iPresas
Risk Analysis

Dam risk analysis for Bhadra dam and reservoir system

July 2018

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DAMSAFE

Innovative technologies for enhancing dam safety and water management in India

DAM RISK ANALYSIS FOR BHADRA DAM AND RESERVOIR SYSTEM

D2.1

July 2018

iPresas Risk Analysis

DISCLAIMER

Dam risk analysis for Bhadra dam and reservoir system is a report conducted within the framework of the DAMSAFE project (Deliverable D2.1), based on available information kindly provided by KaWRD and CWC. Conclusions and recommendations derived from the analysis described in this document in no way restrict neither reduce dam owner responsibilities concerning conducted and future dam safety actions for Bhadra dam reservoir system.

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- Karnataka Water Resources Department (KaWRD).
- Central Water Commission of India (CWC).

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Abbreviations

ANCOLD	Australian National Committee on Large Dams
CWC	Central Water Commission of India
DRIP	Dam Rehabilitation and Improvement Project
DSO	Dam Safety Organization
EAP	Emergency Action Plan
F	Cumulative annual exceedance probability
FM	Failure Mode
FERC	Federal Energy Regulatory Commission of United States
ICOLD	International Commission on Large Dams
IFM	Identification of Failure Modes
KaWRD	Karnataka Water Resources Department
MAGRAMA	Spanish Ministry of Agriculture, Food and Environment
MOL	Maximum Operating Level
PAR	Population at Risk
PMF	Probable Maximum Flood
QRA	Quantitative Risk Analysis
SPANCOLD	Spanish National Committee on Large Dams
SQRA	Semi-Quantitative Risk Analysis
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

1. Introduction

1.1. Motivation

Demand for water is steadily increasing throughout the world and conflicting interests generate a complex and delicate field of work. Multi-purpose water reservoirs and dams play a major role for water supply and flood protection in India.

There are 5254 large dams in India and 447 under construction, based on the ICOLD Register Database (2013) and several thousand of smaller dams provide a range of economic, environmental, and social benefits, including hydroelectric power, irrigation, water supply, flood control, and tourism. Consequently, **India** ranks **third in number of large dams worldwide**.

However, like all other infrastructures, dams age and deteriorate, posing a potential threat to life, health, property, and the environment. In addition, dam owners are facing different circumstances than when these dams were designed, often decades or more ago. This is due to changes in land use, socio-economic developments and climate change. In order to ensure long-term operation and safety of dams, investments have to be made in inspection, maintenance, repair and retrofitting.

India has a history of dam failures. Recently, India has extended actions, policies and legislation to **improve dam safety and to secure water supply**. Water reservoirs in India are of vital importance to urban and rural areas. Reservoirs are used for irrigation (food production), water distribution for domestic and industrial use (e.g. drinking water supply), power generation (energy) as well as for protection against flooding. Therefore, the responsible government agencies both at national and state level are looking for methods to regulate their reservoir system in an optimal and sustainable manner to improve water management and safety considering social, environmental and economic aspects.

The following report includes the **Risk Assessment performed for Bhadra Dam (Karnataka)** within the framework of the **DAMSAFE project** (Deliverable D2.1), a project co-funded by the Dutch Partners for Water program (Reference PvW4S16024) in the period 2016-2018. The DAMSAFE consortium consists of the Dutch based research organisation Deltares (coordinator) and the companies SkyGeo, Royal Eijkelkamp and iPresas. Deliverable D2.1 is part of WP2 entitled *Risk informed dam safety management*.

The overarching goal of the DAMSAFE project is to develop and demonstrate an integrated platform with innovative tools, technology and approach in the form of a pilot project, which will be applied to enhance dam safety and reservoir management in India. This goal is achieved by delivery of the following actions:

- Dam safety and water reservoir management:
    - Set up monitoring program with real-time observation associated with weather, water quantity and quality as well as structural behavior.
    - Develop and demonstrate forecasting system of reservoir inflow and outflow to improve reservoir performance and more controlled release of water.
    - Demonstrate innovative tools and technology for assessment of the dam condition resulting in optimization of Operation and Maintenance (O&M).
    - Develop and demonstrate innovative tools for risk assessment in order to provide information for dam safety management and emergency response.
- Training and knowledge dissemination:
    - Provide training, capacity building and exchange of data, knowledge and technology.

  - Organise open sessions with stakeholders, end-users and the broader water and dam safety communities in order to discuss project plans, execution and dissemination.

The key end-user of project outcomes is Karnataka Water Resources Department (KaWRD). KaWRD is one of the major departments in the Government of Karnataka, headed by the Minister for Major and Medium Irrigation, accounting 230 large dams.

1.2. Content and structure of the document

The described Risk Assessment for Bhadra Dam was performed while different remedial actions were being implemented in the dam under DRIP project. The base case (current situation) presented for the Bhadra Dam is based on the dam's situation when it was visited in February 2017. Therefore, the following actions have been considered not to be implemented at the time of analysis and they have been included in the list of risk reduction actions to be prioritized:

- Recent grouting actions performed in 2017 and 2018 in the main dam.
- Piezometers installed in the dam foundation in 2017 as part of DAMSAFE actions.
- Repair actions to improve reliability of spillway gates in 2017.

These assumptions also allow quantifying the added value in terms of risk reduction of these corrective actions.

This report describes all processes that have been carried out to perform a quantitative risk analysis for Bhadra dam, owned by Karnataka Water Resources Department (KaWRD) and located in Bhadra River, a tributary of Tungabhadra River.

The work is based on available information on the dam-reservoir system and outcomes from the working session conducted in February 2017 in India, after the dam site visit.

The report is structured as follows:

- Section 1: Introduction.
- Section 2: Dam description.
- Section 3: Risk assessment and management framework.
- Section 4: Identification of failure modes.
- Section 5: Quantitative risk assessment.
- Section 6: Semi-quantitaitve risk assessment.
- Section 7: Conclusions.

1.3. Communication and dissemination of results

Outcomes from this analysis have been used as a reference case study by the Central Water Commission of India (CWC) for developing the *Guidelines for Assessing and Managing Risks Associated with Dams*, one of the several dam safety guidelines being developed under the Dam Rehabilitation and Improvement Project (DRIP). In addition, results from this analysis have been presented in two forums: the XI Edition of the Spanish Dam Safety Conference, organized by the Spanish National Committee on Large Dams (SPANCOLD), held in León from June 26 to June 29, 2018; and the 26th Edition of the ICOLD Congress and 86th ICOLD Annual Meeting, organized by the International Commission on Large Dams (ICOLD), held in Vienna (Austria) from July 1 to July 7, 2018.

2. Dam description

In this section, a brief description of the Bhadra Dam-reservoir system is included.

2.1. Location

The Bhadra Dam Project is located on the River Bhadra, a tributary to the River Tungabhadra in the District of Chikmagalur in the state of Karnataka. The River Tungabhadra is a tributary to the River Krishna. Bhadra Dam is located at latitude 13°42'05.51" north and longitude 75°38'12.59", in the Upper Krishna basin.

A sketch of the Bhadra Dam's location is shown in Figure 2.1.

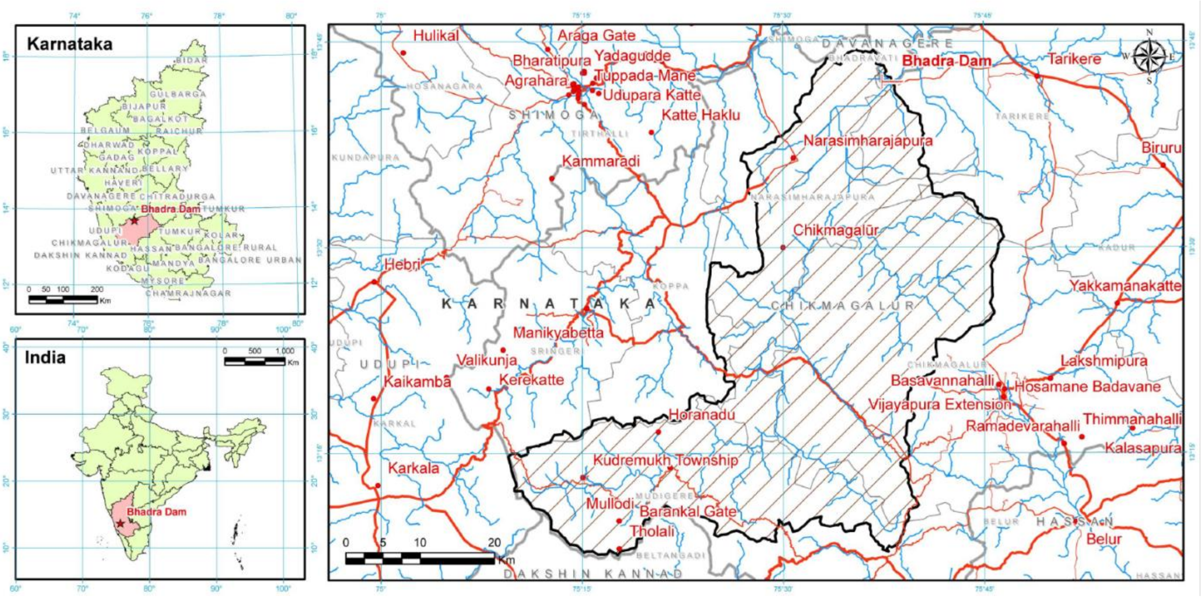


Figure 2.1. Bhadra Dam location. Source: Draft Design Flood Study of Bhadra Dam (2017).

The River Krishna originates near Mahabaleshwar in the Mahadev range of the Western Ghats, at an altitude of about 1360 m above the mean sea level. The Krishna Basin is the second largest eastward draining river basin in Peninsular India.

The climate of the basin is dominated by the southwest monsoon, bringing in the major fraction of the annual rainfall. Climatic type ranges from per-humid to sub-humid in the west, which changes to semi-arid over the central and the eastern parts. About 90% of the annual rainfall is received during the monsoon period extending over mid-June to mid-October.

The catchment area up to Bhadra Dam has been estimated as 2038.73 km². The catchment area spreads over the District of Chikmagalur in the state of Karnataka. A few habitations near to the dam are Byrapura, Shankarghatta, Thavaraghatta, Malenahalli, Vadiyuru, Nellisara, Lakkavalli, Upparbeeranahalli, Hunasanahalli and Dodda Kunduru. The elevation within the catchment varies between 661 to 1903 m.

Figure 2.2 shows a scheme with the top view of Bhadra dam reservoir system. Figure 2.3 includes a sketch of Bhadra Dam river catchment.

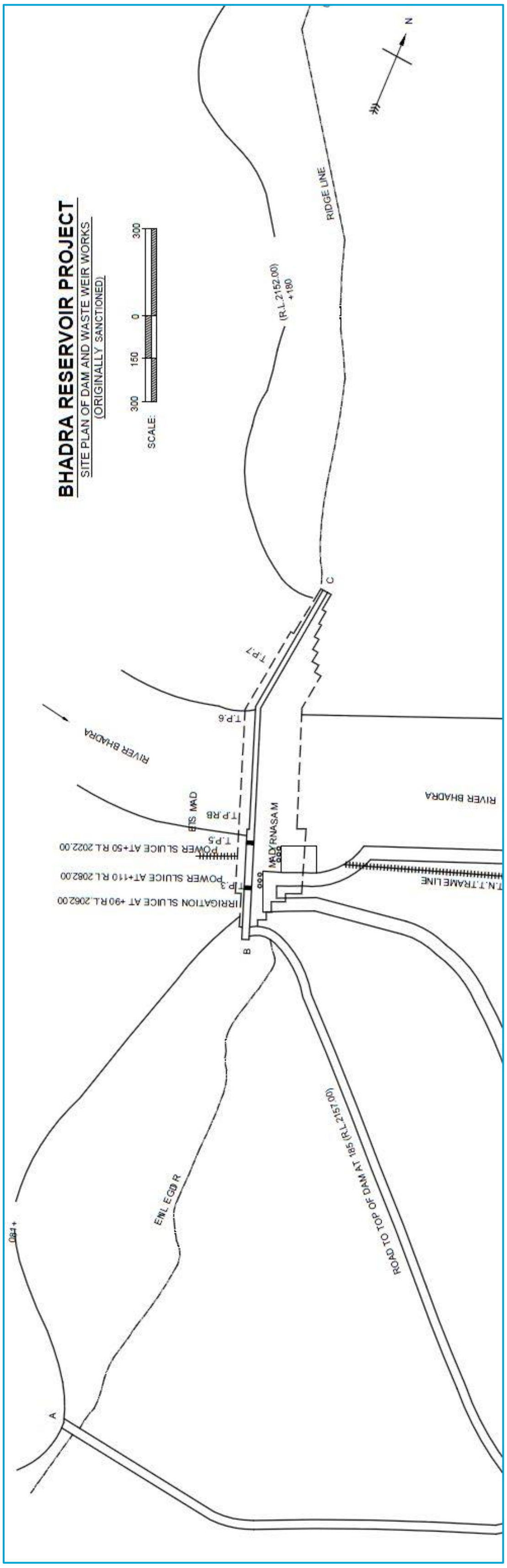


Figure 2.2. Main dam. Top view. Source: Bhadra reservoir project.

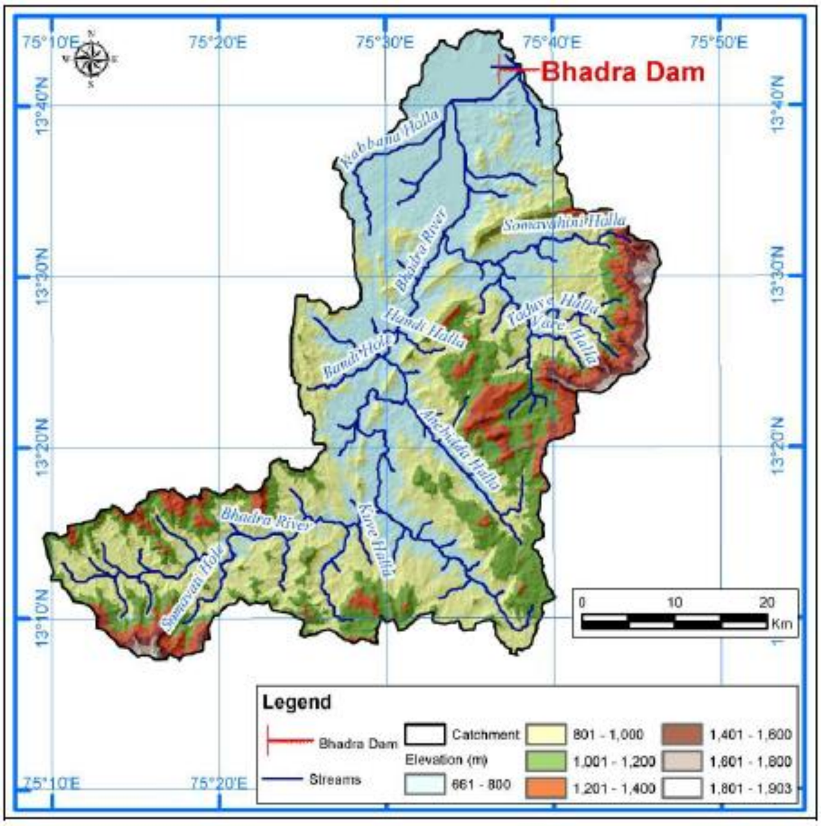


Figure 2.3. Bhadra Dam river catchment. Source: Draft Design Flood Study of Bhadra Dam (2017).

2.2. Main dam characteristics

The dam was built in 1962 and it is used for irrigation, water supply and hydropower generation. The dam has a total reservoir capacity of 2026 hm³.

Bhadra dam reservoir system is composed by a main dam and three saddle dams. The maximum height is 76.8 m for the masonry dam (main dam). The dam has a total length of 1708 m, including 440.43 m masonry section and earthen embankment on the remaining. The maximum height is 49.4 m for saddle dam 1 and 32.3 m for saddle dam 2. The base level is located at 1914 ft (583.39 m) in the masonry dam and at 2011 ft (612.95 m) and 2067 ft (630.02 m) for saddle dams 1 and 2, respectively.

Table 2.1 includes key levels of Bhadra Dam-reservoir system.

Dam-reservoir component	Crest level (ft)	Crest level (m)	Base level (ft)	Base level (m)	Height (m)
Main dam	2166	660.20	1914	583.39	76.8
Saddle dam 1	2173	662.33	2011	612.95	49.4
Saddle dam 2	2172	662.03	2067	630.02	32.3

Table 2.1. Bhadra Dam characteristics: crest levels.

Bhadra Dam is categorized as a large dam based on storage capacity (> 60 hm³) and dam height (> 30 m). The maximum water level in normal operation (MOL) is established at 2158 ft (657.76 m), being at 2156 ft (657.15 m) during the monsoon season.

The original design flood had a magnitude of 3,397.83 m³/s. However, details of the estimation procedure are not available. Table 2.2 lists reference characteristics of Bhadra Dam-reservoir system.

Description	Value
Gross storage capacity	2025.87 hm³
Live storage capacity	1785.15 hm³
Maximum Water Level	657.76 m
Spillway crest level	650.60 m
Length of dam at top	1708 m (440.43 m masonry)
Type of Gates	Vertical
Size	7.62 m (H) × 18.28 m (W)
No. of gates	4
Total Spillway Capacity	3021.34 m³/s

Table 2.2. Bhadra Dam characteristics: key figures.

2.3. Cross section drawings

The following figures show cross sections of Bhadra Dam through the spillway and dam body sections, respectively. These figures are obtained from drawings of the Bhadra Dam reservoir project.

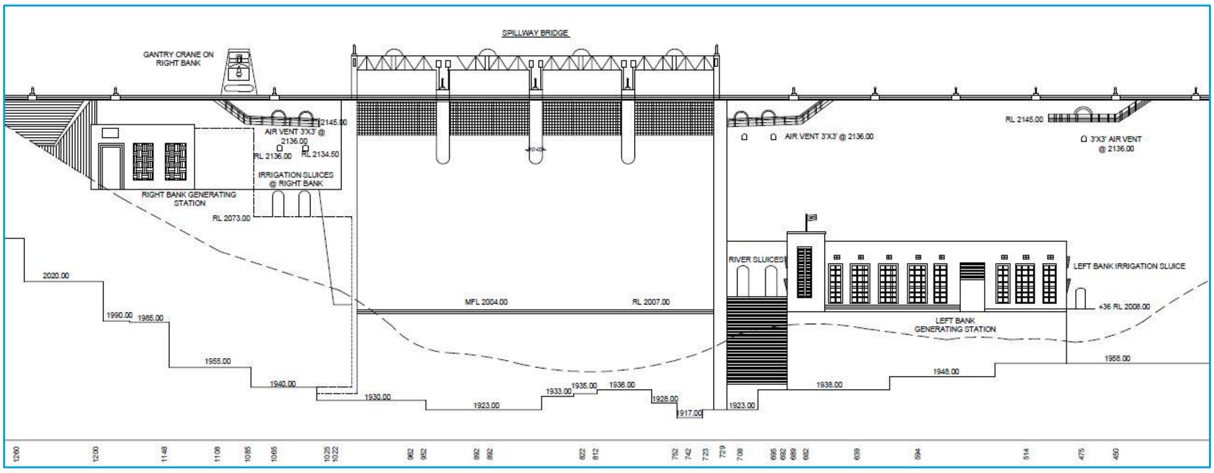


Figure 2.4. Main dam. Downstream view. Source: Bhadra reservoir project.

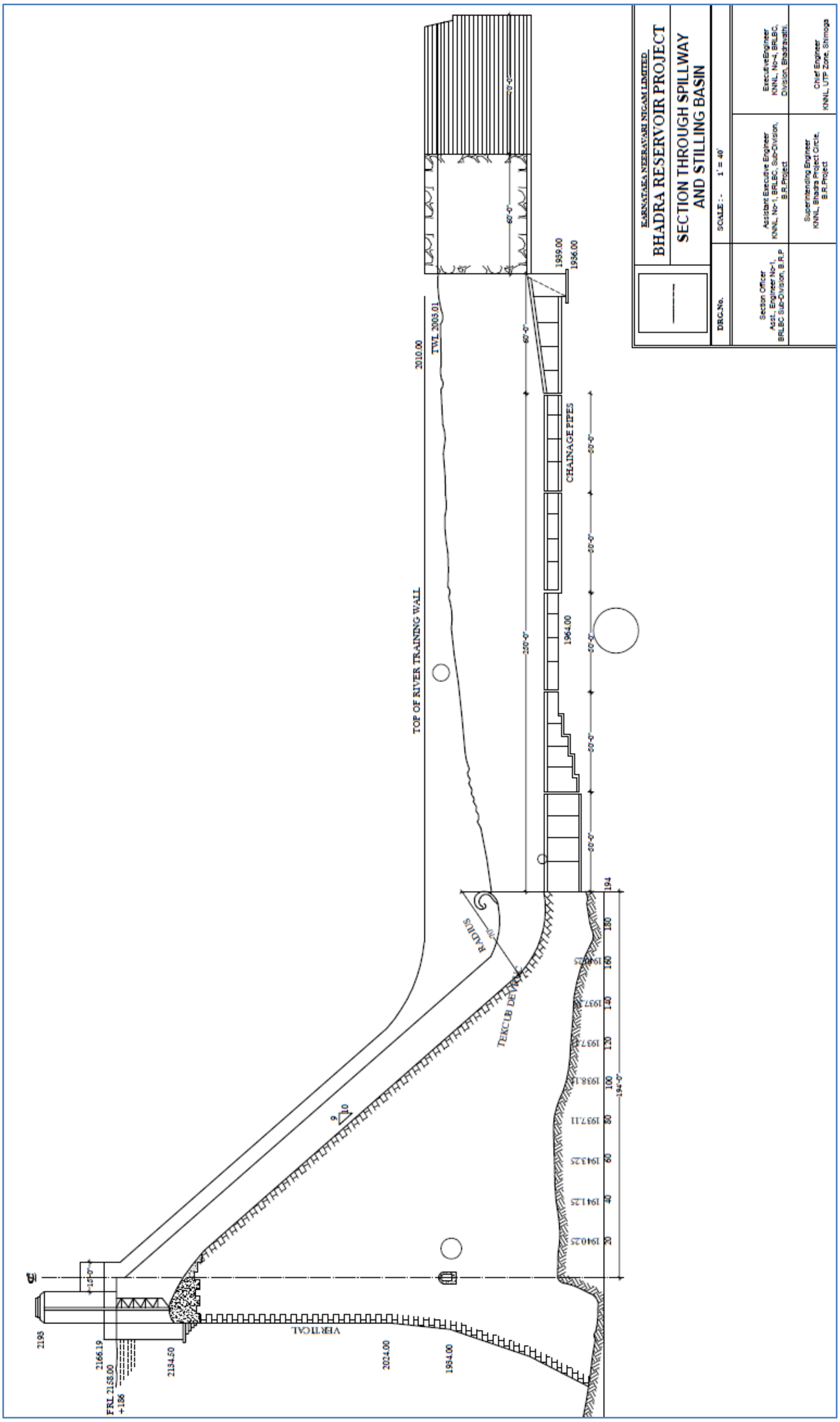


Figure 2.5. Spillway cross section of Bhadra Dam. Source: Bhadra reservoir project.

