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D&R Wing

Dr. M. K. Sinha
Chairman

Message

The Central Water Commission (CWC) plays a vital role in the development and management of India's water resources, addressing key areas such as irrigation, hydropower generation, flood management, and water supply, all in consultation with the states. To achieve these objectives, CWC operates through its three wings: the Design & Research Wing (D&R Wing), the River Management Wing, and the Water Planning & Projects Wing. As you know, the Central Water Commission is considered the apex technical organization in the water resources sector, primarily due to its Design & Research Wing.

The D&R Wing focuses on providing consultancy to states and other project authorities in the planning and design of river valley projects. It is responsible for conducting hydrological studies, offering guidance on project design and construction, and advising state governments and dam-owning agencies on dam safety. The wing also makes key policy decisions regarding design and research activities, standardizes the designs of river valley projects, and conducts special studies on critical issues such as dam break disasters, reservoir sedimentation, and Glacial Lake Outburst Floods (GLOF).

For over 70 years, the D&R Wing has been instrumental in planning and designing hundreds of river valley projects both within India and internationally. Over this period, it has developed considerable expertise, keeping pace with the latest methodologies and technologies that meet international standards. Today, the D&R Wing is considered the technological hub of CWC, providing innovative solutions to all technical challenges in the domain of water resources development across the country.

It is especially encouraging to see the launch of a technical journal "*Design & Research Journal of Water Resources*' by the D&R Wing of CWC. This journal will serve as a key platform to highlight the vast array of technical work being undertaken by the Wing. By sharing the knowledge and experience accumulated over decades, the journal will foster greater collaboration and learning within the water resources sector. Additionally, it will contribute significantly to the development of a knowledge base that can benefit professionals and organizations in this field.

This initiative represents a significant step toward the development of a knowledge-sharing culture and strengthening the technological foundation in water resources management.

I extend my best wishes for the success of this journal, and may it serve as a valuable resource for all those involved in water resource development and management.

(Dr. Mukesh Kumar Sinha)

Bhopal Singh
Member D&R

Message

Since the inception of the Central Water Commission (CWC) in 1945, the Design & Research (D&R) Wing has contributed immensely towards the development of water resources in India and abroad. Hundreds of projects have been planned and designed, which have contributed significantly to the development of the country. The D&R Wing has developed expertise in this area that is on par with international standards.

Using the latest technologies and modern tools, the D&R Wing has become a leading organization in the planning and design of water resource projects. The expertise developed is also being used to solve various special technical problems of water resources projects that are under operation.

Using advanced scientific methodologies, the D&R Wing has also developed expertise in hydrological studies, design flood computation, and reservoir sedimentation studies. These studies are crucial for judicious water resources planning and the design of projects. Specialized studies, such as Glacial Lake Outburst Flood (GLOF) studies, dam break modeling, back-water computations, and the finalization of site-specific seismic parameters for river-valley projects through the National Committee on Seismic Design Parameters, are also carried out for various projects.

The technical journal "*Design & Research Journal of Water Resources*" of the D&R Wing, CWC, has been planned to disseminate and share knowledge, technologies, and best practices used in the works of the D&R Wing of CWC. It will encourage officers not only to share their knowledge and best practices but also to adopt and utilize state-of-the-art technologies in their work.

I wish all the success to the journal

(Bhopal Singh)

Journal Secretariat

D&R (Co-ord.) Dte.
4th Floor (S), Sewa Bhawan
R.K.Puram, New Delhi -66
Ph.No: 011-29583716
E.Mail : drcdte@nic.in

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About Design & Research (D&R) Wing:

This wing is responsible for, providing guidance in the planning, preparation of lay-out studies, specifications, detailed designs and drawings and standardization of designs of river valley projects in the country including hydrological studies for the projects, advising state Governments/Dam owning agencies on safety aspects of dams, taking policy decisions on design and research activities, conducting site inspection at all critical stages of construction of projects for which CWC provides design consultancy for advising the adequacy of foundation conditions and foundation treatment, adherence to design specifications etc. and providing advices on landslide/dam break disaster management issues.

The Wing is headed by an engineering officer designated as Member (D&R) with the ex-officio status of Additional Secretary to Government of India. The wing comprises of organizations headed by Chief Engineer and consisting of various Directorates each headed by Directors.

1. **Guidance in Planning and Preparation of River Valley Projects**

   This wing plays a pivotal role in ensuring that river valley projects, which can involve large-scale infrastructure such as dams, canals, and irrigation systems, are well-planned from the very beginning. The responsibilities include preparing comprehensive layout studies, which examine the feasibility of construction, the potential environmental impact, and the best utilization of available resources. Additionally, the wing sets clear specifications, defining the quality, materials, and standards that must be adhered to during the project. These specifications ensure safety, efficiency, and sustainability throughout the project lifecycle. Moreover, the wing is responsible for creating detailed designs and technical drawings, which include every aspect of construction, from structural components to electrical and mechanical systems.

2. **Standardization of Designs**

   To ensure uniformity and consistency across multiple river valley projects, the wing focuses on the standardization of designs. Standardized designs help in reducing risks associated with variability and innovation. The wing creates design templates and guidelines for similar projects, ensuring that these designs meet the necessary safety and performance standards. This uniform approach helps minimize errors during construction, reduces costs, and improves the efficiency of implementing projects across various regions.

3. **Hydrological Studies for Projects**

   Hydrology—the study of water systems, including rainfall, rivers, and groundwater—is a core focus of the wing’s activities. Hydrological studies are vital for understanding water flow patterns, assessing flood risks, and evaluating the availability of water resources for the project. These studies are crucial to ensure that infrastructure can handle expected water levels, including during extreme weather events. The wing also conducts impact assessments to evaluate the potential consequences of the project on surrounding water bodies and ecosystems, aiming to prevent any negative environmental effects.

4. **Advising State Governments and Dam Owning Agencies on Dam Safety**

The safety of dams is paramount, as failures can lead to catastrophic outcomes, including flooding and loss of life. The wing provides expert advice to state governments and dam-owning agencies on various aspects of dam safety, including design, construction, and operation. It helps assess the structural integrity of dams, advising on potential weaknesses and recommending improvements where necessary. The wing also assists in emergency preparedness, establishing protocols for monitoring the dam's condition and responding effectively in case of potential failures.

5. **Policy Decisions on Design and Research Activities**

Another critical function of this wing is shaping the policy framework for the design and research related to river valley projects. It plays a vital role in establishing or revising design standards, ensuring that they reflect the latest advancements in engineering and hydrology. The wing also guides research priorities, identifying areas that require further study to enhance the design, safety, and sustainability of future projects. Policy decisions made by the wing help align the ongoing development of river valley projects with evolving technological and environmental standards.

6. **Conducting Site Inspections During Critical Construction Stages**

The wing's responsibilities extend to site inspections, which are carried out during critical stages of project construction. These inspections ensure that the work is proceeding according to the approved designs and specifications. One of the main areas of focus during these inspections is the foundation conditions. The wing evaluates the soil, bedrock, and other materials at the project site to determine if they are suitable for the intended construction. In addition, the inspections verify that the construction team is adhering to the technical design specifications, identifying any deviations and working to correct them before they affect the project's integrity.

7. **Advising on Landslide and Dam Break Disaster Management**

The wing also provides guidance on disaster management, particularly in cases of natural events such as landslides or potential dam breaks. Landslides can jeopardize the safety of river valley projects, especially in mountainous or unstable terrain. The wing offers prevention strategies, such as reinforcing slopes and implementing proper drainage systems, to mitigate the risk of landslides. Additionally, in the event of a dam failure, the wing has a crucial role in developing disaster management protocols, including evacuation plans, early warning systems, and strategies for managing the downstream impacts of a dam break.

8. **Ensuring Overall Safety, Efficiency, and Sustainability**

Beyond specific tasks, the overarching goal of this wing is to ensure the safety, efficiency, and sustainability of river valley projects. Sustainability is considered in every stage of the project, from design to construction and operation, with a focus on minimizing environmental impact, preserving water quality, and promoting long-term resource management. The wing also ensures that projects comply with both national and international standards for safety, engineering, and environmental protection, aligning with best practices in the industry.

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Automated real-time reservoir operation based on runoff forecast and mathematical optimization: current state-of-the-art with a case study in India

Rakesh Kashyap[1], Bikram Kesharee Patra[1]

Nesa Ilich[2]

[1] Central Water Commission, New Delhi, India, 110066, India
[2] SMEC India Pvt, Haryana, 110066, India

Corresponding author: bikrampatracwc@gmail.com

Abstract. Automated real-time reservoir operation has emerged as a critical solution for optimizing water resource management in an era of increasing climate variability and extreme weather events. While manual dam operations often rely on rule-based approaches and operator intuition, they are prone to errors, particularly during emergencies. Advances in short-term runoff forecasting and mathematical optimization offer transformative potential to address these challenges by enabling data-driven decision-making. This paper explores the integration of runoff forecasts with the WEB.BM reservoir optimization model to achieve efficient and reliable dam operations, with a case study focusing on the Damodar River Basin in India. The case study presents preparation for integrating a runoff forecasting model developed by AECOM with a reservoir optimization framework tailored for the Damodar Valley Corporation (DVC) reservoir system. The study utilizes historical flood events and a 6-hour timestep to test the combined framework. The optimized model, configured for the basin's unique hydrology, subdivides the catchment into key sub-regions to align with the forecasting model and incorporates hydrological channel routing to simulate flow dynamics accurately. Testing scenarios include three historical floods (2000, 2006, and 2009) with forecast horizons of 1, 2, and 3 days, assessing the model's ability to maintain downstream flow within the safe channel capacity of 2850 m^3/s at Jamalpur. The findings demonstrate significant improvements over historical operations, with peak flow reductions of up to 50 percent achieved through optimized pre-flood and automated drawdowns conducted within 1, 2, or 3 days before the incoming flood, thus mimicking responses to the information from the runoff forecasting system. The model effectively balances reservoir releases, downstream channel flows, and tributary inflows, mitigating flood risks even under conservative assumptions of starting storage levels. For the 2009 flood, the model reduced peak flows at Jamalpur from 7649 m^3/s to 5500 m^3/s, 3517 m^3/s, and 2850 m^3/s for the respective 1, 2 and 3-day available runoff forecasts. The other two historical floods in 2000 and 2006 required only 1 and 2 days of respective flood forecasts to keep downstream flows within the threshold boundaries, thus eliminating flood damage. This showcases the model's ability to dynamically adapt reservoir operations to evolving inflow conditions, significantly outperforming traditional rule-based systems. The uniqueness of this approach lies in its integration of real-time data acquisition systems (RTDAS), runoff forecasting, and optimization within a single operational framework. This eliminates reliance on static rule curves, offering a scalable and adaptable solution for multi-reservoir systems worldwide. With ongoing advancements in remote sensing and forecasting technologies, the framework presented here serves as a template for modernizing dam operations and enhancing flood resilience globally. This research underscores the potential for transformative improvements in water resource management through predictive and automated solutions.

Keywords: Dynamic Channel Routing, Model Predictive Control, Real-Time Data Acquisition Systems, Real-Time Reservoir Optimization

Introduction and literature review

Efficient and reliable reservoir operation is critical for water resource management, balancing flood control, irrigation, hydropower generation, and municipal water supply. As climate-driven extreme weather events grow in intensity and frequency, traditional manual and rule-based reservoir operations reveal their limitations. These methods often rely on static operating rules and operators' intuition, which can lead to suboptimal decisions, especially during emergencies. Integrating real-time runoff forecasting and mathematical optimization offers a transformative opportunity to address these challenges by enabling dynamic, data-driven decision-making. With over 6,000 large dams, India faces acute challenges in managing floods and droughts. The Damodar River Basin, located in eastern India and known for its flood-prone nature, served as a case study highlighting the complexities and potential of modern reservoir optimization techniques. With multi-reservoir systems designed for flood mitigation, hydropower, and irrigation, optimizing the basin's operations has significant implications for disaster risk reduction and sustainable water management.

Various models have been developed for reservoir optimization, ranging from traditional rule-curve-based approaches to advanced mathematical programming methods. Rule-curve models, though widely used, are static and often fail under dynamic inflow conditions. Various optimization strategies have been used in the past. Among else, these include Linear programming (LP), Dynamic programming (DP) and numerous heuristic solvers that employ various evolutionary strategies that mimic the evolution and behaviour of biological systems. A comprehensive coverage of the state-of-the-art optimization solution strategies is provided by Rardin [1]. Although there have been numerous attempts to apply various solution strategies in reservoir optimization, there is no universally accepted tool among practitioners that can handle all existing complexities of modern water resources systems. As documented by Ilich and Todorović in their recent literature review paper [2], only a small fraction of 2.5% of all publications have been applied to the real world in some way by the relevant reservoir management agencies. Reliable runoff forecasts are quickly improving, using the satellite-based data obtained through remote sensing and sophisticated algorithms that utilize various forms of machine learning and artificial intelligence [3]. The solution concept presented here is known as the Model Predictive Control (MPC) [4], and it relies on the combined use of runoff forecasts and mathematical optimization. The process eliminates the need to use the "upper rule curves" on reservoirs, thus offering a compromise solution between hydropower producers and dam operators, since it does not require lowering the FRL over the entire wet season, but only during the flood events. The emergence of this solution approach was foreseen long before the development of the internet and the currently available computer power by Yazicigil et al. [5], which later gained further momentum with the improvements in remote sensing and runoff forecasting technology, as boldly forecasted by Howard in his paper titled "Death to Rule Curves" [6]. Other early attempts include Wasimi et al. [7] who examined the short-term operation of multi-reservoir systems during floods to regulate reservoirs and minimize flood damage, while Karamouz et al. [8] developed a Bayesian stochastic dynamic programming model, incorporating forecast uncertainties and updating probabilities using Bayesian decision theory, which provided a robust framework for managing reservoirs under uncertain conditions. Other researchers have explored optimization techniques such as genetic algorithms, which Merabtene et al. [9] utilized for drought risk management in water resource systems. Hsu et al. [10] developed a real-time flood control operation model specifically designed for typhoon-induced floods, while Chang [11] implemented a penalty-type genetic algorithm for rational reservoir flood operation. Wei et al. [12] focused on real-time operations for flood control using the tree-based release rules. Xu et al. [13] expanded on these advancements by proposing an integrated flood risk identification model for multi-reservoir systems, emphasizing forecast uncertainties.

