Risk Assessment of existing major dams using RPN analysis - A Case Study of Central India region

Tanushree Sinha, Neeraj Mishra, Praveen Kumar, Dr. Harish Kumar Dwivedi, Kuldeep Mehra, Yugendra Samdariya

Abstract: *India's dam safety management has its hands full: most of the country's big dams are getting old, more people are living downstream, and resources are stretched thin. This research dives into that gap. It creates and tests a new risk assessment framework for gravity dams, mixing two five-factor indices — one for likelihood, one for consequences — to spit out a Risk Priority Number (RPN) for each site. The framework gets used on eight major dams in Madhya Pradesh state of Central India viz Gandhi Sagar, Indira Sagar, Omkareshwar, Rajghat, Bansagar, Bargi, Tawa, and Barna dam projects. These dams were built during different decades, juggle different construction styles, and face different problems downstream. Together, they store nearly 27,700 MCM of water, irrigate about 2.5 million hectares, and crank out close to 1,700 MW of hydro power.*

The Likelihood Index checks out five big things: seepage, spillway capacity for the worst floods, structural strength, foundation quality, and whether the gates and emergency procedures work when they're needed. Meanwhile, the Consequence Index looks at how many people are at risk downstream, what kind of infrastructure could get hit, warning time in a flood, economic fallout, and how ready the Emergency Action Plan is. Each factor gets scored from one to five, and the final RPN is just the product of those two indices.

As the result, dams Gandhi Sagar (RPN 10.2), Bargi (RPN 10.1), Tawa (RPN 9.0), and Barna (RPN 9.0) — are flagged for urgent action. Omkareshwar (RPN 7.2) comes in as moderate priority, while Indira Sagar (RPN 5.8) rates

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lower on structural risk but needs serious attention for consequence management because so many people live downstream. A few stand-out takeaways: older dams are more vulnerable structurally, but age doesn't always line up with overall risk for society. Inadequate spillways are the most urgent structural concern across all six dams. The weakest piece of consequence management is EAP readiness, but fixing that is actually the most cost-effective move right now. The dissertation wraps up with tailored, step-by-step recommendations for each dam, plus advice to Madhya Pradesh's dam safety program: start using risk-based asset management.

Keywords: *Dam Risk Assessment, Likelihood Index, Consequence Index, Risk Priority Number*

Introduction

Water is at the core of India's survival, it powers farms, lights cities and keeps the nation alive. But when it comes to managing that precious resource, its the big dams which store and store water, most of which comes from the monsoons, in India, and release it when it is required. If these concrete giants are in place, it will be running smoothly, keeping millions of people safe and their fields in place. However when it fails lives are lost, the devastation that floods bring is immense livelihoods in just a few hours. India presently has about 6,100 big dams in operation. These are defined in the Dam Safety Act 2021 as: Buildings 15 m or higher (or slightly lower in case of sufficient water-holding capacity). But here's the thing: nearly 80 per cent of the population are aged 40 and older. That is far over halfway done. Their normal life span is of 100 years. Decades of heat, rain, earthquakes and the passage of time consume. They fled away at their vigor. And one can't always spot those problems by walking around with a checklist. Meanwhile, downstream everything is different. The Dam Safety Act 2021 and the Central Water Commission guidelines have been stepping initiatives in India to enhance dam safety. However, the majorities of dam evaluations focus only on structural issues, and are conducted on a fixed schedule. Inspectors identify problems, record the problem and recommend solutions. It's good but not enough. Reason being, firstly, this process treats every dam like it's standing alone, instead of part of a bigger group. If you examine each dam individually there is no way of gaining an appreciation of which dams may pose the greatest risk overall. And secondly, considering only the physical state of a dam is unrelated to the actual repercussions should something go wrong. Consider that a poorly maintained dam, located far away from any populated areas is not as dangerous as a well constructed dam sitting over a populated city. However, the existing system is unable to differentiate. This results in unnecessary costs being made on minor risks when large risks are allowed to go undetected.

