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

Developing Protocol and Monitoring Framework for

Mahanadi River Basin

July 2025

cMahanadi

cGanga

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National River Conservation Directorate (NRCD)

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

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Centres for Mahanadi River Basin Management and Studies (cMahanadi)

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

www.cmahanadi.org

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

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Preface

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

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

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

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

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

Centre for Mahanadi River Basin
Management and Studies (cMahanadi)
NIT Raipur & NIT Rourkela

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Abbreviations and Acronyms

cMahanadi	Centre for Mahanadi River Basin Management and Studies
BCM	Billion Cubic Meters
CG	Chhattisgarh
CGL	Central Gauge Line
CWC	Central Water Commission
HEC	Hydrologic Engineering Centre
IIT	Indian Institute of Technology
MCM	Million Cubic Meters
MRB	Mahanadi River Basin
NIT	National Institute of Technology
NRSC	National Remote Sensing Centre
OD	Odisha
RAS	River Analysis System
sq.km.	square kilometer
SoI	Source of Information
SWMM	Storm Water Management Model
WRIS	Water Resource Information System

1. Summary

The report presents a comprehensive framework for effective river basin management, with a specific focus on the Mahanadi River Basin, India. It emphasizes the importance of monitoring and feedback mechanisms in generating essential data for evidence-based decision-making, policy formulation, and adaptive water management. The primary objective of the proposed monitoring protocol is to assess the status and trends in water quality and quantity, detect environmental pressures, and support sustainable planning and governance. A step-by-step approach is advocated, beginning with general assessments and progressing toward more detailed, data-intensive evaluations using advanced technologies. The framework incorporates real-time water quality monitoring systems (RTWQMS), hydrological data collection, GIS mapping, and artificial intelligence (AI) for spatial analysis and network optimization. These tools allow for ongoing monitoring of water's physical, chemical, and biological qualities, help compare current conditions, set standards to spot differences, and guide necessary actions.

In the context of the Mahanadi Basin, the report highlights the importance of long-term monitoring to evaluate the impacts of human activities and climate variability. The socio-hydrological feedback loop is emphasized, where human interventions, such as water abstraction and discharge, alter the natural hydrological cycle and vice versa. Understanding this interplay is crucial for designing adaptive management strategies that can respond to changing conditions in the basin. Institutional arrangements at both the national and transboundary levels are identified as essential prerequisites for effective implementation. The report recommends establishing River Basin Organizations (RBOs) with a three-tier structure: Council, Board, and Secretariat, to define policies, coordinate planning, and ensure execution. These bodies should be supported by robust quality control systems based on ISO and WMO standards to ensure the reliability of data and assessments.

Participatory approaches are also central to the report’s recommendations. It calls for the inclusion of diverse stakeholders, including women, Indigenous groups, and local institutions like Water Users’ Associations and gram panchayats, in the planning, operation, and monitoring of water infrastructure. The report draws from international best practices, including the Murray-Darling Basin in Australia, basin management systems in France, and River Basin Commissions in China, to propose context-appropriate models for India. Independent audits and third-party monitoring are stressed as vital for ensuring transparency, regulatory compliance, and public trust. These audits offer unbiased evaluations, identify management inefficiencies, and provide actionable recommendations to improve water governance and ecosystem health.

Modelling is presented as an indispensable tool for assessing river systems, forecasting scenarios, and optimizing monitoring networks. However, the report cautions that models must be calibrated and validated with empirical data to avoid misleading results. Pilot projects are proposed as an initial step to test methodologies, build capacity, and engage stakeholders before scaling up to basin-wide monitoring programmes. These projects should be tailored to the specific socio-political and ecological characteristics of each basin. Furthermore, the report

highlights the need for prioritizing monitoring efforts using risk-based approaches and aquifer vulnerability mapping, especially in resource-limited settings. It also identifies key government agencies, research institutions, and NGOs that can be instrumental in commissioning and supporting efforts for managing river basins based on evidence.

It serves as a strategic guide for integrating technology, participatory governance, and institutional capacity to ensure the sustainable use and management of river basin resources. The suggested plan aims to improve the strength, fairness, and environmental quality of India's river systems, especially in areas that cross borders, like the Mahanadi Basin, by using real-time monitoring, involving stakeholders, ensuring quality, and planning flexibly.

2. Introduction

The primary objective of monitoring (https://www.wef.org/resources/for-the-public/public-information/glossary/) is to generate essential information required for effective planning, informed decision-making, and efficient water management at local, national, and transboundary levels. Monitoring programmes are also vital for safeguarding human health and protecting the environment as a whole. A key component of monitoring[11] is assessment, which involves interpreting collected data to provide insights into the current condition of a water body. This process forms the foundation for identifying changes and trends that can be associated with various pressures and impacts, and subsequently linked to environmental goals or targets (Figure 1). Moreover, assessment includes evaluating boundary conditions and considering the broader social and environmental contexts that influence the state of the environment.

A critical aspect of developing an effective monitoring and assessment programme is the identification, documentation, and prioritization of the various uses and functions of surface water or groundwater basins, along with related water management concerns. The Driving Forces–Pressures–State–Impact–Responses (DPSIR) framework can serve as a valuable tool in elucidating the interconnections among diverse water management issues (Figure 1).

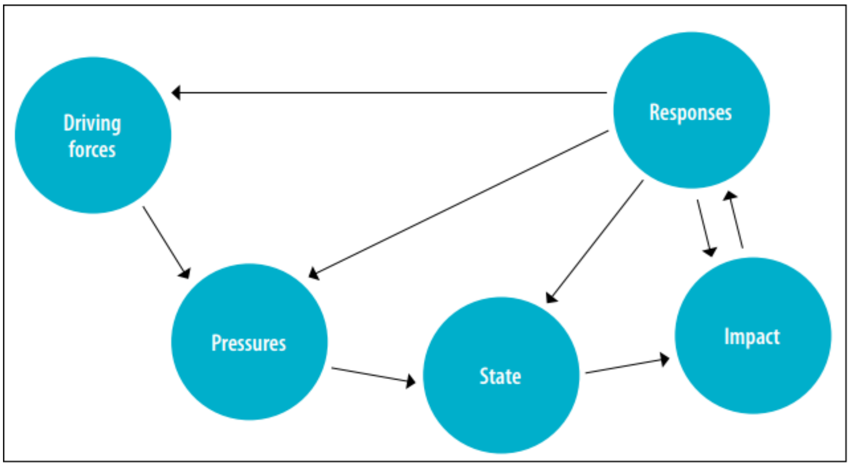

Figure 1. Driving forces-Pressures-State-Impact-Responses (DPSIR) framework (Source: EEA, 1998).

Monitoring is generally understood as the process of conducting repetitive measurements and observations for specific, predefined purposes, focusing on one or more elements of the environment. To ensure comparability over time, these monitoring activities are carried out at consistent locations, at regular intervals, and using standardized methodologies for environmental sensing and data collection.

Monitoring facilitates the assessment of the current status of water quantity and quality, including their spatial and temporal variability. These assessments often evaluate hydrological, morphological, physicochemical, chemical, biological, and microbiological conditions, including reference conditions, human health impacts, and existing or planned water uses. Reference conditions reflect the natural variability of geophysical and geochemical processes that may influence the concentration of particular variables.