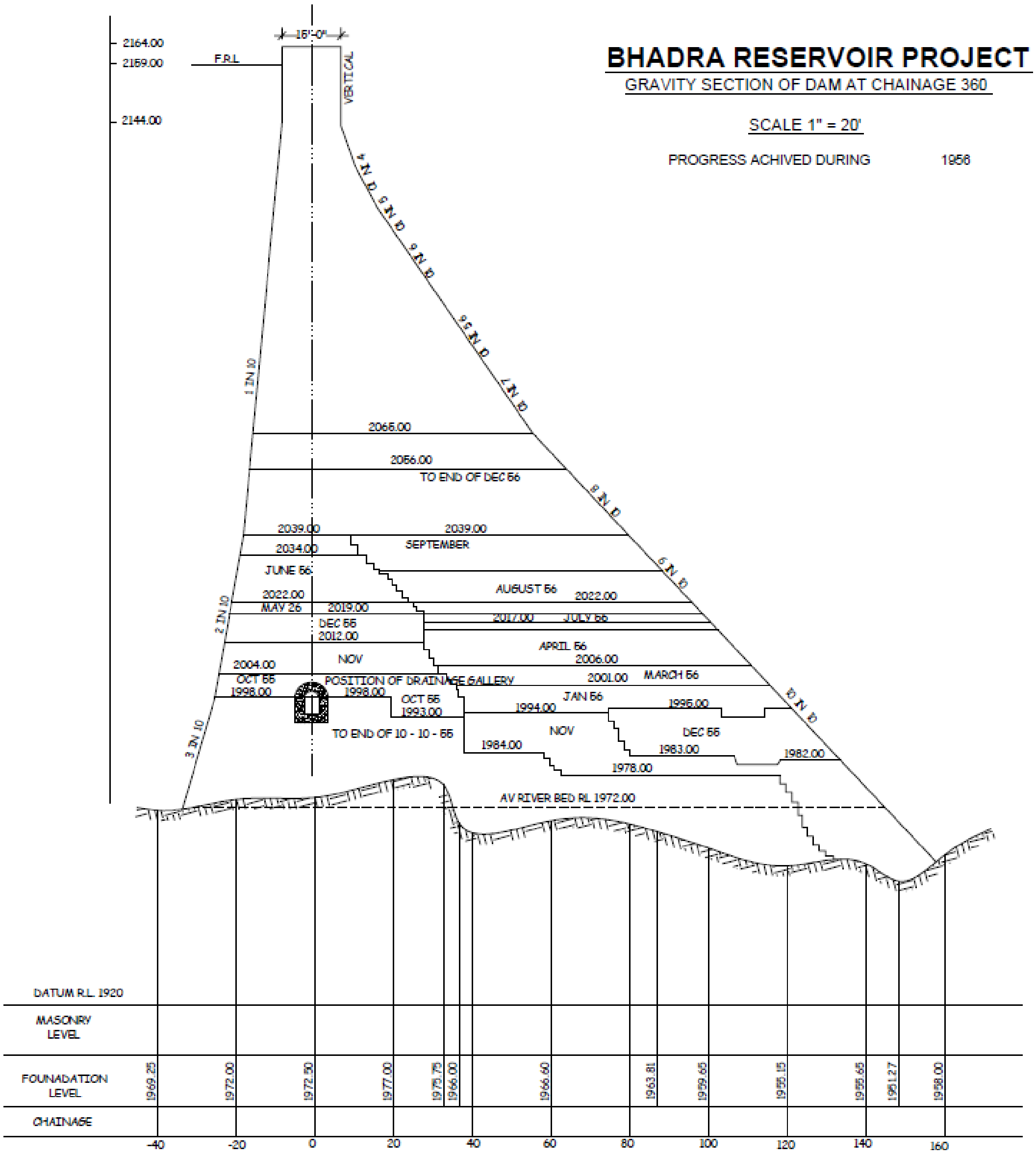


Figure 2.6. Dam body cross section of Bhadra Dam. Source: Bhadra reservoir project.

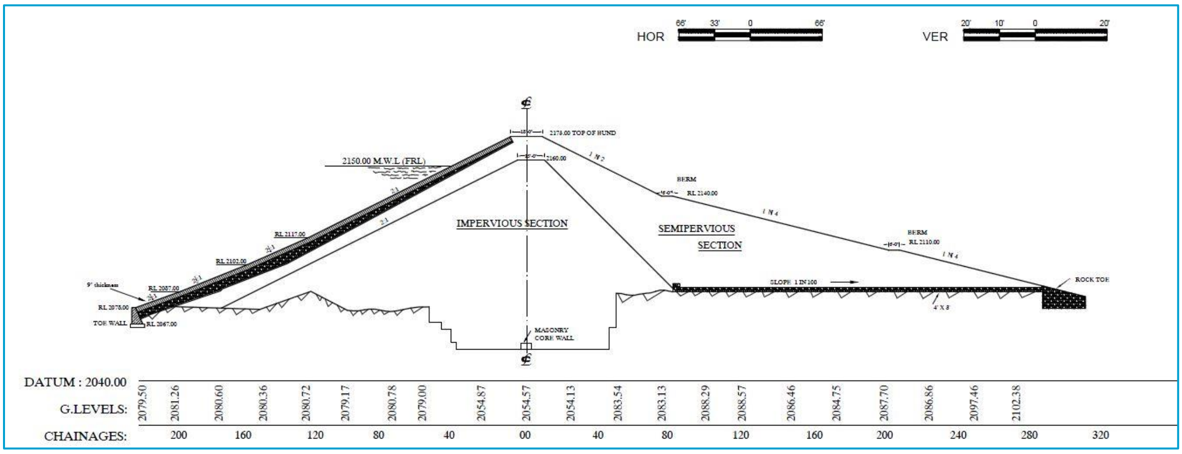


Figure 2.7. Saddle dam 1. Cross section. Source: Bhadra reservoir project.

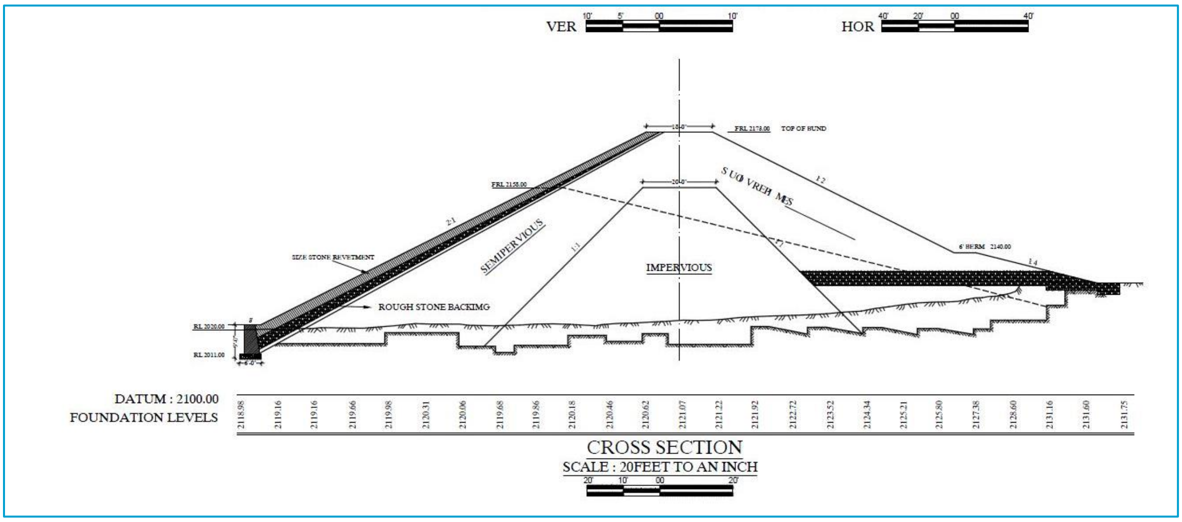


Figure 2.8. Saddle dam 2. Cross section. Source: Bhadra reservoir project.

2.4. Description of outlet works and spillways

The spillway is composed of four gates with a total length of 273.29 ft (83.3 m) and a maximum discharge of 106700 cusecs (3012 m³/s). The spillway crest level is located at the elevation 2134.5 ft (650.60 m). The maximum spillway opening height is 23.5 ft (7.16 m).

Energy dissipating arrangements for Bhadra Dam consists of a stilling basin of 320 ft (97.5 m) in length at (-) 20 feet (EL 1952 feet). Beyond the stilling basin there is a tail channel.

Figure 2.9 shows a detail of spillway gates at Bhadra Dam.

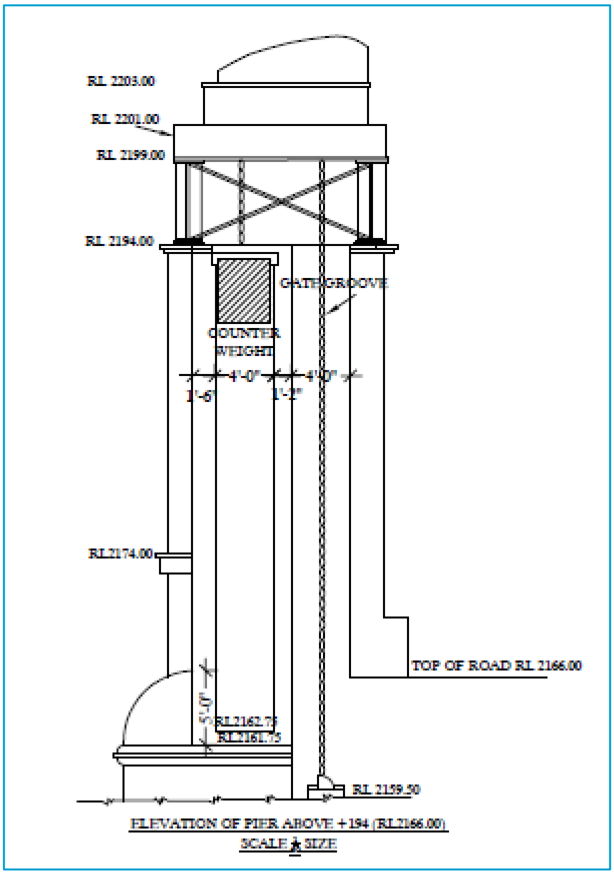


Figure 2.9. Detail of spillway gates.

2.5. Brief description of major problems and rehabilitations in the past

- **Seepage and leakage** through dam body at the main dam.

Seepage through the foundation drains in the gallery of the main dam has been observed in past and recent safety reviews and it is ongoing. It indicates that there is leakage through the masonry section of the dam which was also indicated by the downstream face wetting of the entire dam section. Grouting actions were carried out during the first stage of the DRIP project.

- **Stilling basin.**

The stilling basin has been recently repaired as part of dam safety actions conducted in Bhadra Dam during the first stage of the DRIP project. The main objective was to rehabilitate a damaged portion of the stilling basin bed.

- **Collapse** of right bank guide wall and the construction.

The left side guide wall in the right bank of Bhadra dam collapsed suddenly on 18 September 1991 resulting in disruption of irrigation to Bhadra right bank canal. The reconstruction work started in 1991 and was completed in 1996. From 1996 onwards water has been allowed from this reconstructed wall. The total cost incurred was Rs 11.7 Crores.

2.6. Potential Hazard Classification

Potential Hazard Classification for Indian dams is described in the draft document *Guidelines for Classifying the Hazard Potential of Dams* (CDSO 2018). Hazard categorization is a commonly used method of classifying dams according to the degree of adverse incremental consequences of failure. However, hazard classification does not reflect current dam performance neither the probability of occurrence of potential dam failure.

Based on the classification proposed within the draft document *Guidelines for Classifying the Hazard Potential of Dams*, Potential Hazard Classification depends on Population at Risk downstream. For Bhadra Dam, the estimated population at risk, based on the document *Flood Inundation Maps for Bhadra Dam* (August 2017), is over 1,00,000 inhabitants (estimated population at risk within the presumed settlement boundaries is 5,72,572 inhabitants), thus corresponding to the highest Hazard Class IV, noted as ‘Catastrophic’.

3. Risk Assessment and Management Framework

First publications relating risk and dam safety are dated more than 35 years ago (Baecher, Paté, and De Neufville 1980). However, it was in the end of the 80s and the 90s when different working groups and institutions began to apply these techniques in Australia (University of New South Wales, ANCOLD, and so forth), Canada (BC Hydro, and so forth) and the United States (Utah State University, Bureau of Reclamation, and so forth).

In the United Sates, the first institution to applying Risk Assessment in dam management was the Bureau of Reclamation (USBR 1997). Risk-informed procedures have been used to assess the safety of USBR structures, to aid in decision-making to protect the public from the potential consequences of dam failure, to assist in prioritizing the allocation of resources, and to support justification for risk reduction actions where needed. In the USBR dam safety program (USBR 2011), Risk Assessment integrates the analytical methods of traditional engineering analyses and risk-based analysis along with the professional judgment of engineers, review boards, and decision-makers in determining reasonable actions to reduce risk.

Since 2005, the United States Corps of Engineers (USACE) and the Federal Energy Regulatory Commission (FERC) developed their own dam safety management policies based on Risk Assessment (FERC 2016; USACE 2014), collaborating with USBR.

Other countries have also experience on dam risk assessment. Spain is a reference example. Spain ranks first among the European Union countries according to the number of large dams, resulting in a water regulatory capacity which is approaching 50% of all renewable water resources. This capacity would not reach 10% without the 1200 large dam port-folio, making dams critical for the country.

First publications relating risk and dam safety were led by professors and researchers at Polytechnic University of Valencia at the beginning of the 21st century. The first cases of application of Risk Assessment to dam safety were led by the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA), which owns and operates one third of Spanish dams.

A pilot portfolio risk assessment was applied in Spain to inform safety management in the 26 large dams within the Duero River Authority (Ardiles et al. 2011). This first pilot case was the basis to develop the SPANCOLD Technical Guide on Risk analysis as applied to dam safety (SPANCOLD 2012). This guide today serves as a reference guide to apply risk-informed dam safety management for several public and private operators in Spain and other countries (Escuder-Bueno et al. 2016; Galán Martín, Escuder-Bueno, and Morales-Torres 2017; Setrakian-Melgonian et al. 2017) and it is the key manual for capacity building on the matter in Spain (Escuder-Bueno and Halpin 2016).

As shown in Figure 3.1, SPANCOLD Guidelines enforces Quantitative Risk Assessment to prioritize risk reduction actions. These risk models are elaborated based on the existing documents in the Dam Safety File (Safety reviews, Operation rules and Emergency Action Plans, among others).

The current Risk Assessment Report is based on the recommendations provided by the Spanish National Committee on Large Dams (SPANCOLD) through the Technical Guide on Dam Safety Nr. 8, entitled "Risk analysis applied to dam safety management", published in 2012 and applied for dam risk assessment in different dams worldwide (SPANCOLD 2012).

This document describes the general process for the application of Risk Analysis in dams with the objective of supporting decision making and the prioritization of risk reduction measures. The structure and procedures used in this document have been performed in accordance with the methodology explained in the aforementioned guide.

The main purpose of this document is describing the identified failure modes, the results of the semi-quantitative and quantitative risk analysis, and the prioritization made for new studies and potential risk reduction actions, how outcomes can be used to support decision-making for improved dam safety management as shown in Figure 3.1.

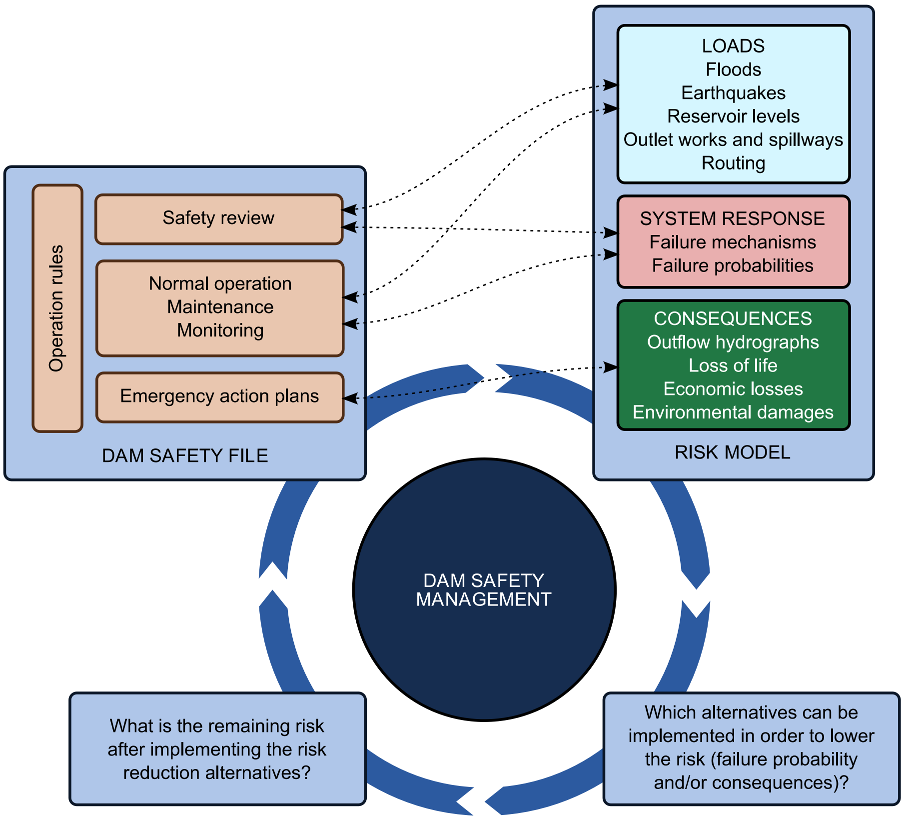


Figure 3.1. Risk-informed management of dams. Source: (SPANCOLD, 2012)

The process for dam risk analysis is shown in Figure 3.2. This process is generally divided into two stages. First, a **qualitative phase** which includes: definition of the scope of the analysis, review of the available information, technical visit, discussion about current dam situation and multidisciplinary group working sessions for **identifying and classifying potential failure modes**. This last step is the most relevant part of the first qualitative stage and is described in Section 4, including the classification of failure modes in the four categories shown in Figure 3.2.

Second, a **quantitative phase** is conducted for selected failure modes and includes: definition of the risk model architecture, estimation of input data for the risk model, risk calculation, risk evaluation, uncertainty analysis and prioritization of risk reduction measures. Outcomes from this quantitative stage are described in Section 5.

In addition, a **semi-quantitative analysis** has been conducted for failure modes classified as Class III and includes: definition of the risk model architecture, estimation of input data for the risk model, risk calculation, risk evaluation, uncertainty analysis and prioritization of risk reduction measures. Outcomes from this quantitative stage are described in Section 6.

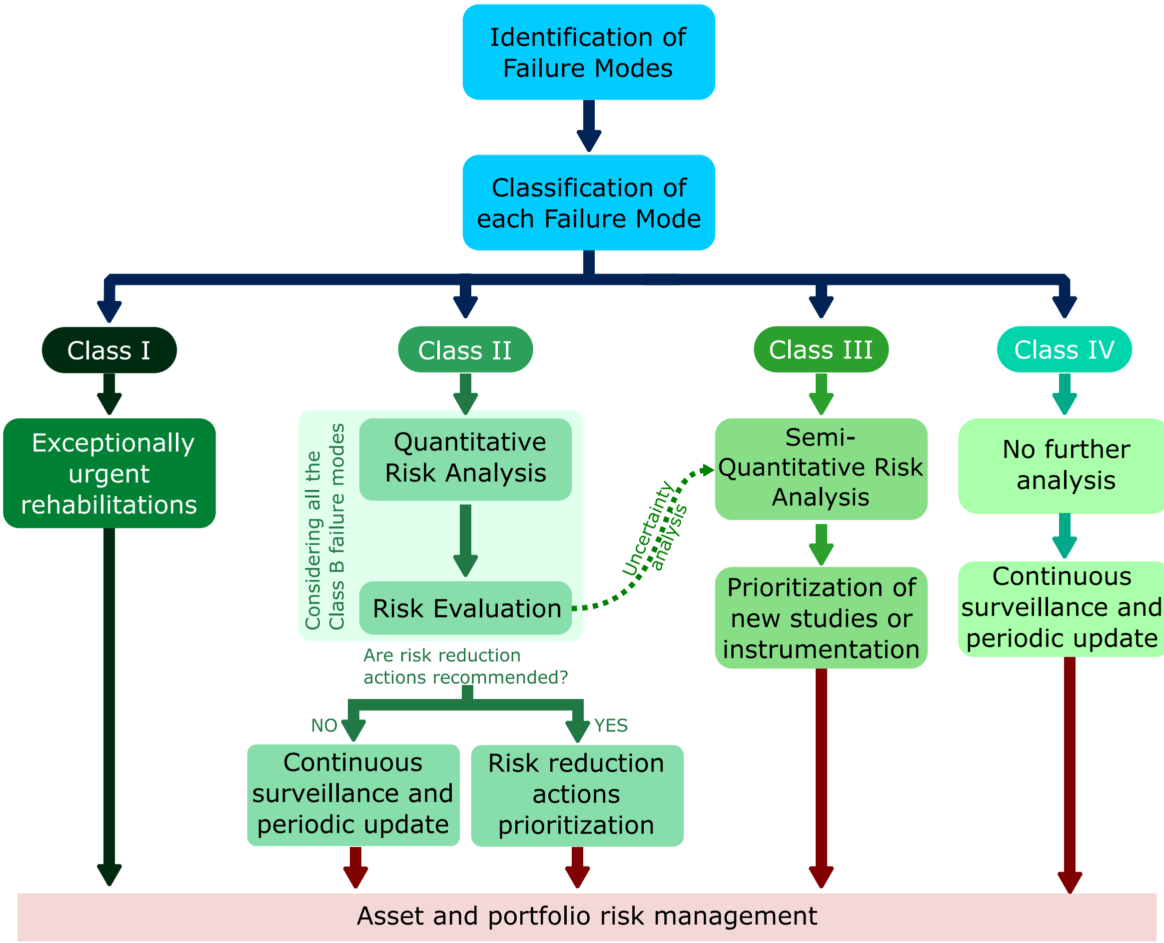


Figure 3.2. Dam risk assessment process.

4. Identification of Failure Modes

4.1. Introduction

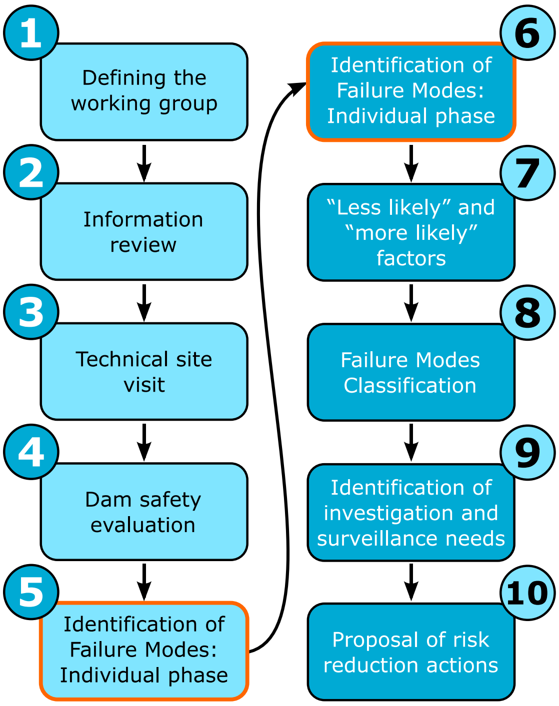
A **failure mode** is a specific sequence of events that can lead to a dam failure. This sequence of events must be linked to a loading scenario and will have a logic sequence: starting with an initiating event, one or more events of progressive failure and will end with dam failure or mission disruption of the dam-reservoir system.

In general, any failure mode with the potential to produce adverse social or economic consequences could be analysed. However, in this case the analysis was focused on the failure modes that could produce an uncontrolled release of water downstream and therefore leading to potential loss of life. The identification is not limited to the dam structure and it may include any feature or component of the dam-reservoir system.

To structure a risk calculation and analysis, failure modes were linked with several **loading scenarios**, according to the loading event that triggers the failure mode. The three loading scenarios analysed were:

- **Normal scenario:** What can happen in an ordinary day and normal operation?
- **Hydrologic scenario:** What can happen when a flood occurs?
- **Seismic scenario:** What can happen when an earthquake occurs?

The process for Identification of Failure Modes in Bhadra Dam was made during a working session conducted in 2017 as shown in Figure 4.1.



Step	Date
1	Jan - Feb 2017
2	21 February 2017
3	21 February 2017
4	22 February 2017
5	22 February 2017
6	22 February 2017
7	22 February 2017
8	22 February 2017
9	22 February 2017
10	22 February 2017

Figure 4.1. Identification of Failure Modes steps and dates.

Figure 4.2. Working session on Failure Mode Identification for Bhadra Dam. Shimoga, 22 February 2017.

As can be observed, this process was made by a collaborative work of several engineers and technicians, including a comprehensive review of available information, a technical visit to the dam and a group discussion about the current state of the dam.

Failure modes were identified in two phases: individual (where each participant made a first identification) and group phase (where all the failure modes identified by the participants were put in common). Finally, identified failure modes were analysed in detail and classified, proposing potential actions for uncertainty and risk reduction. This process is explained in detail in the following sections.

Identification of Failure Modes was made by a multidisciplinary group that included engineers and technicians in charge of the daily operation of the dam to regional/national experts in some of the topics addressed. The working group for Bhadra Dam included more than 30 engineers, including staff members from KaWRD and partners of the DAMSAFE project.

During this session, a more reduced group of 10 participants, including expert engineers on dam risk analysis and the Bhadra Dam reservoir system conducted the dam safety evaluation.

This failure mode identification session for Bhadra Dam was facilitated by Adrián Morales (iPresas) who has proved experience in coordinating these types of sessions.

4.2. Information review

The information available about Bhadra Dam was reviewed during the period from January to February 2017 to support the Failure Mode Identification session conducted in Shimoga on 22 Feb 2017. This review was further completed with additional information obtained in the period 2017-2018. The main documents reviewed before and during the failure mode identification session and during the Risk Assessment process are shown in Table 4.1.

Document title	Author	Date	Acronym
Technical note of Bhadra Dam-reservoir system, including recommendations made by Dam Safety Review Panel during inspection of Bhadra Dam in 2014	Government of Karnataka, Water Resources Department	2017	TN2017
Conclusions from the failure mode identification session conducted on 22 February 2017	Government of Karnataka, Water Resources Department	2017	WS2017
PMP Atlas for different river basins in India, including West Flowing River Basins and Cauvery and Other East Flowing River Basins	RMSI	2015	Atlas2015
Flood Inundation Maps	Central Water Commission	Aug 2017	FIM2017
Draft Design Flood Study	EGIS and Central Water Commission	May 2017	DFS2017
Project Screening Template and Site Visit Report	EGIS and Central Water Commission	Jan 2015	PST2015a
Project Screening Template Revised Compliance Review	EGIS and Central Water Commission	Jul 2015	PST2015b
Construction Site Visit Reports	EGIS and Central Water Commission	2016-2018	CSV
Drawings of Bhadra Dam reservoir system (Bhadra Reservoir Project)	Government of Mysore, Public Works Department and Government of Karnataka, Irrigation department	Not defined	BRP
Hydrologic model (HEC-HMS)	Central Water Commission	2017	Not applicable
Hydraulic model (HEC-RAS)	Central Water Commission	2017	Not applicable

Table 4.1. Review of information for Bhadra dam.