This study goes at those blind spots head-on. It is presenting a new method of calculating risk, which itcalls Risk Priority Number, which is both an assessment of the likelihood of failure, and an assessment of the consequences of failure. With this composite score, you can evaluate all of the dams and make better decisions on where to invest dollars—finally matching resources with risk.

Literature Survey

The literature reviewed on dam safety and risk assessment demonstrates a clear shift from conventional condition-based inspection towards integrated and risk-informed approaches for managing existing dam infrastructure. The reviewed studies collectively indicate that dam safety is influenced by a combination of structural, hydraulic, geotechnical, environmental, operational and management-related factors. Yang et al. (2024) emphasized the multidimensional nature of dam safety by incorporating deformation, seepage, stress–strain behaviour, reservoir level and rainfall into an integrated assessment framework. Their study further demonstrated the usefulness of uncertainty-handling techniques such as cloud modelling and Dempster–Shafer evidence theory for improving the reliability of dam-safety evaluation.

The reviewed studies indicate that deterioration may occur through mechanisms such as cracking, joint deterioration, seepage, drainage-system deficiencies, foundation degradation and ageing of mechanical components. Palmstrøm and Stille (2010) reported an accelerating deterioration trend in ageing gravity dams, particularly after several decades of service. Similarly, Maheshwari and Sharma (2011) identified drainage-gallery blockage, joint-mortar deterioration and transverse cracking as important deficiencies in masonry dams, with deterioration becoming more prominent in older structures. **Hydraulic safety and spillway adequacy emerge as important contributors to dam risk.** Historical failure and incident studies indicate that inadequate flood-discharge capacity, inappropriate reservoir operation and mechanical failure of spillway gates can contribute substantially to overtopping risk (Zhu et al., 2011). The reviewed Indian studies also highlight concerns regarding the adequacy of existing spillways under revised estimates of extreme floods (Central Water Commission, 2018). Climate variability and changes in extreme precipitation may further increase the hydraulic loading on existing dams, indicating the need for periodic reassessment of spillway capacity and design flood estimates.

The literature also establishes the importance of **seepage, foundation behaviour and structural monitoring** in assessing existing gravity dams. Fell et al. (2014) identified concentrated leak erosion, backward erosion, contact erosion and suffusion as important erosion mechanisms and emphasized the value of seepage discharge, piezometric measurements and geophysical investigations for early identification of abnormal behaviour. Monitoring-based approaches have also been enhanced through data-driven methods. Ranković et al. (2014), for example, demonstrated the applicability of artificial neural networks for predicting piezometric water levels in dams, indicating the potential of computational techniques for interpreting long-term monitoring data. However, such approaches require sufficiently long and reliable datasets, which may not be consistently available across regional dam portfolios.

Another important finding is that **dam risk cannot be represented adequately by structural condition alone**. Risk-informed approaches require consideration of both the likelihood of failure and the consequences associated with that failure. Bowles et al. (2003) demonstrated that rankings based on structural condition can differ substantially from rankings incorporating downstream consequences. The literature further demonstrates the relevance of **Failure Mode and Effects Analysis (FMEA) and Risk Priority Number (RPN)** as practical tools for prioritizing risks. The principal advantage of this approach is its simplicity and ability to combine several risk attributes into a single prioritization index. Hartford and Baecher (2004) demonstrated the applicability of semi-quantitative FMEA-based assessment to gravity-dam safety and showed that such approaches can provide useful risk estimates with substantially lower analytical requirements than complete probabilistic assessments. Fell et al. (2000) similarly indicated that semi-quantitative approaches can be appropriate for portfolio screening and investment prioritization when the available data do not justify a highly detailed probabilistic analysis.