Most of the above publications focus on the importance of runoff forecasting skills, while the inclusion of complex flood routing constraints into mathematical optimization gets very limited attention. Yet, this aspect of optimal flood operation is just as important as the accuracy of the forecast, since the optimization program must include the differential equations of flow as constraints to optimization in order to properly account for flood propagation mechanisms. There is only a handful of tools that focus on modeling capabilities to generate globally optimal solutions such as the WEB.BM model used in this study [14], and their real-world applications are covered in a tiny fraction of the available literature [14, 2]. The principal reason is that most publications ignore the routing transformation as constraints embedded in dynamic optimization networks, especially when minimizing flood damage is not the only objective. This study aims to address the proper inclusion of difficult channel routing constraints within the multi-reservoir framework that could also be used within the multi-purpose operational framework [15].

This study uniquely integrates short-term runoff forecasting with real-time reservoir optimization, providing a seamless framework tested using historical flood events in the Damodar Basin. By incorporating dynamic channel routing transformations at 6-hour intervals into the optimization process, the study enhances operational accuracy and offers a scalable solution for multi-reservoir systems worldwide. The results demonstrate the effectiveness of pre-flood drawdowns enabled by optimization, significantly reducing peak flows and downstream flood risks. With advancements in remote sensing and real-time data acquisition systems, this approach modernizes reservoir operations to meet contemporary challenges. By combining predictive models with optimization, this research not only enhances flood resilience but also contributes to global efforts for sustainable water resource management.

Study objectives and methodology

The principal objective of this study is to verify the WEB.BM model capability to manage floods subject to the available short-term forecasts with 1-, 2-, or 3-days lead time by using the Damodar River Basin in India as a case study. The approach begins with data preparation, where historical inflow and outflow records for key reservoirs, including Tilaiya, Konar, Maithon, and Panchet, are collected. The eventual use of the model in real-time will be based on the short-term runoff forecasts with 1, 2, and 3-day horizons generated using the runoff forecasting model based on weather forecasts and rainfall-runoff relationships established through calibrated hydrological simulations. The runoff forecasting model is still under development [16]. The integrated model will be tested using real-time forecasts over the next three monsoon periods. In the absence of real-time data, a hindcast approach is used in this study where historical daily data are interpolated into 6-hourly intervals assumed to be available much like the 6-hourly runoff forecasts will be available after the forthcoming integration.

Hydrological channel routing

Most hydrology textbooks explain hydrological channel routing as a transformation of inflow into a river channel into outflow by using the Muskingum linear model [17], while ignoring the fact that this model can only be calibrated for a single hydrological event of a specific and known magnitude by defining the routing coefficients that correspond to the average travel time a flow along a given river reach during the specific flood. The problem is that the magnitude of future floods is not known, thus requiring a non-linear routing scheme where the routing coefficients are determined as a function of travel time, which is a function of the channel flow. An elegant solution to dynamic flood routing with coefficients that vary as a function of the channel flow has been around for over 50 years as defined by Williams [18], although often overlooked by the mainstream textbooks on hydrology. The first significant application of the Williams routing equation was originally developed by the US Corps of Engineers, the Stream Synthesis and Reservoir Routing (SSARR) [19]. A major advantage of this model is that it does not need any channel geometry as input data, nor does it require Manning's coefficients. Once the travel time vs flow relationship is available, the calibration consists of deciding how many sequential phases a given river reach should be divided into, which is conducted using repeated simulation trials until the observed downstream hydrograph closely matches the simulated channel outflow. As with the other river routing methods, the governing equation is related to channel storage change over a time step, which is a function of average inflow and outflow:

$$\frac{I_{t-1}+I_t}{2} - \frac{O_{t-1}+O_t}{2} = \frac{\Delta S}{t} \tag{2}$$

By subtracting both sides of the above equation with Ot-1, multiplying by t/(Ot-Ot-1) and by letting ΔS/(Ot-Ot-1) = TS, the above equation becomes:

$$O_t = \frac{\left[\frac{I_{t-1}+I_t}{2} - O_{t-1}\right] \cdot t}{TS + \frac{t}{2}} + O_{t-1} \tag{3}$$

where the term TS represents the average travel time along a river reach for given flow conditions, evaluated either by reading from the TS vs Q table or by using a functional form of the travel time vs flow curve as:

$$TS = \frac{Kts}{\left(\frac{O_{t-1}+O_t}{2}\right)^n} \tag{4}$$

The routing coefficients Kts and n must previously be determined by finding the best-fit curve for a given set of the available (TS, Q) coordinates. In physical terms, *Kts* represents the length of the river reach, while the exponent *n* is related to the slope of the reach. Alternatively, TS can be determined for any given flow rate by linear interpolation from a table of (TS, Q) points obtained from observations. In the above definition of TS, the base of the denominator:

$$\frac{O_{t-1}+O_t}{2} \tag{5}$$

which is powered by exponent *n* that represents the estimate of the average outflow from a given reach during the time step *t*. For sufficiently small-time steps, the variations of flow are also small, so it is common to assume $O_{t-1} = O_t$. The model typically conducts two to three iterations by updating O_t and recalculating the travel Ts time by using the updated coefficients before it converges to the final solution. Expression (5) can also be converted to the following form:

$$O_t = \frac{t}{2T_s+t} I_{t-1} + \frac{t}{2T_s+t} I_t + \frac{T_s-t/2}{T_s+t/2} O_{t-1} \quad (6)$$

The above form is identical to the well-known Muskingum linear routing form:

$$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} \quad (7)$$

It can be noted that the SSARR routing coefficients listed in equation (6) sum up to 1 (i.e. C1+C2+C3 = 1), which is also the condition for the Muskingum routing coefficients. In other words, the SSARR routing method uses an identical formula as does the Muskingum routing procedure, except that the values of the routing coefficients *Ci* are determined in a different way, which has some obvious advantages:

- The only required information for the values of routing coefficients is the time of travel vs flow relationship for a given river reach and the length of the calculation time step. No other data related to the channel geometry, gradient or roughness are required.
- The values of routing coefficients undergo dynamic adjustments as the modelling moves through different flow regimes between dry seasons and wet seasons, in a much more elegant and precise way than in the case of using the classical Muskingum method, which is used with fixed coefficients developed for a specific hydrological event.

Implementations of the SSARR method may rely on different estimates of the average channel flow during a given time step. Input data requirements include the time of travel versus the flow table for a river reach, where the time of travel is given in hours while flows are given in m^3/s. To ensure the numerical stability of this approach, the calculation time step is selected such that the travel time along the reach is at least more than twice the length of the calculation time step, i.e. Ts ≥ t/2. If this condition is not satisfied, the routing coefficients that multiply I_t and I_{t-1} become greater than 0.5, and the mass conservation rule which requires that the sum of all three coefficients be equal to 1 is no longer maintained. Similar conditions exist in the classical Muskingum method. Since the routed flows are not precisely known in advance, the SSARR routing method is iterative, requiring recalculation of the routing coefficients as a function of Q_t at the end of each iteration until the convergence criteria are satisfied. The WEB.BM model executes several repeated runs for each simulated time step by using the steady-state solution as the initial starting solution, which is then corrected for the effects of routing from one iteration to another until the convergence criteria are fulfilled. This approach is particularly useful when solving several time steps simultaneously since it moves the reservoir releases earlier in time in each iteration such that the effects of routing can be combined with the operational objectives.

Mathematical definition of the problem

If the optimization problem is defined using maximization of benefits in LP formulation, the pricing vector P_i associated with flood damage would have a negative sign for any flow that exceeds the full bank channel capacity, indicating that benefits would be maximized if the reservoirs could be operated such that the overbank spills are minimized or completely avoided if possible. The objective function would be applicable for all time steps that are solved simultaneously, and for all river reaches that may be associated with the flood damage, which explains the double summation over both time (*t*) and space (*i*):

$$Objective\ Function = Max \sum_{t=1}^{m} \sum_{i=1}^{l} Q_{i,t} P_i \quad (8)$$

Subject to:

$$\sum_{i=1}^{m} A_i Q_i = b_n \qquad \forall\, i, n \in N \tag{9}$$

$$0 \le Q_{i,t} \le U_{i,t}$$
$$0 \le Q_{i,t} \le f(Q_{k,t}) \qquad \forall\, i, t \tag{10}$$

Equation (9) represents the mass balance at network node *n*, with A_i representing the incidence matrix coefficient that is typically equal to either -1, 0 or 1, with -1 and 1 denoting the incoming and outgoing flows for network arcs that are associated with a given node *n*, while b_n represents local inflow into node *n*, which is set to zero for nodes that have no tributary inflows. Index *i* represents each link (also known as "arc") in the network. Expression (9) is applied to all nodes in the network. Furthermore, when solving multiple time step optimization, the mass balance equation (9) is applied to each node *n* in the network and to each time step *t* over the selected solution horizon. Expression (10) represents the upper bound on flows, which can be either set to constants $U_{i,t}$ representing for example the maximum storage or canal capacity that should not be exceeded, or it can be defined as a function of flow in some other network component *k*, such as the channel flow relationship defined by the channel routing equation.

Understanding the Weight Factors

The purpose of the weight factors is to define the importance of allocating water to each model component, where some components may be broken down into several operating zones to enable the use of LP. The conceptual use of weight factors is explained in Figure 1 which shows two reservoirs, three diversion canals and several river reaches.

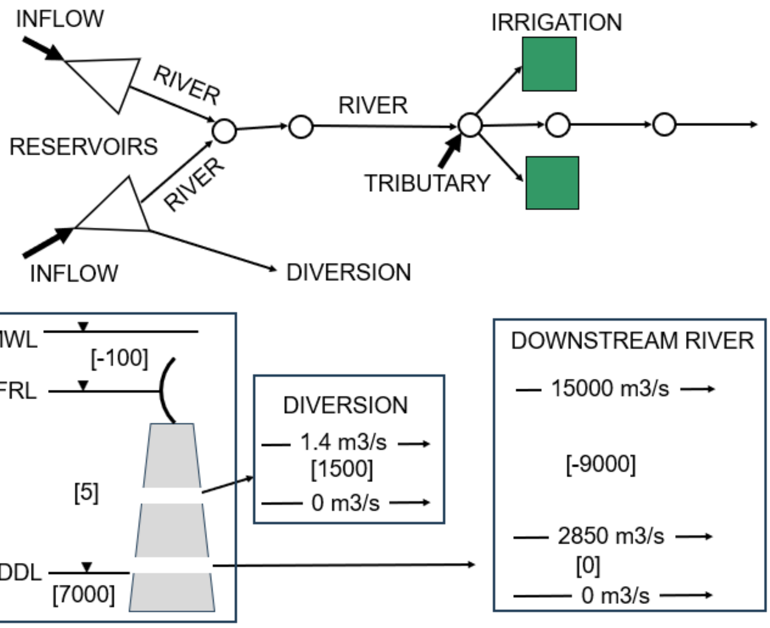

Figure 1. Schematic representation of weight factors

There are typically at least three operating zones associated with reservoirs, representing the dead storage zone, conservation zone, and flood storage zone, with their respective weight factors of 7000, 5, and -100 shown in Figure 1. The mechanism of setting up and using these weight factor values is explained further below. There is only one operational zone for a diversion canal that takes water out of storage, with its corresponding weight factor of 1500.

The most downstream river reach for which flood protection needs to be implemented through optimal reservoir operation has two zones in the above example. The zone with flow values up to 2850 m^3/s has a weight factor of zero, while the flow zone that accepts any flows above 2850 m^3/s has a weight factor set to -9000. Since the model uses maximization of the objective function, the high negative value signifies a highly undesirable condition of allocating flows to this zone. Several important rules should be noted:

- Each zone has a positive upper bound which is greater than the lower bound
- Weight factors are assigned to each zone arbitrarily by the user
- There is more than one set of weight factors that will give identical flow allocation

The weight factors represent the importance of maintaining desired flow levels. For example, the storage level should never drop below the Maximum Draw Down Level (MDDL), also known as the top of the dead storage zone, hence the high priority of 7000 applied for each unit of storage below MDDL. One can think of the weight factor as the value of water in monetary units per m^3 of storage in a particular zone, or better yet per m^3/s of flow, since storage is internally converted to the units of flow by dividing the target storage with the length of the simulated time step. For storage between MDDL and the Full Reservoir Level (FRL), the weight factor is only 5. Since the objective is to maximize the product of flow allocated to each zone with its related weight factor, the model would allocate water from storage to the diversion canal where the weight factor is 1500, much larger than the priority of storing water in the reservoir. Hence, the final allocation in each time interval will take water from storage, where its value is only 5, to the diversion canal, where its value is 1500. Diversion canals can be used to supply municipalities or irrigation. The upper bound of the diversion canal may represent canal capacity, or it may represent water demand as is the case above, where the diversion limit set to 1.4 m^3/s may correspond to the municipal demand in one particular time step. It is easy to see that any solution that keeps the storage at FRL, meets the diversion requirement from the reservoir, and keeps the downstream flow below 2850 m^3/s is optimal since it maximizes the value of the objective function.

If the reservoir starts at FRL and the reservoir inflow is greater than 2850 plus the diversion target, the downstream channel will begin to spill, which marks the beginning of flooding. The cost of flooding is very high (-9000 per m^3/s, where the negative sign indicates a monetary loss per unit of flow above the threshold). Consequently, the model would not flood the river valley right away but would rather begin to fill the flood storage zone at the reservoir, which has a weight factor of -100. This also represents a loss (reduction) to the value of the objective function which is to be maximized by -100 per unit of flow, but this loss is not as large as the loss of -9000 per unit of flow associated with spills at the downstream channel. In other words, the model will first put extra inflow into the flood storage zone above FRL before allowing downstream channel spills. When solved simultaneously for several 6-hourly periods, the model begins to release flows from storage (without violating the downstream limit of 2850 m^3/s) before the peak inflow arrives, thus increasing the flood storage zone dynamically based on inflow forecast, starting storage levels and all other runoff forecasts on the tributaries upstream of the critical river reach which is designated for flood protection.