The two aforementioned models, a hydrologic model developed in HEC-HMS and a hydraulic model developed in HEC-RAS (both developed by the CWC), were available and used for obtaining input data for the Risk Assessment process. The table lists the acronym used in the following sections to refer to information included in each document.

After the detailed review of information on the Bhadra Dam, the main conclusions about the available information are summarized below:

- In general, there exist up-to-date information on conducted recent actions to improve dam safety of the Bhadra Dam, mainly related to recommendations derived from Dam Safety Review Panels conducted in 2002 and 2014.
- A new hydrologic study was recently done to evaluate design flood. However, the Bhadra river basin is not included in recent statistical analyses on rainfall events conducted for different river basins in India and there is no available information on flood analysis from a probabilistic approach.
- There is no available rainfall data from stations located within the Bhadra river basin. Consequently, results from other stations located in nearby river basins have been used for estimating input data to be incorporated into the quantitative risk analysis. Therefore, a detailed hydrologic study for the Bhadra river basin would be desirable and would help to better probabilistically characterize flood events into the reservoir.
- There is no information on soil conditions at the dam-foundation contact. Therefore, there is high uncertainty on the resistant characteristics at the dam foundation that should be better characterized for analysing potential failure modes related mainly to sliding failure mechanisms. Consequently, a geotechnical study at Bhadra Dam is required to reduce uncertainty and gain better knowledge on foundation materials.

4.3. Technical site visit

The site visit to Bhadra Dam was held on 21 February 2017, before the failure mode identification session conducted in Shimoga on 22 February 2017. This visit represented a very valuable source of information since it allowed verifying current conditions of the dam-reservoir system. This site visit was conducted with enough time to exhaustively inspect the main dam, saddle dams 1 and 2 and the reservoir.

Figure 4.3. Technical site visit of Bhadra Dam. 21 February 2017.

Special attention was paid to the main problems identified during the review of information of Bhadra Dam, including aspects such as the general state of dam body and equipment, seepage, leakage, settlements and maintenance of outlet works, among others.

The main conclusions drawn after the technical site visit are:

- In general, the masonry dam is in satisfactory condition. Repairs and routine maintenance were on-going at the time of the visit.
- The drainage gallery is well lighted and is easily accessible for inspection.
- In general, significant leakage was observed along the non-overflow section of the main dam during the site visit. The masonry dam appears to have become pervious in some reaches through which the water is finding access from the reservoir as evidenced from the leakage. In the period of the site visit, drilling works were conducted as part of rehabilitation actions as suggested by experts who were involved in the 2002 and 2014 safety reviews.
- Several drainage holes were blocked at the time of the site visit.
- There is no instrumentation on the main dam or saddle dams, except for several V notches to measure leakages. Therefore, information on dam monitoring includes measures of water levels at the reservoir.
- Spillway gates appeared in satisfactory condition during site visit but there was end-around seepage in corners.
- Saddle dam sections appeared to be quite stable and well maintained.
- However, at saddle dams slightly uneven settlements are observed on the upstream face. This settlement has been regularly monitored for the last six years. There is no information to conclude the potential cause for such movements on the upstream face.
- As stated by dam engineers, operation and maintenance of spillway gates and electrical equipment has improved after implementing recommendations from the 2002 and 2014 safety reviews conducted by a panel of experts.

4.4. Dam safety evaluation

After the field visit performed on 21 February 2017 and the information review, a comprehensive evaluation on dam safety of Bhadra Dam was made as a basis for the identification of failure modes and it is here summarized.

In addition, main conclusions from other site visits were discussed during the failure mode identification session conducted on 22 February 2017 and are also included. These are:

- A site visit was conducted between the 23rd and 26th of January 2015 conducted as part of the review of Project Screening Template (PST) for Bhadra Dam.
- Site visits conducted during Dam Safety Review Panels developed in 2002 and 2014.

4.4.1. Flood hazard and hydrological adequacy

Concerning hydrology adequacy of the Bhadra Dam, the spillway was designed to pass a maximum discharge of 3,021.24 m^3/s and can be supplemented by two river sluices. Based on recommendations from the Dam Safety Review Panel of 2014, it was required to assess the Probable Maximum Flood (PMF) and verify the adequacy of the spillway capacity and the existing freeboard and take corrective measures accordingly. The assessment of the PMF conducted in 2017 is described in this section.

Present-day norms related to the analysis of design floods in India are contained in the Indian Standard–Guidelines for Fixing Spillway Capacity (IS: 11223 – 1985, reaffirmed in 1995). The IS: 11223 Standard considers three categories of inflow design floods – namely, 100 year return period flood, Standard Project Flood (SPF) and Probable Maximum Flood (PMF). The SPF (computed by using the Standard Project Storm) is expected from the most severe combination of hydrological and meteorological factors. On the other hand, the PMF (computed by using the Probable Maximum Storm) corresponds to the physical upper limit to maximum precipitation. However, SPF and PMF values are not related to probabilistic estimates of their corresponding rainfall events, although in some cases it is assumed that these floods correspond with an order of magnitude up to 1,000 year and 10,000 year return period, respectively, or even higher.

A substantial proportion of Indian dams are getting subjected to revisions in their design floods as part of the Dam Rehabilitation and Improvement Project (DRIP) project. A comparison of the revised design flood values of analysed dams with their respective original design flood values can be found in (Pillai and Gupta 2017), and, in general, outcomes from the analysis indicate that there is an upward revision of over 50% for 63% of the dams and an upward revision of over 100% for 40% of the dams. Thus, in general, the revised design flood values have exceeded their earlier adopted values by substantial orders. Several reasons can be found for such a difference, including the availability of additional data on observed flood peak discharges used in flood frequency analysis or changes in the design storm duration or used river basin response function, e.g. unit hydrograph, as a result of analysis of more events.

For Bhadra Dam, the Draft Design Flood Study (DFS2017) conducted during the DRIP project includes the following information and conclusions:

- The original design flood had a magnitude of 3,397.83 m^3/s. However, details of the estimation procedure could not be obtained.
- Estimation of the inflow design flood for Bhadra Reservoir was carried out using hydro-meteorological approach (unit hydrograph method). The flood hydrographs for 4 sub-catchments were combined at the point of confluence and routed through the corresponding river reach.
- The design storm rainfall associated to the Probable Maximum Precipitation (PMP) was used. The 1-day Probable Maximum Precipitation (PMP) was estimated in 26.9 cm (269 mm) and the 2-day PMP value was set at 35.9 cm (359 mm) as design rainfall values.
- The design storm duration adopted was 48 hours. The rainfall within this duration has been considered to be divided into 4 spells of 12 hour each, following current practice.
- For assessment of the design flood for Almatti Dam and Narayanpur Dam in the Krishna Basin, a loss late of 0.1 cm / hour (48 mm in total) was considered. The same loss rate was adopted for Bhadra Dam.
- For finding the worst critical sequence of rainfall that yields the largest flood peak at Bhadra Dam, the analysis was carried out considering all the feasible bell sequences. The combination 4-2-1-3 was finally established as the worst case scenario.
- Based on aforementioned characteristics of the design flood analysis, the peak of PMF was estimated as 7,544 m^3/s.

Based on information from DFS2017, the original design flood was estimated as 3,397.83 m^3/s. However, this recent study shows a value of PMF as 7,544 m^3/s. The following figure depicts the resulting PMF event obtained from the review analysis described in DFS2017, with a peak discharge of 7,544 m^3/s after 38 hours from the initiation of the rainfall event.

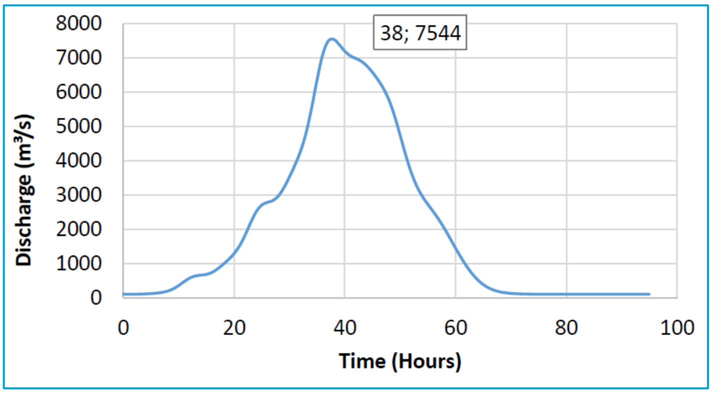


Figure 4.4. Estimated PMF hydrograph. Source: DFS2017.

Given the existing differences on original and reviewed design floods, additional information on rainfall patterns is required in order to characterize flood hazards for Bhadra Dam. Consequently, data from the *PMP Atlas for different river basins in India, including West Flowing River Basins and Cauvery and Other East Flowing River Basins*, published by RMSI, has been used for estimating rainfall events in the Bhadra river basin. In a first approach, the hydrologic model developed in HEC-HMS by the CWC as part of the DRIP project was used to obtain probabilistic flood events in the Bhadra reservoir system. Storm durations, storm distribution (bell sequence 4-2-1-3) and loss rates from DFS2017 are used for estimating input data for the Quantitative Risk Analysis process as described in Section 3.3.

In addition, for Bhadra Dam, the spillway capacity has been reviewed and estimated as 4,224 m³/s (Revised Flood Routing) as stated in FIM2017.

However, the assessment of hydrological adequacy requires a more detailed flood routing analysis as described in Section 3.3., including different reservoir levels, gate performance combinations and the whole range of potential flood events.

4.4.2. Gates operation and hydraulic behaviour

Operational rules are briefly described in a document provided by engineers from Karnataka Water Resources Department (KaWRD), in which the formulae for estimating the rating curve for the spillway is included. Draft rules, as stated in this document, for operating the Bhadra Dam are summarized below and include the following highlights:

- The monsoon period is roughly extended from June to November, with the peak period from mid July to mid September.
- The maximum observed flood discharge is 94,600 cusecs (2678.77 m³/s) and the spillway capacity is 1,06,700 cusecs (3021.41 m³/s). The two scouring sluices provide an additional discharge of 13,300 cusecs (376.61 m³/s).
- The reservoir level should be kept as near as possible to MOL (RL 2158 ft, 657.76 m).
- This document includes the following rule “Do not bring down the level below RL 2090 (637.03 m) except for repairs”.

In addition to the aforementioned general rules, as stated in TN2017, “It is proposed to have 2.5 TMC (Thousand Million Cu Ft) storage capacity for flood absorption below Maximum Operating Level (MOL) during active monsoon season to be able to have safe and effective reservoirs operation schedule”. The rainfall in the catchment area of Bhadra Dam generally starts from the 1st week of June and it is very active generally during July, August and September.

The following general recommendations are described in TN2017, “if the flood absorption capacity of 2.5 TMC (70.8 hm³) is maintained, the reservoir level has to be kept at 2156 ft e.g., 2.00 ft (0.6 m) below MOL (set at 2158 ft, 657.76 m). It is better to start the reservoir operation schedule duly predicting the inflow in the reservoir based on gauged discharge at Balehonnur and also from the daily rainfall records of upstream rain gauge station in the catchment from the first week of June itself. However the reservoir level of RL 2156 (657.15 m) with a cushion of 2 ft should be maintained till the end of August by suitably matching the inflow and outflow discharges. During the month of September depending up on the inflow pattern, the reservoir water level may be raised (e.g., 1 ft below the MOL). From October and onwards the reservoir water level may be brought to the MOL level depending up on the inflow pattern and forecast of floods/ monsoon”.

4.4.3. Gates and electromechanical equipment condition

The spillway at the main dam has a length of 270 ft (82.3 m) consisting of 4 vertical crest gates the size of 60 ft x 25 ft (18.3 m x 7.62 m). The spillway is of gravity type with OGEE profile and the coefficient of discharge is 3.98. Maximum depth of spillage allowed is 23.5 ft (71.63 m) having a total discharge capacity of 1,06,700 cusecs (3021.41 m³/s). Spillway piers carry a RCC T Beam bridge with a 4.57 m wide roadway.

As stated in TN2017, in the period 1999-2000 it was stated that for the rollers for all 4 of the crest gates were damaged and needed immediate replacement. All gate rollers assemblies were refixed and realigned with new cast steel rollers.

Figure 4.5. View of spillway gates during site visit on 21 February 2017.

Recently, the following repair actions have been taken up under the DRIP project, as stated in TN2017. All these listed actions were implemented after the site visit and the review of information conducted in February 2017, so they are not considered in the “Current situation case”, but they are implemented in the risk reduction actions prioritization.

4.4.4. Current state of spillway and stilling basin

Energy dissipating arrangements at Bhadra Dam consists of a stilling basin of 320 ft (97.5 m) in length at (-) 20 ft (EL 1952 ft, 594.97 m). Extensive seepage along right guide wall and erosion in the stilling basin was reported in previous dam safety reviews. In 2017, the stilling basin was dewatered, for the first time since the failure of the right bank channel in 1991. That wall collapse resulted in a 2-m deep gouge along the base of the guide wall.

As stated in PST2015b, the stilling basin was partially mapped by a ROV (Remote Operated Vehicle) mounted camera but dewatering to confirm proposed repair work was suggested.

Repair works in the stilling basin were conducted under the DRIP project in 2017. Some pictures of the process are included here. Demolition of the old eroded stilling basin concrete was conducted and stilling basin repairs included drilling of holes for fixing rock anchors at the stilling basin, reinforcement of concrete in the stilling basin area and repair of the wall between the stilling basin and scour sluice channel. In addition, removal of loose debris from the tail channel was performed. Some pictures of these repairs are shown below.

Figure 4.6. View of the stilling basin after dewatering and cleaning. Source: CSV20170921.

Figure 4.7. View of the right side protection wall of tail channel for left bank after completion of work. Source: CSV20170921.

4.4.5. Foundation and abutments

In 1950, geotechnical tests were made on the dam with the following results:

- Section 1: Soft and clearable chlorite schist devoid of quartz veins for about 50 ft. width from the centre line of the dam upstream.
- Section 2: Hard and tough chlorite schist for 45 feet width from the center line of the dam axis. Highly crumpled and folded Chlorite schist with quartz veins.
- Section 3: Massive grey, crystalline talc, schist for 135 feet width thus occupying major part, composed of calcite and talc. In this rock, lenticular ribbons of altered schist are found.

The alignment of the dam is a little askew to strike direction of North 30º West –South 30º East but the dam is resting along the strike of rock with beds dipping downstream 60º to 80º. It is also reported the folding of rock types, banded chlorite schist at the NW comer of excavation. No major faults, wide joints and fissures are reported.

However, there is uncertainty on foundation materials, as stated in the dam safety review conducted in 2014. “Physical characteristics of the rock mass of the foundations rock should be determined by taking core samples on the downstream side of the dam”. Provision for this action is made under DRIP but has not yet been conducted.

Seepage through the right abutment hill was observed during previous dam safety inspections in Bhadra Dam. Excessive quantity was not reported nor observed during the site visit.

Additional studies for identifying the path of seepage from the right bank abutment were suggested as part of the proposed catalogue of rehabilitation and improvement works under the DRIP programme.

The collapse of the right bank guide wall occurred in 1991. “The Bhadra’s right bank left side guide wall was collapsed suddenly on 18 September 1991 resulting in disruption of the irrigation to Bhadra’s right bank canal and its branch canals.” After this event, saddle dam 4 was converted into a spillway. “After the collapsing of the tailrace training wall at the irrigation sluice of the right bank canal during 1991, to save the standing crops and to ensure continuous irrigation, earthen dam at saddle dam nr. 4 on the right bank was excavated and converted into a chute spillway and was constructed in its location to meet the emergent situation. The saddle dam 4 on the right bank is therefore does not have earthen embankment now.”

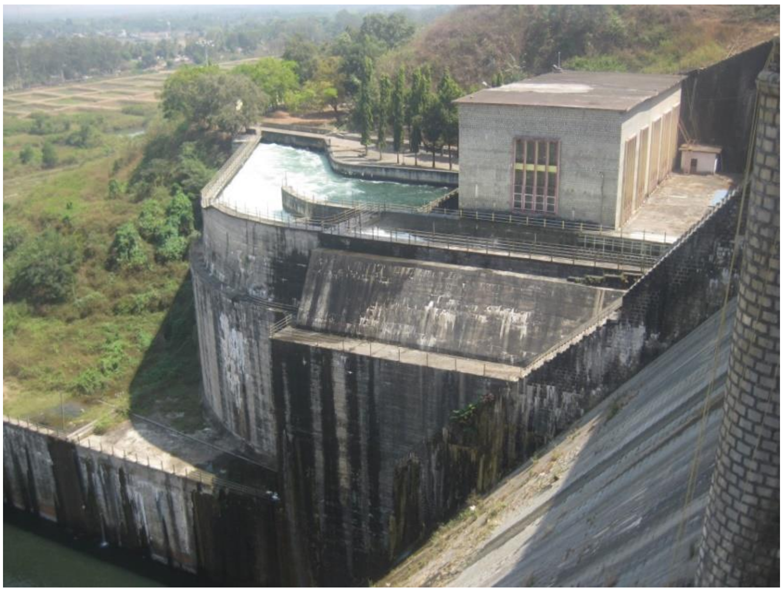


Figure 4.8. View of the right bank channel during site visit on 21 February, 2017.

4.4.6. Monitoring data and state of monitoring system

There is no instrumentation available at Bhadra Dam. There are V-notch weirs to measure leakage flow rates and register of reservoir level. Installation of piezometers to monitor uplift pressures is recommended in available dam safety review reports as stated in TN2017.

4.4.7. Dam body state: Main dam

The masonry far left flank monolith shows very little downstream face seepage as stated in PST2015b. Previous work on this section included directional grouting of the monolith and it shows to be effective. The monolith between the left flank monolith and the spillway section has through seepage exposed at various levels, as stated in PST2015b and observed during the site visit. Porous drains are marked with light to moderate leakage (estimated at <50 l/min, PST2015b). However, there are drains that are clogged with calcareous materials.

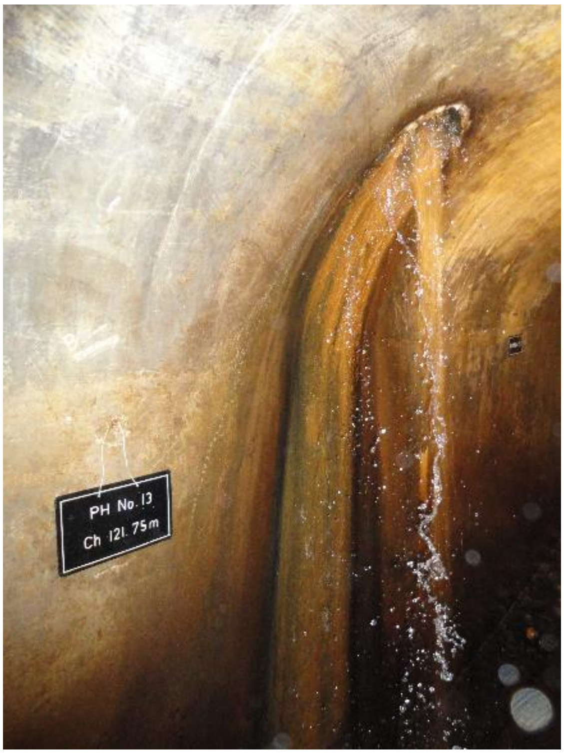


Figure 4.9. Example of drain at main dam and location mark.

Leakage in the foundation gallery was significant during site visit, and it is also reported in previous reports. There are V-notch weirs placed in the drain but there is no method to separate and measure the flows between the non-overflow blocks and the spillway section.

Since there is no dam instrumentation, conclusions cannot be drawn on general dam performance regarding movements, joints and other key variables.

There is no information on quality or resistant parameters of dam body materials in the main dam. There are some obtained from drills conducted in 2016-2017 as shown below.

Figure 4.10. Core samples at main dam. Source: CSV20170921.

This picture shows 150-mm diameter core samples taken from the main dam. Veins of pink coloured Surkhi lime used for mortaring are observed. Reports on construction site visits conducted in 2017 state that this type of lime material are noted to work well in underwater conditions but can alter during periods of cyclic wet-dry periods.

Grouting actions are recommended in reports of past dam safety review inspections, as stated in TN2017.

4.4.8. Dam body state: Saddle dams

Saddle dams 1 and 2 have significant settlements on the upstream slope and on the left flank of saddle dam 1. At saddle dam 2 slightly uneven settlements are also observed on the upstream face. These settlements are being regularly monitored for the last six years, but their origin is still unknown. A proposal for installing a surface settlement gauges is included under the DRIP project, but has not yet been implemented. These settlements in Saddle Dam 1 can be observed in the following picture:

Figure 4.11. Settlements observed in upstream face of Saddle Dam 1. Source: Technical inspections.

There are no signs of potential internal erosion problems. Since there is no dam instrumentation, conclusions cannot be drawn on general dam performance. Control of vegetation appears satisfactory on both saddle dams.

There are currently no survey or level benchmarks to determine how much settlement or downstream deflection has occurred in saddle dams. Analysis of satellite images from PS-InSAR technology is under process in 2018 as part of the DAMSAFE project.

4.4.9. State of drainage systems

For the main dam, V-notch weirs are undersized for the observed leakage flow both inside the drainage gallery and along the downstream toe. Some of the dam body and foundation drains were clogged with calcareous materials, so drainage system could not be working properly.

There are no boils observed in the vicinity of the downstream toe of the dams.

In PST2015b, re-establishment of toe drains in saddle dams as part of a monitoring plan is suggested.

4.4.10. Dam stability in normal loading conditions

In the document TN2017, it is stated that "…the dam stability of both over flow and non over flow dams have been analyzed for normal operating conditions with water level at F.R.L. and with uplift force of 2/3 h at the upstream face reducing uniformly to zero at the downstream toe […]". However, there is no information on hypotheses applied for resistant parameters at the dam foundation contact in this study. In addition, date of this analysis is not available.

There is high uncertainty on uplift pressures at dam foundation since there is no available dam monitoring data.

4.4.11. Seismic hazard and dam stability in seismic events

Bhadra Dam is located in Zone 2 based on the Earthquake Zone Map for India. Zone 2 is classified as Low Damage Risk Zone (least active seismic zone in India, among the four classes set for active areas, ranging from Zone 2 to Zone 5). It is found, based on information available, that "seismic forces were not considered in the design", as stated in TN2017. Stability analysis for seismic scenarios is suggested in previous dam safety inspection reports.

Installation of a seismic station is included as part of the proposed catalogue of rehabilitation and improvement works under the DRIP programme.

4.4.12. Landslide in the reservoir

No evidences of potential landslide within the reservoir are found neither reported.

4.4.13. Emergency action planning

Main urban areas located downstream Bhadra Dam with a population at risk of over 10,000 inhabitants are included in Table 4.2.

Urban area	Distance to Bhadra Dam (km)	Population at risk (inh.)
Thavaraghatta /Shankarghatta	1	10,050
Jannapura / Bhadravati	13.9	46,719
Kanaka Nagar / Siddharudha Nagara / Hosamane / Gowdrahalli/ Hanumantha Colony	16.6	27,688
Harige / Sandal Colony /Sandvidya Nagar	22.8	12,868
Vinoba Nagar / Gopal	24.2	48,689
Gowda / Shivamogga	24.7	10,843
Anjanapura /Devanayakanahalli / Honnali / Honnali Rural	58.2	11,170

Table 4.2. Summary of main urban areas located downstream of Bhadra Dam.

An emergency action plan is currently under development as part of the DRIP project, but not yet implemented. A flood inundation analysis was conducted by CWC and reported in FIM2017, including identification of main urban areas located downstream Bhadra Dam and a consequence estimation analysis including population at risk and the hydraulic characteristics of three dam failure scenarios:

- A dam failure in masonry dam caused by overtopping from the inflow design flood leading to dam breach and uncontrolled release of water.
- A non-flood dam failure in saddle dam caused by internal erosion (piping) with the reservoir at full supply level leading to breaching and uncontrolled release of water.
- A large controlled-release flood without dam failure.

As described in this document, dam failure floods were simulated by numerically solving the two-dimensional, depth-averaged flow equations on an unstructured computational mesh using HEC-RAS. Breaches were modelled as trapezoidal openings that form at the crest of the dam and then grow in size, first vertically downward until the specified breach bottom elevation is reached, and then horizontally as outflows continue to widen the opening .

In this flood inundation analysis, flood hazard reference values consisting of maximum water depth, maximum depth-averaged velocity, and flood wave arrival time at various locations downstream from Bhadra Dam were obtained, along with a general classification to represent the vulnerability and severity of inundated areas taking into account parameters such as people, vehicles and buildings stability under flooded conditions. This classification was conducted in qualitatively terms, estimating hazard vulnerability in a range from Class H1 to Class H6.