One specific purpose of monitoring is to support decision-making and operational water management, particularly in critical situations. For instance, during extreme hydrological events such as floods, ice drifts, or droughts, the availability of timely and reliable hydro-meteorological data is crucial. This often necessitates the use of telemetric systems to ensure the continuous transmission of information. Similarly, reliable data are essential during pollution incidents, which may require early warning systems to alert authorities when critical pollution thresholds are exceeded or when toxic effects are detected. In such instances, decision-making can often be enhanced by using predictive models.

Given that monitoring and assessment are critical for developing sound policy actions, monitoring systems must be gender-responsive and inclusive, with accessible data and information. Identifying the factors that influence the inclusion or exclusion of women and men from various social, cultural, or ethnic backgrounds, such as Indigenous communities, and understanding how these groups interact with water resources for diverse uses can improve water resource provision, management, and conservation for the benefit of all. Ensuring the representation of diverse stakeholder groups throughout all stages of the monitoring cycle is a fundamental starting point (https://unesdoc.unesco.org/ark:/48223/pf0000367971.locale=en). Additionally, gender-disaggregated statistics are vital to highlight the circumstances, life conditions, and specific needs of both men and women (http://www.includegender.org/toolbox/map-and-analyse/gender-statistics).

In the case of transboundary waters, data are often collected through national monitoring systems, which are typically established and operated per national laws, regulations, and international agreements, rather than by joint bodies created specifically for this purpose. Therefore, national legislation, obligations under international agreements, and other relevant commitments should be thoroughly reviewed when planning to establish, upgrade, or operate such systems.

a. Overview of the Mahanadi River Basin

The Mahanadi River (Maha: mighty and Nadi: river), is one of the major inter-states, east-flowing rivers in peninsular India which originates at 442 m above mean sea level (MSL) near Pharsiya village in the Dhamtari district of Chhattisgarh. The basin lies between the geographical coordinates of 80°30’ E to 86°50’E and 19°20’N to 23°35’N. It traverses through the plains of Chhattisgarh and Odisha and further narrows down to form a large deltaic region in Puri and Cuttack of Odisha before meeting the Bay of Bengal. The total length of the river is 851 km, of which 357 km falls in Chhattisgarh and 494 km in Odisha. On its way, it is joined by major tributaries like the Seonath (Seonath), Hasdeo, Mand, Ib, and Jonk above the Hirakud dam, whereas Ong and Tel join the Mahanadi below the Hirakud dam. Rivers Seonath, Ib, and Tel together constitute 46.63 percent of the total catchment of the Mahanadi.

b. Importance of Monitoring and Feedback in Basin Management

Monitoring and feedback are crucial in basin management, as they provide data for informed decision-making, enabling the identification of issues, tracking progress, and adapting management strategies to ensure sustainable water resource use and environmental health.

A more detailed explanation of the importance of monitoring and feedback is given below:

(a) Data for Informed Decision-Making

Monitoring collects data on water quality, quantity, and other relevant parameters, providing the basis for evidence-based decisions about water resource management.

(b) Identifying Issues and Problems

Monitoring helps detect problems like pollution, water scarcity, or ecological degradation, allowing for timely interventions to address these issues.

(c) Tracking Progress and Evaluating Effectiveness

Monitoring data allows basin managers to track the progress of implemented strategies and evaluate their effectiveness in achieving desired outcomes.

(d) Adapting Management Strategies

Feedback from monitoring data allows for adjustments to management plans based on observed changes in the basin's condition, ensuring that strategies remain relevant and effective.

(e) Ensuring Sustainability

By providing insights into the health and status of the basin, monitoring and feedback help ensure the sustainable use of water resources and the protection of ecosystems.

(f) Accountability and Transparency

Monitoring data can be used to demonstrate accountability and transparency in basin management, building trust with stakeholders.

i. Importance of long-term monitoring

Long-term monitoring provides valuable insights into trends and changes in the basin's condition, helping to understand the impacts of human activities and climate change.

3. Framework for Monitoring and Feedback

a. Key Monitoring Components

A multi-faceted approach is necessary to effectively monitor and provide feedback for a river basin in India, encompassing real-time water quality monitoring, hydrological data collection, and the use of GIS and AI for analysis and optimization of monitoring networks [1, 2, 3, 4].

Here's a breakdown of key aspects:

1. Real-time Water Quality Monitoring

- **RTWQMS (Real-Time Water Quality Monitoring System):** Deploy sensor-based instruments in rivers and water bodies to continuously measure parameters such as temperature, pH, conductivity, and dissolved oxygen.
- **Data Logging and Transmission:** Store data in data loggers and transmit it to a central server via the Internet for continuous monitoring.
- **IoT Integration:** Consider using Internet of Things (IoT) technology for real-time data collection and analysis [3, 5].

2. Hydrological Monitoring

- **Water Balance:** Determine the water balance within the river basin to understand the quantity and quality of available water.
- **Hydrological Data Collection:** Collect data on rainfall, runoff, evaporation, and other hydrological parameters.
- **Interrelation Analysis:** Analyze the interrelations and aggregations of various hydrological processes

3. Data Analysis and Feedback

- **GIS Mapping:** Use Geographic Information Systems (GIS) to spatially represent collected data and identify areas with water challenges.
- **Indicator Assessment:** Choose a set of indicators to assess different water challenges in the basin.
- **Data Comparison:** Compare the current state of each indicator with the desired state to identify gaps and their causes [4].
- **AI-powered Optimization:** Apply artificial intelligence algorithms to optimize the water quality monitoring network [2].

4. Basin Reports and Planning

- **Basin Reports:** Create comprehensive basin reports that describe the present status of water resources development, including major projects, hydro-meteorological observations, and socio-economic profiles [7].
- **Top-down and Bottom-up Approaches:** Adopt both top-down (basin to site level) and bottom-up (site to basin level) approaches for planning and management.
- **Sustainable River Management:** Develop scientific approaches that blend hard and soft measures for sustainable river management [8].

5. Specific Parameters to Monitor

- **Physical Parameters:** Temperature, color, odor, specific conductivity, total dissolved solids, pH, dissolved oxygen [1].
- **Chemical Parameters:** Salinity, conductivity with TDS, CDOM/FDOM (Colored/Fluorescent Dissolved Organic Matter), Chlorophyll Fluorescence Analysis.
- **Biological Parameters:** Algae, bacteria, and other aquatic life [5].

b. Feedback Mechanism

In river basin development, feedback mechanisms involve the interconnectedness of social and natural systems, where human actions (like water intake and consumption) influence the natural water cycle (rainfall, runoff), which in turn impacts water availability and ecosystems, creating a cyclical feedback loop [9, 10, 11, 12].