Case study -- development and results of modelling scenarios

Figure 2 shows the current layout of the system, which ends before the bifurcation near Jamalpur. It is felt that keeping the flows within full bank capacity at Jamalpur would be the best way for reservoirs to minimize the negative effects of downstream flooding. The following labels are used in the schematic in Figure 2:

- Blue lines represent natural water courses (river reaches and tributaries)
- Blue coloured areas represent the surface water of the reservoirs created by dams
- Red lines with arrowheads represent diversion canals
- Green areas in square format represent irrigation blocks

It should be noted that all reservoirs have flood storage zones since their initial design included flood management as one of the operational objectives. The remaining objectives are water supply to municipalities, industry, and irrigation, along with the generation of power at the Maithon, Panchet, and Tilaiya dams with installed capacities of 60, 80, and 4 MW, respectively. This modeling exercise is intended to investigate possible responses of the model to the known inflows assuming 1, 2, or 3-day inflow forecasts. Three distinct historical floods from the historical years 2000, 2006, and 2009 were selected for this purpose. Floods in 2000 and 2006 were recorded in the second half of September, while the 2009 flood was recorded in August. Designation STO-1, STO-2, or STO-3 implies a solution based on the assumed runoff forecasting horizon of one, two, or three days ahead. The goal of the model is to find the best way to operate the four reservoirs to maintain the downstream flow at Jamalpur at or below 2850 m^3/s, which is its current full-bank capacity. The model minimizes the deviations from this flood threshold when they are inevitable. All model runs were executed assuming the starting storage is at the Full Reservoir Level (FRL). The distance between Tilaiya and Maithon reservoirs along the river thalweg is subdivided into four sub-catchments, each one represented by two sequential river reaches and a tributary at the end of the reach. The two river reaches are used to implement hydrological river routing depicted for some of them in Figure 2.

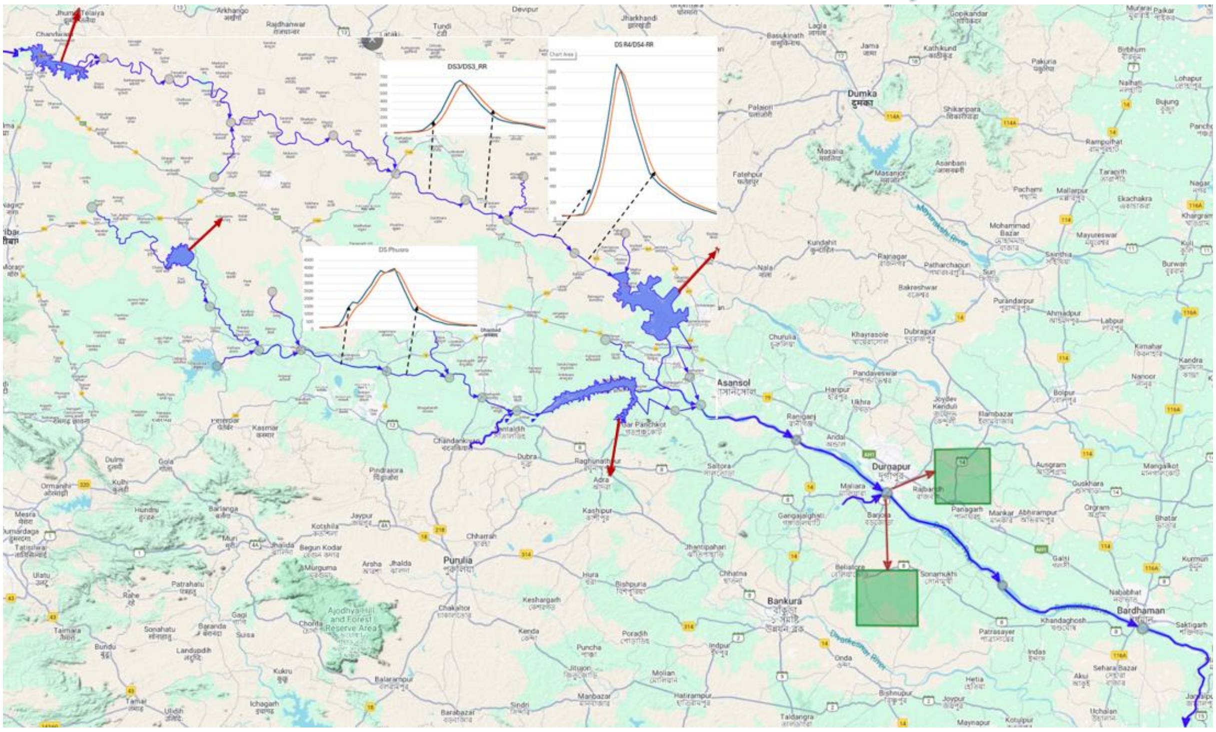

Figure 2. Damodar River Basin modeling schematic

Reservoir operation is aimed at minimizing flows above 2850 m^3/s at the Jamalpur located at the downstream end of the system. Finding the right reservoir releases is complicated by the transformation of flow caused by river routing processes on river reaches both upstream and downstream of the reservoirs, by the influx of flow from the tributaries, and by reduction at diversion canals. There is often a substantial local inflow downstream of the reservoirs which must be taken into account when setting the reservoir releases, along with all other constraints related to river routing throughout the river basin. The starting reservoir levels were set to correspond to the full supply levels, which is the most conservative assumption. From the three historical floods analyzed, the worst flood was in 2009, resulting in a mean daily maximum of 7649 m^3/s. Assuming only 1-day runoff forecast, the model managed to lower the flood peak to 5500 m^3/s at Durgapur and 5000 m^3/s at Jamalpur.

There is still some violation of the flow target of 2850 m^3/s at Jamalpur with a 2-day forecast scenario for the 2009 flood that reached 3517 m^3/s as seen in Figure 4, but once the 3-day forecast is introduced the flood damage completely disappears, as shown in Figure 5.

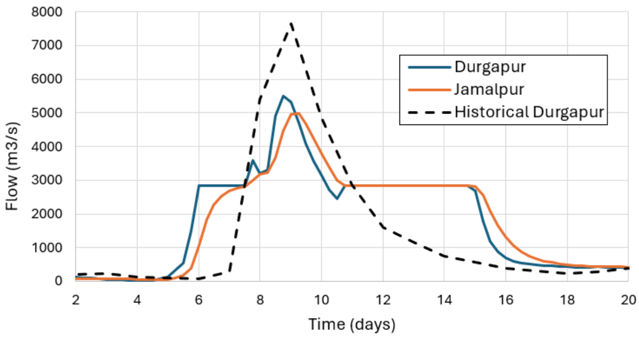

Figure 3. Historical and simulated 2009 flood at Durgapur Barrage, 1-day forecast

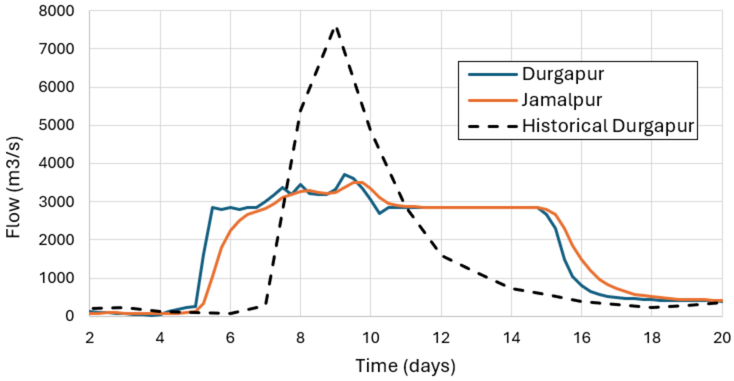

Figure 4. Historical and simulated 2009 flood at Durgapur Barrage, 2-day forecast

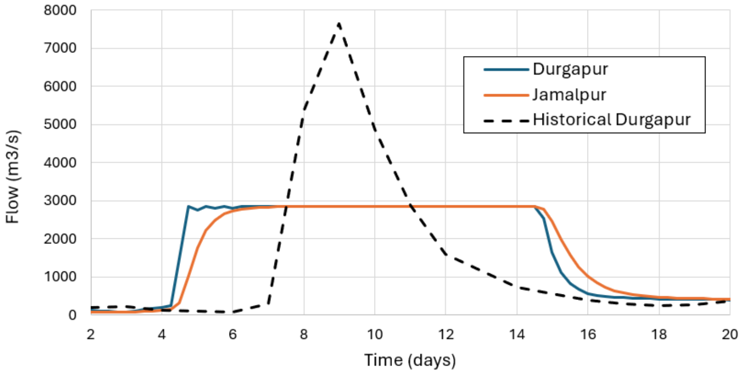

Figure 5. Historical and simulated 2009 flood at Durgapur Barrage, 3-day forecast

The above improvements are possible by initiating pre-flood drawdown by the model which results from the use of optimization within the multiple-time step solution framework. The longer the forecast, the larger the pre-flood drawdown. Figure 6 shows the Maithon reservoir levels for all three scenarios (1, 2, and 3-day forecasts). A similar trend can be observed with the Panchet Reservoir levels in the three scenarios for the 2009 flood, as shown in Figure 7. Figures 8 and 9 show the 2006 flood at Durgapur and Jamalpur for 1 and 2-day forecasts. In this case, the 2-day forecast only marginally exceeds the flood threshold, while the 2000 flood could have been handled with a single-day forecast, as shown in Figure 10. Given that the tributary inflows and diversions are subject to fluctuations, the reservoir releases also show fluctuations. This results in the plots of the time series of reservoir elevations that do not look smooth, as seen in Figures 6 and 7. However, this is an expected result from combining all available variables and routing transformations that must be included in the model.

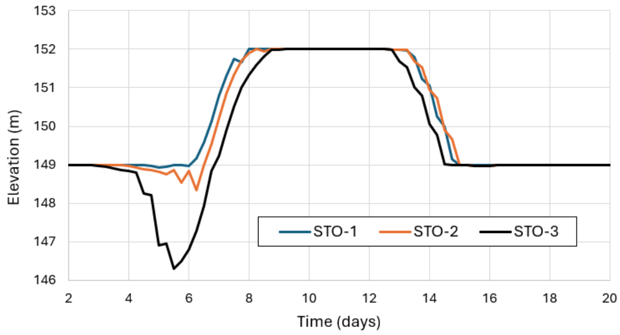

Figure 6. Maithon storage, 2009 flood, 1,2 and 3-day forecasts

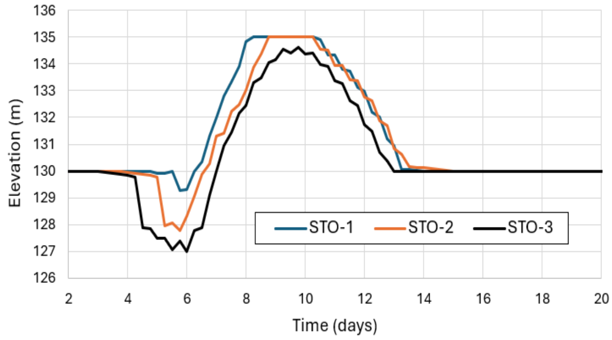

Figure 7. Panchet storage, 2009 flood, 1,2 and 3-day forecasts

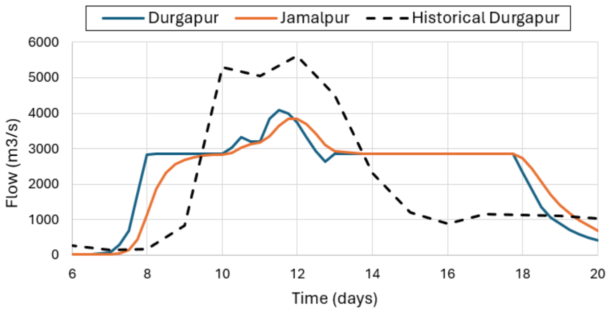

Figure 8. 2006 flood at Durgapur Barrage, 1-day forecast

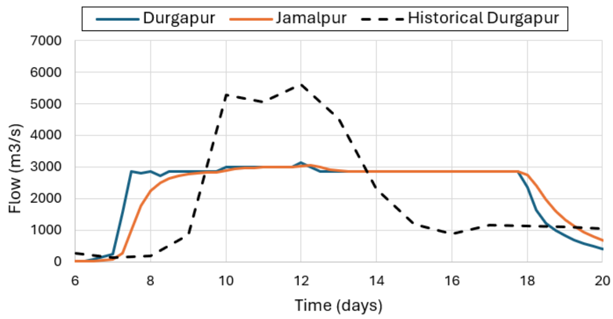

Figure 9. 2006 flood at Durgapur Barrage, 2-day forecast

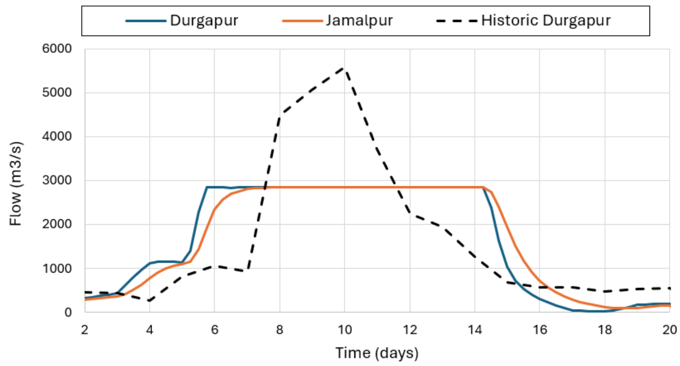

Figure 10. 2000 flood at Durgapur Barrage, 1-day forecast

Conclusions and Recommendations

The numerical tests presented above are based on hindcast historical inflows available for 1, 2 or 3 days ahead. The model shows significant improvements compared to historical operations as a function of the length of the forecasting horizon. The ability to simultaneously balance multiple reservoirs based on their unique inflow hydrographs and common downstream objectives to minimize flood damage can be significant in large river basins with multiple reservoirs, showing a reduction of around 50 percent compared to the historically recorded peak flows at Durgapur Barrage. The use of forecasting models should be verified in real-time by taking advantage of the RTDAS connected to the existing SCADA systems. The work presented here shows that one of the two key components of automated reservoir operation is readily available and available for testing using historical data. Future tests should involve the use of real-time data along with testing its integration with the runoff forecasting models.