Breach parameters used in FIM2017 (shown in the following table) were applied for simulating different dam failure scenarios for water levels above dam crest level as described in section 3, aiming at estimating key hydraulic characteristics for required life-loss and damage estimations for the Quantitative Risk Analysis.

Breach parameter	Units	Overtopping (main dam)
Height	m	40.19
Bottom width	m	206
Average slide slope	-	Vertical
Formation time	h	0.5
Peak discharge	m^3/s	121,847

Table 4.3. Breach parameters for overtopping failure mode in the main dam used in FIM2017

There is no available information on availability of dam access routes in case of emergency.

4.4.14. Engineering assessment

Engineering assessment consists in asking the participants to individually assess whether the dam is meeting established good international engineering practices. In this process, the different aspects related with dam safety described previously were evaluated.

Each participant rated each aspect as pass/apparent pass/ apparent no pass/no pass /not applicable according to his/her understating of international best practices on this dam safety aspect.

The only purpose of scaling the judgments was to facilitate a discussion on the current state of the dam, linking the different "risk" components and the safety standards in a very qualitative way before a robust and consistent failure mode identification was undertaken. This discussion serves as a starting point for discussion about current dams' situation and uncertainties.

The table includes results from this dam safety evaluation diagnosis, where colours depict different descriptors: **pass**/**apparent pass**/ **apparent no pass**/**no pass** /not applicable or no available information/no answer (white).

Results show that there is significant variability on assessments regarding dam response in case of seismic scenario, internal erosion and leakage and, monitoring and equipment. These differences are mainly due to the lack of information on dam-foundation characteristics, existing uplift pressures and the state of dam body materials. Consequently, results reflect the need for reducing uncertainty on dam foundation materials and better characterizing dam response (loads, leakage and resistance).

From this preliminary evaluation, it may be concluded that spillway capacity seems to meet international standards, however results show also high uncertainty and more detailed analysis of flood routing for different inflow events was conducted within the Risk Assessment process described in Section 5.

Emergency management procedures are not yet established but an Emergency Action Plan is currently under development within the DRIP project. Therefore, this measure will be considered as one of analysed future risk reduction actions.

	Participant									
Is in line with international standards on current dam safety practices? Dam body stability	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Central section	🟩	🟨	🟨	🟨	🟧	🟥	🟩		🟩	🟨
Spillway section	🟩	🟨	🟨	🟨	🟧	🟧	🟩		🟩	🟨
For seismic scenario	🟨	🟧	🟨	🟧	🟧	🟧	🟨		🟨	
Left abutment	🟨	🟨	🟨		🟩		🟩		🟩	🟨
Right abutment	🟨	🟨	🟨		🟩		🟩		🟩	🟧
Abutment performance in case of sudden water lowering	🟩	🟨	🟨		🟩		🟩			🟨
Dam body situation										
Impermeabilization and leakage	🟨	🟨	🟨	🟨	🟨	🟧	🟨	🟥	🟨	🟧
Vegetation and external erosion	🟨	🟥	🟧	🟨	🟨	🟩	🟥	🟥	🟥	🟨
Filters and internal erosion	🟩	🟥	🟨	🟨	🟩	🟩	🟨	🟥	🟥	🟨
Dam foundation										
Resistance	🟩	🟩	🟨	🟨		🟧	🟩	🟩	🟩	🟨
Leakage	🟩	🟩	🟨			🟧	🟨	🟥	🟨	🟧
Drainage system	🟩	🟩	🟧	🟧		🟨				🟧
Outlet works										
Hydrologic capacity of spillway	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩		🟨
Current conditions of spillway channel and stilling basin	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟨
Spillway gates	🟩	🟩	🟩	🟨	🟨		🟨	🟥	🟩	🟧
Mechanical equipment of bottom outlet works	🟩	🟩	🟩	🟨	🟧	🟨	🟨	🟥	🟨	
Mechanical equipment of water intakes	🟩	🟩	🟩		🟧		🟩	🟥	🟨	🟨
Electrical equipment	🟩	🟩	🟩	🟨	🟧		🟨	🟥	🟩	🟨
Landslide stability of reservoir area	🟩	🟧	🟧							
Monitoring and equipment										
Dam body	🟨	🟥	🟨	🟧	🟧	🟨	🟧		🟩	🟥
Dam foundation	🟨	🟥	🟨	🟧	🟧	🟨	🟧	🟩	🟩	🟥
Emergency management and action planning	🟨	🟥	🟨	🟧	🟧		🟨			🟧

Table 4.4. Results from dam safety evaluation assessment.

4.5. Failure Mode Identification

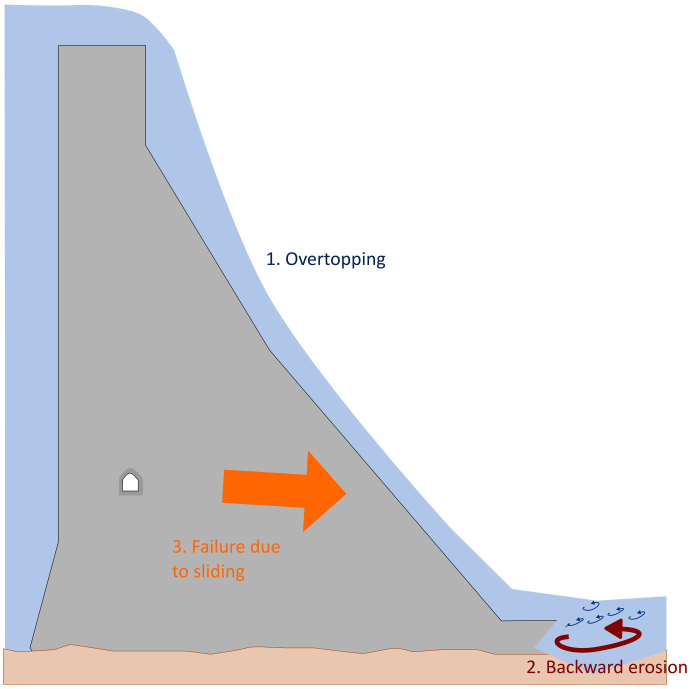
Failure modes for Bhadra Dam were identified on 22 February, 2017, during the failure mode identification session held in Shimoga, including an individual phase and a discussion group phase.

During the first phase of the identification of failure modes, each participant in the session individually made a preliminary identification of failure modes for Bhadra Dam, using the provided booklet. Once each participant finished the individual phase, all identified failure modes were put in common and combined.

In addition, for each failure mode, the factors that make them likely were discussed. “Less likely” and “more likely” factors describe all the recognized aspects of the dam-reservoir system that could make more (or less) probable the occurrence of a given failure mode.

The results of this failure mode identification process are shown in the following tables, including a total of eleven potential failure modes for the Bhadra Dam reservoir system, as listed below:

- FM1: Overtopping failure in the main dam.
- FM2: Overtopping failure in saddle dams.
- FM3: Sliding in the main dam along a failure surface at rock foundation.
- FM4: Sliding in the main dam along the dam-foundation surface.
- FM5: Sliding in the main dam due to degradation of masonry material.
- FM6: Sliding in a seismic event in the main dam.
- FM7: Overtopping in a seismic event in saddle dams.
- FM8: Internal erosion in saddle dams.
- FM9: Failure due to settlement at upstream face in saddle dams.
- FM10: Stilling basin failure in the main dam.

Failure Mode 1	Overtopping failure in the main dam
Description	
In a hydrologic scenario, due to a severe flood and/or inadequate spillway capacity and/or inability to open spillway gates, adequate freeboard cannot be maintained and this results in overtopping over dam crest level. Flow over the crest washes out material in the dam toe and causes massive erosion that progresses leading to the failure of the main dam.	
Graphical scheme	
	

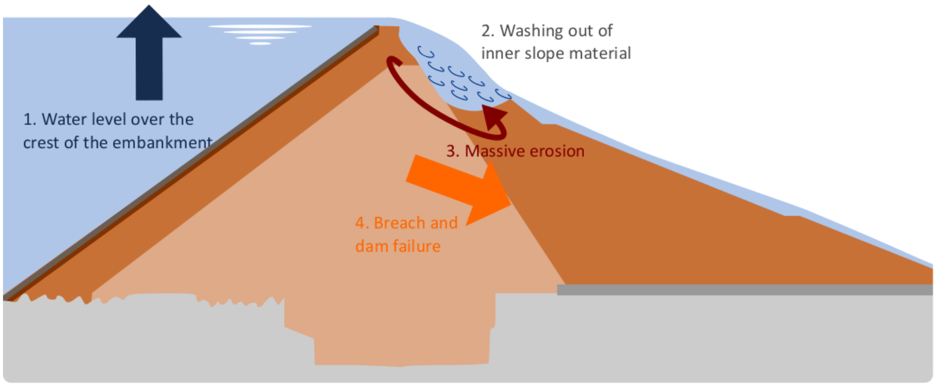
More likely factors	Less likely factors
Lack of detailed probabilistic hydrologic studies on Bhadra Dam-reservoir upstream river basin.	During the monsoon season, a different maximum reservoir level is fixed at RL 2156 ft, 2 ft below MOL.
Differences between original and reviewed design flood events (3,397.83 m³/s vs. 7,544 m³/s, respectively). The spillway capacity is 3,021.24 m³/s for Maximum Operating Level (MOL).	Spillway gates are, in general, well maintained.
Reservoir levels are 30% of time above RL 2154 ft. Maximum Operating Level (MOL) is established at RL 2158 ft during the dry season.	There are two sluices that provide additional discharge capacity up to 13,300 cusecs (376.6 m³/s).
Estimated rainfall data at nearby catchments (Cauvery and West Flowing Rivers) shows precipitation rates higher than those used for past design flood analyses.	The stilling basin has been recently repaired.

Failure Mode 2	Overtopping failure in saddle dams

Description

In a hydrologic scenario, due to a severe flood, the spillway at the main dam has insufficient hydraulic capacity to pass the flood event and maintain adequate freeboard and water level raises over saddle dams. Flow over the crest washes out material in the downstream slope of the embankment and causes massive erosion that progresses leading to slope instability, breach and dam failure.

Graphical scheme



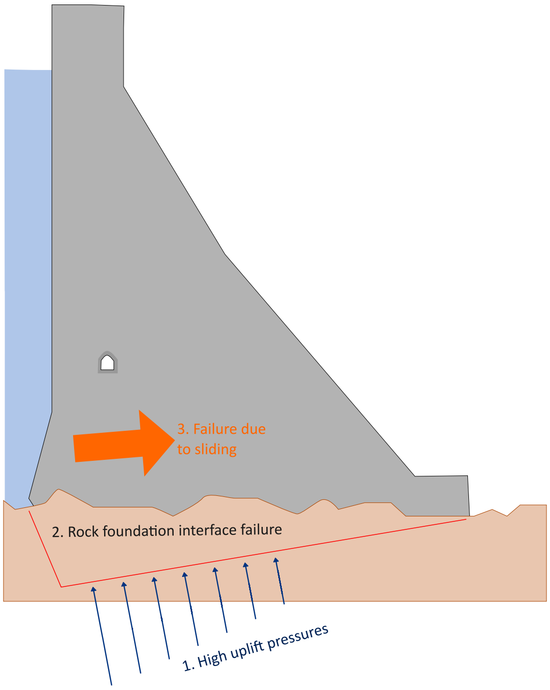
More likely factors	Less likely factors
There is no available information on the geometry of both saddle dams and the location of the top level of the impervious core, threfore resulting in high uncertainty on the initiation of the potential wash-out process.	Dam crest levels in saddle dams 1 and 2 (RL 2173 ft, 662.33 m) are higher than at the main dam (RL 2166 ft, 660.2 m). Consequently, overtopping at the main dam would initiate before overtopping of saddle dams.
Lack of detailed probabilistic hydrologic studies on Bhadra Dam-reservoir upstream river basin.	Spillway gates in the main dam are in general well maintained.
Differences between original and reviewed design flood events (3,397.83 m³/s vs. 7,544 m³/s, respectively). The spillway capacity is 3,021.24 m³/s for Maximum Operating Level(MOL).	During the monsoon season, a different maximum reservoir level is fixed at RL 2156 ft, 2 ft below MOL.
Reservoir levels are 30% of time above RL 2154 ft. Maximum Operating Level (MOL) is established at RL 2158 ft during the dry season.	Spillway gates are, in general, well maintained.
Estimated rainfall data at nearby catchments (Cauvery and West Flowing Rivers) shows precipitation rates higher than those used for past design flood analyses.	There are two sluices that provide additional discharge capacity up to 13,300 cusecs (376.6 m³/s).

Failure Mode 3	Sliding in the main dam along a failure surface at rock foundation

Description

In a normal or hydrologic scenario, the combination of hydrostatic loads and uplift pressures produces a movement or deformation in dam foundation over a surface, resulting in loss of foundation strength and failure due to sliding of a block or partial zone of the main dam.

Graphical scheme



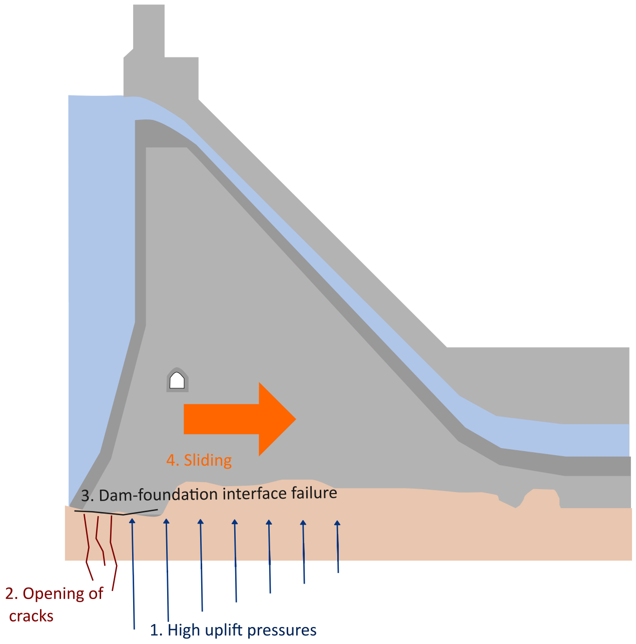
More likely factors	Less likely factors
Detection of high uplift pressures is not possible (there is no instrumentation in the main dam).	The maximum reservoir water level specified during the monsoon season is set 2 ft below MOL.
Detection of movements, as an indicator of an initiating failure mode, is not possible (there is no instrumentation in the main dam).	In the dam life, signs of foundations instabilities or sliding failures have not been observed.
There is no detailed information on material properties at dam foundation (dam subsoil conditions are unknown).	Available data on the foundation indicates that this failure mode is hardly viable.

Failure Mode 4	Sliding in the main dam along the dam-foundation surface

Description

In a normal or hydrologic scenario, there is an increase on hydraulic loads and uplift pressures that produces a tensile crack at the foot of the dam-foundation interface, and produces an increment in the hydraulic gradient at foundation joint close to the dam-foundation interface, this results in erosion in the foundation material resulting in the sliding of part of the dam body along a failure surface.

Graphical scheme



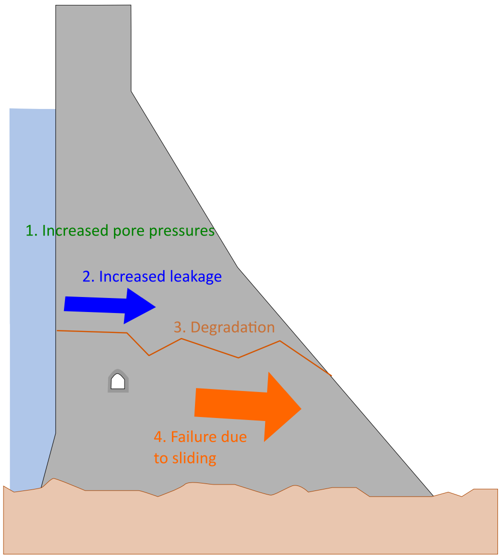
More likely factors	Less likely factors
Detection of high uplift pressures is not possible (there is no instrumentation in the main dam).	The maximum reservoir water level specified during the monsoon season is set 2 ft below MOL.
Detection of movements, as an indicator of an initiating failure mode, is not possible (there is no instrumentation in the main dam).	In the dam life, signs of foundations instabilities or sliding failures have not been observed.
There is no detailed information on material properties at dam foundation (dam subsoil conditions are unknown).	

Failure Mode 5	Sliding in the main dam due to degradation of masonry material

Description

In a normal, seismic or hydrologic scenario, due to a severe deterioration at the main dam, a horizontal crack initiates and evolves leading to large instability and dam breach that requires partial or total reparation, with a complete degradation of the dam toe due to water release.

Graphical scheme



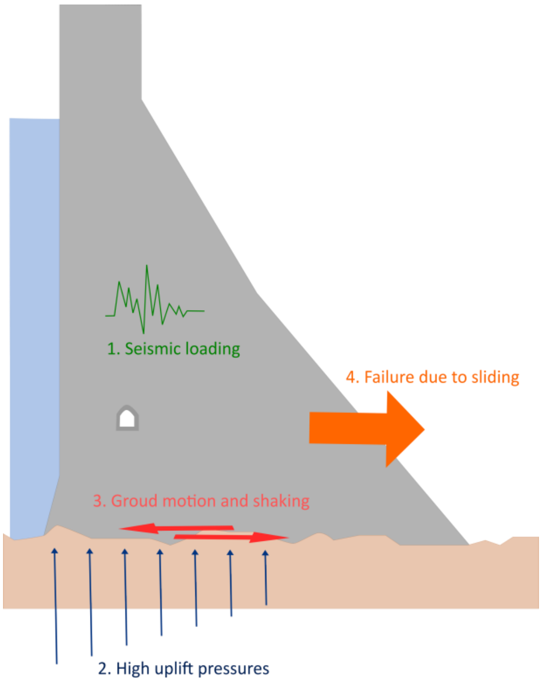
More likely factors	Less likely factors
There is no detailed information on dam body material properties.	The maximum reservoir water level specified during the monsoon season is set 2 ft below MOL.
There are evidences of seepage and leakage through dam body. Excessive leakage is a sign that excessive stress is occurring.	Despite observed leakage, there is no evidence of an initiating failure mechanism or movements that might indicate material degradation.
Detection of movements, as an indicator of an initiating failure mode, is not possible (there is no instrumentation in the main dam).	Cleaning actions for drains have been conducted to avoid clogging.
There is no available information on pore pressures (there is no instrumentation in the main dam).	
No information or testing of dam body material strength or durability.	

Failure Mode 6	Sliding in a seismic event in the main dam

Description

In a seismic scenario, a combination of previous degradation of masonry material and dam foundation and a state of high uplift pressures with an earthquake that causes a ground motion with shaking, leads to a reduction of resistance capacity of dam-foundation interface and dam failure due to the sliding of part of the main dam.

Graphical scheme



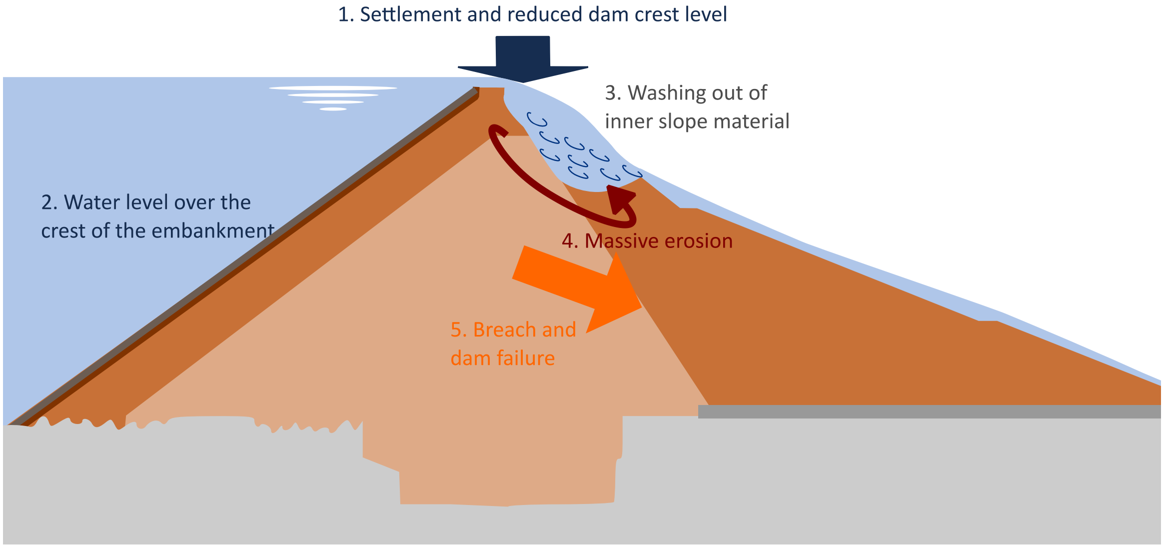
More likely factors	Less likely factors
Bhadra Dam is located in Zone 2 based on the Earthquake Zone Map for India. Seismic forces were not considered in the design.	Zone 2 is classified as Low Damage Risk Zone (least active seismic zone). The zone factor defined for this category is 0.1, used for the design horizontal seismic coefficient, and it is assumed in the BIS Code IS 1893 standard.
There are no studies to evaluate the potential and magnitude of a seismic scenario.	Despite observed leakage, there is no evidence of an initiating failure mechanism or movements that might indicate material degradation.
There is no detailed information on dam body material properties.	Cleaning actions for drains have been conducted to avoid clogging.
There are evidences of seepage and leakage through dam body.	
Detection of movements, as an indicator of an initiating failure mode, is not possible (there is no instrumentation in the main dam).	

Failure Mode 7	Overtopping in a seismic event in saddle dams

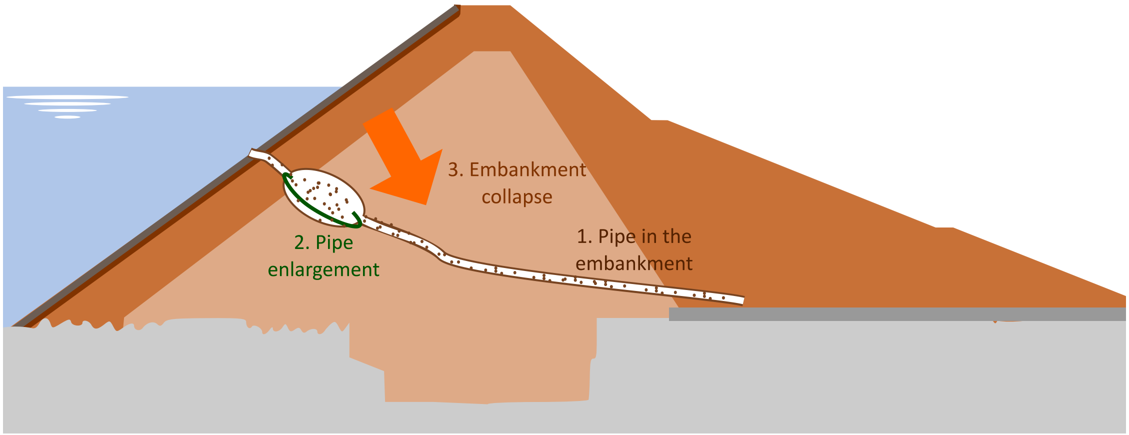
Description

In a seismic scenario, an earthquake causes a ground motion with shaking and settlement of embankment dams with reduced dam crest level, then resulting in uncontrolled flow over the dam crest, degradation of inner slope material, massive erosion and dam collapse.

Graphical scheme



More likely factors	Less likely factors
Bhadra Dam is located in Zone 2 based on the Earthquake Zone Map for India. Seismic forces were not considered in the design.	Visual observations that provide the earliest indicators of a developing failure mode are conducted frequently.
There are no studies to evaluate the potential and magnitude of a seismic scenario.	Reservoir level is 5 m below saddle dam crest level for MOL. Consequently, settlements should be very important to produce overtopping in the saddle dam.
There are evidences of settlements in the upstream face but causes are unknown.	Zone 2 is classified as Low Damage Risk Zone (least active seismic zone). The zone factor defined for this category is 0.1, used for the design horizontal seismic coefficient, and it is assumed in the BIS Code IS 1893 standard.
No information is available on material properties of the impervious layer (material properties for core and pervious layers are unknown).	
Detection of saddle dam movements through instrumentation is not possible (piezometer and seepage measurement trends can be indicative of slowly developing settlements, but there is no instrumentation on saddle dams).	