Here's a more detailed explanation of these feedback mechanisms:

1. Socio-Hydrological Unit and Mutual Feedback

- **Socio-hydrological unit:** This concept highlights how social and natural water cycles interact within a specific geographical area (a river basin).
- **Social water cycle:** This includes human activities like water intake, consumption, and discharge.
- **Natural water cycle:** This encompasses natural processes like rainfall, evaporation, runoff, and confluence.
- **Mutual feedback:** The social water cycle affects the natural water cycle, and vice versa, creating a continuous feedback loop.
    - For example, social discharge in the upper stream can change the river runoff in the middle stream, affecting water availability and drainage downstream.
    - Similarly, changes in the natural water cycle, like altered runoff, can impact water availability and drainage, which in turn affect social water use [9].

2. Impacts of River Basin Development Activities

- **Water allocation and management:** Decisions about water allocation and management can have significant impacts on the natural environment and downstream users [11, 13].
- **Infrastructure development:** Dams, canals, and other infrastructure can alter natural flow regimes, impacting ecosystems and water availability [11, 14].
- **Land use changes:** Deforestation, urbanization, and agricultural practices can alter runoff patterns and soil erosion, affecting water quality and quantity [11].
- **Pollution:** Industrial and agricultural pollution can degrade water quality, harming aquatic ecosystems and human health.

3. Importance of Feedback Mechanisms in River Basin Management

- **Understanding Inter-connectedness:** Recognizing the inter-connectedness of social and natural systems is crucial for effective river basin management.
- **Predicting Impacts:** Understanding feedback mechanisms allows for better prediction of the potential impacts of development activities.
- **Developing Sustainable Solutions:** By considering feedback mechanisms, it's possible to develop more sustainable and resilient river basin management strategies [11, 13].
- **Adaptive Management:** River basin management should be adaptive, meaning that it should be able to respond to changing conditions and feedback from the system [13, 15].
- **Stakeholder Participation:** Involving stakeholders in the decision-making process is essential for ensuring that river basin management is equitable and sustainable.

c. Role of participatory monitoring in existing frameworks

Management of the water resources for diverse uses should incorporate a participatory approach by involving not only the various governmental agencies but also the users and other stakeholders effectively and decisively in various aspects of planning, design, development, and management of water resources schemes. Necessary legal and institutional changes should be made at various levels for this purpose, duly ensuring an appropriate role for women. Water Users' Associations and local bodies such as municipalities and gram panchayats should particularly be involved in the operation, maintenance, and management of water infrastructure/facilities at appropriate levels, progressively, to eventually transfer the management of such facilities to the user groups/local bodies.

The above policy provisions for the integrated development and management of water resources of a basin or sub-basin can be achieved through an organization, namely the River Basin Organization. The proposal for the establishment of River Basin Organizations has been under consideration for a long time to suggest the form and role of the basin-level organizations. Many authorities and boards have been formed in the past to accomplish specific objectives. Some models of River Basin Organizations (RBOs) being practiced in different countries are given below:

(a) Murray-Darling Basin of Australia

The model of the RBO for the Murray-Darling Basin in Australia promotes and coordinates effective planning and management for the equitable, efficient, and sustainable use of the basin's water, land, and other environmental resources. The structure of the Murray-Darling Organization consists of a Ministerial Council, a Community Advisory Committee, and a Basin Commission. The Ministerial Council is the initiative decision-making forum. The Basin Commission is the executive arm of the Ministerial Council, which advises the Council on matters related to the use of water, land, and other environmental resources of the Murray-Darling Basin and carries out its decisions. The Commission comprises a President, two Commissioners from the Contracting Government, and a non-voting representative from the Australian Capital Territory. The Community Advisory Committee provides the Ministerial Council with advice and serves as a two-way communication channel between the Council and the community.

The responsibilities of the Murray-Darling Basin Organization include water allocation of the River Murray waters to the states and administration of various key natural resource strategies. It has technical responsibility for water quality, land resources, nature conservation, and community involvement. In respect of water management, the responsibilities include regulation of the River Murray and a programme of water quality monitoring to maintain flows and water quality for a range of purposes, including supply for domestic users, livestock, and irrigation. The Commission coordinates river management to encourage appropriate land-use practices, the best practical means of waste treatment, and off-river disposal. It also has responsibility for developing programmes for the preservation of native fish and the coordination of the management of wetlands.

(b) Basin Management System in France

The basin management system in France is organized for six major hydrographic basins, which correspond to the four main catchment areas of the country and two areas of dense population and intense industrial activity. Each of the six basins has a Basin Committee and a corresponding executive agency called the River Basin Agency/Water Board. The Basin Committee, a Water Parliament, is made up of local elected authorities, users, and governmental organizations. The power of the Committee lies in drawing up a master plan for water resources management and development and coordinating river development schemes according to the Water Act, which defines the main guidelines for the implementation of rules and strategy and approves the five-year strategic plan of the River Basin Agency. The River Basin Agency, while executing the Committee’s directives, is also responsible to the central government for compliance with certain technical matters such as upholding national standards.

(c) River Basin Commissions in China

In China, there are seven large River Basin Commissions. The River Basin Commissions integrate planning, implementation, and supervision responsibilities for local, provincial, and state agencies and coordinate activities of different ministries (such as the National Environmental Protection Agency) for land and water management in the basin. The Chinese government acknowledges the need to clarify overlapping mandates and activities between ministries to modernize institutional arrangements, improve programme delivery efficiency, and increase technical capacity at all levels. The responsibilities of the River Basin Commissions are:

- To enforce the national water law on behalf of the Ministry of Water Resources and to cooperate with water departments at local levels in the implementation of the law.
- To implement water management and flood control based on the plan approved by the State Council.
- To carry out overall planning, development, utilization, and protection of water resources in the basin.
- To coordinate water-related activities between provinces and local agencies in the basin.

(d) Recommendation of the Committee constituted by MoWR

Considering various aspects and some models of existing RBOs in different countries, the Committee recommended a three-tier arrangement for RBOs, i.e., the Council, the Board, and the Secretariat.

- **Council:** The Council, under the Chairmanship of the Minister of Water Resources/Irrigation of one of the co-basin States (by rotation), would be responsible for defining the policies and guidelines. The composition of the Council shall comprise the Minister of Water Resources/Irrigation/other water-related subjects, the Leader of Opposition, MPs, MLAs of the basin states, stakeholders, Water Users Associations (WUAs), etc., from co-basin States.

- **Board:** The Board, under the Chairmanship of the Principal Secretary of Water Resources/Irrigation of one of the co-basin States (by rotation), would consider various issues and take appropriate decisions for implementation in light of the policies and guidelines framed by the Council. The River Board would comprise an equal number of representatives from all the co-basin States. The composition of the Board may include Secretaries (Water Resources/Irrigation/other water-related subjects), Chief Engineers of Water Resources Departments/Irrigation Departments (in charge of the projects in the basin), and representatives of stakeholders/WUAs.

- **Secretariat:** The Secretariat should provide technical and other inputs to the Board in discharging its functions and powers and ensure the implementation of the decisions. The constitution of the Secretariat may differ from basin to basin, given the varying issues and priorities. However, adequately staffed, the Secretariat would be multi-disciplinary and include experts from relevant disciplines.