Nevertheless, the literature identifies **important limitations of conventional RPN methodology**. Bhattacharjee et al. (2020) noted that the conventional multiplication of severity, occurrence and detection scores can produce identical RPN values for different combinations of risk factors and implicitly assumes comparable importance of the three parameters. Uncertainty in expert judgment and the ordinal nature of the scoring system can further affect the reliability of rankings. Consequently, transparent scoring criteria, appropriate interpretation of the resulting rankings and, where feasible, uncertainty or sensitivity analysis are important when applying RPN to dam safety.

The reviewed literature also highlights the importance of **operational reliability and emergency preparedness**. Spillway-gate reliability, reservoir operating practices and emergency action plans can significantly influence the overall risk associated with an existing dam. The studies reviewed indicate that operational deficiencies may increase risk even where the primary structure remains in satisfactory condition. Consequently, dam-safety assessment should extend beyond physical infrastructure to include operation, monitoring, warning systems and emergency-response capability. The Dam Safety Act, 2021 has further strengthened the institutional framework for surveillance, inspection, operation, maintenance and emergency planning. In parallel, the Dam Rehabilitation and Improvement Project has promoted systematic rehabilitation and increasingly risk-informed management of existing dams.

Objectives of The Study

Objectives of the study are given as following:

- To review various methodologies used for "Risk Assessment of existing major dams using RPN analysis - A Case Study of Central India region" and to develop a report in the form of literature review.
- To identify appropriate technique from the reviewed literature for "Risk Assessment of existing major dams using RPN analysis - A Case Study of Central India region"
- To procure relevant data for the identified area for problem formulation.
- To establish a simple and generic approach to gravity dam risk assessment. The concept is to estimate the probability of a dam failing, and the consequences of such failure, based on information that dam inspectors typically gather.
- To implements this on eight major gravity dams of Madhya Pradesh: Gandhi Sagar, Indira Sagar, Omkareshwar, Bargi, Tawa and Barna. It is hoped that a more transparent ranking of the most risky dams will be created.
- To Transform observed rankings into actionable and prioritized dam safety management recommendations. A particular focus on construction planning and risk reduction is given to these suggestions.

About The Dams Under Study

We picked eight dams from Madhya Pradesh using four main criteria, all at the same time. Firstly, they sought dams that were very old and very young, and so they obtained both newer concrete gravity dams and older masonry dams which were half way through their design life or older. Second, they required a blend of these two types -- some concrete gravity dams and some masonry -- to determine if the framework could be a solution for various dam designs. Third, they ensured that all five areas in which they had an interest (likelihood, consequence) had good data available for each dam. Finally, each dam needed to be of regional significance for storing water, irrigating land, generating electricity or serving a population on the downstream side of the dam.