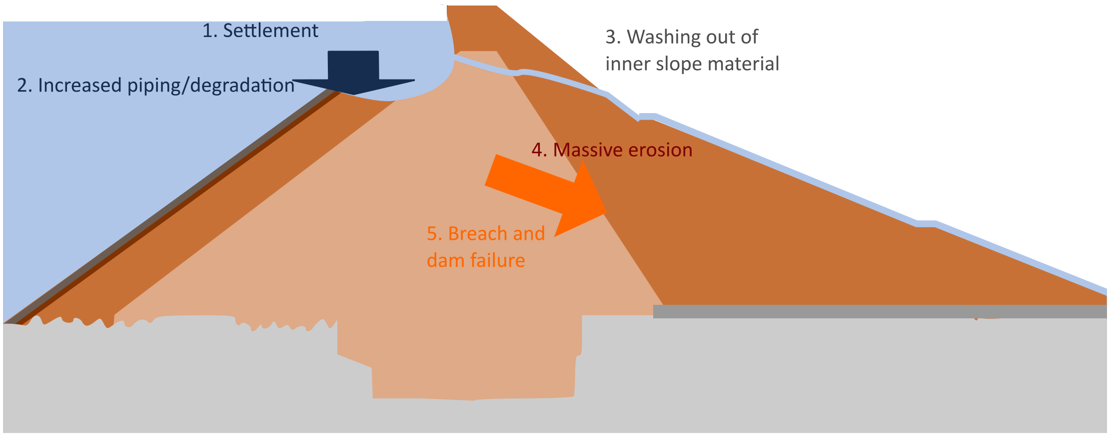
<table>
<tr><th>Failure Mode 8</th><th>Internal erosion in saddle dams</th></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">In a normal scenario during a period of high reservoir elevation, tan increase in permeability and/or reduction in strength of core occur over time, then piping of the embankment core initiates at the foundation interface. Backward erosion occurs until a “pipe” (seepage path) forms through the core, not detected or avoided, reaching the upstream face below the reservoir level. Rapid erosion and enlargement of a pipe occurs, followed by collapse of the embankment, loss of freeboard, and overtopping.</td></tr>
<tr><td colspan="2">Graphical scheme</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>More likely factors</td><td>Less likely factors</td></tr>
<tr><td>No information is available on filtering materials (if any) neither properties of impervious layer.</td><td>Visual observations that provide the earliest indicators of a developing internal erosion failure mode are conducted frequently.</td></tr>
<tr><td>Detection through instrumentation and observations is not possible (piezometer and seepage measurement trends can be indicative of slowly developing internal erosion failure modes, but there is no instrumentation on saddle dams).</td><td>Embankments height is relatively low and reservoir levels are 5 m below saddle dam crest level for MOL, so hydraulic gradients are not high.</td></tr>
<tr><td>There are evidences of settlements in the upstream face but causes are unknown.</td><td>Saddle dam body layouts, including a toe drain, seem aligned with general practice on embankment dam construction.</td></tr>
</table>

Failure Mode 9	Failure due to settlement at upstream face in saddle dams

Description

During a rapid dropdown of water level in the reservoir, one or more slips occur within the embankment because design loads are exceeded or through deterioration of embankment-fill materials over time, resulting in settlement of the upstream slope and increased degradation of core material and piping, resulting in degradation of downstream slope and dam collapse.

Graphical scheme



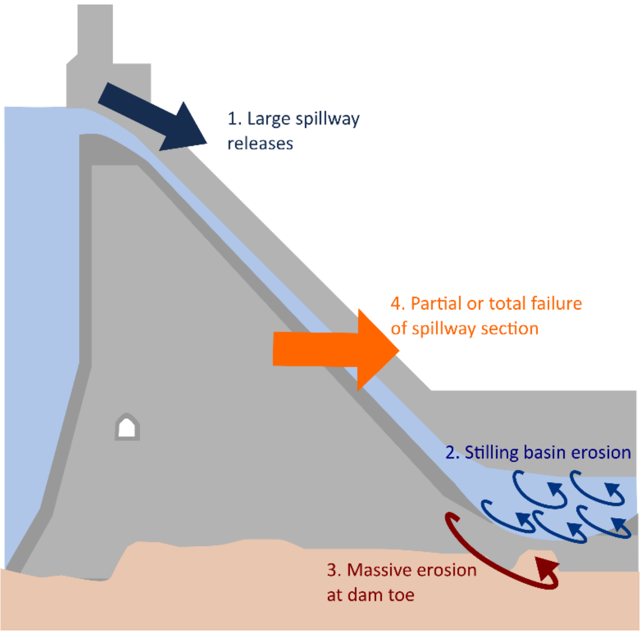
More likely factors	Less likely factors
No information is available on core materials neither the geometry of the impervious layer.	Visual observations that provide the earliest indicators of a developing failure mechanism due to settlements are conducted frequently.
Detection of evolving settlements through instrumentation is not possible (piezometer and seepage measurement trends can be indicative of slowly developing failure modes, but there is no instrumentation on saddle dams).	Reservoir levels are 5 m below saddle dam crest level for MOL.
There are evidences of settlements in the upstream face but causes are unknown.	Saddle dam body layouts, including a toe drain, seem aligned with general practice on embankment dam construction.

Failure Mode 10	Stilling basin failure in the main dam

Description

In a hydrologic scenario, large releases through the spillway result in erosion of the stilling basin, then erosion at the dam toe initiates and progress backwards until the corresponding partial or total failure at the spillway section of the main dam occurs.

Graphical scheme



More likely factors	Less likely factors
Previous evidences of stilling basin erosion and deterioration of the structure.	The stilling basin has been recently repaired.
Additional foundation erosion in the stilling basin can be caused by reservoir seepage, flowing groundwater, or seepage from local precipitation and cannot be monitored.	Site inspection is performed frequently to review stilling basin performance.
There is no drainage system in the stilling basin.	
No available flood routing studies neither structural analyses that determine if the structure can withstand flood loading conditions and potential high uplift pressures in the stilling basin.	

4.6. Classification of Failure Modes

After discussing the "less likely" and "more likely" factors of each failure mode, they were classified to decide the type of Risk Assessment that should be made in further steps. All the failure modes are classified during the working sessions in four categories, based on the categories proposed by FERC (FERC 2005):

- **Class I:** Failure is in progress or imminent, so exceptionally urgent rehabilitation measures and/or emergency actions are needed. The need for urgent rehabilitations can also be identified during technical inspections. Failure Modes should only be classified as A in very exceptional cases when failure seems imminent in the short term. These actions should be carried out as soon as possible, without waiting for risk assessment results.
- **Class II:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class II failure modes are introduced within a quantitative risk model to compute risk in the dam. This risk is evaluated and if needed, potential risk reductions are proposed and prioritized.
- **Class III:** These potential failure modes have, to some degree, lacked information to allow a confident judgment of significance. Hence, available information is not enough for a Quantitative Risk Assessment. In these cases, a Semi-Quantitative Risk Analysis is used to prioritize the studies and instrumentation needed to reduce the uncertainty on these failure modes.
- **Class IV:** Failure mode is not credible or its consequences are very low. These potential failure modes can be ruled out because the physical possibility does not exist, or existing information shows that the potential failure mode is clearly extremely remote. They should be documented and reviewed in the following updates of the Risk Assessment process.

The ten failure modes identified were classified in the following grades after group discussion:

Number	Failure Mode short description	Class
1	Overtopping failure in the main dam	**II**
2	Overtopping failure in saddle dams	IV
3	Sliding in the main dam along a failure surface at rock foundation	IV
4	Sliding in the main dam along the dam-foundation surface	**II**
5	Sliding in the main dam due to degradation of masonry material	**II**
6	Sliding in a seismic event in the main dam	III
7	Overtopping in a seismic event in saddle dams	III
8	Internal erosion in saddle dams	III
9	Failure due to settlement at upstream face in saddle dams	III
10	Stilling basin failure in the main dam	IV

Table 4.5. Classification of failure modes for Bhadra dam.

In summary, the following failure modes are considered to be incorporated as part of the Quantitative Risk Analysis: **FM1, FM4 and FM5**. It should be noted that although there is not a probabilistic flood analysis, FM1 was classified as II since flood probability can be analysed based on rainfall probability data in *PMP Atlas (CWC).*

4.7. Identification of investigation and surveillance needs

Once failure modes have been identified and classified, potential investigation and monitoring measures were defined. In general, these measures are mainly focused in reducing uncertainty of modes classified as III, to define the new studies and instrumentation required. The recommendations made in this stage are the basis for the prioritization of new studies and instrumentation with a semi-quantitative analysis.

In addition, surveillance and monitoring needs can also be identified to support the detection of failure modes classified as II. These measures will help to reduce dam failure probability, since they help to detect the progression of the failure mode before it happens. These monitoring actions are explained in detail and prioritized with the rest of risk reduction measures using quantitative risk results, as explained in Section 5.

The following investigation and surveillance needs were identified in Bhadra Dam:

Proposed actions	Related Failure Modes
Detailed probabilistic hydrologic study to analyse rainfall-runoff data on Bhadra river basin and better characterize flood events and related probabilities of occurrence.	FM1 and FM2
Monitoring actions, mainly focused on measuring uplift pressures at the main dam, will help to better characterize failure modes related to sliding stability. Estimating water pressures within the foundation is of high importance to determine its stability.	FM4
Data gathering on information of soil characteristics at the foundation to reduce uncertainty on geotechnical parameters at the dam-foundation contact.	FM4 and FM10
Study to clarify the causes of exiting settlements in the saddle dams. This study can be accompanied with actions to monitor seepage conditions and control of movements in saddle dams to analyse feasibility of failure modes related to internal erosion or potential settlements.	FM8 and FM9
Detailed seismic studies to analyse feasibility of failure modes related to seismic events	FM6 and FM7

Table 4.6. Identified investigation and surveillance needs for Bhadra dam.

4.8. Proposal of risk reduction actions

Actions proposed to reduce risk in failure modes **(especially in Class II failure modes)**, are the basis for the prioritization of risk reduction actions using quantitative risk results and they are explained in detail in Section 5.7. The following risk reduction actions were proposed for Bhadra Dam:

Proposed actions	Related Failure Modes
Implementation of the Dam Emergency Action Plan and improved flood forecasting systems	All Failure Modes
Improved gate reliability, to ensure that all dam gates are available when the flood arrives	FM1, FM4, FM5
Grouting actions using cement in the main dam body to improve its performance and reduce leakage	FM5
Foundation drains rehabilitation to ensure a proper working of drainage system and a good dissipation of uplift pressures	FM4

Table 4.7. Proposed actions for Bhadra dam.

5. Quantitative Risk Assessment

5.1. Introduction

Participants on the Risk Assessment process for Bhadra Dam are summarized in Table 5.1.

Name	Title (s)	Entity
Ignacio Escuder	Phd. Civil Engineer	iPresas Risk Analysis
Adrián Morales	Phd. Civil Engineer	iPresas Risk Analysis
Jessica Castillo	PhD Civil Engineer	iPresas Risk Analysis
Yevhen Zobal	Civil Engineer	iPresas Risk Analysis
Daniel Cervera	Civil Engineer	iPresas Risk Analysis
Ignacio Aranguren	Civil Engineer	iPresas Risk Analysis

Table 5.1. Participants on Risk Assessment process for Bhadra Dam.

Quantitative Risk Assessment was coordinated and supervised by Adrián Morales who has proven experience in risk analysis for several dams worldwide.

5.2. Risk model architecture

Based on outcomes from the failure mode identification session, three failure modes were considered to be included in the Quantitative Risk Analysis phase, classified as Class II. The risk model architecture defined for Bhadra Dam includes the following failure modes:

- **FM1: Overtopping failure in the main dam.** Failure of the masonry dam due to overtopping.
- **FM4: Sliding in the main dam (interface at dam-foundation contact).** Failure of the masonry dam due to sliding through the dam-foundation contact. The spillway section is considered for the stability analysis.
- **FM5: Sliding within dam body (degradation of masonry material).** Failure of the masonry dam due to degradation of material of the dam body.

iPresas software (iPresas 2016) was used for risk calculation, analysis and prioritization of actions. This tool allows the definition and development of the influence diagram that represents the system and includes all required information for risk quantification.

Influence diagrams are compact conceptual representations of the logic of a system. An influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and consequences. In this case, an influence diagram is defined for representing the Bhadra Dam reservoir system. The influence diagram of the quantitative risk model is shown in Figure 5.1.

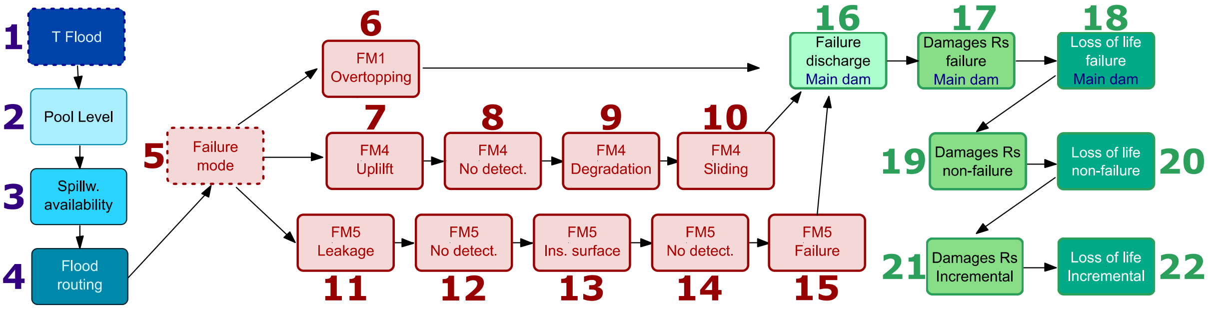


Figure 5.1. Risk model architecture for Bhadra Dam.

The risk model architecture includes 22 nodes and is used for computing incremental and total dam risk. Nodes include input data on loads, system response and consequences. In this architecture, the red nodes correspond to the failure modes probabilities. To the left, the nodes that define loads (blue colour) are included, and, to the right, the nodes that define the potential consequences for failure and non-failure cases (green colour).

This influence diagram is converted by the iPresas software in an event tree with 3780 branches, resulting from the combination of 21 flood events, 12 possible water pool levels, 5 combinations of gate performance and 3 potential failure modes. In this event tree, probability and consequences of each branch are computed to estimate failure probability, economic and societal risk due to dam failure, as shown in Figure 5.2.

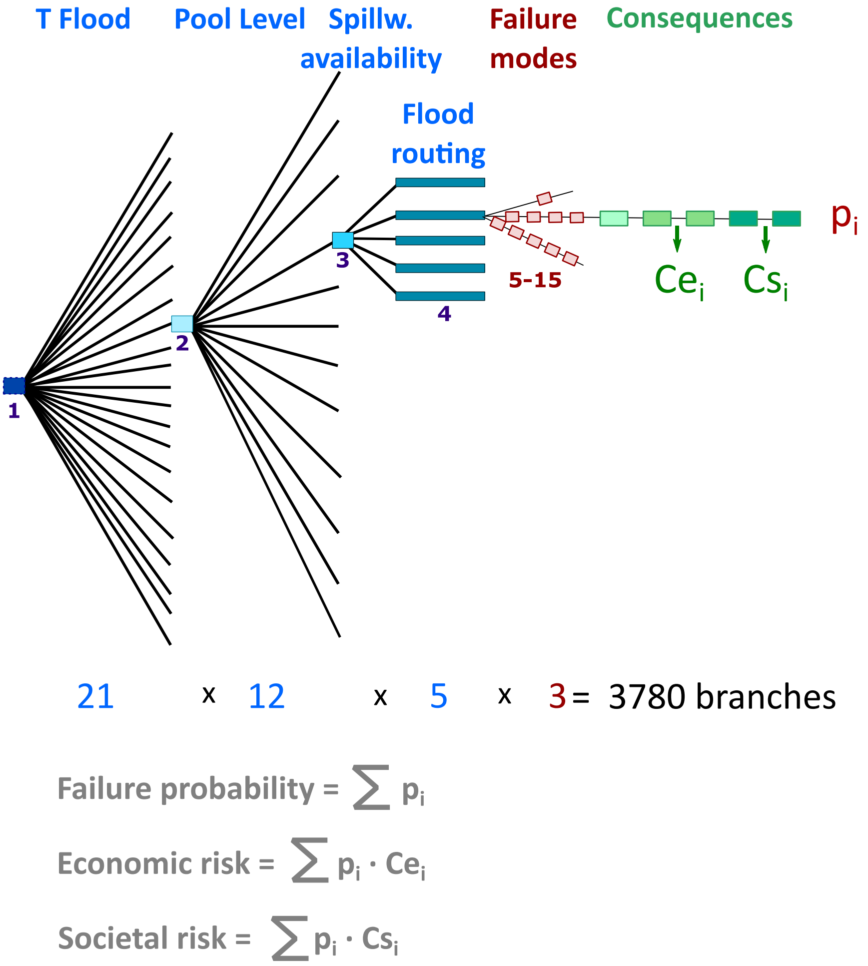


Figure 5.2. Event tree used to calculate risk in Bhadra Dam.

In this risk analysis software, failure mode probabilities has been adjusted following Common Cause Adjustment techniques and using the average between the upper limit and the lower limit adjustments.

5.3. Risk model input data

Hydrological hazard: Node 1

Currently, there is not a probabilistic hydrologic analysis available for the Bhadra Dam. In addition, hydrological studies show significant uncertainties due to the existing differences on original and reviewed design floods for Bhadra Dam.

In order to introduce different floods in the risk model with their corresponding probability, a simplified probabilistic hydrologic analysis was made based on the data from the *PMP Atlas for different river basins in India, including West Flowing River Basins and Cauvery and Other East Flowing River Basins*, published by RMSI (India). This data describes probability of extreme rainfall events in different meteorological stations across India.

For this probabilistic analysis, three stations were selected based on distance to Bhadra catchment: Chickmagalur, Ginikallu and Mudigere. Table 5.2 includes main characteristics of these stations:

Station	Elevation (m)	Lat.	Long.	Distance to Bhadra Dam (km)	River Basin
Ginikallu	785	13º43'	75º03'	63	West Flowing Basin
Chickmagalur	1040	13º18'	75º45'	45	Cauvery Basin
Mudigere	970	13º08'	75º38'	62	Cauvery Basin

Table 5.2. Data of selected stations for the analysis.

The location of these stations in relation with Bhadra catchment can be observed in the following figure:

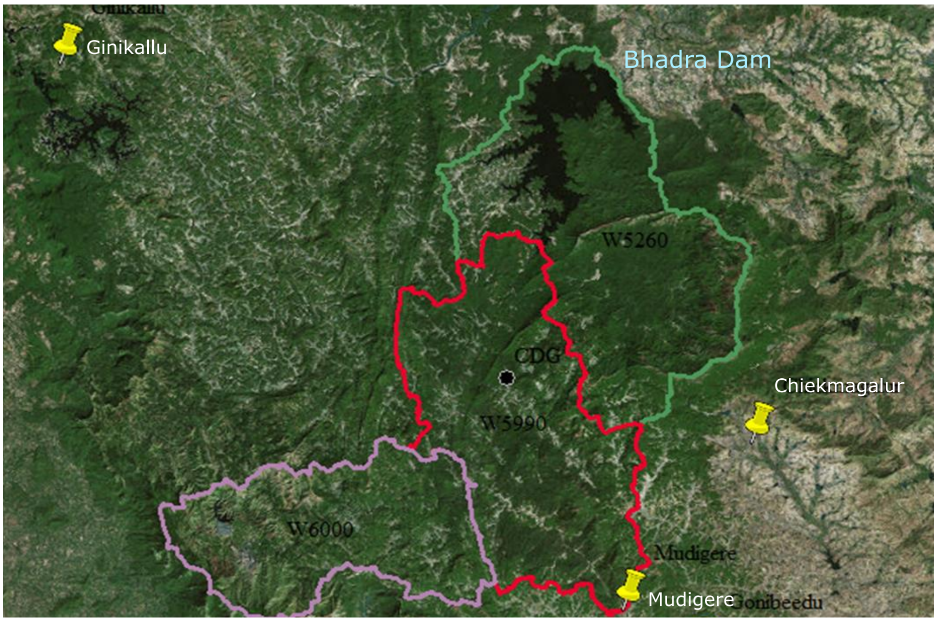


Figure 5.3. Location of selected stations from PMP Atlas related to Bhadra catchment.

For these stations, the *PMP Atlas* includes estimated precipitation values for different storm duration and return periods. Table 5.3 includes estimated 2-day rainfall values at each station.

Precipitation (mm) for a 2-day rainfall event										
T (years)	2.33	5	10	25	50	100	500	1000	5000	10000
Ginikallu	363	439	500	578	636	693	825	882	1014	1071
Chickmagalur	90	112	129	151	167	183	221	237	274	290
Mudigere	232	298	351	419	469	518	633	683	797	847

Table 5.3. Rainfall rates at each selected station.

The hydrologic model developed in HEC-HMS by the CWC as part of the DRIP project was used to obtain flood events in the Bhadra reservoir system based on estimated rainfall distributions within the Bhadra river basin catchment. For each of the 3 subcatchments defined within the model (depicted in the previous figure in green, red and violet colours), rainfall rates were estimated based on the distance of each selected station to the sub-catchment centre. In addition, a reduction factor of 0.75 for this rainfall was considered (estimated for river basin catchment with a surface of 2,000 km²). Consequently, the following rainfall rates are considered for each sub-catchment, including loss rates:

Precipitation (mm) for a 2-day rainfall event										
T (years)	2.33	5	10	25	50	100	500	1000	5000	10000
Subcatchment SC1	112.2	153.8	187.0	229.6	261.0	291.9	364.1	395.4	467.1	498.3
Subcatchment SC2	93.6	131.3	161.5	200.2	228.6	256.6	322.3	350.7	415.7	444.1
Subcatchment SC3	75.2	105.9	130.3	161.6	184.6	207.4	260.7	283.6	336.3	359.3

Table 5.4. Rainfall rates estimated at each subcatchment.

These precipitation rates were included within the HEC-HMS model using the storm duration (48 hours), storm distribution and loss rates (48 mm) proposed in the report DFS2017. Results are shown in Table 5.5.

Flood hydrographs for Bhadra Dam										
T (years)	2.33	5	10	25	50	100	500	1000	5000	10000
Peak discharge (m^3/s)	2208	3036	3707	4557	5189	5806	7262	7884	9317	9945
Volume (hm^3)	217.8	292.9	353.5	430.4	487.6	543.4	674.8	731.7	861.2	918.3

Table 5.5. Results from hydrologic modelling for different return periods.

Figure 5.4 shows obtained flood hydrographs for a range of return periods from 2.33 to 10,000 years.

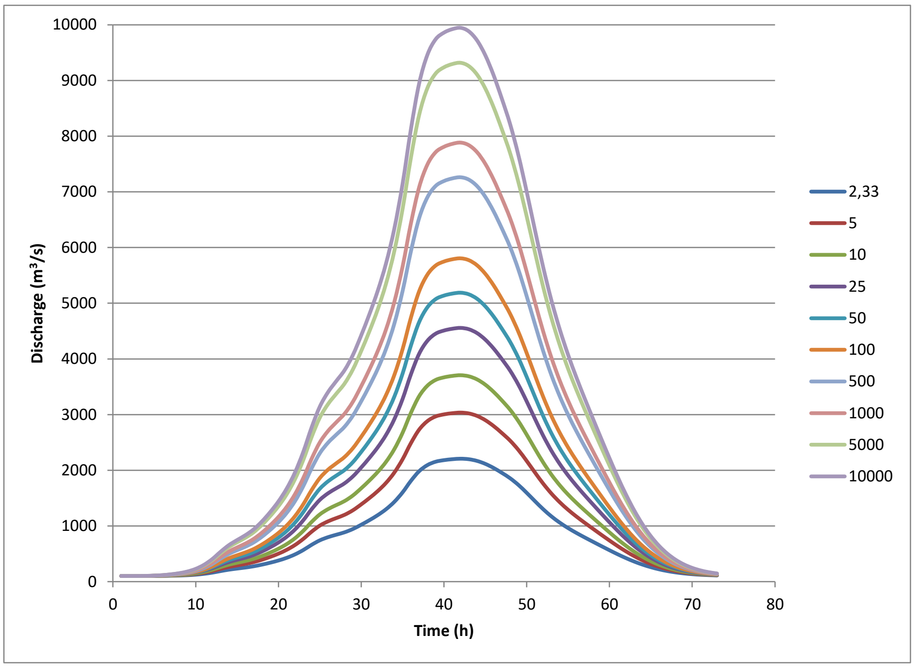


Figure 5.4. Estimated flood hydrographs for Bhadra Dam: Base Case.

In addition, the objective of **Node 1** is to introduce the range of load events and its probability, that is, to discretize the range of flood probabilities in different intervals to perform risk calculations through the event tree.

Therefore, the data to be incorporated in this node are the range of return periods considered in the flood routing analysis. In the case, the range of return periods varies from T = 1 year to T = 10,000 years.

The range of return periods is discretized into 21 equidistant intervals in a logarithmic scale, to define different branches of the event tree and their corresponding probability. This division can be observed in the event tree graphical representation shown in Figure 5.2.

The scheme for calculating flood probabilities for each interval is shown in Figure 5.5. For the sake of simplicity, this figure is represented using only 11 intervals (21 are considered in this case). A last interval is used to include flood events with return periods higher than 10,000 years.