4. Identification of issues for river-basin management

i. Multi-functional approach

Various functions and uses human and ecological of water bodies can be identified from existing policy frameworks, international conventions, bilateral and multilateral agreements, and strategic action plans for river basins and seas. These uses may compete or even conflict, particularly when water is scarce or its quality is deteriorating. A multi-functional approach seeks to strike a balance between all desired uses, including ecosystem functioning. It allows for the introduction of a hierarchy of uses and provides flexibility for different stages of water resource management policy development and for prioritization over time. This can be especially important for countries where basic needs such as the supply of safe drinking water are so urgent that other uses take lower priority, or for countries where water resources have deteriorated to such an extent that "higher" uses can only be gradually restored over a long period and in a prioritized order.

ii. Source of conflict

Water management is always faced with conflicts of interest. Most issues in a river basin are, more or less, closely linked to these conflicts. The sources of conflict are threefold:

- Competition for water (consumptive uses vs. non-consumptive uses, e.g., navigation or the river as a recipient of wastewater);
- Conflicts between human interventions and nature (and vice versa, e.g., when watercourses need to be revitalized);
- Different interests of riparian countries (e.g., upstream/downstream countries, political priorities).

In the analysis of water management issues, political priorities should be identified; analyzing the sources of conflict is a prerequisite for setting these priorities.

iii. River basin management plan

The preparation of concerted (harmonized or joint) water management plans for the transboundary river basin falls within the scope of the Convention. These plans are based on the results of existing monitoring programmes. The basic requirements for a more developed monitoring and assessment programme should be derived from these water management plans. These requirements pertain to water transfers, the intake and release of used water (uses and discharges, irrigation, and drainage of excess water), and flood protection.

They also include aspects such as land use, deforestation, erosion, and diffuse pollution of water. Preferably, they should also include an analysis of additional information needs, a strategy for tailor-made monitoring and assessment, sharing information among the riparian countries, and evaluating the effectiveness of the measures taken under these plans.

iv. Analysis of water management issues

The information needed for managing a transboundary river should be based on agreed management issues and the decision-making process in river basin management. To identify issues and priorities for the protection and use of a transboundary river, several activities are required, such as the identification of the functions and uses of the river basin, compilation of inventories based on available (and accessible) information, conducting surveys where information is lacking, identification of criteria and targets, and evaluation of the water legislation in the riparian countries (Figure 2). A well-developed international river basin management plan provides for all of these.

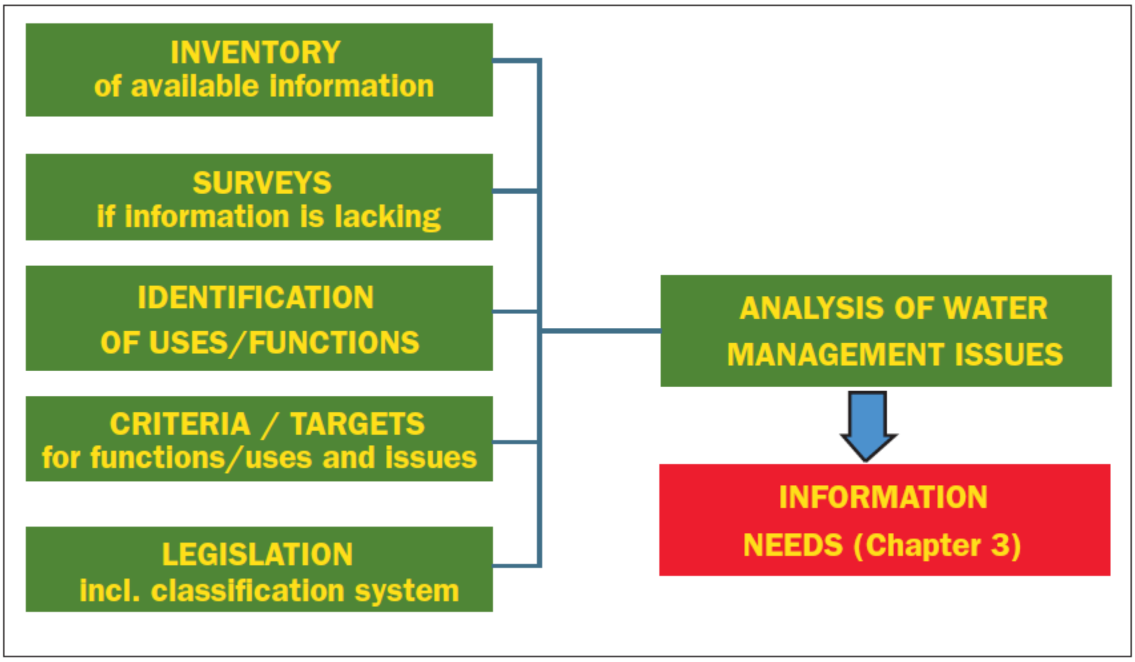

Figure 2. Procedure for identification of water management issues [16].

a. Missions under cGanga: Aviral, Nirmal, Ecological Restoration (how do we know if these are achieved

The success of the Ganga rejuvenation missions (Aviral, Nirmal, and Ecological Restoration) is assessed through monitoring water quality parameters, observing biodiversity, and evaluating the progress of related projects. For "Nirmal" (clean), water quality tests such as Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD) are crucial. For "Aviral" (continuous flow), gauging stations track river flow and discharge, and for ecological restoration, biodiversity indicators like fish populations and wildlife sightings are monitored, along with the success of afforestation and wetland restoration efforts.

Elaboration:

1. **Water Quality Monitoring:**
   - **Dissolved Oxygen (DO):** A key indicator of water health. High DO levels suggest a healthy river ecosystem, as DO is essential for aquatic life.
   - **Biochemical Oxygen Demand (BOD):** This measures the amount of oxygen consumed by microorganisms when decomposing organic matter in the water. Lower BOD indicates less pollution and better water quality.

- **Other parameters:** Water quality monitoring also includes checking for other pollutants such as heavy metals, pesticides, and pathogens.

2. **Biodiversity Monitoring:**
   - **Fish and Wildlife Sightings:** Increased sightings of species like dolphins, turtles, otters, and gharials indicate an improvement in the river's ecosystem and the presence of a healthy habitat.
   - **Fish Population Studies:** Monitoring fish populations, including the Indian Major Carps (IMC) fingerlings, helps assess the effectiveness of conservation efforts.
3. **Project Implementation and Progress:**
   - **Sewerage Infrastructure Projects:** The progress of projects like sewage treatment plants (STPs) and interception and diversion systems is monitored to ensure they function effectively and reduce pollution.
   - **Afforestation and Wetland Restoration:** The success of these projects is assessed by tracking the growth of planted trees, the restoration of wetland areas, and their impact on water quality and biodiversity.
4. **Community Participation:**
   - **Ganga Praharis:** The involvement of local communities through the Ganga Prahari initiative is monitored to ensure community engagement in river conservation efforts.
5. **Other Indicators:**
   - **Water Level and Discharge:** Monitoring water levels and discharge rates helps determine if the river flow is maintained, which is crucial for the "Aviral" aspect.
   - **Riverfront Development:** Assessing the impact of ghats and riverfront development projects on river connectivity and the protection of sociocultural and religious importance.

b. Identification of issues

i. Core elements in water management

The need for information should be based on the core elements in the management of a river basin and the active use of information in the decision-making process. These elements can be defined as the functions and uses of the river, the issues (where criteria for use and functioning are not met), and the measures with their specific targets and impacts on the overall functioning of the river basin (Figure 3).