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Assessment and Management of Reservoir Sedimentation in India – At a Glance

Patra Bikram Kesharee [1], Harshitha M S[2], Chaudhary Randhir[3]

[1, 2, 3] Central Water Commission, New Delhi, 110066, India

Corresponding author: bikrampatracwc@gmail.com

Abstract

India, akin to many nations, is ramping up efforts to tackle reservoir sedimentation, a critical threat to its water security. With over 6,000 large dams holding 259 billion cubic meters (BCM) of live storage, the country grapples with erratic water availability and substantial infrastructure costs, demanding a strong sediment management strategy. Over the last two decades, growing awareness spurred by conferences, guidelines, and widely distributed publications has positioned India as a leader in sustainable water management. Since the 1990s, policymakers have focused on regular sedimentation assessments, using compiled data to shape future strategies. A recent study of 548 reservoirs utilizing hydrographic and integrated bathymetric surveys alongside remote sensing provides vital insights into sediment patterns. India's annual sedimentation rate stands at 1.62 thousand cubic meters per square kilometer ($m^3/km^2/yr$), with Himalayan basins showing the highest impact. This paper explores these results, focusing on sediment yield variations and their effects on dam durability. Beyond assessment, India is adopting forward-thinking management at basin and reservoir levels. Catchment area treatment (CAT), a basin-wide tactic, is increasingly popular, curbing sediment inflow through erosion control and soil stabilization. At the reservoir level, dam design has evolved from a rigid "design life" approach to one prioritizing sustainability. In high-sediment areas, new projects feature dual-function spillways for flood and sediment management, deep sluice designs, and operational methods like drawdown flushing and sluicing, marking a departure from earlier neglect of sediment issues. These efforts highlight India's dedication to aligning infrastructure needs with ecological resilience. By merging cutting-edge assessment with proactive solutions, this study showcases India's response to sedimentation challenges, offering a blueprint for sustaining water resources in a shifting global context.

Keywords: Reservoir sedimentation, bathymetric survey, sediment yield, sustainability, catchment area treatment

Introduction

Reservoir sedimentation, the accumulation of eroded soil and organic material in dam impoundments, is a pressing engineering challenge threatening water infrastructure globally. In India, over 6,000 large dams, with a live storage capacity of 259 billion cubic meters (BCM), face capacity loss, reduced flood mitigation, and ecological degradation issues intensified by high water variability and significant infrastructural investments. These losses disrupt water supply for irrigation, potable use, and hydropower generation, which are critical for a nation where engineering solutions must balance growing demand with finite resources. As favorable dam sites diminish, land costs rise, and environmental regulations evolve, mastering sedimentation management emerges as a cornerstone of modern water resource engineering, essential for both existing structures and future designs.

Globally, engineers are advancing sedimentation strategies, and India is at the forefront, driven by two decades of heightened awareness through technical conferences, guidelines, and widely disseminated publications. Since the 1990s, Indian policymakers and engineers have prioritized systematic sedimentation assessments, leveraging data to refine planning and design. This paper presents a unique engineering perspective through a comprehensive study of 548 reservoirs, utilizing hydrographic surveys, integrated bathymetric systems, and remote sensing to quantify India's sedimentation rate at 1.62 thousand cubic meters per square kilometer per year ($m^3/km^2/yr$). It highlights regional disparities, notably in sediment-laden Himalayan basins, and their implications for dam longevity. Distinctively, it examines India's shift from a traditional "design life" approach to a sustainable engineering framework, incorporating catchment area treatments (CAT) to curb sediment inflow and advanced reservoir designs with dual-function spillways and deep sluice systems for flood and sediment control. By integrating rigorous assessment with innovative management—spanning basin-level erosion control to operational tactics like drawdown flushing—this study offers a pioneering analysis of India's engineering response to sedimentation. It underscores a commitment to resilient infrastructure, providing a technical blueprint for sustaining water resources amid global challenges.

Reservoir sedimentation

Reservoir sedimentation originates from well-established river fluvial dynamics, where sediment transport hinges on flow velocity. Rivers carry sediments ranging from coarse gravel to fine silt that settle abruptly at reservoir inlets as velocities drop sharply upon entering the still water body. Seminal works by Morris and Fan (1997) [1], Schleiss et al. (2014) [2], and ICOLD Bulletin 115 (1999) [3] detail this process: heavier, coarser sediments deposit first near the reservoir mouth, while finer particles, governed by Stokes' law, settle in deeper zones with minimal flow. Figure 1 illustrates this classic zonation, showing a gradient from coarse deltaic deposits to fine sediment layers downstream—an essential pattern for engineers to grasp.

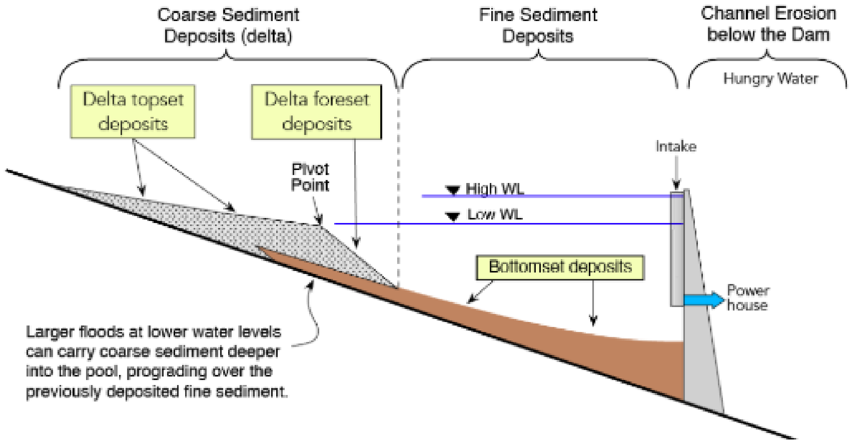

Figure 1 Typical zonation of sediment deposits in a reservoir and channel erosion downstream resulting from the sediment-free 'hungry' water passing the dam [4]

The extent and nature of sedimentation depend on reservoir operation and physical characteristics, such as bed slope and valley shape. Storage dams, characterized by high capacity-to-inflow ratios (gross capacity divided by annual inflow), trap both bedload and suspended sediments effectively. In contrast, run-of-river hydropower schemes, with lower ratios, primarily retain bedload while allowing suspended sediments to pass downstream more readily. These distinctions, rooted in hydraulic and geomorphic principles, underscore the need for tailored engineering approaches. Accurate sedimentation assessment extends beyond mere volumetric estimates; it requires understanding sediment type, distribution, and deposition patterns. Such data are critical for devising optimal management strategies, whether mitigating storage loss, enhancing flood control, or preserving ecological balance. For instance, misjudging sediment composition could lead to inefficient flushing designs or underestimating capacity reduction. This section lays the technical foundation for analyzing India's sedimentation challenges, linking fluvial processes to practical reservoir management solutions explored later in the paper.

Assessment of Reservoir Sedimentation

Reservoir sedimentation assessment is a complex engineering task, broadly categorized into three approaches: (1) analytical/empirical methods, (2) stream flow analysis, and (3) reservoir capacity surveys. Each method varies in precision, application, and technological demand, reflecting the intricate interplay of sediment transport and deposition. Historically, pre-20th-century engineers relied on analytical methods (e.g., Khosla et al., Varshney et al.) and empirical models like Brune's trap efficiency [5], Churchill's method, or Sumi classification to estimate sediment yield and retention. These approaches, while foundational, provided only coarse approximations, lacking the granularity needed for modern design. Stream flow analysis offers a more dynamic alternative, measuring discharge and sediment at reservoir inflow and outflow points. Suspended sediment is directly observed, while bedload is inferred from basin-specific relationships. The difference between inflow and outflow quantifies deposition over time. Advances in computational power have elevated this method, with numerical modeling now simulating not just sediment volume but also spatial patterns within reservoirs. While suspended sediment transport modeling yields reliable estimates, bedload dynamics remain less resolved due to high variability across time (years) and space (kilometers), compounded by uncertain input parameters. Despite these limitations, numerical methods are widely favored for their desktop convenience. For existing reservoirs, capacity surveys deliver the most accurate data. Three techniques dominate: hydrographic surveys, integrated bathymetric surveys (IBS), and remote sensing. Traditional hydrographic surveys, using sounding rods and range finders, are labor-intensive, taking 2–3 years for large dams like Hirakud, India, and are increasingly outdated. IBS, enhanced by GPS and acoustic systems (Hilgert et al., 2024 [6]), balances speed and precision when time permits. Remote sensing, a rapid desktop method, is gaining traction despite challenges like cloud cover and depth inaccuracies, which researchers are addressing with machine learning. Engineers often combine these methods, tailoring choices to project needs and constraints, ensuring actionable sedimentation insights.

Reservoir Sediment Management - Global trends

Reservoirs worldwide, with an estimated storage of 7,000 billion cubic meters (BCM) (World Bank, 2023 [7]), are losing capacity at an alarming rate. White et al. (2001 [4]) report an annual global storage loss of 0.5–1.0% due to sedimentation, a figure starkly illustrated by the decline in total capacity despite ongoing dam construction. This cumulative effect has reversed gains in storage, with per capita capacity plummeting since the 1960s, a trend signaling a critical challenge for water resource engineering. Sedimentation's seriousness lies not just in reduced volume but in its cascading impact on flood control, hydropower, and water supply.

Historically, dam engineering treated sedimentation as a deferred problem, with little focus on management before the 1980s. Pre-1980s designs assumed future generations would address the issue, sidelining sustainability. However, mounting adverse effects, such as capacity loss, ecological damage, and operational inefficiencies, shifted this mindset post-1980s, spurred by a global push for long-term resilience. This evolution is marked by key developments: (1) Technical publications surged 3–4 times after the 1990s, reflecting intensified research; (2) Organizations like ICOLD prioritized sedimentation, addressing it at the 2009 Congress and issuing dedicated bulletins (e.g., B115 [3], B144 [8]) since the late 1990s; (3) The traditional "design life" approach, which ignored sediment management during planning, gave way to sustainable design principles. The World Bank (2023 [7]) encapsulates this shift: "The 20th-century-built reservoirs; the 21st must sustain them, transforming non-sustainable assets into enduring infrastructure." Consequently, (4) Sediment management strategies, flushing, bypassing, and dredging are now integrated into both new and retrofitted projects globally. These trends underscore a paradigm shift, offering engineers a framework to adapt and innovate, a context India leverages as explored later in this paper.

Scenario in India

Reservoir Sedimentation

India's experience with reservoir sedimentation mirrors global patterns, yet its scale and environmental context amplify the challenge. A peek into the scenario of sediment related problems in Indian dams is brought out by Patra.et.al [9]. Receiving approximately 4,000 billion cubic meters (BCM) of annual precipitation (per early studies), the country contends with significant spatial and temporal variability in water availability. This necessitated a robust storage infrastructure post-independence, when capacity stood at just 15.6 BCM in 1947, constrained by limited technology and resources. Today, the National Register of Large Dams (NRLD, 2023 [10]) reports 6,281 reservoirs boasting a gross storage capacity of 344 BCM and live storage of 259 BCM critical assets for irrigation, hydropower, and domestic supply.

Sedimentation, however, erodes this capacity at an alarming rate. Annual soil erosion is estimated at 6,000 million tonnes from sheet erosion alone, with gully and ravine erosion further degrading 8,000 hectares of land yearly (source pending verification). This relentless sediment influx, coupled with aging infrastructure—over half of India's dams exceeded 25 years by 2020—has accelerated storage depletion. By the 1990s, engineers and policymakers recognized sedimentation as a critical threat, not merely a natural process but a pressing engineering problem impacting water security and economic viability. Unlike some nations with more uniform hydrology, India's diverse climate and topography, from Himalayan sediment traps to monsoon-driven plains, intensify the issue. The sheer volume of eroded material underscores the urgency for tailored management strategies, distinguishing India's scenario within the global narrative. This section sets the stage for examining how India has responded, leveraging advanced assessments and innovative designs to mitigate the sedimentation's toll on its vital reservoir network, a topic explored in subsequent sections.

Assessment of Reservoir Sedimentation

Assessment of reservoir sedimentation in India has evolved significantly, transitioning from sporadic efforts to systematic, technology-driven surveys. This section outlines the historical progression, methodologies, and key findings underpinning India's approach. Sedimentation surveys in India date back to the 1870s, but structured efforts began in the 1950s under the Central Board of Irrigation and Power, with various research organizations contributing. By the late 20th century, the Central Water Commission (CWC), the nation's apex water resources body, assumed leadership. Surveys have since been conducted under initiatives like the Research & Development Scheme and the National Hydrology Project (NHP), with NHP leading the effort, completing 373 surveys by November 2024.

Since the 1990s, India has systematically collected and analyzed sedimentation data, culminating in the CWC's "Compendium of Sedimentation of Reservoirs in India." First published in 1991 (covering 46 reservoirs), subsequent editions in 2001 (144 reservoirs), 2015 (243 reservoirs), and 2020 (369 reservoirs) reflect growing scope and precision, with a new edition underway. These compilations, based on reservoir capacity surveys, aim to refine sedimentation rate estimates for project planning and basin management. Early assessments relied on hydrographic surveys, using conventional tools like sounding rods. Over time, advanced techniques emerged: Integrated Bathymetric Surveys (IBS) employ echo sounders, multi-beam sonar, LIDAR, and differential GPS (DGPS) for enhanced accuracy, while remote sensing leverages 10m-resolution satellite data (e.g., Sentinel-2, LANDSAT) for rapid analysis. IBS, predominantly under NHP, follows a rigorous process—survey planning, data collection, calibration, processing, and reporting—to update Elevation-Area-Capacity curves, sedimentation rates, and reservoir life estimates. Hydrographic surveys use a 100m x 100m grid (50m x 50m for reservoirs under 25 km²), with sediment sampling scaled to reservoir size (e.g., 21 samples for 0–25 km², up to 170 for >200 km²). Remote sensing, despite limitations, tracks water spread variations to infer volumetric changes. The most recent study analyzes 548 reservoirs, up from 96 in 1991. Of these, 466 were hydrographically surveyed, and 82 used Satellite Remote Sensing (SRS), though this paper focuses on hydrographic data. Workable datasets from 439 reservoirs (gross storage) and 330 reservoirs (live storage) reveal critical trends, detailed in subsequent sections, shaping India's sedimentation management strategies.

a. **Gross and Live Storage Losses**: The 439 hydrographically surveyed reservoirs exhibit an annual gross storage loss of 0.74%, equating to 1.81 million cubic meters (MCM) per year—down from 0.95% in 2015 estimates. Live storage loss averages 0.49% annually (1.16 MCM), with a range of 0.01–6.7%, reflecting variability in sediment impact across reservoirs.
b. **Small Dams' Vulnerability**: Reservoirs under 20 MCM capacity show significantly higher average losses: 23.65% for gross storage and 0.77% for live storage. These figures indicate that smaller dams, particularly in minor basins, face a greater risk of rapid storage depletion due to sedimentation.

