic development with the need to protect and restore ecological health. The document highlights that while each basin exhibits unique characteristics, common themes emerge: the critical role of integrated water resource management, the importance of robust data collection and early warning systems, and the necessity of engaging local communities in decision-making. For policymakers, the major takeaway is that addressing issues such as pollution, flood management, groundwater depletion, and transboundary conflicts requires a coordinated, multi-stakeholder approach that leverages both modern technologies and traditional practices. This approach must be supported by clear, enforceable regulatory frameworks and dynamic governance mechanisms that are sensitive to regional disparities and local needs.

Best Practices, across basins

- Promotion of community-based management models that integrate local traditional knowledge with modern water management practices.
- Implementation of environmental flow assessments and decentralized wastewater treatment facilities to enhance water quality and ecological health.
- Fostering strong partnerships among governmental agencies, research institutions, and NGOs to share data, resources, and best practices.
- Utilizing integrated hydrological models that incorporate climate change scenarios and land-use dynamics for planning and decision-making.
- Establishment of automated and decentralized data collection systems (e.g., automated weather stations, real-time hydro-observation points) to improve forecasting and timely response.

Comparison of major issues across basins

Pollution and Water Quality: While basins such as the Ganga face severe industrial and municipal wastewater challenges, others (e.g., Barak) contend with agricultural runoff and industrial effluents, leading to ecosystem degradation and public health risks.

Flooding and Sedimentation: The Brahmaputra and Barak basins exhibit frequent flooding and rapid sediment erosion, adversely impacting agriculture and displacing communities, whereas basins like the Narmada require careful floodplain management due to limited natural flows.

Groundwater Depletion: Overextraction is a significant problem in basins like Sabarmati and Pennaiyar, where excessive groundwater withdrawal for urban and agricultural use is rapidly diminishing water tables.

Transboundary and Interstate Conflicts: Basins that cross state or national boundaries, such as the Brahmaputra and parts of the Narmada system, face unique challenges related to data sharing, water allocation, and cooperative governance.

Biodiversity Loss and Ecosystem Degradation: Each basin faces threats to its native flora and fauna, necessitating focused conservation efforts, as seen in the cases of declining fish stocks in the Ganga and habitat fragmentation in the Barak Valley.

Policy learnings

The collective experience from India's river basins underscores several broad policy imperatives. First, an integrated river basin management (IRBM) framework is essential—one that brings together cross-sectoral data, encourages inter-state and transboundary cooperation, and integrates local community voices into the decision-making process. Policy frameworks must be adaptive, enabling rapid responses to the dual challenges of climate change and increasing human demand. Emphasis on decentralization and community-based monitoring can help tailor solutions to regional nuances, while robust legal instruments and enforcement mechanisms are required to ensure compliance with environmental standards. Finally, public-private partnerships and sustained investment in research and technological innovation are critical to building resilient water infrastructure, improving forecasting accuracy, and safeguarding ecological sustainability. These learnings advocate for a policy

landscape that is both holistic and flexible, capable of evolving with emerging challenges and opportunities across India's vast and varied river basins.