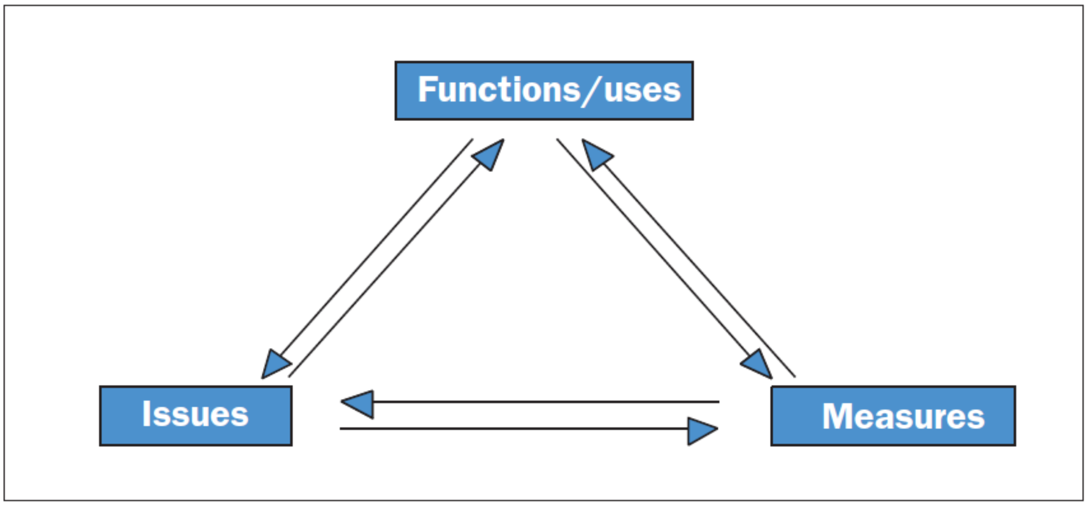

Figure 3. Core element in water management [16].

5. Establishing the Institutional Framework

a. Institutional arrangements at the national level

Effective institutional arrangements at both national and local levels are essential prerequisites for the monitoring and assessment of transboundary waters. Such arrangements facilitate cooperation among governmental entities, the private sector, and other stakeholders. When establishing these frameworks, it is important to recognize that the responsibility for monitoring and assessing groundwater, particularly in terms of water quality and quantity, may fall under geological survey organizations rather than environmental or water agencies. On the other hand, environmental agencies often provide critical data on ecological and biophysical parameters of water bodies, including ecological status, biodiversity, hydro-morphology, land degradation, and waste. Therefore, significant attention must be given to capacity development for all individuals involved in these processes.

At the national level, coordination of monitoring and assessment activities is a key requirement for achieving effective and efficient water management. This necessitates collaboration among various organizations engaged in water management, including river basin agencies. Furthermore, cooperation among water, environmental, and health authorities is crucial to ensure the collection and application of data relevant to human health and safety.

Hydro-meteorological services play a vital role by supplying data on water quantity and providing early warning information for extreme hydrological events. Organizations responsible for emergency response systems, particularly those involving water regulation structures and industrial facilities, are also important contributors, as they help mitigate the adverse impacts of failures or accidents affecting transboundary waters. Additionally, industrial enterprises that monitor their own water abstractions and wastewater discharges contribute data for regulatory compliance purposes.

The assessment of watercourses further requires socio-economic data, such as population and economic statistics, which are typically collected by national statistical offices. In many cases, it is also necessary to draw upon the expertise of research institutions, universities, or private sector entities.

b. Institutional arrangements at the transboundary level

Functioning institutions and appropriate institutional arrangements for monitoring and assessment at both national and local levels are essential prerequisites for effective international cooperation. This is particularly important in the context of joint bodies, which are responsible for implementing tasks related to monitoring and assessment. These joint bodies should serve as platforms for the exchange of information and data, including details on planned measures and activities, and for the harmonization of monitoring methodologies. Therefore, special efforts should be made to develop and enhance their capacity [21].

Riparian countries may choose to establish a dedicated working group within the joint body, where experts from various disciplines convene regularly to coordinate the implementation of monitoring and assessment activities, addressing technical, financial, and organizational aspects.

Basic requirements for joint monitoring and assessment, which can be outlined in an agreement, annex, or protocol, may include: coordinated or harmonized methods for data collection and processing, the establishment of databases and digitalization of data, online access to information, compatibility among participating laboratories, collaborative research and studies, knowledge exchange, the use of models, regulations for monitoring arrangements, and synchronized monitoring and assessment programmes [22]. In the absence of a joint body, riparian countries may choose to establish a specific arrangement solely for monitoring and assessment purposes.

c. Institutional arrangements related to quality control procedures

Quality control procedures are vital to ensure the reliability of information obtained through monitoring. A comprehensive quality system should encompass all elements of the monitoring and assessment cycle, beginning with the documentation of procedures for identifying information needs and formulating an information strategy. Standards developed by the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), and other bodies provide the foundation for quality systems in areas such as sample collection, transportation, storage, and laboratory analysis. The World Meteorological Organization (WMO), as a standard-setting entity, has also issued a series of guidelines and regulations related to hydro-meteorological practices.

Protocols for data validation, storage, sharing, analysis, and reporting must be established and thoroughly documented. In transboundary contexts, where applicable, riparian countries should assign responsibilities related to quality systems to joint bodies or through joint arrangements. Promoting local-level transboundary cooperation, including direct communication among laboratories and involved institutions, is highly encouraged.

Since many decision-makers lack awareness of quality control procedures, a step-by-step approach is recommended to strengthen quality assurance. This process typically begins with basic internal quality control measures, progresses toward organizational accreditation, and eventually aligns with international standards [23].

Quality management (QM), which encompasses both quality assurance and quality control, offers four main benefits:

- It enhances process management and organizational effectiveness.
- It fosters employee satisfaction and organizational commitment.
- It improves the quality of products and services.
- It increases customer satisfaction and enhances the image of hydrological services [24].

The implementation of quality management systems supports hydrological services in adopting sound management practices, thereby boosting confidence in the quality of their data, products, and services. As part of the Monitoring and Assessment Cycle (Figure 4), the quality management process includes the following components:

- Definition of objectives (monitoring, management, environmental, etc.);
- Specification of information requirements, including acceptable levels of uncertainty;
- Adoption of a holistic value chain approach, integrating QM throughout the entire system;
- Selection of monitoring variables;
- Establishment of operational processes, including data rescue and validation;
- Data handling and management; and
- Institutional arrangements to support QM implementation.