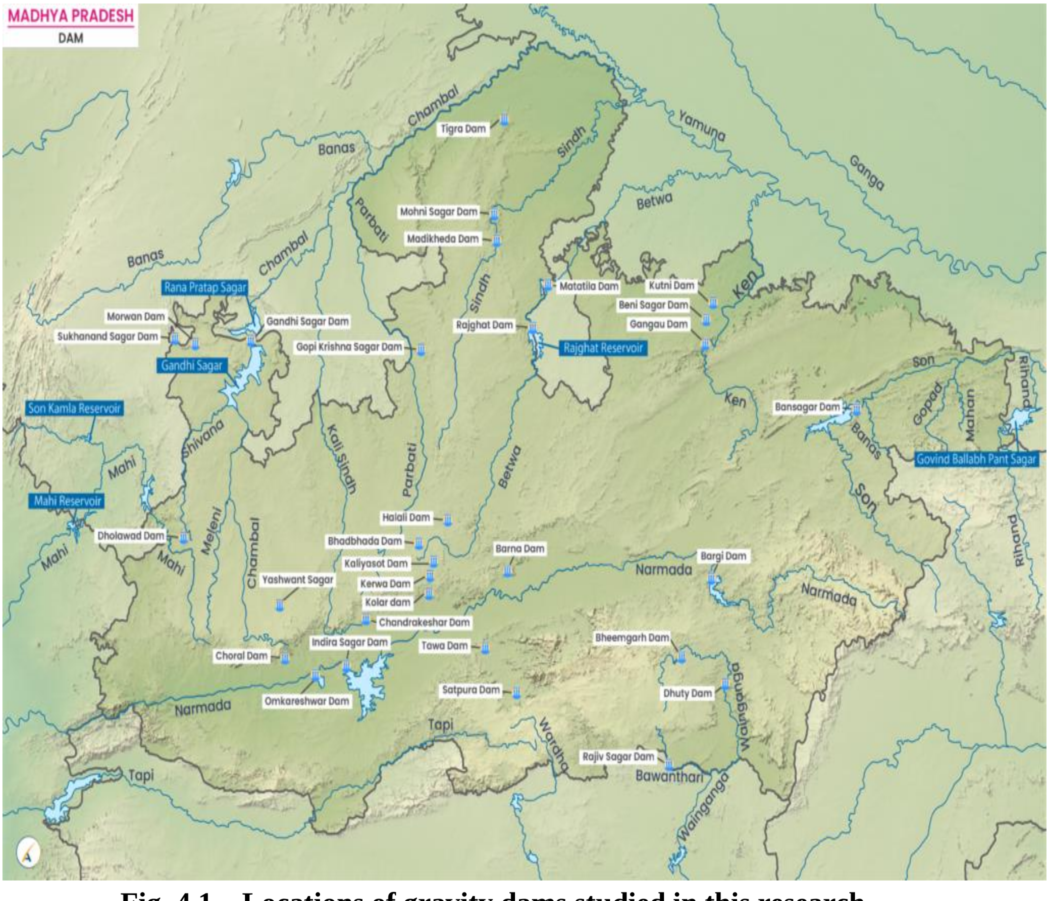

Fig. 4.1 – Locations of gravity dams studied in this research

Table 4.1: Physical Characteristics of the dams under this study

S.No.	Dam	Year	River	Type	Height (metres)	Capacity (MCM)	Primary purpose
1	Gandhi Sagar	1960	Chambal	Masonry / Concrete	62.17	7,746	Irrigation, Power
2	Indira Sagar	2005	Narmada	Concrete Gravity	92.00	12,220	Power, Irrigation
3	Omkareshwar	2007	Narmada	Concrete Gravity	49.50	971	Power, Irrigation
4	Bargi	1990	Narmada	Masonry / Concrete	69.80	3,811	Irrigation, Power
5	Tawa	1978	Tawa	Masonry	58.00	2,413	Irrigation
6	Barna	1970	Barna	Masonry	47.00	530	Irrigation
7	Rajghat	1997	Betwa	Concrete Gravity	45.80	1,094	Irrigation, Power
8	Bansagar	2006	Son	Concrete Gravity	67.00	5,410	Irrigation, Power

The Risk Assessment Framework

A risk assessment framework, which applies Failure Mode and Effect Analysis (FMEA) with multi-criteria semi-quantitative approach is introduced in this study. It is intended to be completely comprehensive rather than too cumbersome with calculations. The primary objective is to produce understandable, auditable, and comparable risk rankings for very different dams. In essence the framework is divided into two paths: probability of failure and consequences of failure. Ultimately it takes both of these together and creates one Risk Priority Number.

Simple scores (1 to 5) are used instead of complicated mathematical probabilities. There are a few good reasons for this choice. First, it is simply impractical to obtain the type of detailed information necessary to accurately calculate probabilities in this project, such as exact failure rates or uncertainty curves for each of the dams. Second, this is a scoring approach that is consistent with complex probabilistic models, at least for comparable dam portfolios of like risk types. Last but not least, the use of simple scoring allows the results to be much more easily understood and applied by non-experts. That's important, because the object here is to assist real people in making decisions on how to allocate resources for dam safety.