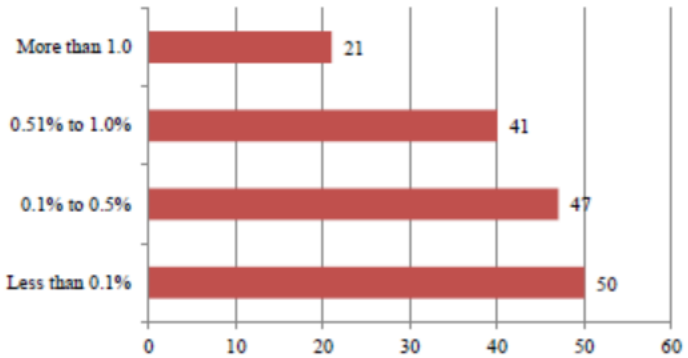

Figure 2 Average age of reservoirs in years (from impoundment till last survey) against various rates of annual gross capacity loss (%)

c. **Age-Related Trends**: Newer reservoirs demonstrate a higher annual rate of gross storage loss compared to older ones, as depicted in Figure 2. This trend suggests that initial sedimentation rates peak early in a dam's operational life, as expected due to the increased trap efficiency during the early years of a reservoir
d. **Absolute Storage Loss Distribution**: Among the 439 reservoirs, approximately 5% have lost over 50% of their gross storage, while 64% retain more than 80% of their original capacity (i.e., loss <20%). This distribution highlights a skewed impact, with a minority of dams experiencing severe sedimentation.
e. **Regional Disparities**: The Himalayan region records the highest gross storage loss at 4.7 BCM (17.19% of capacity), with an annual rate of 2.87% far exceeding other basins like the Deccan Peninsula or West Flowing Rivers (see Table 1). Notably, this elevated rate persists despite fewer reservoirs in the Himalayan sample, underscoring the region's intense sediment yield.
f. **Sediment Deposition Rates**: India's average sediment deposition rate is 1.62 thousand cubic meters per square kilometer per year ($m^3/km^2/yr$) for gross storage. The Himalayan region and West Flowing Rivers beyond Tapi (including South Indian rivers) exhibit the highest rates at 2.49 and 3.37 thousand $m^3/km^2/yr$, respectively, far exceeding other basins such as the Indo-Gangetic Plains, East Flowing Rivers up to Godavari, Deccan Peninsula, West Flowing Rivers up to Narmada, and Narmada-Tapi Basin. These region-specific rates

serve as practical benchmarks for engineers designing projects, with the Himalayan basin's elevated yield driven by steep topography and erosion standing out as anticipated.

Table 1 Region-wise loss in Gross Storage Capacity as per the Hydrographic Survey

Region	Number of Reservoirs	Total Designed Gross Capacity (BCM)	Total Surveyed Gross Capacity (BCM)	Total Loss in Gross Storage (BCM)	Percentage Loss in Gross Storage	Average Annual Percentage Loss
Himalayan Region	45	27.20	22.50	4.70	17.19	2.87
Indo-Gangetic Plains	35	31.90	27.50	4.50	14.03	0.43
East-flowing Rivers	33	20.57	17.36	3.21	15.61	0.37

	up to Godavari						
	Deccan Peninsular	141	76.40	63.05	13.35	17.48	0.62
	West Flowing Rivers up to Narmada	120	8.04	6.96	1.08	13.38	0.45
	Narmada and Tapi Basin	21	22.92	19.78	3.16	13.73	0.59
	West-flowing rivers beyond Tapi and South Indian Rivers	44	13.24	12.22	1.02	7.73	0.37
	India	439	200.31	169.34	30.9	15.46	0.74

Table 2 Comparison between actual and designed rate of sedimentation of reservoirs

Ratio of actual rate of sedimentation To the design rate of sedimentation	Number of Reservoirs	Average age of the reservoirs in years
Less than 1	33	41
1-2	27	44
2-3	12	48
3-4	6	53
4-5	3	44
Greater than 5	22	34

g. **Severely Affected Reservoirs**: Of the 439 reservoirs analyzed, 23 have suffered extensive storage loss due to sedimentation. Notable examples include Chamera-I, Salal, and Baira, where sediment accumulation has significantly diminished capacity, highlighting the need for targeted management in high-impact zones.

h. **Design vs. Actual Rates**: Observed sedimentation rates substantially exceed design assumptions, prompting a comparative analysis of 103 reservoirs (detailed in Table 2). Actual rates often surpass design values by 2–3 times, and in some cases, more, revealing systematic underestimation in earlier planning. This discrepancy necessitates a significant upward revision of sediment yield assumptions—potentially doubling or tripling prior estimates—for future studies, design, and operational strategies to ensure resilience against accelerated storage loss.

Management of Reservoir Sedimentation

India is aligning with global trends by integrating sustainability and sediment management into the planning, design, and operation of water resource projects. This shift reflects a proactive response to the sedimentation challenges outlined earlier, evidenced by policy reforms, basin-level interventions, and reservoir-specific innovations. Below, these efforts are detailed in three key areas:

a. Policy Making and Sensitization

India's commitment to sediment management is formalized through robust policy frameworks and awareness campaigns. The "National Framework on Sediment Management (NFSM)" (2022 [11]), issued by the Department of Water Resources, River Development, and Ganga Rejuvenation under the Ministry of Jal Shakti, provides a comprehensive guide for holistic sediment management, including reservoirs. It serves as a manual for state governments, project authorities, and ministries, promoting coordinated action. Over the past decade, technocrats have bolstered this effort with widely circulated publications, such as the "Compendium of Sedimentation of Reservoirs in India" (2020 [12]), which compiles bathymetric survey data and siltation trends across regions; the "Handbook for Assessing and Managing Reservoir Sedimentation" (2019 [13]), detailing assessment techniques; and the "Guidelines for Sediment Management in Water Resource Projects" (2019 [14]), offering a suite of management options. These documents equip dam owners with practical tools—covering erosion control, sediment bypassing, and flushing—while raising awareness among engineers and stakeholders. The compendium's iterative updates reflect evolving data, while the handbook and guidelines provide actionable strategies, bridging theory and practice. This policy-driven sensitization, rooted in technical documentation, positions India to address sedimentation systematically, fostering a culture of proactive management that complements global sustainability goals.

b. Basin-Level Management Methods

At the basin level, India employs comprehensive strategies to curb sediment inflow by stabilizing upstream catchment areas, blending structural and non-structural measures under Catchment Area Treatment (CAT) and watershed management. These approaches are vital for both new and existing reservoirs, reducing erosion and sediment loads effectively. For instance, Maithon Reservoir saw its annual capacity loss drop from 7.38 million cubic meters (MCM) to 1.37 MCM following watershed interventions, a 81% reduction over decades. Similarly, Panchet Reservoir's annual storage loss decreased from 14.98 MCM (1959–1966) to 4.06 MCM (1996–2019) at a flood management pool of 132.62 m (435 ft), largely due to the upstream Tenughat Dam acting as a sediment-trapping check dam. The Gosi Khurd catchment in Maharashtra exemplifies CAT implementation: engineers assess erosion potential (illustrated in Figure 3), dividing the basin into sub-regions prioritized for interventions. Structural measures—nala bunds, check dams, and toe/retaining walls—target high-erosion zones, while non-structural efforts like afforestation stabilize soil naturally. Napier grass (Pennisetum purpureum), with its dense root system, is widely planted along riverbanks and catchments, effectively reducing soil displacement during monsoons. These basin-level tactics not only mitigate sediment inflow but also enhance upstream land resilience, offering a scalable model for India's diverse topography. By addressing the root cause of sedimentation—erosion—these measures extend reservoir lifespans, aligning with sustainable engineering principles.

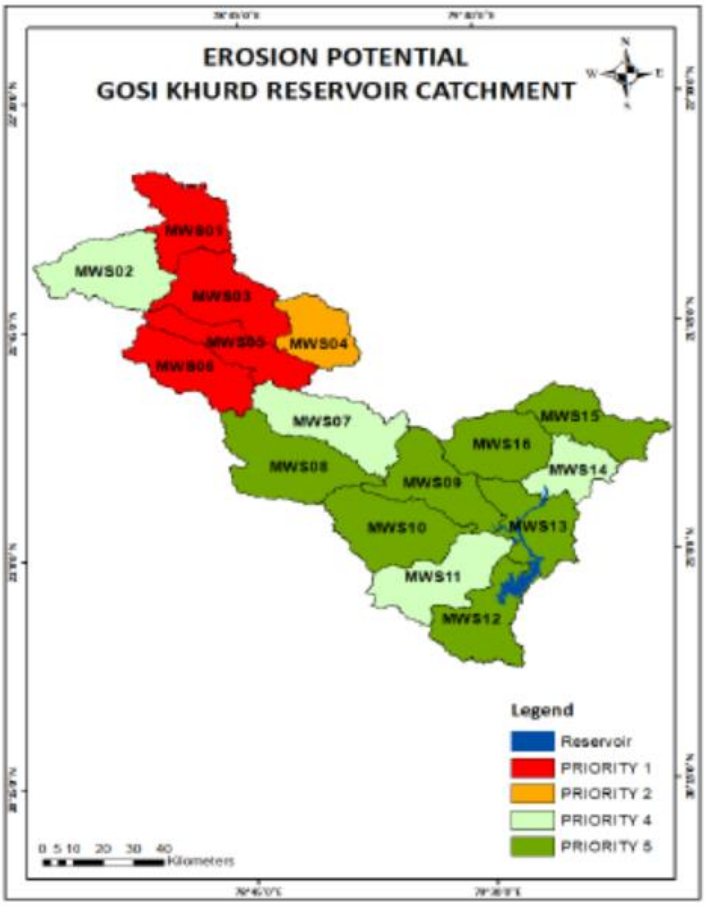

Figure 3 Erosion Potential of Gosi Khurd Catchment

c. Reservoir-Level Management Methods

At the reservoir level, India is redefining dam design and operation to manage sedimentation directly, shifting from a finite "design life" philosophy to one prioritizing sustainability. This transformation is driven by site-specific factors topography, sediment load, functional needs, and economics shaping the applicability of various techniques. A key innovation is the adoption of dual-function spillways, designed for both flood control and sediment expulsion via low-level outlets and large-sized gates. Operational strategies like sluicing and drawdown flushing (pressurized or full) are now standard in new projects and retrofitted into existing ones where feasible. For example, Naptha Jhakri employs drawdown flushing – it helped to recover capacity lost to a massive sediment influx (peak concentration 151,000 ppm) triggered by an upstream natural dam failure just 2–3 years after commissioning; low-level spillways facilitated significant reclamation. The 200 m plus high Lakhwar Dam, under construction, incorporates deep sluice spillways explicitly for sediment management, with outlets exceeding 7m in dimensions. Larger sluices (>10m) feature in projects like Chamera I, Chamera II, Tanakpur, Teesta Low Dam III and IV, Teesta V, Lower Subansiri, and Upper Subansiri, optimizing sediment passage during high-flow events. These designs reflect a proactive shift, contrasting with the past neglect of sediment dynamics. Less viable options, such as dredging and sediment bypassing, are rarely used due to high costs and limited techno-economic feasibility, though small-scale projects occasionally adopt them for short-term relief. This reservoir-level evolution—emphasizing durable infrastructure over temporary fixes—underscores India's engineering adaptation to sedimentation, ensuring long-term functionality amid growing environmental pressures.

Conclusion

Assessment of Reservoir sedimentation poses a multifaceted challenge that water resource engineers must address to sustain India's critical infrastructure. This paper synthesizes extensive assessments and management strategies, drawing actionable insights for India's 6,000+ reservoirs. Below, the key takeaways, management efforts, and future imperatives are outlined:

Sedimentation Assessment Insights

Sedimentation's toll on reservoirs—capacity loss, ecological disruption, and structural erosion—underscores the need for rigorous assessment, a priority recognized by water professionals globally and in India. Data from the National Register of Large Dams (2023 [10]) catalog 6,000 major and medium dams, while this study focuses on 548 reservoirs, with 439 hydrographically surveyed providing a representative sample. Analysis reveals India's sedimentation rate at 1.62 thousand cubic meters per square kilometer per year ($m^3/km^2/yr$), with annual gross and live storage losses of 0.74% (1.81 MCM) and 0.49% (1.16 MCM), respectively—within the global range of 0.5–1% but away from extremes of 0–5%. Regionally, the Himalayas (2.49 thousand $m^3/km^2/yr$) and West Flowing Rivers beyond Tapi (3.37 thousand $m^3/km^2/yr$) exhibit the highest siltation, driven by steep terrain and erosion. Critically, actual sediment yields exceed design estimates by 3–5 times, exposing flaws in past planning assumptions. While total storage exhaustion is not imminent, these findings signal sedimentation as a stealthy threat to long-term water security if unchecked.

Management Strategies and Progress

India's focus on sediment management, intensifying over the past 2–3 decades, mirrors global sustainability trends. National and regional efforts—via conferences, the "Compendium of Sedimentation" (2020 [12]), and technical guidelines—equip engineers to combat sedimentation's adversities. Practical measures span reducing sediment yield (e.g., Catchment Area Treatment at Gosi Khurd, check dams), routing sediments (e.g., sluicing, low-level spillways), and eroding deposits (e.g., drawdown flushing). A transformative shift in design philosophy—from a finite "design life" to a sustainable approach—marks a milestone among Indian dam engineers, integrating sediment management into project lifecycles. These techno-economically viable strategies, tailored to India's diverse basins, demonstrate proactive adaptation, balancing infrastructure needs with environmental resilience.

Future Imperatives

Reservoir sedimentation remains an urgent engineering dilemma as viable dam sites dwindle. Unaddressed, it risks rendering reservoirs obsolete by eroding storage capacity—a fate India cannot afford given its water demands. Bathymetric surveys, though resource-intensive, are indispensable for ground planning and design in reality, as evidenced by this study's insights. Moving forward, engineers must refine sediment yield estimates, adopt real-time monitoring, and scale sustainable practices like CAT and advanced design and operational measures nationwide. This paper's findings and strategies offer a blueprint not just for India but for global water management, urging a proactive stance to secure reservoirs for future generations.

Acknowledge

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Disclaimer

The views expressed and suggestions presented in this paper are solely those of the authors and do not reflect the official stance or opinions of any institution. The analysis and recommendations are based on independent research and interpretation of available data.