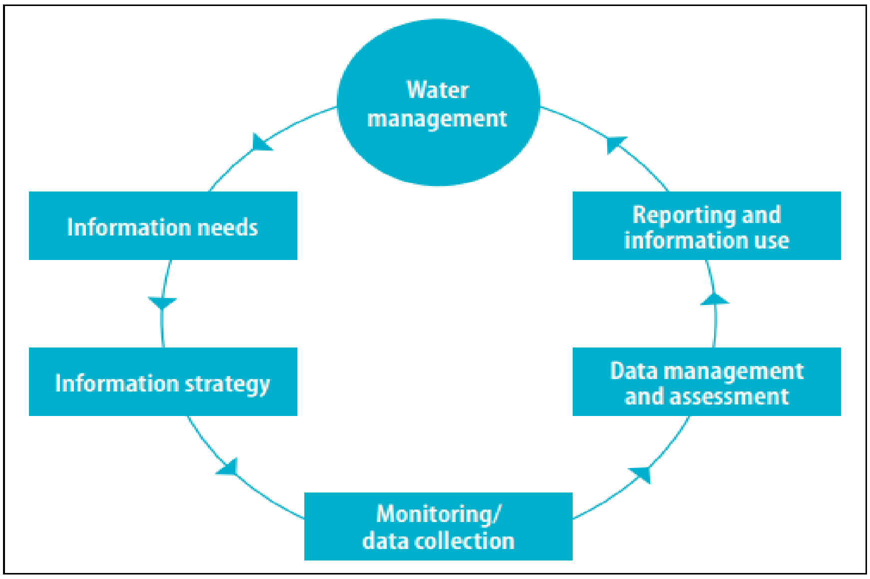

Figure 4. Monitoring and assessment cycle [25].

6. Developing step-by-step approaches

a. An overview of step-by-step approaches

The monitoring and assessment of transboundary waters serve multiple purposes. To optimize the use of available resources and knowledge, a step-by-step approach is recommended (Figure 5). This approach involves identifying and agreeing on priorities for monitoring and assessment, progressing from general evaluations to more detailed assessments, and gradually transitioning from labor-intensive techniques to more advanced technological methods. It also helps to clarify specific information needs, thereby making assessment activities more focused and effective. Such a method is also endorsed by the Guidelines on Monitoring and Assessment of Transboundary Rivers [26-28]. In a transboundary context, adopting a step-by-step approach may have additional implications. For instance, it may begin with informal cooperation at the operational level, gradually evolving into formal agreements and the establishment of joint bodies as mutual trust strengthens. Experience shows that it is often beneficial to set modest initial objectives, such as regularly exchanging data and information regarding sampling techniques and instruments used. This can eventually lead to jointly agreed-upon measurement and sampling procedures, as well as standardized analytical methodologies, paving the way for collaborative sampling, data analysis, and routine joint assessments based on harmonized monitoring designs.

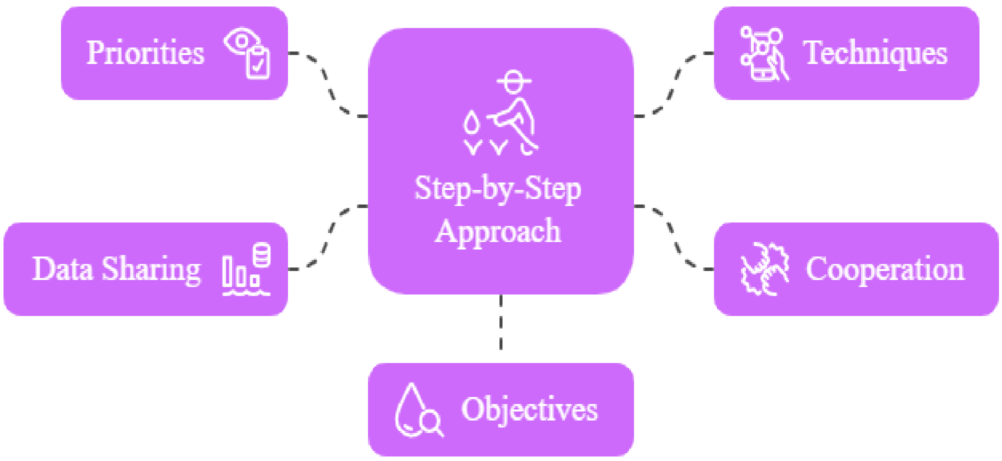

Figure 5. Overview of step-by-step approaches.

This phased approach might also start with data sharing at stations and sampling points located near borders. Once this activity becomes well established, it can then be expanded to encompass the entire transboundary basin or aquifer [29]. Furthermore, it may begin with sharing information on the current status of water resources (in terms of quality and quantity), and as cooperation between riparian countries deepens, progress to sharing data on pressures and driving forces. This would allow for the evaluation of impacts on key water uses and the consideration of appropriate responses, effectively applying the DPSIR (Driving forces, Pressures, State, Impact, Responses) framework.

Achieving the objectives of monitoring and assessment can be likened to constructing a roadmap towards a long-term goal. It involves building “modules” for transboundary water monitoring and assessment, beginning with tasks that are feasible under existing conditions. Subsequent tasks can be pursued as human and financial resources improve, along with enhanced knowledge, mutual understanding, and overall conditions for cooperation.

In cases where amending national legislation is challenging in the short term, the step-by-step approach may also include accepting water-quality objectives, or even ecologically based objectives, as the foundation for monitoring and assessment efforts within joint bodies. These objectives could later be integrated into jointly agreed rules or protocols in bilateral or multilateral agreements, without the need for immediate changes to national legislation.

b. Prioritizing monitoring efforts

Identification of the primary functions and uses of water, along with associated key issues, is essential for determining priority information needs related to both water quality and quantity. It also helps in identifying the relevant variables that require monitoring. National surveys and land-use maps can be valuable tools in this context, offering researchers a quick overview of potential pressures within a basin.

The application of risk assessment techniques, along with documentation of their implementation, can assist decision-makers in identifying which monitoring activities should be prioritized. A central concept in this process is "expected damage," which helps evaluate the potential consequences of insufficient information due to inadequate monitoring. This concept also illustrates the potential losses that may result from suboptimal decision-making (Figure 6).

Nevertheless, it is not feasible for any monitoring programme to measure all variables at numerous sites with the desired frequency. Therefore, a risk-based approach should guide the selection of variables for monitoring. For many parameters, existing literature on their environmental occurrence, especially in freshwater systems, along with information about pollution-generating activities within the basin, can provide a basis for prioritization. Furthermore, the likelihood of certain chemicals reaching surface water or groundwater can be predicted based on their intrinsic properties.

Figure 6. Prioritizing monitoring efforts.

For groundwater, a well-established and widely used method involves defining and mapping aquifer vulnerability to pollution. This approach evaluates and maps the potential for pollutants to be attenuated or delayed, based on the physical and chemical characteristics of the soil and geological layers above the water table. Where such vulnerability maps exist, they can support targeted monitoring efforts in areas where groundwater serves critical functions and is particularly at risk.

Risk assessment can also help determine whether a proposed monitoring strategy sufficiently meets information needs. Statistical modelling can be applied to optimize monitoring design in terms of spatial coverage and sampling frequency, incorporating an element of risk analysis. Such modelling can indicate whether reduced data density or sampling frequency would still satisfy the specified information requirements.

c. Use of models in monitoring and assessment

Models, whether numerical, analytical, or statistical, play a vital role in environmental monitoring and assessment (Figure 7). They can be employed to estimate water quality and quantity at specific locations, thereby minimizing the extent of field monitoring required. Nonetheless, regular calibration with empirical measurements remains essential to ensure model accuracy and reliability.