5.1 Likelihood Index Assessment

The Likelihood Index gives us a clue as to the probability that a dam will fail or cause a significant safety concern in the future. It's based on the five factors identified as frequently occurring risks in dam safety reports: seepage, spillway adequacy, structural condition, foundation condition, and operational reliability. They each receive a score of 1 (very low risk) to 5 (very high risk).

The Likelihood Index formula is:

$$\mathbf{LI = (F_1 + F_2 + F_3 + F_4 + F_5) \div 5}$$

where F_1 = Seepage, F_2 = Spillway Adequacy, F_3 = Structural Condition, F_4 = Foundation Quality, and F_5 = Operational Reliability.

5.2 Consequence Index Assessment

The key new concept of this study is the Consequence Index. It is a measure of the damage a dam failure would do, independent of the probability of failure. In other words, the index considers five large-scale factors: the number of people who might be affected downstream, infrastructure that may be affected, warning time for residents, economic losses, and readiness of the Emergency Action Plan. Each of these factors is given a score of 1–5, similar to the likelihood factors, with a higher score indicating more severe consequences.

Consequence Index formula is:

$$\mathbf{CI = (C_1 + C_2 + C_3 + C_4 + C_5) \div 5}$$

Where: C_1 = Downstream Population, C_2 = Infrastructure Exposure, C_3 = Flood Warning Time (inverse), C_4 = Economic Impact, and C_5 = EAP Readiness (inverse, where lower readiness = higher consequence).

5.3 Risk Priority Number (RPN)

The Risk Priority Number (RPN) is simply the Likelihood Index (LI) x the Consequence Index (CI).This yields RPN = LI × CI. The score ranges from 1.0 (lowest possible) to 25.0 (highest possible), depending on the overall rating of the factors.

For management responses there are three bands: High Priority (RPN ≥ 9.0): The dam needs an immediate safety review and an EAP update. A comprehensive inspection should be undertaken within three months. Begin rehabilitation within a year, and report to the state Dam Safety Organization every year of progress made. Increase monitoring efforts for Moderate Priority (RPN 6.0-8.9). Ensure the EAP is developed or updated within 1 year, maintenance is undertaken within 3 years and a comprehensive inspection is undertaken every 2 years. Lower Priority (RPN < 6.0): Continue normal monitoring and regular maintenance. Continue to maintain the EAP. Perform detailed inspection every three years and reassess risk in case of significant changes in dam condition or land use downstream.

The high priority threshold (9.0) is intended to identify dams with moderate or higher risk of failure and moderate or higher consequence of failure. This allows for the awareness of dams with limited downstream impacts or dams with high downstream impacts to be heard and not lose ground.