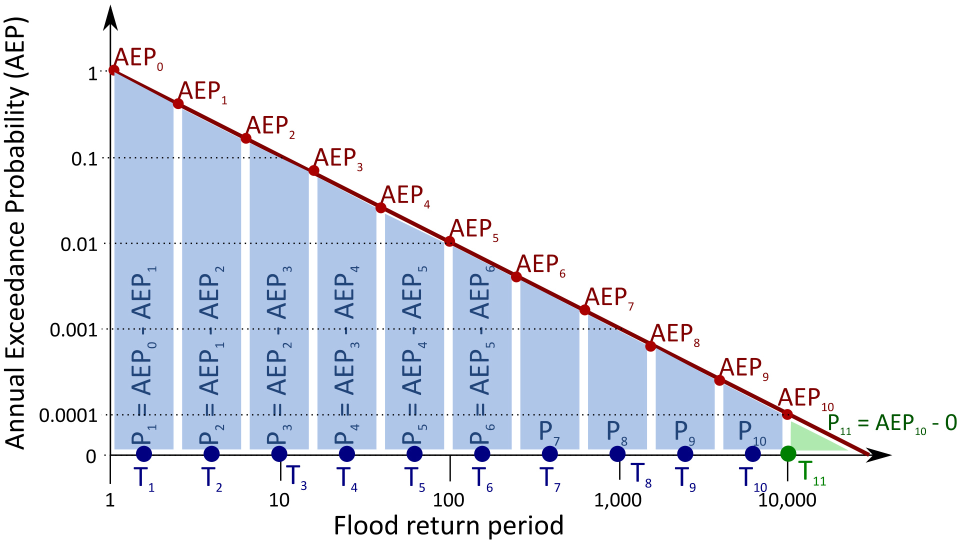


Figure 5.5. Division of Intervals for the range of Flood Events.

Pool levels probabilities: Node 2

In the risk model, the study of previous water levels provides information that is used to calculate the maximum level reached in the reservoir when the flood arrives and therefore a node with this information must be included before the nodes that include outcomes from flood routing.

The probability of being at a certain previous water level when the flood arrives to the reservoir is included in this node.

These probabilities are estimated using the exceedance probability curve of reservoir levels, which can be obtained by adjusting an empirical curve to historical records. This requires a representative record of current dam operation. For the study of reservoir levels for Bhadra Dam, registered data provided by KaWRD from the period of June 2004 to May 2015 have been used. Figure 5.6 shows the historical record of water reservoir levels.

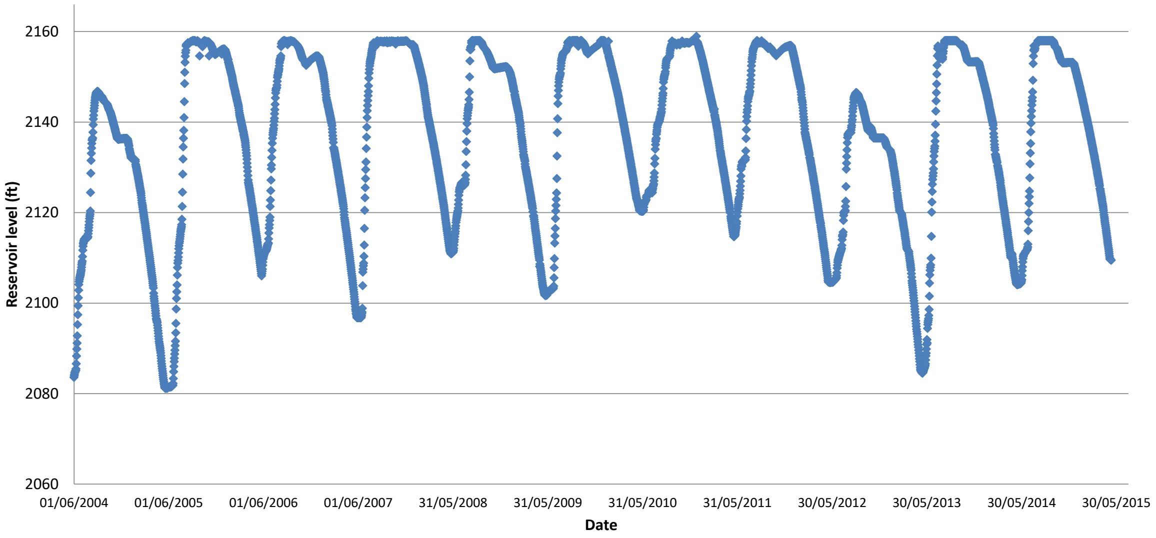


Figure 5.6. Register of reservoir level in Bhadra Dam.

The exceedance probability curve has been obtained and discretized in order to analyze the probabilities of the different previous levels and to select characteristic values, following the process below:

- The historical series of levels has been sorted by increasing order.
- For each level, the probability of exceedance has been calculated. This curve has been corrected to take into account that a freeboard is implemented (2 feet) during monsoon season.
- The range of possible levels is divided into 12 intervals, defining more intervals for the steeper part of the curve, as shown in Table 5.6.
- Average levels of each interval have been calculated.
- Each average level is associated with probability obtained as the difference between the exceedance probabilities of starting and ending points of its interval as shown in the table below.

Figure 5.7 shows exceedance probabilities of water reservoir levels for Bhadra Dam (the crest level of the main dam at 2166 ft is shown in red and the Maximum Operating Level at 2158 ft is shown in green).

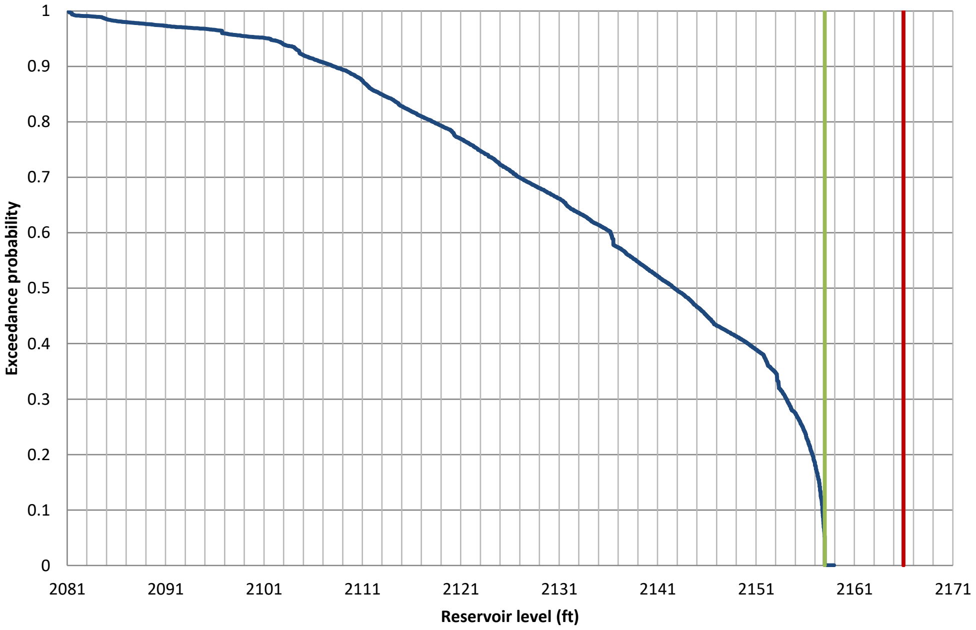


Figure 5.7. Exceedance probability curve for Reservoir Levels in Bhadra Dam.

The division on intervals made for the exceedance probability curve and the probabilities introduced in the risk model are shown in Table 5.6.

Water level (ft) Interval Min	Water level (ft) Interval Max	Water level (ft) Interval Average	Water level (m) Interval Average	Probability
2081.15	2101.15	2091.15	637.38	4.87%
2101.15	2111.15	2106.15	641.95	7.93%
2111.15	2121.15	2116.15	645.00	10.23%
2121.15	2131.15	2126.15	648.05	10.71%
2131.15	2141.00	2136.08	651.08	13.68%
2141.00	2151.00	2146.00	654.10	13.17%
2151.00	2154.00	2152.50	656.08	8.61%
2154.00	2156.00	2155.00	656.84	12.04%
2156.00	2157.00	2156.50	657.30	9.76%
2157.00	2157.50	2157.25	657.53	3.13%
2157.50	2158.00	2157.75	657.68	4.33%
2158.00	2158.00	2158.00	657.76	1.53%

Table 5.6.Intervals of previous water pool levels used for Bhadra Dam.

Gates performance: Node 3

Input data from outlet availability should be included in the risk model before the nodes that include results of the flood routing analysis, since this depends on which outlet works can be used during the flood event.

Therefore, information included in these nodes refers to the probability that each outlet work can be used for that purpose, that is, the probability that at the moment in which the flood arrives, each component can be used or not for flood routing.

In this case, the objective of this node is to introduce the probability of spillway availability. The individual reliability value has been assigned according to the following recommended values (SPANCOLD 2012):

- 95%: When the outlet is new or has been very well maintained.
- 85%: When the outlet is well maintained but has had some minor problems.
- 75%: When the outlet has some problems.
- 50%: When the outlet is unreliable for flood routing.
- 0%: When the outlet is not reliable at all or it is not used.

A probability of 85% is considered for individual gate reliability, since some minor problems can be observed in these gates as explained in Section 4.4.

It is assumed that each gate operates independently. Consequently, once the individual reliability of each gate has been established, a binomial distribution has been used to calculate the probabilities of each case of spillway availability, as shown in the following equation:

$$\boldsymbol{p(X=x)=\binom{n}{x}r^{x}(1-r)^{n-x}} \tag{1}$$

Where *x* is the number of gates that can be used for flood routing, *n* is the total number of gates and *r* is the individual reliability.

Therefore, the following data for gates performance probability is introduced in the risk model:

Number of gates working properly	Probability
0	0.05%
1	1.15%
2	9.75%
3	36.85%
4	52.20%

Table 5.7. Probabilities for each combination of gate availability.

Flood routing analysis: Node 4

The main scope of the flood routing analysis is to obtain maximum levels reached at the reservoir for analysed loads to estimate failure probability of failure modes. These results were also used to define consequences downstream of the reservoir due to dam releases. Both results are obtained directly from the flood routing study.

The flood routing computation was made using a spreadsheet that represents the behaviour of the dam-reservoir system, analysing inflow and outflow in the reservoir with a time interval of 1 hour. In the computation, the following stage-volume curve in the reservoir was used:

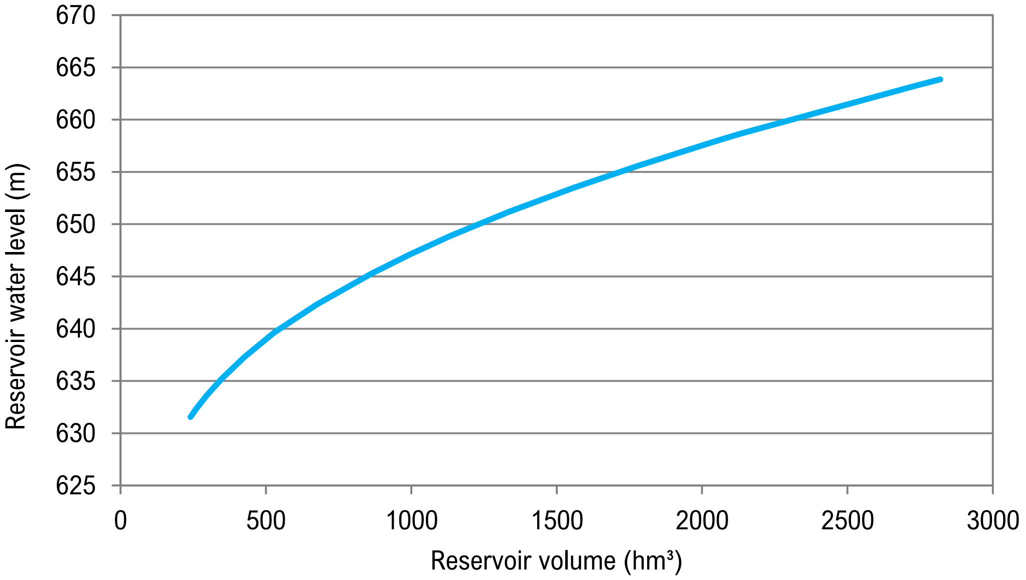


Figure 5.8. Reservoir capacity curve.

This curve has been extended to include water levels above Maximum Operation Level (MOL), which is 657.76 m (2158 ft).

The rating curve for the spillway at the main dam is considered for flood routing, based on each case of gate availability, ranging from 0 to 4 as follows: these curves were estimated based on hydraulic equations and existing information about the capacity of these spillways. The rating curves obtained for each gate performance combination are shown in Figure 5.9.

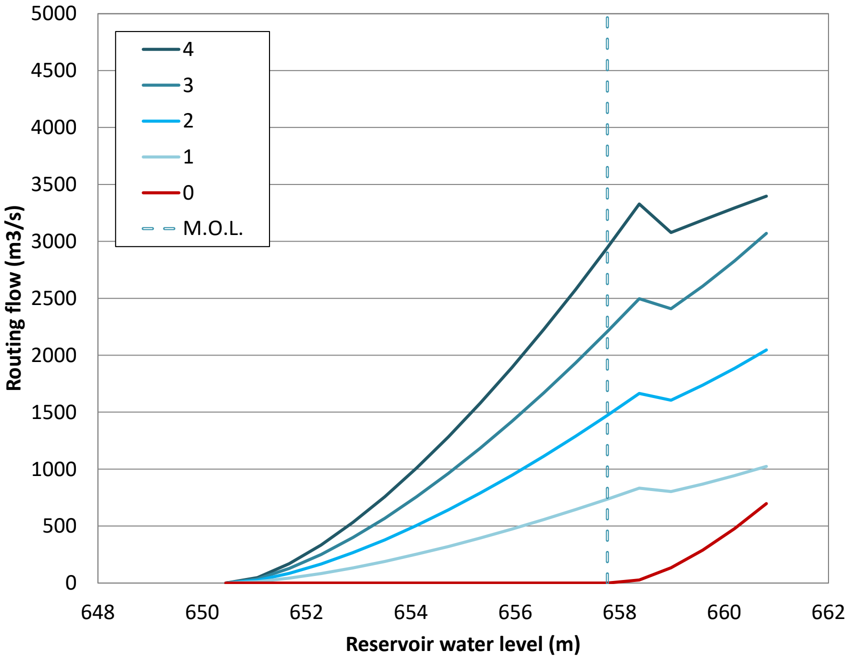


Figure 5.9. Rating curve for different cases of gates availability.

The following operation rules have been considered to analyse flood appurtenance:

- Gates are closed for reservoir levels below MOL (WL < 657.76 m).
- Gates are partially open for reservoir levels up to 1.5 m above MOL.
- Gates are totally open for reservoir levels above 659.26 m.

This flood routing analysis was made for all combinations of the following cases:

- 11 flood events: Return periods of 1, 2.33, 5, 10, 25, 50, 100, 500, 1000, 5000 and 10000 years.
- 12 cases of previous pool levels in Bhadra reservoir.
- 5 cases of gate availability: 0, 1, 2, 3 or 4 gates work properly when the flood arrives.

In total, 600 combinations for flood routing analysis were made (11 x 12 x 5), obtaining results of maximum water level in the Bhadra reservoir and peak outflow discharge (dam release) for each one. With such approach it was possible to characterize the hydraulic behaviour of the dam-reservoir system based on the above variables and, thus, be able to analyse the influence of different combinations on results, instead of analysing a single case of flood routing as it is usually done for a previously unique water level in the reservoir. An example of these flood routing computations is shown in Figure 5.10.

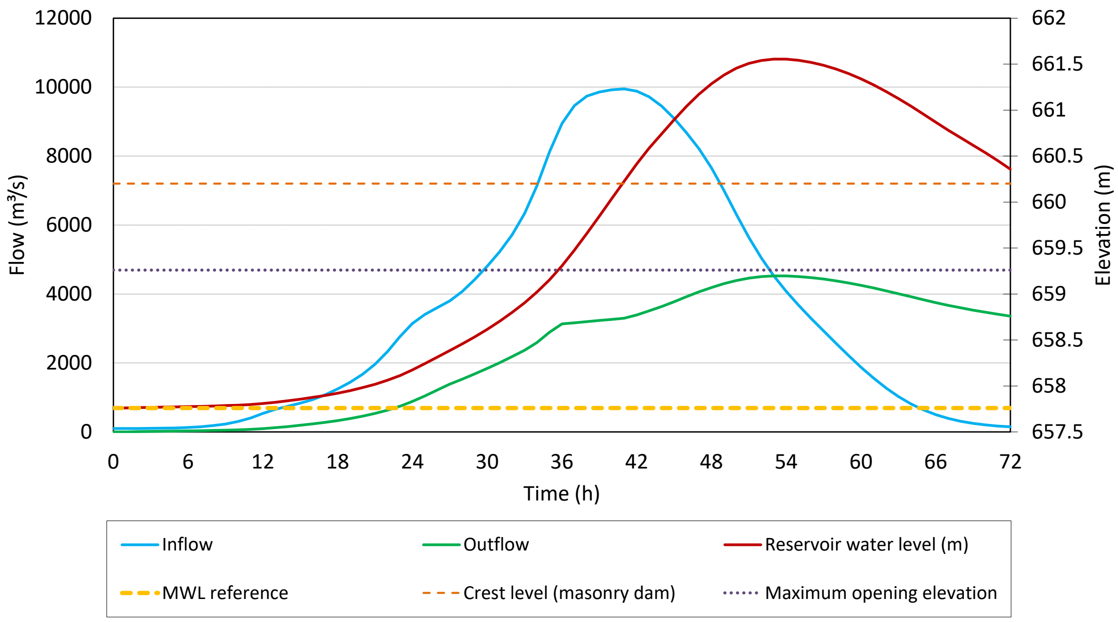


Figure 5.10. Example of flood routing calculation case for 10,000-years return period flood with 4 gates available and previous level of 65.76 m.

Therefore, the flood routing study has been carried out based on previously defined water reservoir levels, income floods, the stage-volume curve of the reservoir (relating water level and volume) and rating curves of outlet works. Thus, in this node, results for each calculated flood routing case are incorporated into the risk model using a spreadsheet.

From these results, the software tool performs an interpolation to obtain in each branch of the event tree the maximum level reached in the reservoir and the corresponding flow discharge. Results of reference flood events are used to obtain flood routing outcomes for the 21 cases of flood events analysed using the risk model.

Failure probabilities for Failure Mode 1: Node 6

This node includes the probability of dam failure due to overtopping as a function of the maximum water pool level reached in the reservoir. For this purpose, published reference curves have been used for this failure mode according to the typology of the main dam. These reference curves are shown in Figure 5.11.

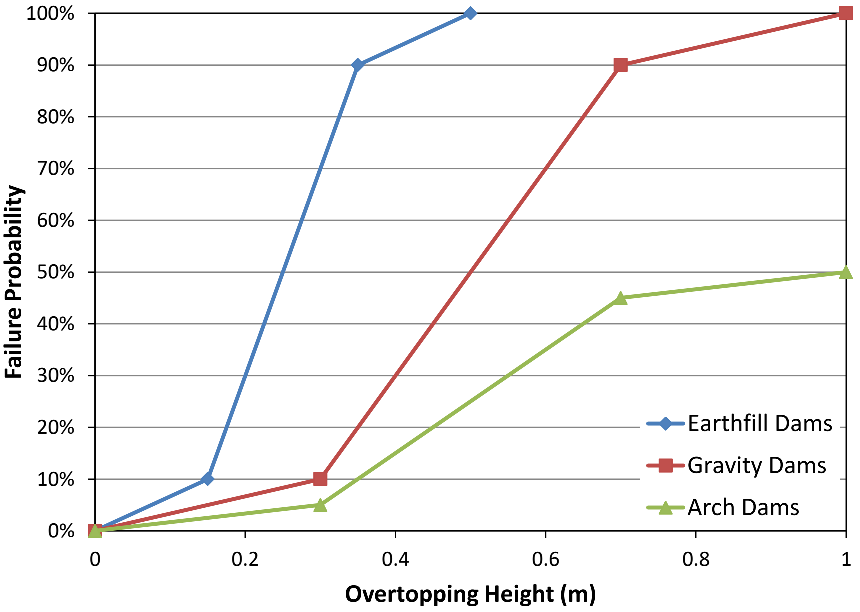


Figure 5.11. Fragility curves recommended for the overtopping failure mode. Source: (Altarejos García et al. 2014).

As can be observed from this graph, resistance to overtopping is greater in arch gravity dams, since for the same overtopping height, the probability of failure is lower. On the other hand, earthen dams are more vulnerable to overtopping. For the Bhadra risk model, the curve for gravity concrete dams is used.

Failure probabilities for Failure Mode 4: Nodes 7, 8, 9 and 10

The failure mode FM4 (sliding along the dam-foundation interface) has been included into the risk model based on the structure presented in Figure 5.12.

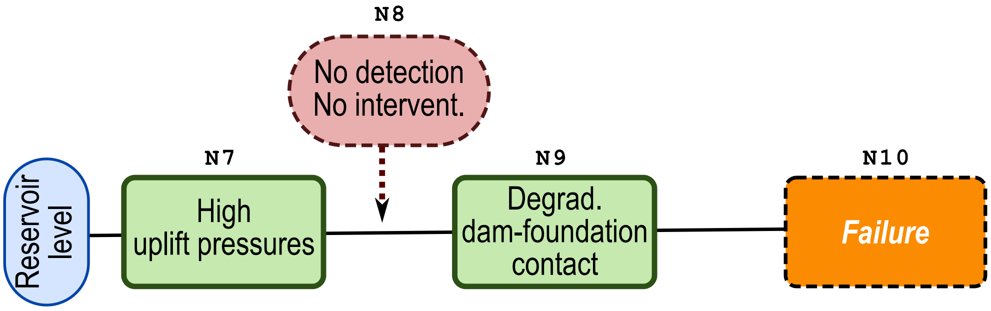


Figure 5.12. Failure Mode 4 scheme (four events).

Three events are considered for this failure:

- Event 1 (Node 7): Development of high uplift pressures in the dam-foundation interface. According to numerical model of this dam, sliding failure probabilities are only obtained with high uplift pressures in the foundation.

- Event 2 (Node 8): No detection and/or no intervention of these high uplift pressures with the current monitoring system.
- Event 3 (Node 9): Degradation of fam-foundation interface.
- Event 4 (Node 10): Failure due to dam instability. Failure probability for this node was estimated with a reliability analysis and a Limit Equilibrium Model.

In **Node 7**, probability of high uplift pressures in the foundation was estimated by expert judgment in 70%, between 50% and 90%. This probability was estimated after reviewing exiting information and dam documentation. This probability was estimated based on the lack of data about uplift pressures in the foundation and the observance of clogged drains with calcareous materials during technical visits.

In **Node 8**, probability of not detecting (or intervening to avoid) high uplift pressures in the dam-foundation interface was estimated by expert judgment in 90% (best estimate), between 75% and 95%. This probability was estimated after reviewing exiting information and dam documentation. This probability was estimated high because currently there are no measurements about uplift pressures at foundation; hence, probability of detecting high uplift values is low.

In **Node 9**, probability was also estimated by expert judgment in 50% (best estimate), between 30% and 70%. In this node, probability of deterioration of the dam-foundation interface due to high uplift pressures and leakage is introduced. This estimation is based on the current knowledge of dam foundation.

A Monte Carlo analysis is carried out for providing input data for **Node 10** (node Failure) with the aim of obtaining the fragility curve for the main dam. In the risk analysis context, fragility curves represent a relationship between conditional failure probability and the magnitude of loads that produce failure. Fragility curves provide a representation of the uncertainty about the structural response for a load event.

In this case, a 2D Limit Equilibrium Model was used to evaluate sliding failure along the foundation-concrete interface. The most critical section for sliding was selected for this model, which is the section in the non-overflow part shown in Figure 5.13.

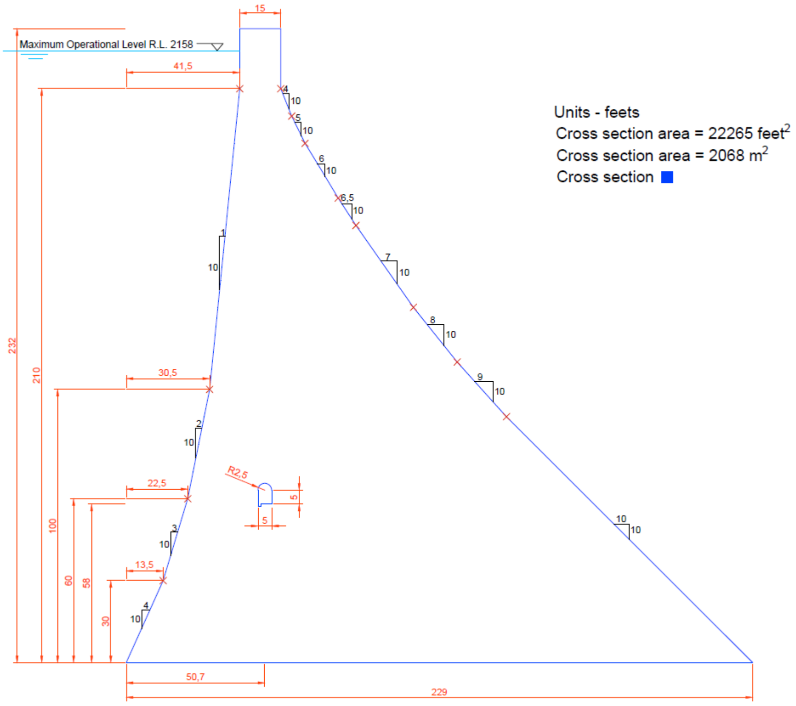


Figure 5.13. Cross section of Bhadra dam (non-overflow section).