For assessment purposes, computer-based models of river systems and adjacent areas, integrated with geo-referenced databases, can be utilized to evaluate the potential effects of proposed interventions. For example, these models can simulate changes in river flow and water levels on floodplains during flood events. Additionally, models can be employed to assess various management strategies and policy options, optimize the design of monitoring networks, and evaluate potential impacts on water bodies, as well as associated risks to human health and ecosystems (e.g., through scenario analysis). Moreover, models serve a crucial function in flood forecasting and early warning systems. They are instrumental in predicting flood events and calculating travel times in emergency warning scenarios, such as accidental pollution or spillages.

However, for models to yield dependable results, they must be thoroughly calibrated and validated against historical data. Inaccurate modelling can lead to flawed interpretations of basin or aquifer behavior. Therefore, effective mathematical modelling requires close integration with data collection, data processing, and other assessment techniques used to characterize the entire transboundary water system.

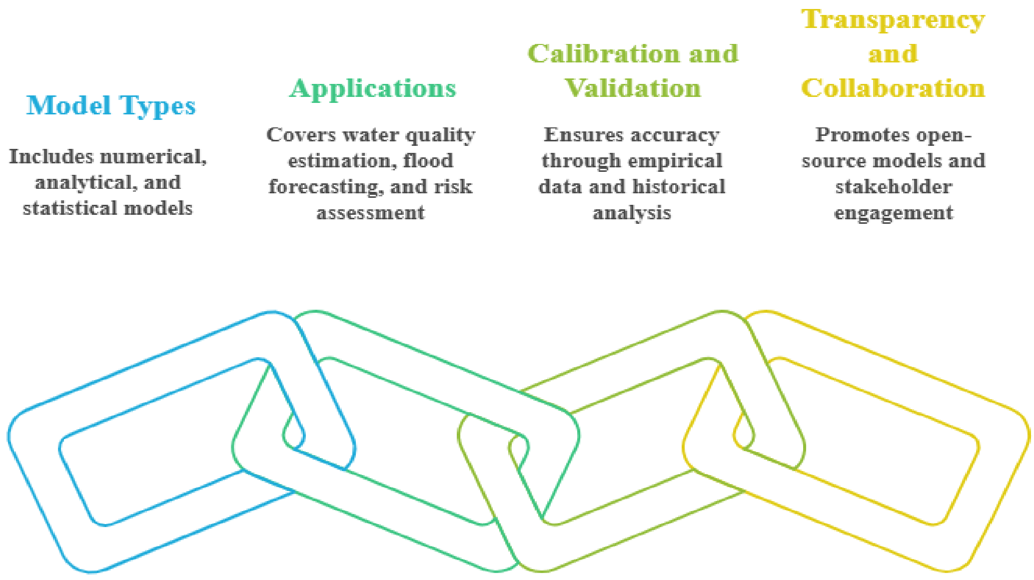

Figure 7. Use of models in the monitoring and assessment.

To ensure transparency and reliability, it is recommended that the modelling system be open-source whenever possible. The structure of the model and the selection of parameters should be clearly understood and communicated to all relevant stakeholders, including joint bodies. A robust approach involves using multiple models (i.e., cloud modelling) and presenting the resulting projections in joint expert discussions. When there is consensus on both the conceptual model and the foundational validation data, model comparisons can be conducted effectively even if different modelling software is used by the riparian states.

d. Using pilot projects

Pilot projects play a crucial role in developing effective and efficient monitoring and assessment programmes. They also serve to foster bilateral and multilateral cooperation, thereby contributing to institutional strengthening and capacity-building. As part of a phased approach, it is advisable to implement pilot projects before establishing comprehensive monitoring and assessment systems for all riparian countries sharing transboundary waters. This approach facilitates the active participation of stakeholders directly or indirectly involved in the use and management of transboundary water resources.

A road map is an essential and integral component of every pilot project, outlining achievable objectives and clearly defined, realistic tasks. It must consider the unique characteristics of the basin, lake, or aquifer, such as the number and proportion of riparian countries involved; their political, social, institutional, and economic contexts; and the specific nature of the water body. However, it is important not to underestimate the level of commitment, resources, and time required for the successful implementation of pilot projects.

7. Identification of the right nodes/people/agencies who can help in commissioning evidence

To commission evidence-based river management work, focus on government agencies, research institutions, and non-governmental organizations (NGOs) with expertise in water resources, environmental science, and policy. Key nodes include the Department of Water Resources, River Development and Ganga Rejuvenation (DoWR, RD & GR), and the National Mission for Clean Ganga (NMCG), as well as organizations such as the Central Water Commission (CWC) and the India Environment Portal (Figure 8).

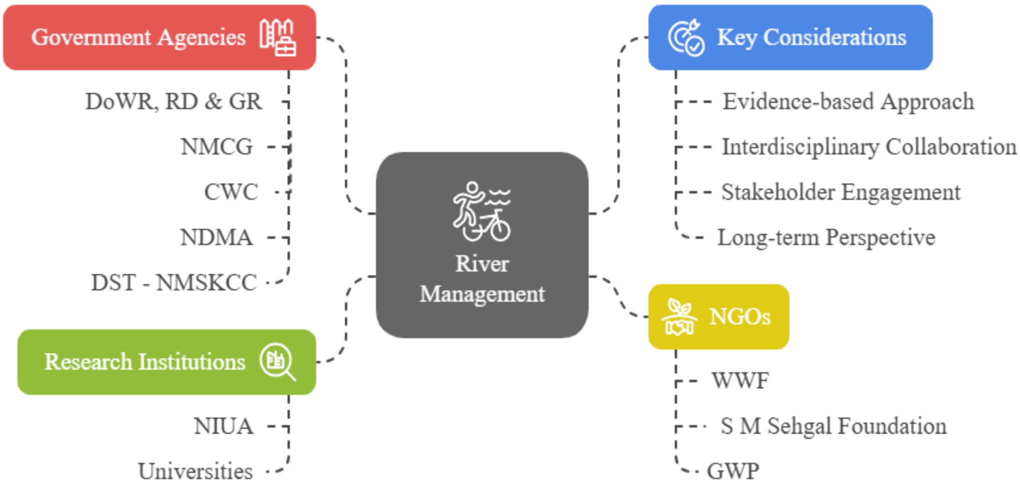

Figure 8. Right nodes/ people/ agencies who can help in commissioning evidence.

Government Agencies:

- **DoWR, RD & GR:** Sets policy guidelines and programs for water resource development and management.
- **NMCG:** Focuses on river rejuvenation and pollution control.
- **CWC:** An apex organization for water resources, promoting dam safety and the development of guidelines.
- **National Disaster Management Authority (NDMA):** Involved in urban flood disaster management and related policies.
- **Department of Science & Technology (DST) - NMSKCC:** Addresses knowledge gaps in climate change through networks and research programs.
  Research Institutions and Universities:
- **NIUA:** NIUA supports research and innovation on water management and engages with various stakeholders, including governments, companies, and international experts.
- **Universities with expertise in hydrology, environmental science, and engineering:** These institutions can provide research-based data and insights for river management.