Observations and Resuls

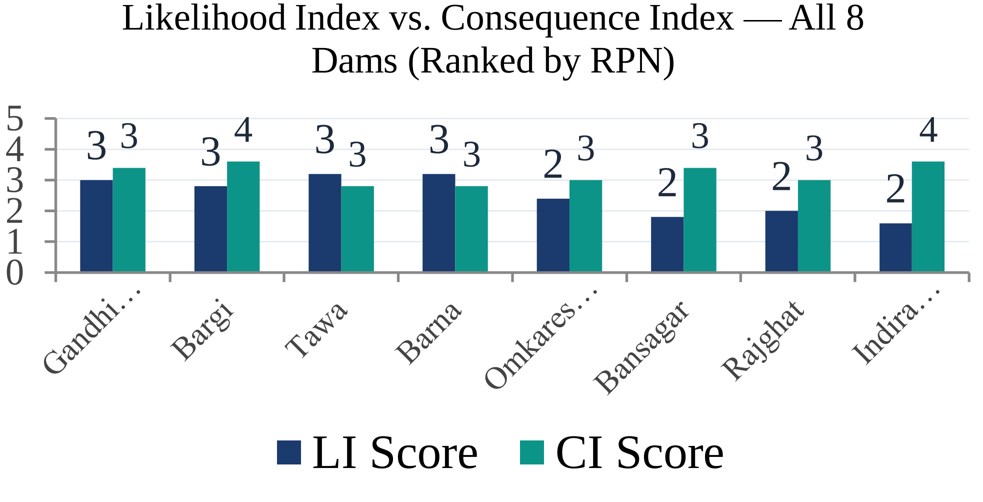

Table 6.1: Final Risk Priority Number Ranking of All Eight Dams

Rank	Dam	LI	CI	RPN	Priority Classification
1	Gandhi Sagar	3.0	3.4	10.2	HIGH PRIORITY — Immediate Action Required
2	Bargi	2.8	3.6	10.1	HIGH PRIORITY — Immediate Action Required
3	Tawa	3.2	2.8	9.0	HIGH PRIORITY — Immediate Action Required
4	Barna	3.2	2.8	9.0	HIGH PRIORITY — Immediate Action Required
5	Omkareshwar	2.4	3.0	7.2	MODERATE PRIORITY — Enhanced Monitoring
6	Bansagar	1.8	3.4	6.1	MODERATE PRIORITY — Consequence Management Focus
7	Rajghat	2.0	3.0	6.0	MODERATE PRIORITY — EAP Upgrade Required
8	Indira Sagar	1.6	3.6	5.8	LOWER PRIORITY — Consequence Management Focus

Table 6.2: Risk Reduction Interventions Implementation Timeline

Phase	Time frame	Dam focus	Key actions recommended
Phase 1	0-12 Months	All Eight dams EAP update and rehearsal	installation of real-time monitoring, commissioning of spillway capacity review, and coordination protocol for Indira-Omkareshwar

Phase 2	Year 2-3	Gandhi Sagar, Bargi, Tawa, Barna	Gate automation at Tawa & Barna; seepage monitoring at Bargi & Gandhi Sagar; installation of crack gauges; preparation of DPR for spillway works
Phase 3	Year 4-7	Gandhi Sagar, Tawa, Barna	Spillway augmentation construction, masonry rehabilitation, automated basin-wide flood warning system for Narmada valley, cascade dam-break flood routing study

Conclusion of The Study

Combined in this Risk Priority Number system are the five-factor Likelihood Index and five-factor Consequence Index, allowing for an easy comparison of dam risk within a set of dams. The best part is that it uses data already collected as part of the routine dam safety evaluations, with no need for additional sensors or for advanced computer models to be developed. The framework is quite resilient during a sensitivity check: If you change one of the scores by a small amount, the part you are interested in remains intact. If a dam has been flagged as high-risk, its analysis can be trusted.

The standout from this study is the Consequence Index. It actually provides figures of the impact downstream—often overlooked in Indian dam safety routines. Typically, people have a laser-like focus on the state of the dam and see consequence management as a side note, not something that can be quantified. However, the risk ranking changes once the consequences are taken into account. Otherwise you're spending money on the wrong things. So any dam safety framework that lacks consequence assessment is going to miss the mark in terms of resource allocation.

Of course, the framework isn’t perfect. Equal weighting of each factor may not reflect what's most important at each site. Later on, consideration of weighting techniques such as Analytic Hierarchy Process or Delphi could be undertaken to fine-tune the process. The PMF scores could be adjusted for climate changes to better reflect spillway adequacy. Furthermore, when considering the uncertainty in consequence factors probabilistically, real confidence intervals for the Risk Priority Numbers will be obtained. Scaling this approach up to include all the dams in Madhya Pradesh would provide an easy road map to better decisions on where to invest for dam safety across the state.

- The study concludes that some dams like Gandhi Sagar and Bargi are at high risk.
- Spillway inadequacy and seepage are major issues. Older dams are more vulnerable, and high population increases consequences.
- The study suggests improving maintenance, spillway capacity, and emergency action plans.
- Proper maintenance and spillway improvement can significantly reduce dam risk.

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