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Navigating Geohazards: Engineering Strategies for Safe and Sustainable Himalayan Dams

Pramod Narayan[1], M S Harshitha[1], Bikram Kesharee Patra[1], Randhir Kumar Choudhary[1]

[1] Central Water Commission 1 RK Puram, New Delhi, 110066, India

Corresponding author: bikrampatracwc@gmail.com

Abstract. India, ranking third globally with 6,138 large dams, relies heavily on its dam infrastructure for water management, irrigation, and hydroelectric power generation. However, as ideal dam sites become scarce, many of the 143 new dams under construction are being pushed into the Himalayan region, a geologically complex and environmentally fragile area. The Himalayas, known for high seismic activity, unstable geology, extreme weather conditions, and glacial hazards, pose formidable challenges to dam construction and operation. These risks necessitate innovative engineering solutions, real-time hazard monitoring, and adaptive management strategies to ensure the long-term safety and sustainability of critical infrastructure. Without strategic interventions, these projects risk structural failures, economic losses, and irreversible environmental consequences. The Himalayan region presents multifaceted challenges that demand immediate attention. Seismic hazards pose a significant risk, as earthquakes can induce ground shaking, destabilizing dam foundations and increasing the probability of failure. The region's complex geology, characterized by fractured rock formations and active fault zones, complicates tunneling, excavation, and foundation treatments, necessitating advanced geotechnical investigations and reinforcement techniques. High sedimentation rates, driven by rapid erosion of the young Himalayan landscape, lead to reservoir siltation, reduced storage capacity, and increased turbine wear, threatening the efficiency of hydropower projects. Additionally, glacial lake outburst floods (GLOFs), exacerbated by climate change, pose an unpredictable but catastrophic risk to downstream infrastructure. Landslides and debris flows, often triggered by heavy rainfall and seismic activity, obstruct diversion tunnels, block spillways, and damage critical structures, as seen in recent disasters. Cloudbursts and flash floods, coupled with operational failures such as gate malfunctions due to debris accumulation, further complicate dam management, increasing the likelihood of overtopping and structural failure.

Recent extreme events highlight the severity of these risks. The Teesta-III and Teesta-V Hydro-Electric Projects (2023) suffered extensive damage when a GLOF triggered by the collapse of Lhonak Lake led to dam overtopping and infrastructure destruction. The Malana-II HEP (2023) encountered severe operational setbacks when slush and boulders jammed its radial gates, causing uncontrolled overtopping and scouring on the left bank. The Subansiri Lower HEP (2023) faced major construction delays due to a landslide blocking its diversion tunnel, emphasizing the vulnerability of Himalayan dams to geohazards. The Tapovan Vishnugad HEP (2023) experienced geotechnical and geological challenges, reinforcing the need for enhanced tunneling methods and slope stabilization. The Rishi Ganga hydro project (2022) was destroyed by a massive mudslide, demonstrating the urgent need for real-time monitoring and predictive landslide risk assessment. This paper explores engineering solutions and policy interventions essential for mitigating risks in Himalayan dam infrastructure. Ensuring long-term safety requires proactive risk management, interdisciplinary collaboration, and advanced monitoring technologies to address seismic hazards, extreme weather, and geotechnical challenges. As climate change intensifies, a reactive approach is no longer viable. Instead, technology-driven, sustainability-focused strategies must define the future of dam safety, protecting infrastructure, communities, and ecosystems in this high-risk region.

Keywords: Seismic Hazards, Glacial Lake Outburst Floods (GLOFs), Climate Resilience, Geotechnical Challenges, Sustainable Infrastructure

1 Introduction

The Himalayan region is one of the most geologically dynamic and environmentally fragile landscapes in the world, making infrastructure development, particularly dam construction and operation, a complex and high-risk endeavor. With the region's high seismic activity, extreme weather events, glacial lake outburst floods (GLOFs), and landslides, dams in this terrain face unique and evolving challenges. As India expands its hydropower capacity with 143 new dams under construction, many of these projects are situated in geologically unstable zones, necessitating robust engineering solutions, real-time hazard monitoring, and adaptive management strategies. This paper explores the seismic risks, climate threats, and engineering innovations required to enhance the resilience and sustainability of dam infrastructure in the Himalayas. Navigating geohazards is central to ensuring the safety and long-term viability of Himalayan dams. Studies from the Three Gorges Reservoir Area in China emphasize the importance of assessing and mitigating geohazards to protect infrastructure and communities [1]. Similarly, the Coalition for Disaster Resilient Infrastructure [2] highlights the role of wetlands in mountain disaster risk reduction, reinforcing the need for nature-based solutions alongside engineered interventions. The Norwegian University of Science and Technology (NTNU) underscores the necessity of safe and economical design solutions for embankment dams, focusing on both construction and operation [3]. These insights underline the need for comprehensive risk assessments, adaptive engineering strategies, and sustainable dam operation protocols in high-risk environments like the Himalayas.

One of the most pressing concerns in Himalayan dam infrastructure is seismic risk. The region, lying in Seismic Zones IV and V, experiences frequent moderate to large-magnitude earthquakes, which can trigger landslides, ground shaking, and infrastructure failures [4]. The Dudhkoshi Hydropower Project (2023) in Nepal highlights how seismic activity, combined with warming-induced GLOFs, poses significant risks to dam stability, necessitating advanced structural reinforcement, seismic-resistant designs, and emergency preparedness protocols [5]. Additionally, displacement caused by climate change adaptation projects raises concerns about engineered interventions in seismically sensitive zones, emphasizing the importance of socio-environmental impact assessments [6]. Climate change further exacerbates the challenges facing Himalayan dams. Rising temperatures have accelerated glacier retreat and the expansion of glacial lakes, increasing the frequency and intensity of GLOFs, which can breach dam defenses and overwhelm spillways [7]. Studies indicate that climate-induced extreme weather events, including cloudbursts and monsoon-driven floods, disrupt dam operations and heighten flood risks [8]. Risk management and decision-making frameworks are crucial in integrating climate resilience measures into hydropower infrastructure planning [9].

This paper presents a holistic approach to addressing seismic and climate risks in Himalayan dam infrastructure. By reviewing engineering advancements, policy interventions, and case studies of recent dam failures, this study provides actionable recommendations for enhancing resilience, minimizing environmental and social risks, and ensuring the long-term sustainability of hydropower projects. As hydropower remains critical to South Asia's energy future, multi-disciplinary collaboration and adaptive risk management will be key to safeguarding the region's infrastructure and communities.

2 Geohazards and Environmental Challenges

The Himalayan region is one of the most geologically active and environmentally fragile landscapes on Earth, making dam construction and operation particularly challenging. The region's tectonic activity, steep topography, extreme weather events, and glacial dynamics pose serious risks to infrastructure. Understanding these geohazards is critical for ensuring the safety and sustainability of hydropower dams in the Himalayas. This section explores key environmental challenges, including seismic risks, GLOFs, landslides, extreme weather events, and sedimentation, which directly impact dam infrastructure.

2.1 Seismic Risks

The Himalayas lie in Seismic Zones IV and V, where frequent moderate to large-magnitude earthquakes pose a serious threat to dam stability. This region is the result of the ongoing collision between the Indian and Eurasian tectonic plates, leading to active fault lines, high-strain accumulation, and periodic seismic events [4]. Earthquakes in the region can cause ground shaking, differential settlement, liquefaction, and slope failures, all of which compromise the structural integrity of dams. The 2015 Nepal Earthquake, for instance, triggered massive landslides and infrastructure failures, underscoring the vulnerability of Himalayan hydropower projects [8]. Given the seismic risk, earthquake-resistant dam designs, structural reinforcements, and real-time monitoring are essential to ensure resilience in this dynamic environment.

2.2 Glacial Lake Outburst Floods (GLOFs)

One of the most severe hydrological threats in the Himalayas is GLOFs, which occur when unstable glacial lakes breach their natural or artificial barriers, releasing large volumes of water downstream. Rising temperatures due to climate change have led to the rapid retreat of glaciers, forming hundreds of new proglacial lakes in the region [7]. When triggered by ice avalanches, earthquakes, or intense rainfall, these lakes can release floodwaters with devastating consequences for downstream communities and dam infrastructure. The 2023 Teesta-III and Teesta-V Hydro-Electric Projects in Sikkim suffered extensive damage when a GLOF triggered by the collapse of Lhonak Lake overtopped dam defenses, causing severe erosion and infrastructure loss. Effective GLOF mitigation requires remote sensing-based monitoring, reinforced embankments, controlled drainage of glacial lakes, and early warning systems.

2.3 Landslides and Debris Flows

Landslides are a persistent threat to Himalayan dam infrastructure due to steep slopes, unstable rock formations, and high-intensity rainfall. Seismic activity and excessive deforestation further exacerbate slope instability, increasing the frequency of mass wasting events. Landslides can block rivers, obstruct dam spillways, damage reservoirs, and even cause sudden dam failures. The 2023 Subansiri Lower Hydroelectric Project faced significant delays when a landslide blocked its diversion tunnel, halting construction and affecting power generation schedules. Mitigation strategies include slope stabilization using rock bolting, retaining structures, bioengineering solutions, and continuous geotechnical monitoring.

2.4 Extreme Weather Events

The Himalayas are highly susceptible to extreme rainfall events, particularly cloudbursts, which result in intense localized flooding, flash floods, and rapid sediment transport. Cloudbursts often overwhelm dam spillways and flood protection systems, leading to overtopping and uncontrolled water releases. The 2022 Rishi Ganga disaster in Uttarakhand, triggered by extreme rainfall and a subsequent mudslide, destroyed a hydropower project and caused significant loss of life. With climate change increasing the frequency and intensity of such events, improved flood forecasting models, enhanced drainage systems, and resilient spillway designs are crucial for reducing flood-related risks.

2.5 Sedimentation and Reservoir Management

The young and fragile geology of the Himalayas results in high erosion rates, causing excessive sediment deposition in reservoirs. Sedimentation leads to loss of storage capacity, increased turbine wear, and reduced power generation efficiency. Heavy monsoonal rains, landslides, and glacial meltwater further contribute to sediment transport, creating major operational challenges. The Malana-II HEP (2023) suffered severe damage when slush and boulders jammed its radial gates, leading to uncontrolled overtopping and scouring of dam structures. Effective sediment management strategies include sediment flushing, bypass tunnels, silt exclusion systems, and upstream watershed conservation measures to maintain reservoir functionality.

3 Case Studies of Recent Dam Failures and Incidents

3.1 Teesta-III & Teesta-V Hydro-Electric Projects (2023) – GLOF impact

The Teesta-III and Teesta-V Hydro-Electric Projects in the Eastern Himalayas were significantly impacted by a GLOF in 2023. In early October 2023, Sikkim experienced unprecedented rainfall, receiving more than double its normal precipitation. Between October 3 and 4 alone, the state recorded five times its usual rainfall. This excessive rainfall led to the breach of the South Lhonak Lake's banks (Figure 1), triggering a GLOF and releasing a massive volume of water that cascaded down the Teesta River [10]. Despite efforts to open the dam's gates, the floodwaters overwhelmed the Teesta-III dam, causing it to collapse within minutes and resulting in widespread destruction downstream [10]. The Teesta-V project also suffered significant damage due to the flood. The powerhouse was submerged, and the connecting bridge was washed away [10]. While the Teesta projects highlight the destructive potential of GLOFs, they also underscore the importance of proactive risk management. Despite the challenges, advancements in GLOF detection and modeling offer opportunities to better understand and mitigate these hazards, ensuring the resilience of critical infrastructure in the Himalayas. The following sections outline the analysis of event and the lessons learned.

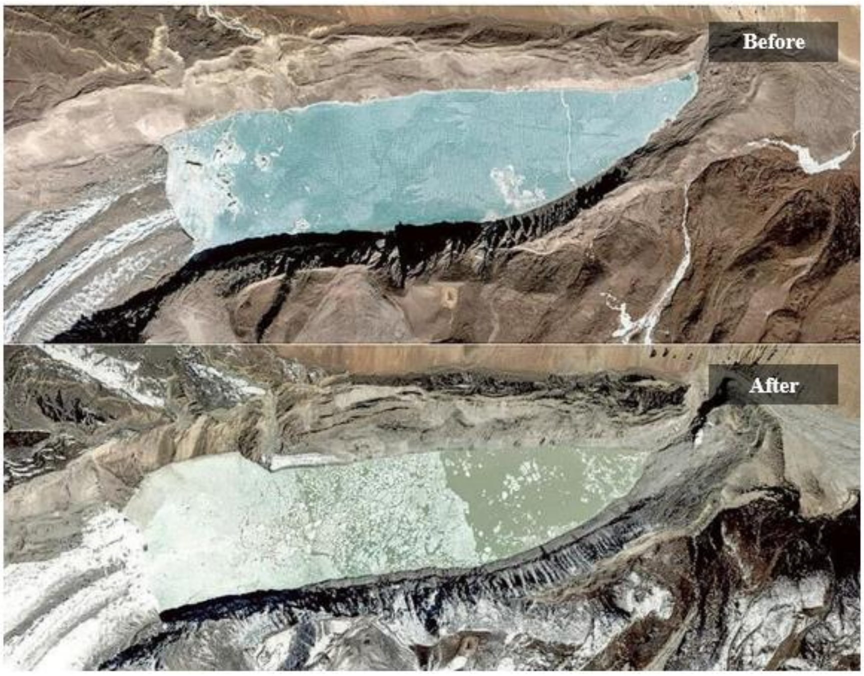

Figure 6 Illustrates the conditions of South Lhonak glacial lake before and after the outburst event on 16.09.2023

Several factors contributed to the severity of the disaster. At Teesta-III, the inability to operate spillway gates promptly was a significant factor in the dam's failure (Figure 2). Delayed responses prevented the timely release of excess water, leading to overtopping [11]. Additionally, Environmental Impact Assessments (EIAs) for these projects did not adequately account for the potential of GLOFs, despite the known glacial dynamics in the region. This oversight led to insufficient structural and operational preparedness [12]. Accelerated glacial melting due to climate change also increases the frequency and magnitude of GLOFs, necessitating updated risk assessments and adaptive management strategies.

The 2023 GLOF disaster highlights several critical lessons for future hydroelectric projects. Mitigating disasters like glacial lake outburst floods (GLOFs) demands a comprehensive strategy. This includes reinforcing lake boundaries and implementing controlled drainage systems, alongside robust remote sensing monitoring coupled with effective early warning systems [13]. Remote sensing, employing satellite and aerial imagery, facilitates continuous observation of glacial lakes and their environment, providing critical data on lake size and volume, glacier melt rates, moraine dam stability, and surrounding terrain, thus enabling early identification of escalating GLOF risk.