Non-Governmental Organizations (NGOs):

- **WWF:** Focuses on river and wetland conservation, research, and policy engagement.

- **S M Sehgal Foundation:** Works on water management programs, including rainwater harvesting and groundwater augmentation.
- **Global Water Partnership (GWP):** A network of organizations focused on water resources management and integrated water resources management (IWRM).
  Key Considerations for Commissioning Work:
- **Evidence-based approach:** Ensure that any commissioned work relies on scientific data, research findings, and best practices.
- **Interdisciplinary collaboration:** River management requires expertise from various fields, including hydrology, ecology, engineering, and policy.
- **Stakeholder engagement:** Involve local communities, government agencies, and other stakeholders in the planning and implementation of river management initiatives.
- **Long-term perspective:** River management is a long-term process that requires sustained effort and investment.

8. Role of Independent Audits or Third-Party Monitoring

Independent audits play a vital role in river basin monitoring by offering objective and transparent evaluations of management practices, regulatory compliance, and the overall health of river systems. These audits help ensure the sustainable use of water resources, safeguard the environment, and address critical issues related to water quality, quantity, and allocation (Figure 9).

Here is a more detailed overview of the role of independent audits:

i. Assessing Compliance and Accountability:

- Independent audits verify whether water management practices align with established regulations, policies, and standards.
- They evaluate the efficiency and equity of water resource allocation and management systems.
- Audits help identify areas of non-compliance, which can lead to enhanced management practices and greater accountability.

Figure 9. Overview of the role of independent audit.

ii. Evaluating Environmental Impact and Sustainability:

- Independent audits assess the environmental impacts of water-related activities, including pollution, habitat degradation, and ecosystem health.
- They examine the effectiveness of protective measures for water resources to ensure long-term sustainability.
- These audits provide insights into the consequences of human activities on river basins and inform strategies to mitigate negative impacts.

iii. Promoting Transparency and Public Trust:

- Independent audits enhance transparency by providing objective, verifiable data on the condition of river basins.
- This transparency fosters public trust in water management institutions and encourages broader participation in decision-making processes.
- Audits help ensure that water management is accountable to the public and that water resources are used responsibly.

iv. Identifying Areas for Improvement:

- Audits reveal inefficiencies and areas requiring improvement in water management, such as water use efficiency, pollution control, and infrastructure maintenance.
- They offer recommendations for better resource utilization and sustainable practices.
- Audits also help identify emerging challenges, such as the impacts of climate change, and guide the development of adaptive strategies.

v. Examples of Independent Audits:

- **Sustainable Rivers Audit (SRA) – Murray-Darling Basin, Australia:** This audit evaluates the ecological health of river systems and highlights areas where management practices can be enhanced.
- **Inspector-General of Water Compliance (IGWC) – Murray-Darling Basin:** This agency ensures adherence to sustainable diversion limits and oversees water management practices.
- **Independent Forest Monitoring – Congo Basin:** Supported by international donors, this form of monitoring promotes transparent and accountable forest management, which indirectly benefits water resource conservation.

Third-party audits play a vital role in river basin monitoring by offering objective evaluations of water quality, pollution levels, and overall environmental health (Figure 10). These audits support regulatory compliance, highlight areas requiring improvement, and encourage sustainable water resource management.

Elaboration:

- **Unbiased Assessment:** Third-party audits provide an independent viewpoint on river basin management, free from potential conflicts of interest that may arise with local stakeholders or polluting industries.
- **Compliance and Enforcement:** These audits help verify adherence to water quality standards and environmental regulations, facilitating the enforcement of environmental laws and identifying areas where compliance is insufficient.
- **Data Collection and Analysis:** Third-party auditors systematically collect and analyze data on various parameters, such as water quality, flow rates, and pollutant concentrations, delivering valuable insights into the condition of the river basin.
- **Identification of Problem Areas:** Audits are instrumental in identifying specific sources of pollution, zones with compromised water quality, and potential shortcomings in water resource management.
- **Recommendations for Improvement:** Based on their assessments, auditors provide actionable recommendations aimed at enhancing water quality, reducing pollution, and encouraging sustainable practices within the river basin.
- **Monitoring and Evaluation:** Regular independent audits enable continuous monitoring of progress toward water quality objectives, assessing the effectiveness of implemented management strategies, and identifying areas needing further intervention.
- **Public Transparency:** The findings from third-party audits can be made publicly accessible, fostering transparency in water governance and encouraging broader public involvement in decision-making processes.
- **Supporting Sustainable Practices:** By ensuring compliance, identifying environmental challenges, and proposing corrective measures, third-party audits significantly contribute to the sustainable use and management of river basin resources.

Figure 10. Role of third-party audit in river basin monitoring.

Therefore, independent third-party audits are essential for safeguarding the long-term health and sustainability of river basins. They offer an impartial and thorough evaluation of environmental conditions and management efforts, making them a cornerstone of effective river basin governance.

8.1 Analyzing data and evidence (Descriptive vs. Causal)

In a river monitoring study, descriptive analysis focuses on summarizing and describing the existing water quality data (e.g., average pollutant levels, trends over time). Causal analysis, on the other hand, investigates the relationships between different factors and changes in water quality, aiming to identify whether one factor causes another.

Here is a more detailed breakdown:

i. **Descriptive Analysis**
   - **Purpose**
     The goal is to provide a snapshot of the river's current water quality while identifying patterns or trends.
   - **Examples**
     This includes tasks such as calculating average pollutant concentrations, identifying seasonal changes in water quality, and mapping the spatial distribution of pollutants.
   - **Methods**
     Descriptive statistics (mean, median, standard deviation), time series analysis, and spatial analysis.

- **Benefits**
  It provides a clear picture of the current situation and can help identify areas for further investigation.
- **Limitations**
  It does not explain why changes occur or establish causal relationships.

ii. **Causal Analysis**

- **Purpose**
  The goal is to understand the mechanisms behind changes in water quality and determine whether one factor directly affects another.
- **Examples**
  Investigating whether industrial runoff causes increased nutrient levels in the river or whether a specific water management policy leads to improved water quality.
- **Methods:**
  Statistical modeling, regression analysis, Granger causality analysis, and other methods can isolate the effects of specific factors.
- **Benefits**
  It provides insights into the underlying causes of water quality problems and can inform effective management strategies.
- **Limitations**
  Establishing strong causal relationships can be challenging due to the complexity of river systems and the presence of many interacting factors.

iii. **Choosing the Right Approach**

- **Descriptive analysis**
  This is a good starting point for understanding the basic characteristics of a river's water quality.
- **Causal analysis**
  It is needed when you want to understand why changes are occurring and identify the specific factors driving those changes.
- **You can combine both approaches.**
  For example, descriptive analysis can be used to identify trends, and then causal analysis can be employed to investigate the underlying causes of those trends.

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