The model includes a single interface in the contact between the dam and the foundation. This interface can mobilize tensile strength up to some limit value. The model allows for crack opening and propagation, with full uplift under the cracked zone of the dam base.

The limit-state function is defined as the ratio between the resistant force and the driving forces. In the cases where the driving forces are higher than the resistant forces, it is considered that the dam would fail. The resistant force is supposed to be controlled exclusively by the friction angle and cohesion at the dam-foundation contact, following the classical Mohr-Coloumb equation.

The driving forces are the reservoir water pressure and the uplift pressure. Water and uplift pressures directly depend on the water level in the reservoir.

Selected random variables are the friction angle and cohesion in the dam-foundation contact. It should be noted that there is large uncertainty on these parameters since there is no much information on foundations properties. Consequently, due to the lack of data on soil properties at the dam foundation, preliminary values were used but will be reviewed upon reception of further information. Values found in the literature for similar foundation materials were used. These distributions are summarized in Table 5.8.

Variable	Mean	St. deviation	Max	Min	Type of distribution
Friction angle (°)	36	3.6	28	44	Truncated Normal
Cohesion (MPa)	0.35	0.1225	0	0.8	Truncated Lognormal

Table 5.8. Key characteristics of variables for analyzing failure for FM4.

For each water level in the reservoir, the probability of failure, *Pf*, is estimated according to:

$$\boldsymbol{P_f = \frac{N_f}{N}} \tag{2}$$

Where *Pf* is the estimation of the probability of failure; *Nf* is the number of simulations where failure occurred and *N* is the total number of simulations. The number of the Monte Carlo simulations performed should be large enough to capture the searched probability. Finally, results from 1,000,000 simulations are used. Therefore, the following fragility curves were obtained to be introduced in Node 10:

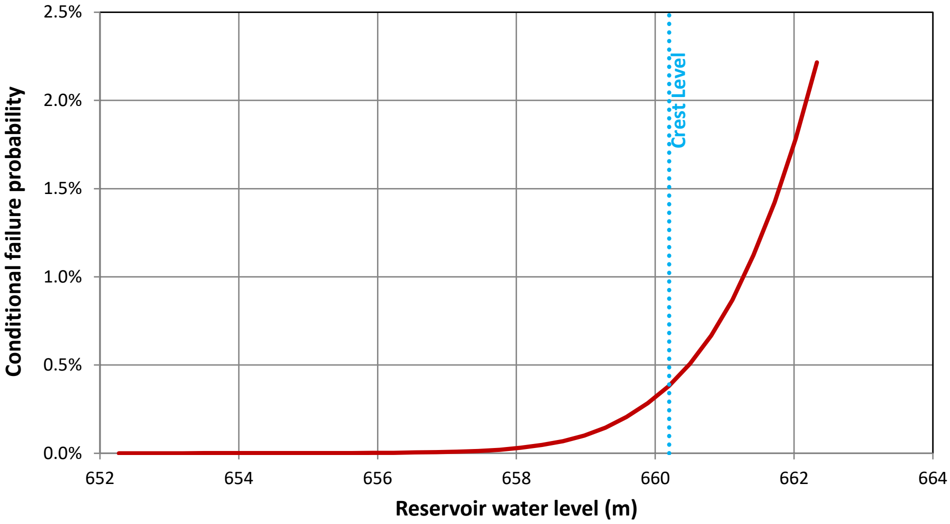


Figure 5.14. Fragility curve introduced in Node 10.

Failure probabilities for Failure Mode 5: Nodes 11, 12, 13, 14 and 15

The failure mode FM5 (sliding within dam body) has been included into the risk model based on the structure presented in Figure 5.15.

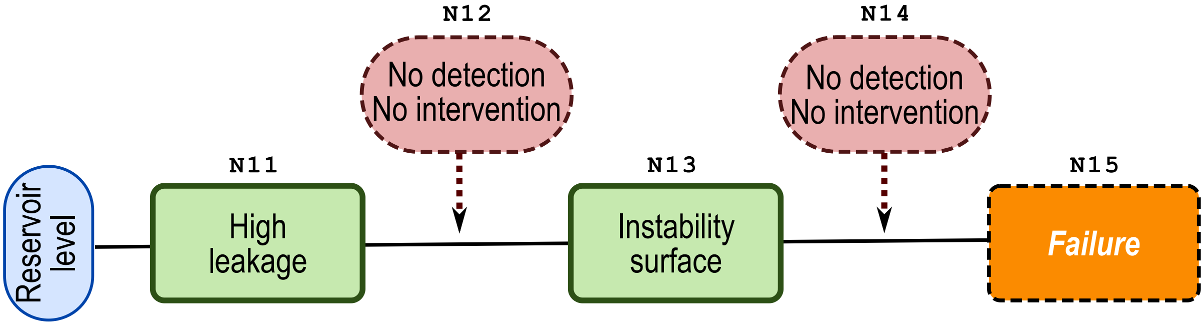


Figure 5.15. Failure Mode 4 scheme (five events).

Five events are considered for this failure:

- Event 1 (Node 11): Higher leakage in dam body and this leakage is enough to degrade and to augment the dam body cracks.
- Event 2 (Node 12): Neither detection nor intervention to stop the progression of this failure mode.
- Event 3 (Node 13): Higher degradation and creation of an instability surface within the dam body.
- Event 4 (Node 14): Neither detection nor intervention to stop the progression of this failure mode.
- Event 5 (Node 15): Sliding failure of the upper part of the dam due to uplift pressures and reservoir water pressure.

Probability of each event was estimated through expert judgment sessions based on the results of the numerical analysis made about the spillway behaviour. It should be remarked that the estimation of probabilities for the Base Case does not include recent grouting actions performed in 2017 and 2018.

For each node, “less likely” and “more likely” factors were discussed in detail, and probabilities were estimated for each event. For instance, the factors taken into account to estimate probability for the first node (exceedance of spillway channel capacity) were:

- There is no detailed information on dam body material properties.
- There is evidence of seepage and leakage through the dam body.
- Despite observed leakage, there is no evidence of an initiating failure mechanism or movements that might indicate material degradation.
- Cleaning actions for drains have been conducted to avoid clogging.

These estimations were made for different spillway discharges, since this failure mode is directly related with them. For instance, the following estimations were made for this node by the session participants:

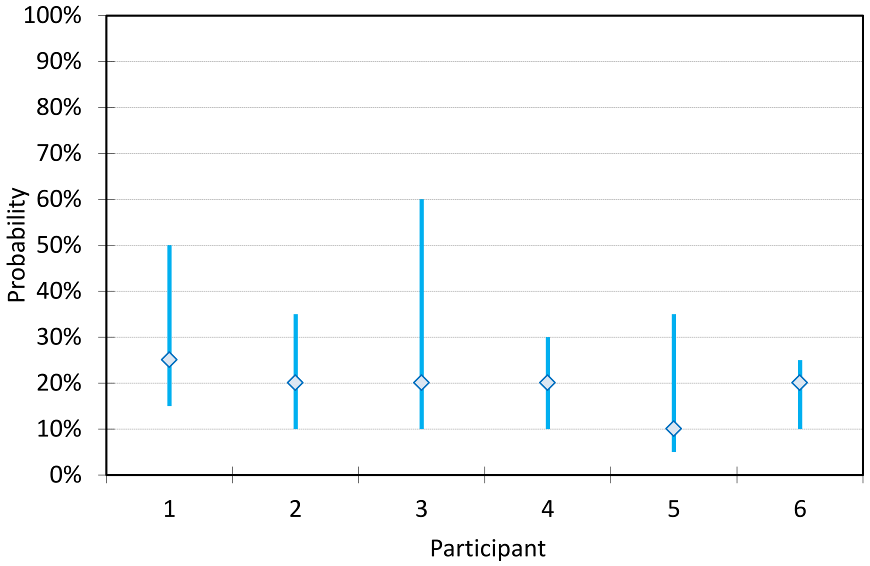


Figure 5.16. Probability estimations for Node 11.

This process was repeated for the five nodes, with the following average probability results that were introduced in the risk model.

Reservoir Level (m)	Node 11	Node 12	Node 13	Node 14	Node 15
583.39	18.0%	26.4%	1.5%	15.1%	0.0%
660.20	18.0%	26.4%	1.5%	15.1%	0.1%
662.20	18.0%	26.4%	1.5%	15.1%	0.3%

Table 5.9. Results from failure probability elicitation for FM5.

Failure hydrographs: Node 16

Dam failure hydrographs were obtained as a first step for consequence analysis and to relate the maximum water levels at the reservoir when the failure occurs and peak flow discharges to downstream areas. In this sense, dam failure hydrographs were characterized by a significant variable (usually the peak flow discharge). Required data from these hydrographs can be divided into two parts:

- Curves that relate the maximum level in the reservoir with the peak flow discharge for each failure mode. These curves are introduced in the risk model.
- Full dam failure hydrographs (not only peak flow discharge). These hydrographs are not included directly into the risk model, but are used to perform hydraulic modelling of failure events and obtain potential consequences in downstream areas. Outcomes from consequence estimation are then related to peak flow discharges of each flood event, which are those used in the risk model.

In order to estimate the potential consequences associated to a failure of the main dam in the Bhadra Dam-reservoir system, outcomes from a HEC-RAS model developed within the context of the DRIP project (Dam Rehabilitation & Improvement Project) was used. Using the dam breach model conducted in HEC-RAS, three different scenarios have been considered related to the different water levels in the reservoir when dam failure occurs.

Dam breach characteristics leading to failure are the same for each scenario and are shown in Table 5.10.

Parameter	Value
Final Base Width (m)	206
Final Base Elevation (m)	600
Left Lateral Slope	0
Right Lateral Slope	0
Weir Coeff. (Breach)	1.3
Developing time (Breach) (h)	0.5
Failure Mode	Overtopping
Failure trigger at	Determined Time
Start Date	20-06-2017
Start Time	0:00

Table 5.10. Characteristics of dam breach used for hydraulic modelling.

Considered reservoir levels at the initial time of dam breaching are the following:

- Case A: Failure at MOL (Maximum Water Operating Level) → 657.76 m.
- Case B: Failure at water level at crest level → 660.2 m.
- Case C: Failure at a water level 1m above crest level → 661.2 m.

Results obtained from the hydraulic model are briefly summarized. A comparison is made for maximum water depths and subsequent hydrographs in three different downstream sections. Downstream sections used to compare hydraulic model results are situated at Dam location, 95 km downstream (section 6 of the hydraulic model) and at 140 km downstream (section 2 of the hydraulic model).

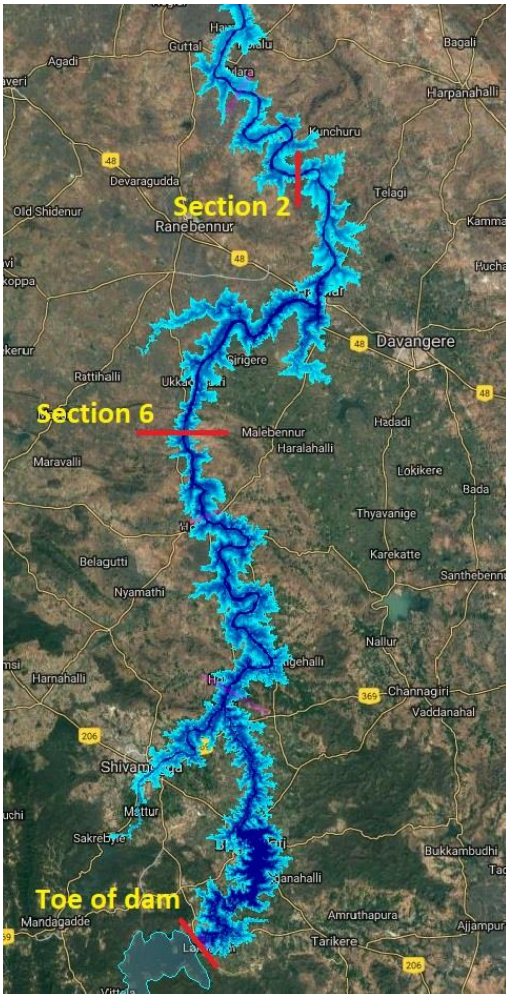


Figure 5.17. Location for the sections considered to show hydraulic model results.

Differences on water depth levels and peak discharges for the three scenarios are shown in the following table:

Section	Max Water Depth (m) Case A: MOL	 Case B: Crest Level	 Case C: Crest Level +1 m
Dam Location	23.4	23.9	24.1
95 km	14.3	15.2	15.5
140 km	15.1	15.8	16.1

Section	Peak discharge (m³/s) Case A: MOL	 Case B: Crest Level	 Case C: Crest Level +1 m
Dam Location	115 397	124 423	128 306
95 km	38 240	44 950	47 779
140 km	17 628	20 737	22 160

Table 5.11.Results from hydraulic modelling for three failure scenarios for Bhadra Dam.

In addition, failure hydrographs at dam location for the three cases analysed are shown in Figure 5.18.

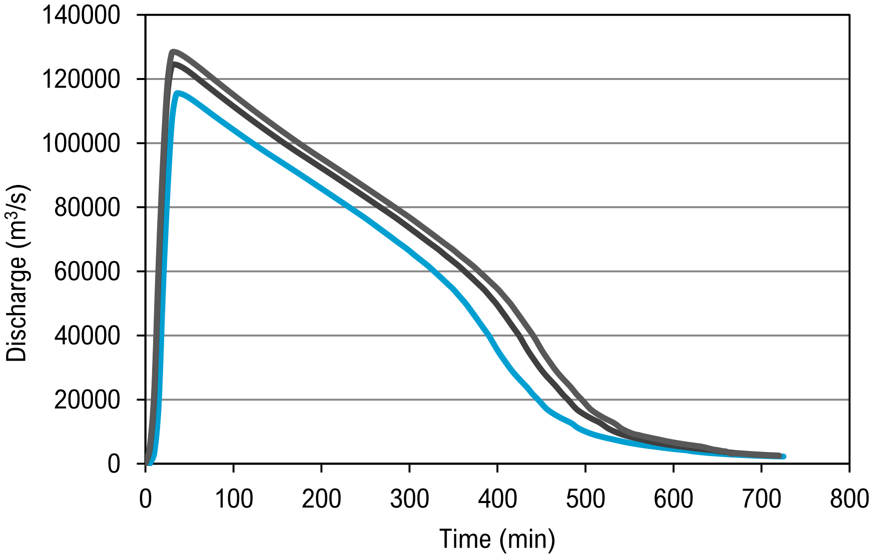


Figure 5.18. Failure hydrograph for the three failure scenarios.

Estimation of economic consequences: Nodes 17, 19 and 21

The other component of risk is the magnitude of potential consequences in case of dam failure. Failure consequences may include life loss, destruction of downstream property, loss of service, environmental damage, and socio-economic impacts.

For quantitative dam risk analyses, the focus is typically on the potential for life loss and economic damages to properties and crops. Input data for economic consequences was based on the estimation of potential economic damages for the three analyzed dam failure cases, including:

- Direct costs obtained as a combination of land use value, flood depth and a percentage of damages based on a depth-damage curve.
- Dam reconstruction costs obtained based on costs of the construction of Bhadra Dam (this cost is only included in dam failure cases).

For dam failure cases, consequences are incorporated into the risk model linked to the peak flow discharge of the failure hydrograph. However, for non-failure cases, consequences are related to the peak outflow discharge of the flood event in each section.

Economic consequence estimation is based on the affected land downstream the dam and thus, the estimation of the land use/cover distribution in the region within the flood plain.

The dam and the inundation boundaries are located inside the Shimoga district in Karnataka region (India). Table 5.12 presents the district and category distribution of land use/cover in Karnataka region according to Indian Geo-Platform and National Remote Sensing Centre (BHUVAN). Seven general categories are discerned: Agricultural, Residential, Wastelands, Forest, Grasslands, Snow and Waterbodies.

Category	Karnataka region	Shimoga district
Agricultural	70.5%	44.6%
Residential	3.2%	4.0%
Wastelands	4.5%	2.1%
Forest	17.7%	41.5%
Grasslands	0.4%	0.9%
Snow and Glacier	0.0%	0.0%
Waterbodies	3.8%	6.8%

Table 5.12. Land use distribution for Bhadra Dam downstream region.

For the economic consequence estimation it is also necessary to establish a depth-damage curve for each land-use type. The Global Flood Depth-Damage Functions technical report (Huizinga, De Moel, and Szewczyk 2017) provides a reference for India. The following damage categories are considered: Residential buildings, Commerce, Industry, Transport, Infrastructure and Agriculture.

In this study, only damage to agricultural and residential land-use is considered since they are the main land uses downstream.

To analyse **agricultural damage**, the most important flood parameter considered in damage functions for agriculture is water depth. For India, the maximum damage cost varies in the range of 0.82 - 1.63 Rs/m^2. Based on collected data by (Jan Huizinga, 2017), the following damage function for agriculture in Asia was considered:

Water depth (m)	Damage factor	Damage (Rs/m^2)
0	0	0.00
0.5	0.17	0.28
1	0.37	0.60
1.5	0.51	0.82
2	0.56	0.91
3	0.69	1.13
4	0.83	1.35
5	0.97	1.58
>6	1	1.63

Table 5.13. Depth-damage curve used for agricultural damages for Bhadra Dam.

The total downstream flooded area for each failure scenario is calculated using a GIS tool. Hence, direct flood economic consequences for agriculture were estimated based on the water depth of each cell and considering that 44.6% of land is agriculture in this district. Results shown in Table 5.14 were obtained for each scenario.

Case	Flooded area (km²)	Agricultural Land (km²)	%Area <6m	%Area >6m	Mean Depth (<6m)	Damage Factor	Agricultural cost (Rs Crores)
Case A	917	431	53%	47%	2.99m	0.83	55.38
Case B	977	460	51%	49%	3.03m	0.84	59.70
Case C	1001	470	49%	51%	3.05m	0.85	61.90

Table 5.14. Damage distribution for agricultural land for Bhadra Dam.

Estimation of damage to **residential buildings** is similar to the aforementioned developed for agricultural land. As stated in (Jan Huizinga, 2017), India has a maximum damage value of approximately 2040 Rs/m^2 in case of rural housing. Table 5.15 presents the relative average damage-depth function used from this source:

Water depth (m)	Damage factor	Damage (Rs/m²)
0	0	0
0.5	0.33	673
1	0.49	999
1.5	0.62	1265
2	0.72	1469
3	0.87	1775
4	0.93	1897
5	0.98	1999
>6	1.00	2040

Table 5.15. Average damage-depth function used from residential land use for Bhadra Dam.

For economic consequence estimation of potential damages in downstream settlements, the 26 main population settlements downstream that represent the 97% of the total potential loss of life downstream are considered. Economic consequences were computed with GIS tools and the results obtained for the three cases of hydraulic modelling are shown in Table 5.16.

In addition, the potential **reconstruction cost of the dam** in case of failure was estimated. As can be found in the literature, this cost was obtained based on a formula proposed by (Ekstrand 2000). The reconstruction cost was estimated as shown in:

$$\mathrm{Rc} = 17{,}606 + 0{,}13965 * \mathrm{KAF} \tag{3}$$

Where *Rc* is the reconstruction cost (in M$, year 2000) and *KAF* is the reservoir volume in thousands acre-feet. The reservoir volume of the Bhadra Dam-reservoir system is 2016 hm^3, resulting a reconstruction cost of 2456 Rs Crores (2017).

In conclusion, Table 5.17shows a summary of the consequence estimation calculations in terms of economic cost for residential buildings and agricultural land. Additionally, the mean water depth (in m) is presented for each scenario.

Settlement	Case A	Case B	Case C
Settlement 1	314.84	324.39	380.96
Settlement 2	301.24	317.46	400.43
Settlement 3	1275.97	1375.28	1336.79
Settlement 4	976.29	1031.81	988.04
Settlement 5	721.35	735.01	793.68
Settlement 6	66.72	76.09	87.69
Settlement 7	400.99	405.24	429.64
Settlement 8	79.80	80.55	98.46
Settlement 9	20.44	20.44	25.69
Settlement 10	45.70	46.00	51.42
Settlement 11	41.36	42.22	54.20
Settlement 12	38.09	38.09	42.66
Settlement 13	2.61	2.67	3.73
Settlement 14	14.83	15.46	20.37
Settlement 15	93.63	93.63	93.63
Settlement 16	68.18	81.36	72.37
Settlement 17	20.56	23.45	26.17
Settlement 18	0.98	1.03	2.92
Settlement 19	7.09	7.68	9.87
Settlement 20	21.64	21.67	27.33
Settlement 21	61.33	61.33	61.33
Settlement 22	0.11	0.16	0.67
Settlement 23	23.52	23.52	24.69
Settlement 24	1.09	1.26	2.99
Settlement 25	1.00	1.17	2.01
Settlement 26	24.81	24.81	24.81
TOTAL	4624.18	4851.78	5062.55

Table 5.16. Results from potential life-loss estimation for Bhadra Dam.

	Case A (MOL)	Case B (Crest)	Case C (Crest +1 m)
Agricultural Estimated cost (Rs Crores)	55.38	59.70	61.90
Residential Estimated cost (Rs Crores)	4624.18	4851.78	5062.55
Total Flood Estimated cost (Rs Crores)	4679.56	4911.48	5124.46
Reconstruction estimated cost (Rs Crores)	2456.33	2456.33	2456.33
No failure estimated cost (Rs Crores)	4679.56	4911.48	5124.46
Failure estimated cost (Rs Crores)	7135.89	7367.81	7580.78

Table 5.17. Results from potential economic consequence estimation for Bhadra Dam.

These results show that potential costs for residential land use are considerably higher than the potential cost of agricultural land damage in case of flooding due to failure of Bhadra Dam. In addition, there is a noteworthy increase of potential damage cost with the increase of the reservoir level at the moment of dam failure. For Case C (reservoir level 1 m above dam crest level) the expected economic losses are 10% higher than for Case A (reservoir level at MOL).

These values are incorporated into the risk model to estimated economic risk. A minimum flow discharge of 906 m^3/s is considered to set the non-damage scenario. It is assumed that discharges below this value do not result in damages downstream (in failure and non-failure cases). This value is the peak outflow resulting from flood routing for a 5-yr flood event and all gates in operation when the flood arrives.

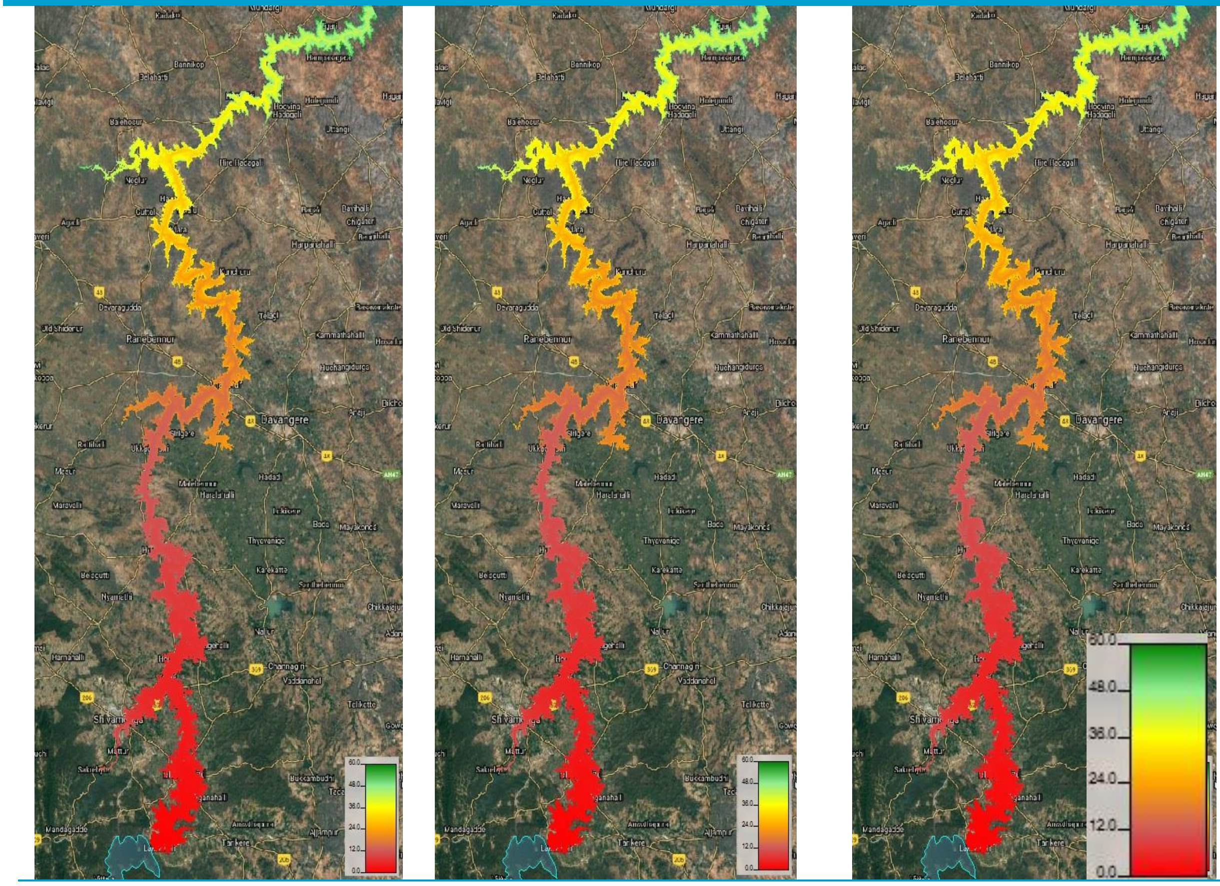
In Node 21 of the risk model, incremental economic consequences were computed for each branch of the event tree by subtracting consequences for failure and non-failure cases.