Figure 7 Depicts the Teesta-III Dam before and after the GLOF event on 04.10.2023

Reinforcing natural lake barriers (moraine dams) involves strengthening them through compaction, stabilization, and the addition of artificial materials like rocks or geotextiles, potentially including the construction of engineered spillways for controlled water release. Controlled drainage techniques, such as siphoning, pumping, or tunneling, aim to artificially lower lake levels, reducing the potential volume of a GLOF. Furthermore, structural and operational measures are crucial for dams and associated infrastructure. Enhancing infrastructure resilience by designing dams and spillways capable of handling sudden large inflows can mitigate structural failures. Comprehensive and updated EIAs that account for climate change and glacial dynamics is essential for informed project planning and risk reduction [14]. Early warning systems are vital for detecting imminent GLOFs and disseminating timely alerts to downstream communities. This involves real-time sensor monitoring, reliable communication networks for warning dissemination. Further, comprehensive active community engagement in disaster preparedness and response planning can improve resilience and ensure timely evacuations during emergencies. A holistic GLOF mitigation strategy integrates these structural and non-structural measures, tailored to the specific project requirements and the unique characteristics of each glacial lake.

3.2 Malana-II HEP (2024) – Radial gate jamming and overtopping

The Malana-II Hydroelectric Project, commissioned in 2012, is a 100 MW run-of-river power plant located on the Malana River in Kullu district, Himachal Pradesh. Developed by Everest Power Private Limited, the project plays a significant role in regional power generation [15]. In July 2024, the region experienced intense rainfall, leading to increased water inflow into the Malana-II dam reservoir. The excessive inflow caused water to overflow the dam (Figure 8), leading to the jamming of its radial gates due to large amounts of silt and boulders [16]. The primary cause of the radial gate jamming was the accumulation of silt and debris following the flash flood. Additionally, the approach road to the dam site was washed away, complicating repair efforts [17]. A similar overtopping event occurred earlier in August 2013 when both operating units, handling a discharge of 16 cumecs in the river, suddenly tripped. The radial gates failed to operate due to sloughing or collapse of silt deposited in front of them, causing the reservoir water level to rise rapidly. Initially at MDDL, the water level surged unexpectedly, leading to the overtopping of the concrete gravity dam.

Several factors contributed to the incident. Firstly, the radial gates, designed to regulate water discharge, failed to operate as intended, preventing the controlled release of excess water. Secondly, heavy rainfall led to increased sediment and debris flow into the reservoir. The obstruction of access roads due to flooding hindered the timely removal of silt and debris, exacerbating the situation. Additionally, delayed maintenance, caused by the inability to clear silt and debris promptly due to road blockages, may have contributed to the malfunctioning of the radial gates.

Sediment-laden flash flood caused a gate malfunction at the Malana Dam, leading to water overflow [18].

The incident underscores several critical lessons. Firstly, the importance of regular maintenance and inspection of radial gates and other critical infrastructure cannot be overstated, particularly before and during the monsoon season. Secondly, effective sediment management strategies, including the timely removal of silt and debris, are crucial to prevent gate obstructions and maintain reservoir capacity. Thirdly, ensuring that access roads and related infrastructure are resilient to extreme weather events is essential for timely maintenance and emergency response. Finally, establishing comprehensive emergency action plans, which include early warning systems and community engagement, can significantly mitigate the impacts of unforeseen incidents.

3.3 Lower Subansiri HEP (2023) – Landslide-induced tunnel blockage

The Lower Subansiri HEP, situated on the Subansiri River along the border of Arunachal Pradesh and Assam, is designed to generate 2,000 MW of power upon completion. The project has faced multiple challenges since its inception, including environmental concerns, local opposition, and geological hurdles. In October 27, 2023, a major landslide further complicated the project's progress by blocking the only functional diversion tunnel, crucial for channeling river flow during construction [19]. This obstruction prevented water from flowing through the construction site, causing the Subansiri River downstream to dry up temporarily. The sudden cessation of water flow raised significant environmental concerns, particularly regarding aquatic life and downstream water availability [19].

The landslide and subsequent tunnel blockage were caused by a confluence of factors (Figure 4). The project's location within a geologically unstable region, characterized by a history of landslides and seismic activity, presented inherent challenges. Heavy monsoonal rains preceding the event likely saturated the soil, further exacerbating the risk of slope failure and suggesting a strong correlation with seasonal weather patterns. Additionally, ongoing construction activities may have altered the natural slope dynamics, potentially contributing to the instability that ultimately triggered the landslide. The blockage of the diversion tunnel had immediate environmental impacts, including the drying up of the Subansiri River downstream, which threatened aquatic ecosystems and disrupted water availability for downstream communities. For the project, the incident caused significant delays and highlighted the need for improved geological assessments and risk mitigation strategies.

The 2023 landslide at the LS HEP offers several key takeaways. It underscores the critical need for thorough and ongoing geological surveys to proactively identify potential hazards and inform both the design and construction phases. Robust risk mitigation strategies are also essential, including proactive measures like slope stabilization and sophisticated monitoring systems to prevent similar occurrences.

Figure 9 Landslide at Lower Subansiri HEP site on 03.05. 2023

Furthermore, the event highlights the value of adaptive project management, emphasizing the importance of flexibility in planning and execution to effectively address unforeseen challenges, thereby minimizing delays and environmental impacts. For instance, despite the Subansiri Dam being a concrete gravity dam, no construction sluices were provided. The absence of these sluices exacerbated the situation, as their presence could have facilitated controlled water regulation during critical phases, thereby mitigating adverse effects. Similarly, the sequence and planning of closure, plugging, and the initial reservoir filling are crucial, especially for dams in the geologically and hydrologically complex Himalayan region. Improper execution of these processes can lead to severe consequences, such as uncontrolled water level fluctuations, sediment accumulation, and structural stress. Meticulous planning and implementation of these measures are therefore paramount for ensuring the dam's long-term stability and operational safety.

The landslide-induced tunnel blockage at the LSHEP in 2023 highlights the complex interplay between large-scale infrastructure projects and the geologically sensitive environments in which they are situated. Integrating thorough geological assessments, proactive risk mitigation, and adaptive management strategies is crucial for the successful and sustainable development of hydroelectric projects in such regions.

3.4 Tapovan Vishnugad HEP (2023) – Geological and construction challenges

The Tapovan Vishnugad Hydroelectric Project (HEP), a 520 MW run-of-the-river initiative on the Dhauliganga River in Uttarakhand's Chamoli district, has encountered significant geological and construction challenges since its inception in November 2006. Initially slated for commissioning between 2012 and 2013, the project has faced multiple delays, cost overruns, and environmental setbacks. The Himalayan region's complex geology has posed substantial obstacles for the Tapovan Vishnugad project. Tunneling through complex geological formations has been slow and challenging, with instances of tunnel boring machines (TBMs) getting stuck due to rock collapses and water ingress. In 2014, the original construction contract was terminated because of these geological constraints, leading to further delays and increased costs. The project was then re-awarded in 2016, but challenges persisted. As of early 2023, the project has been delayed by nearly a decade, with costs escalating by approximately 138% from initial estimates. These overruns are attributed to the difficult terrain, unforeseen geological hurdles, and the need for redesigns to address these issues.

On February 7, 2021, a catastrophic flash flood, triggered by a glacier burst in the Nanda Devi region, devastated the Tapovan Vishnugad project [20]. The deluge caused severe damage to the infrastructure, including the washing away of a dam and the destruction of tunnels. Tragically, over 200 individuals were reported dead or missing, with 140 workers at the construction site among the casualties [21]. This disaster not only resulted in significant human loss but also set back the project's progress substantially. Approximately 60% of the completed construction work was destroyed, necessitating extensive rebuilding efforts and further delaying the project's timeline.

Figure 10 Before & after image of NTPC Tapovan-Vishnugad HEP [22]

The Tapovan Vishnugad HEP incident has provided several important lessons for future hydropower projects in the Himalayan region. Key lessons include the need for thorough geological, geophysical, and geotechnical studies before sanctioning projects, the importance of monitoring and early warning systems, and the necessity for disaster risk assessment and preparedness. Flexibility in design to accommodate geological surprises can prevent extensive delays and cost overruns. Continuous geological monitoring during construction can inform necessary design adjustments. The incident has also underscored the importance of involving local communities in decision-making processes and re-evaluating projects based on current scientific data. Ensuring the safety of workers and nearby communities through regular drills, clear communication channels, and established evacuation plans is essential. In conclusion, while the Tapovan Vishnugad HEP aims to harness renewable energy, its journey illustrates the complex interplay between infrastructure development and environmental stewardship. Balancing these aspects is crucial to ensure the safety, sustainability, and success of such ambitious endeavors.

3.5 Rishiganga HEP (2022) – Debris-laden flood (Mudslide)

The Uttarakhand disaster of February 7, 2021, was a catastrophic event triggered by a massive rock and ice avalanche in the Raunthi glacier region, leading to devastating flash floods in the Rishiganga and Dhauliganga river valleys. The cascading debris flow obliterated the Rishiganga HEP, severely impacted the Tapovan Vishnugad HEP and caused extensive damage to infrastructure, including bridges, roads, and settlements in Raini and Tapovan villages. The Study conducted by identifies multiple contributing factors, including fragile geological conditions, cryospheric and glaciological processes, climate change-induced permafrost degradation, and hydro-meteorological influences such as rising land surface temperatures and anomalous precipitation patterns [23]. Remote sensing, digital elevation models, and field investigations confirmed that a wedge-type failure along pre-existing joints in the rock mass led to the detachment of approximately 29.3 million cubic meters (MCM) of material, including glacier ice and rock, which fell from a height of ~1,740 meters (Figure 6). The resulting high-energy impact created an air blast, disintegrated the rock-ice mass, and caused intense scouring along the valley, entraining moraine deposits, snow, and water to form a debris-laden flood [23].

Figure 11 Demarcation of Snow Avalanche Zone for Flashflood event of 07.02.2021 [23]

The debris-laden flood caused severe damage to the infrastructure project along the river reach starting from a 13.2 MW small hydropower project across Rishiganga. This disaster resulted in the death or disappearance of over 204 workers at the construction site, with many being trapped in tunnels filled with mud and debris. The debris-laden floodwaters inundated the powerhouse and associated structures, completely burying them in sediment or washing away [23]. The flood carried tons of mud and debris, which not only damaged the project but also affected the surrounding environment, including nearby settlements and economic activities. The damage to the Rishiganga HEP resulted in significant economic losses due to the destruction of infrastructure and the cost of rescue and recovery operations. Additionally, this devastation led to a halt on all on-going and proposed hydroelectric projects in Uttarakhand.

Figure 12 Before and after images of the Rishiganga HEP for debris-laden flood event of 07.02.2021 [23]

The Rishiganga disaster served as a stark reminder of the vulnerability of the Himalayan region to natural hazards and the need for more sustainable development practices. The disaster highlighted the complex interplay of local geology, snow, glacier, permafrost processes, and recent climate warming to lead this devastated events. This necessitates regular glacier monitoring, especially near these types of infrastructure and development projects. Small glaciers, being more susceptible to climate change, require regular monitoring, as do similar glaciers in the region. Permafrost studies, including ground temperature monitoring and thermal regime modeling, are also essential early indicators, especially given the current lack of knowledge about permafrost elevations in the Indian Himalayas. Key lessons learned emphasize the importance of enhanced geological surveys, including comprehensive and continuous assessments to identify potential hazards and inform infrastructure design and construction. Robust risk mitigation strategies are also crucial, encompassing proactive measures like slope stabilization, early warning systems, and comprehensive disaster preparedness plans. Furthermore, sustainable development practices are essential, requiring careful planning and execution of development activities in ecologically sensitive areas like the Himalayas, with full consideration of potential environmental impacts and disaster risks. Finally, climate change adaptation is paramount. Recognizing the increasing frequency and intensity of extreme events due to climate change, effective adaptation strategies are necessary to build resilience in these vulnerable regions.

4. Solutions and Technological Innovations

The case studies presented highlight recurring challenges in Himalayan hydropower projects: GLOFs, gate malfunctions due to sedimentation, landslide-induced tunnel blockages, and complex geological conditions. The following paragraphs detail potential solutions for enhancing resilience.

4.1 Real Time Monitoring and Early Warning System

- Automated Early Warning Systems: Integrate remote sensing data with hydrological models and weather forecasts to develop robust early warning systems. Deploy AI-powered, real-time satellite monitoring combined with on-ground LiDAR and IoT sensors to predict potential GLOFs and alert downstream communities. Consider redundant communication systems (satellite phones, etc.) to ensure reliability [24].
- Advanced Remote Sensing & AI: Implement real-time monitoring of glacial lakes using satellite imagery, drone technology, and AI-powered image analysis to detect changes in lake volume, moraine dam stability, and surrounding terrain. Develop algorithms to predict potential GLOFs based on these data.
- Integration of Digital Twin Technology: Create virtual simulations of hydroelectric projects using real-time IoT data to model disaster scenarios and improve design resilience.
- Blockchain for Disaster Response Coordination: Use blockchain-based ledgers for transparent and efficient emergency response and resource allocation.
- AI-Powered Decision Support Systems: Develop centralized control rooms with AI-driven risk assessment models to assist dam operators in making real-time decisions.
- Integrated Risk Management Plans: Incorporating slope failure modeling and emergency response simulations to reduce project vulnerabilities [25].

4.2 GLOF Mitigation and Structural Measures

- Reinforcement of Moraine Dams: Use bioengineering methods like geotextile-reinforced embankments and engineered drainage channels to stabilize natural moraine dams.
- Subsurface Drainage Tunnels: Construct sub-glacial tunnels or controlled siphoning systems to gradually lower water levels, reducing the risk of sudden outbursts [26].
- Climate-Resilient Dam Design: Design dam structures to withstand the impact of large GLOFs, including overtopping and debris flows. This may involve reinforced concrete structures, flexible dam designs, and strategically placed energy dissipation structures.
- Cryosphere Monitoring: Deploying remote sensing, permafrost temperature monitoring, and AI-based early warning systems to detect glacier and permafrost instabilities [27].
- Research & Development: Invest in research and development of new technologies and methods for hazard assessment, monitoring, and mitigation in Himalayan regions. Promote collaboration between researchers, engineers, and local communities.

4.3 Sediment Management & Gate Operation

- Automated Sediment Monitoring & Removal: Implement automated systems for real-time monitoring of sediment levels in reservoirs [28]. Develop robotic or automated systems for sediment removal to prevent gate jamming [29].
- Sediment Bypassing: Design sediment bypass systems to divert sediment-laden flows around the reservoir, minimizing deposition and protecting gate functionality.
- Self-Cleaning Radial Gates: Use hydrophobic coatings and high-pressure water jet systems to prevent silt accumulation and ensure smooth gate operation.
- AI-Driven Sediment Management: Implement AI-based flood forecasting models to predict sediment movement and optimize gate operation in advance.

- Adaptive Reservoir Management: Use real-time weather forecasting and inflow prediction models to adjust water storage levels dynamically before extreme events.
- Resilient Access Infrastructure: Construct elevated and reinforced access roads with modular, easy-to-replace sections to ensure maintenance access during disasters.
- Regular Maintenance & Inspection: Pre-Monsoon Inspection Protocols: Conducting systematic pre-monsoon checks and maintenance schedules to ensure operational readiness, including underwater inspections using remotely operated vehicles (ROVs). Develop predictive maintenance strategies based on sensor data and AI analysis [30].

4.4 Geological Surprises and Landslide Risk Management

- Advanced Geological & Geophysical Surveys: Conduct detailed geological and geophysical surveys using techniques like ground-penetrating radar, seismic surveys, and LiDAR to map unstable slopes and identify potential landslide triggers [31].
- Slope Stabilization Techniques: Implement slope stabilization measures such as retaining walls, soil nailing, and bioengineering to reinforce unstable slopes [32].
- Real-time Slope Monitoring: Install real-time slope monitoring systems using sensors (inclinometers, strain gauges) to detect movement and provide early warning of potential landslides. Integrate these systems with early warning systems for downstream communities.
- AI-Based Landslide Prediction: Utilize machine learning models and ground-based radar to predict landslide-prone zones and trigger preventive measures.
- Tunnel Design & Support: To ensure continuous river flow in the event of a tunnel blockage, a minimum of two diversion tunnels (and construction sluices in case of concrete gravity dams) should be constructed [33]. These tunnels must be designed with robust support systems capable of withstanding potential ground movement and collapse. Regular tunnel inspections and maintenance are essential for long-term stability and functionality.
- Microseismic Monitoring: Install underground acoustic sensors to detect early signs of rock fractures or water ingress.
- Geothermal Mapping: Conduct deep thermographic and resistivity surveys before tunneling to identify weak zones.

4.5 Adaptive Project Management & Climate Change Considerations

- Flexible Design & Construction: Adopt a flexible approach to project design and construction that allows for adjustments based on unforeseen geological conditions and changing climate patterns.
- Climate Change Integration: Incorporate climate change projections into project planning and design, considering increased frequency and intensity of extreme weather events, glacial melt, and permafrost degradation. Use climate-informed design criteria [34].
- Early Warning & Preparedness: Establish comprehensive early warning systems for all potential hazards (GLOFs, landslides, floods) and develop detailed disaster preparedness plans, including community engagement and evacuation procedures.
- Research & Development: Invest in research and development of new technologies and methods for hazard assessment, monitoring, and mitigation in Himalayan regions. Promote collaboration between researchers, engineers, and local communities.

4.6 Community Engagement & Capacity Building

- Community-based Monitoring: Engage local communities in monitoring of glacial lakes, slopes, and other potential hazards. Utilize citizen science initiatives and mobile technology for data collection and sharing.
- Participatory Planning: Involve local communities in all stages of project planning and implementation to ensure that their concerns and traditional knowledge are considered [34].
- Capacity Building: Conduct training programs for local communities on disaster preparedness, early warning systems, and emergency response procedures.
- Worker Safety Protocols: Implementing automated hazard detection and emergency evacuation drills to minimize casualties in case of sudden disasters [35].

By implementing these innovative and technical solutions, hydropower projects in the Himalayas can be made more resilient to the complex and interconnected challenges posed by natural hazards and climate change, ensuring their long-term sustainability and safety.

5. Policy and Risk Management Frameworks

The Government Initiatives to address the environmental challenges in the Himalayan region include the National Mission on Sustaining Himalayan Ecosystem (NMSHE), which is one of the eight missions under the National Action Plan on Climate Change (NAPCC). This mission aims to develop measures to sustain and protect Himalayan glaciers, mountain ecosystems, biodiversity, and wildlife. Additionally, Environmental Impact Assessments (EIA) is mandated for large hydropower projects to evaluate their ecological consequences. To reduce the impact of hydropower projects in the Himalayas, a reassessment of existing and upcoming projects based on current scientific data is crucial, as landslide risks have significantly increased in recent years, making these projects more hazardous. Many hydropower projects were conceptualized 10-15 years ago, and their feasibility must be reconsidered in light of updated research and environmental conditions. Moreover, before proceeding with any project, local panchayats should formally express their approval in writing to ensure community consent. Another key measure is the formation of expert committees to study the impact of hydropower projects in the Himalayan region. For instance, the Ravi Chopra Committee, set up by the Ministry of Environment, was tasked with evaluating the effects of 24 hydropower projects in the Alaknanda and Bhagirathi basins.

In terms of research funding for GLOF monitoring, initiatives like the National Hydrology Project (NHP), funded by the World Bank and the Ministry of Jal Shakti, play a crucial role in advancing hydrological and glaciological studies. Indian institutions, such as the National Remote Sensing Centre (NRSC), in collaboration with its parent organization, the Indian Space Research Organisation (ISRO), are actively involved in satellite-based monitoring and modeling of glacial lakes. These organizations utilize remote sensing and GIS technologies to evaluate GLOF risks and strengthen early warning systems. Additionally, the Government of India funds extensive research initiatives at institutions of national importance, including IITs, the National Institute of Hydrology (NIH), and the Wadia Institute of Himalayan Geology (WIHG), to address various challenges related to Himalayan geology and sustainable settlement development in the region. Central Water Commission (CWC) is actively engaged in developing comprehensive guidelines for both structural and non-structural measures to enhance dam safety in GLOF-prone areas. These guidelines encompass critical aspects such as GLOF modeling, inundation mapping, and risk assessment, ensuring a proactive approach to disaster mitigation. Additionally, the CWC collaborates with key national agencies, including the India Meteorological Department (IMD), Geological Survey of India (GSI), and the National Disaster Management Authority (NDMA), to address the complex challenges posed by Himalayan geology, Landslides, GLOFs, and climate change impacts. This multi-institutional coordination aims to improve early warning systems, resilience strategies, and adaptive management practices for vulnerable hydropower projects and settlements in the region.

6. Conclusion

The construction and operation of dams in the Himalayan region present formidable challenges due to the area's complex geology, high seismic activity, extreme weather events, and increasing climate-induced risks. The case studies revealed critical vulnerabilities in hydroelectric infrastructure located in geologically active, high-altitude environments. The formation of a temporary debris-dammed lake introduced the imminent threat of secondary flooding. These cases highlight the necessity of comprehensive hazard risk assessments, enhanced monitoring and early warning systems, climate-adaptive engineering solutions, and strict adherence to disaster resilience protocols for hydropower and other infrastructure projects within the fragile Himalayan ecosystem. Recent dam failures caused by GLOFs, sediment-induced gate failures, landslide blockages, and extreme rainfall events underscore the urgent need for integrated risk management, advanced engineering solutions, and adaptive policy frameworks to ensure the resilience and sustainability of hydropower infrastructure in this vulnerable ecosystem.

A multi-pronged approach is essential to mitigate these risks. Real-time monitoring systems, including remote sensing, IoT-based hazard detection, and AI-driven early warning systems, can significantly improve disaster preparedness. Structural adaptations, such as reinforced dam spillways, controlled drainage systems for glacial lakes, and self-cleaning sediment management technologies, are crucial for maintaining infrastructure integrity. Comprehensive geological assessments must guide project planning, while slope stabilization techniques and adaptive tunnel designs should be incorporated to address terrain instability. Additionally, community engagement and capacity-building initiatives will enhance disaster resilience at the grassroots level.

Policy interventions, such as rigorous Environmental Impact Assessments (EIAs), enhanced governmental oversight through agencies like CWC, NDMA, IMD, and GSI, and stricter compliance with climate-adaptive infrastructure guidelines, are critical. Research funding through initiatives like the National Hydrology Project (NHP) and institutional collaborations between NRSC, ISRO, NIH, and IITs must be expanded to improve GLOF modeling, seismic risk assessment, and climate adaptation strategies.

Looking forward, future research should focus on developing climate-resilient dam designs, integrating blockchain-based disaster response frameworks, and enhancing machine learning applications for predictive hazard analysis. Given the increasing frequency and intensity of extreme weather events, a reactive approach is no longer viable. Instead, a proactive, technology-driven, and sustainability-focused strategy must define the future of hydropower projects in the Himalayan region, safeguarding both infrastructure and communities against evolving geohazards.

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NE PROCEEDINGS FOR IWT ISSUES

A meeting related to the NE proceedings for IWT issues was held under the chairmanship of Member(D&R), CWC on 28th January 2025 in his chamber. Construction schedule and discussion on drawings shared with the Neutral Expert has been finalized!

Meeting with Member D&R in his Chamber

DISCUSSION ON IMPORTANT MATTERS IN D&R WING

A meeting was held on January 28, 2025, under the chairmanship of the Chairman of CWC, with the Member (D&R) and other senior officers from the D&R wing to discuss important activities, matters, and issues related to the D&R wing, as well as to review the status of ongoing projects.

Meeting with Chairman CWC

D&R Activities

FIELD VISIT TO H.O. SITES

Site visit Narmadapuram HO sites CWC Madhya Pradesh

Sh. Sagar Rawat, Deputy Director, Hydrology (NE) Directorate visited Narmadapuram and Mandla HO sites of CWC in Madhya Pradesh, under 1st intersite showcasing competition on upkeep of HO sites as per standards during 27.01.2025 to 31.01.2025

REVIEW OF WORK STATUS IN HSO

Member(D&R), CWC reviewed the status of work in Hydrological Studies Organization on 22 January 2025. Chief Engineer, HSO and directors of concerned directorates explained the status of consultancy projects and the issues in pending projects.

Meeting with Member D&R

LAKHWAR DAM PROJECT VISITS

Site visit of CWC officers

Lakhwar Multipurpose Project, Uttarakhand is under construction. The breakthrough of Diversion Tunnel (DT3) achieved by Project Authorities on 29th January 2025. A team of CWC visited the project site on 28.02.2025 to observe the ongoing construction works including the lining of DT3, DT3 Inlet and Exit Wing Wall Works, Excavation of Left Bank Vertical Shaft , left bank stripping works. The team discussed the ongoing works with the project authorities

LAKHWAR DAM PROJECT VISITS

Lakhwar Project

Ongoing Construction Works

A site visit of CWC officers led by Member (D&R), CWC along with officers from CSMRS is made to discuss the issues related to Lakhwar Multi-Purpose Project and Renukaji Dam Project from 23-25th January 2025

LAKHWAR DAM PROJECT VISITS

lining of DT3, DT3 Inlet and Exit Wing Wall Work

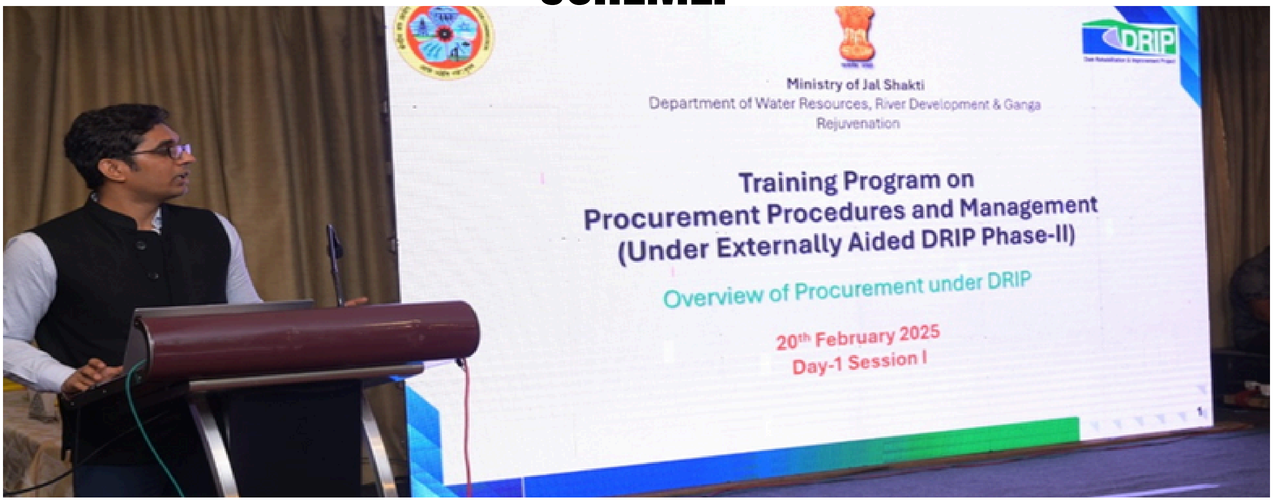
The breakthrough of Diversion Tunnel (DT3) achieved by Project Authorities on 29th January 2025. Ongoing construction works including the lining of DT3, DT3 Inlet and Exit Wing Wall Works, Excavation of Left Bank Vertical Shaft , left bank stripping works.

Excavation of Left Bank Vertical Shaft

D&R Activities

NEW DELHI JANUARY -MARCH 2025

CAPACITY BUILDING OF OFFICIALS UNDER ONGOING DRIP-II SCHEME.



A two-day training on Procurement management was organized by CPMU under DRIP Phase II during 20th to 21st Feb, 2025 at Durgapur, West Bangal. In this training, total 25 officials from 4 IAs were participated. This training was the part of capacity building of the officials under Component-II of ongoing DRIP-II Scheme.

LECTURE TO ITP FOR NEWLY RECRUITED JUNIOR ENGINEERS

Ms. Isly Isaac, Deputy Director, Hydrology (S) Directorate delivered a lecture to induction training program for newly recruited Junior Engineers on subject "Hydrological Aspects of Water Resources Projects" at NWA, Pune on 12.02.2025.

Ms. Isly Isaac, Deputy Director, Hydrology (S) Directorate and Sh. Pratik Raj, Assistant Director-II, Hydrology (S) Directorate visited to ongoing project-Korang Nallah Dam under Andaman Public Works Department during 23.02.2025 to 27.02.2025.