Loss of life estimation: Nodes 18, 20 and 22

Loss of life input data was included in the risk model based on results from failure and non-failure cases for the three hydraulic modelling cases. The method proposed by (Graham 1999) was used, which estimates loss of life based on population at risk multiplied by a fatality rate. This fatality rate depends on available warning time, the understanding of flood severity by the population and flood hydraulic characteristics. In this method, warning time refers to the time between the moment the warning is issued to the population and the time when the flood wave arrives. Therefore, it is the time available for evacuation and protection.

Within the European project SUFRI (Escuder-Bueno et al. 2012), fatality rates of this method were adapted to incorporate different degrees of flood severity understanding depending on available warning systems, the existence of Emergency Action Plan and the coordination between emergency services and authorities, and education and training of the affected population. Fatality rates were divided into ten categories. For the analysis of the Bhadra Dam, Category 3 was selected, since the Emergency Action Plan of the dam is still under development.

First, flood inundations maps obtained from the **hydraulic model** are presented for a graphical visualization/comparison of each dam-failure scenario. The following figures show the results of Wave Arrival Time, Maximum Water Depth and Maximum Water Velocity downstream Bhadra Dam:

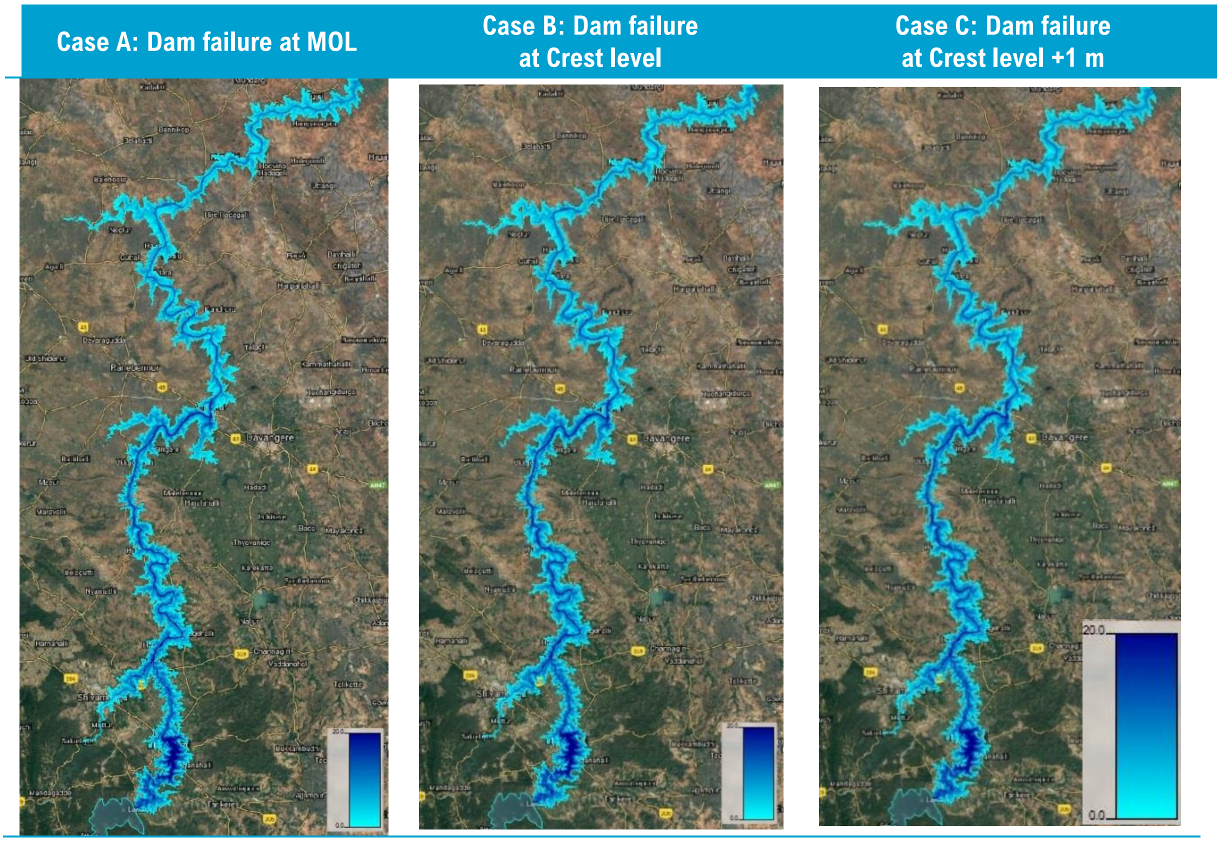


Case A: Dam failure at MOL

Case B: Dam failure at Crest level

Case C: Dam failure at Crest level +1 m

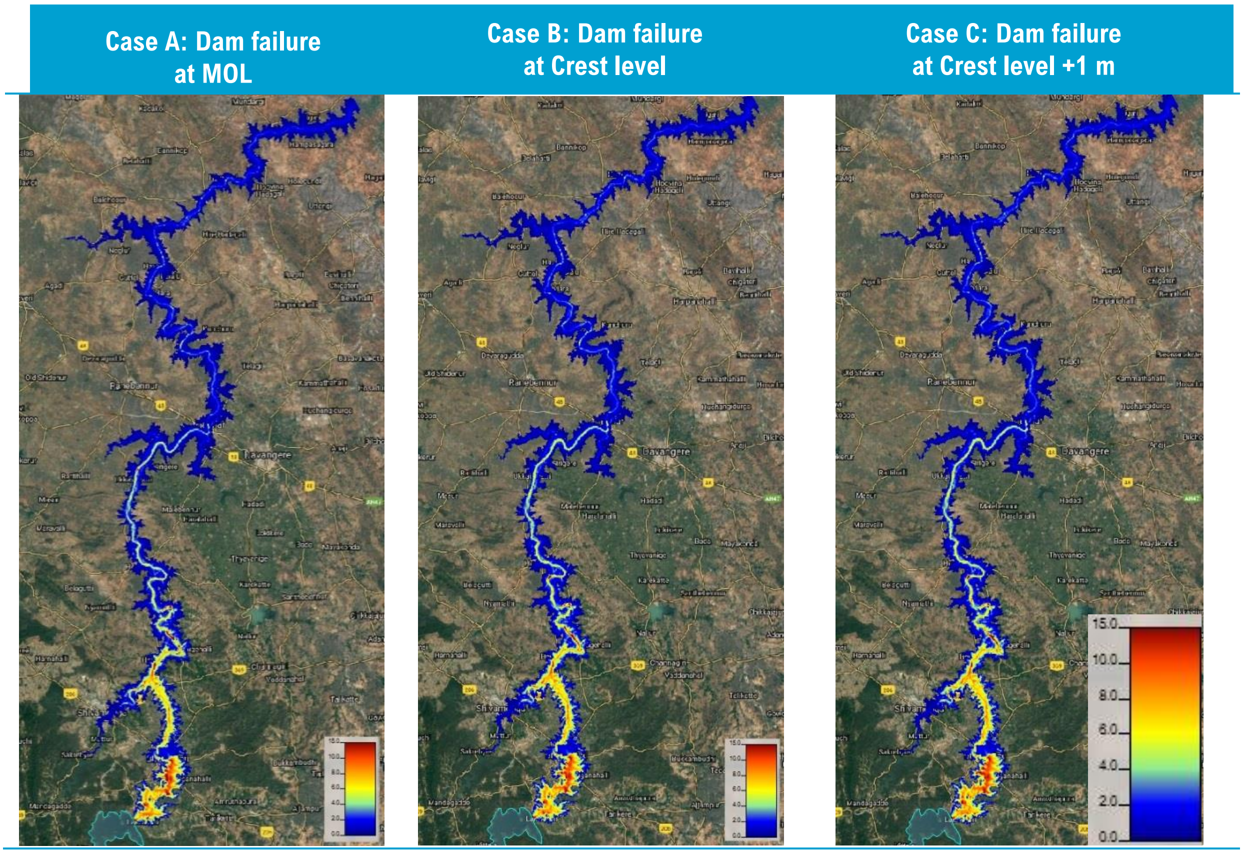
Figure 5.19. Flood inundation Map. Arrival time in min. (Three scenarios)


Case A: Dam failure at MOL

Case B: Dam failure at Crest level

Case C: Dam failure at Crest level +1 m

Figure 5.20. Flood Inundation Map. Maximum Water Depth in m. (Three Scenarios).


Case A: Dam failure at MOL

Case B: Dam failure at Crest level

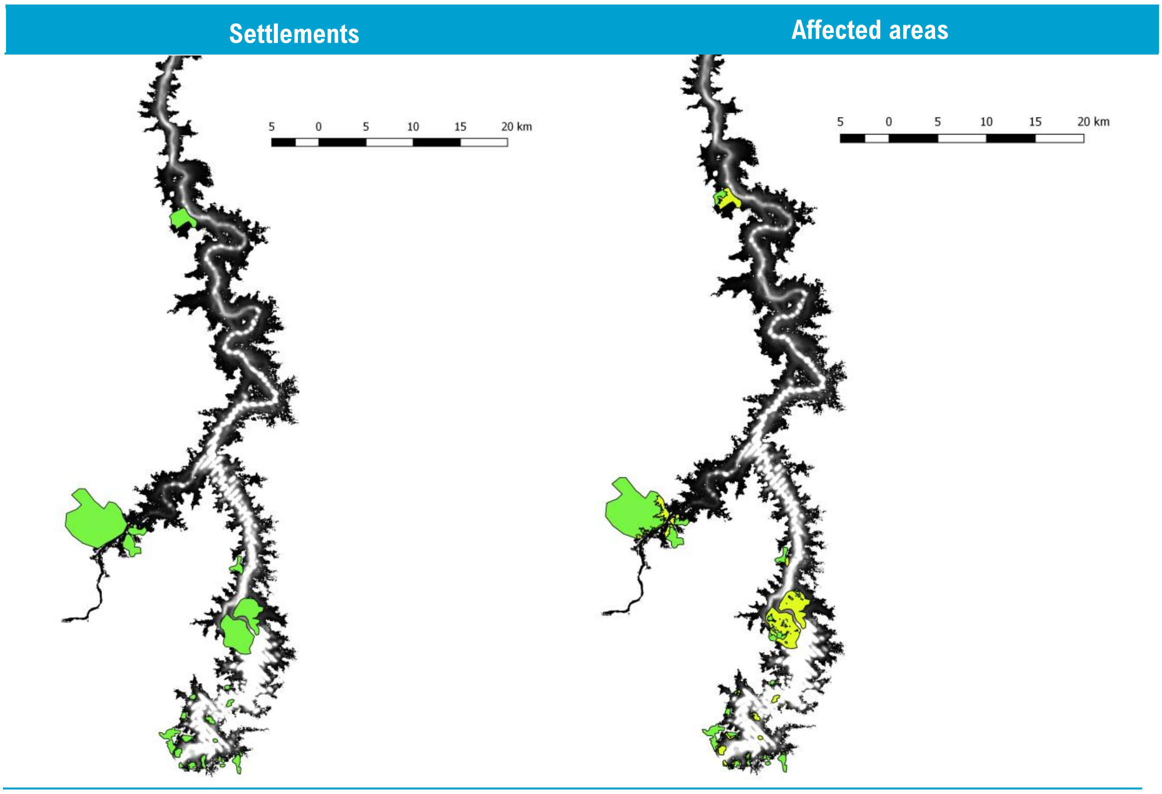
Case C: Dam failure at Crest level +1 m

Figure 5.21. Flood Inundation Map. Maximum Water Velocity in m/s (Three Scenarios).

A GIS tool was used to obtain maximum values of velocity and water depth, along with minimum flood wave arrival times for different settlements downstream. The raster files needed at this step are obtained from the dam breach hydraulic model conducted in HEC-RAS. Once the data was obtained, estimation of the potential loss of life in each settlement was calculated.

Downstream settlements were analysed to estimate **loss of life**. Hundreds of settlements are established within the Bhadra Dam potential floodplain (approximately 300), some of them with a low population rate (for instance Shingalatur: 51 inhabitants) and others with thousands of inhabitants (for instance Jannapura: 50.000 inhabitants). Potential consequences in terms of loss of life will be greater in those settlements located close to the dam-reservoir system and with a larger population.

First, hydraulic results maps were combined with population distribution maps to estimate population at risk and water depth and velocity in each settlement, as shown in Figure 5.22.


Settlements

Affected areas

Figure 5.22. Settlements (Green). Affected areas (Yellow). Inundation Map (Black)

Second, once the values for maximum depth and maximum velocity were obtained for each settlement, it was possible to estimate the flood severity level in each settlement. Following the SUFRI method, warning times in each settlement were also estimated based on the wave arrival time.

Third, fatality rates were estimated for each settlement. The fatality rate varies from 0% to 100% as a function of the flood severity level and the available warning time (in h) as shown in the following table (Escuder-Bueno et al. 2012) for Category 3.

Fourth, potential loss of life was calculated multiplying the fatality rate by the estimated population at risk, which is the total population living in the flooded area for each settlement. Table 5.19 shows potential loss of life estimations for each computed dam failure scenario.

		Fatality Rate		
		Severity		
		3	2	1
Warning time (h)	0	0.9	0.3	0.02
	0.25	0.75	0.15	0.01
	0.625	0.5	0.04	0.007
	1	-	0.03	0.0003
	1.5	-	0.0002	0.0002
	24	-	0.0002	0.0001

Table 5.18. Reference fatality rates used for life-loss estimations.

Settlement	Case A (MOL)	Case B (Crest)	Case C (Crest +1 m)
Settlement 1	4	4	4
Settlement 2	1	1	1
Settlement 3	7	8	8
Settlement 4	5	6	5
Settlement 5	1	1	2
Settlement 6	0	0	0
Settlement 7	1	2	2
Settlement 8	1	1	1
Settlement 9	70	70	88
Settlement 10	0	0	0
Settlement 11	0	0	0
Settlement 12	109	109	122
Settlement 13	0	0	0
Settlement 14	55	57	75
Settlement 15	306	306	306
Settlement 16	63	75	66
Settlement 17	22	25	28
Settlement 18	0	0	1
Settlement 19	0	0	0
Settlement 20	16	16	20
Settlement 21	17	17	17
Settlement 22	0	0	0
Settlement 23	53	53	65
Settlement 24	0	0	0
Settlement 25	0	0	0
Settlement 26	5	5	5
TOTAL	737	755	817

Table 5.19. Results from life-loss estimation for Bhadra Dam.

These loss of life results were introduced in Nodes 18 and 20 to estimate societal risk with the risk model. In this case, a minimum flow discharge of 906 m^3/s is considered to set the non-damage scenario.

Finally, in Node 22 incremental loss of life was computed for each branch of the event tree by subtracting loss of life in failure and non-failure cases.

5.4. Risk results for the current situation

After completion of input data for risk calculation, and once incorporated in the risk model architecture, societal and economic risks were obtained.

Incremental risk

Incremental risk is obtained as the fraction of risk exclusively due to dam failure. It is obtained by subtracting from the consequences due to dam failure the ones that would have happened even in case of non-failure. In the following sections, this type of risk is compared with international tolerability recommendations and is used to prioritize risk reduction actions. Results for the Base Case for Bhadra Dam are shown in the table below.

Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
Failure mode 1: Overtopping	5.700E-04	4.470E-01	4.217E+00
Failure mode 4: Sliding dam-foundation	6.031E-05	4.457E-02	4.321E-01
Failure mode 5: Sliding dam body	9.519E-08	6.325E-05	6.338E-04
Total	6.304E-04	4.916E-01	4.650E+00

Table 5.20. Risk results for the Base Case.

Results show that the predominant failure mode is overtopping, higher than 10-4. This result reflects the importance on current uncertainty about rainfall data considered for hydrological analysis. In addition, sliding along dam-foundation interface is also significant due to the state of drains and lack of uplift pressures data. Finally, probability of Failure Mode 5 is much lower.

In the following figures, these incremental risk results are represented in fN, fD, FN and FD graphs:

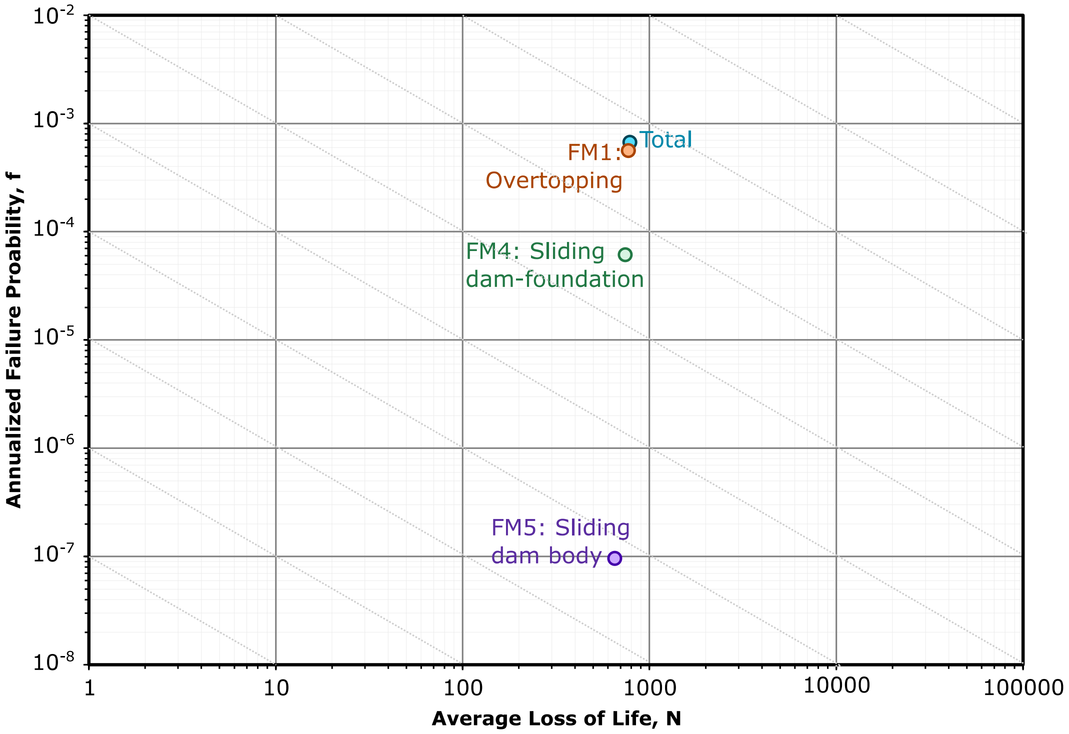


Figure 5.23. fN Graph with incremental risk results in current situation.

Figure 5.24. fD Graph with incremental risk results in current situation.

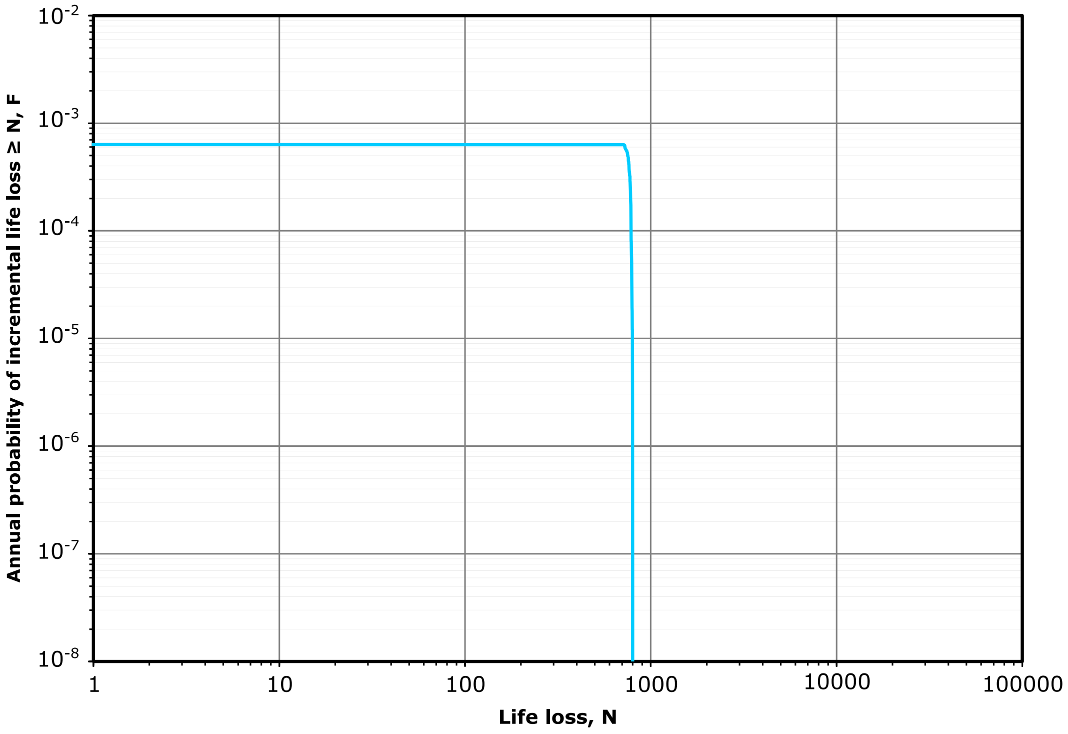


Figure 5.25. FN Graph with incremental risk results in current situation.

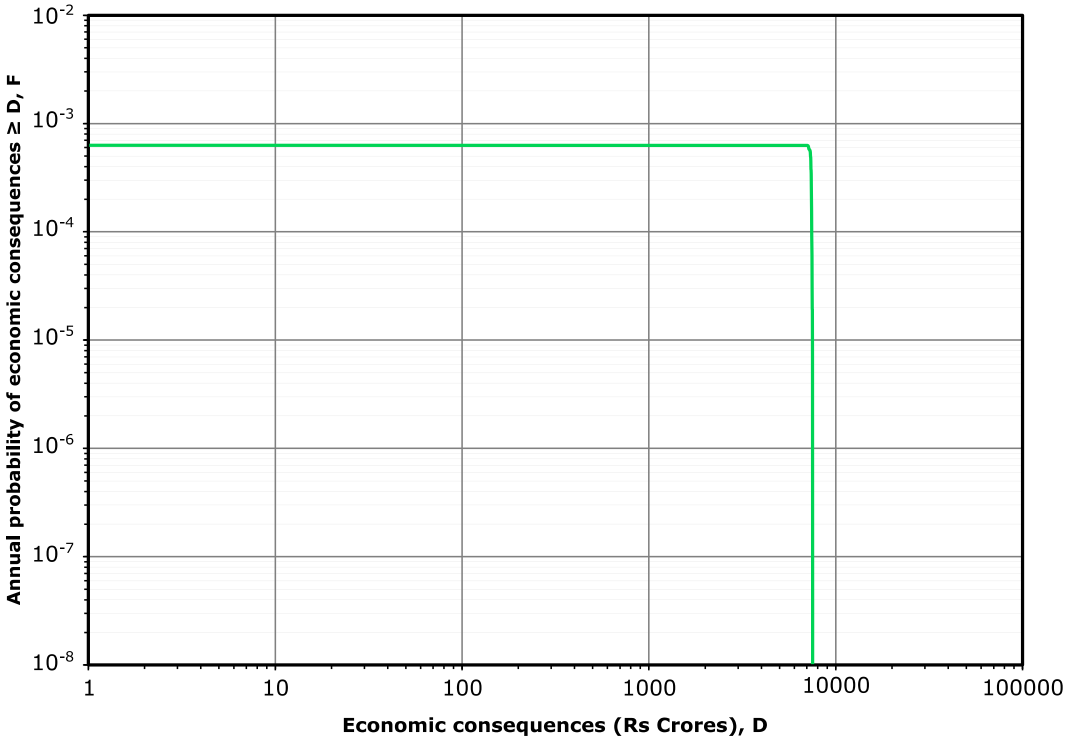


Figure 5.26. FD Graph with incremental risk results in current situation.

Total risk

It represents total risk from flooding in downstream areas and includes risk due to both dam failure and non-failure cases. These results are shown in Table 5.21.

Economic risk (Rs Crores/year)	Societal risk (lives/year)
1.34	10.04

Table 5.21. Total risk results in terms of economic and societal risk for the Base Case.

In the following figures, total risk results are represented in FN and FD graphs:

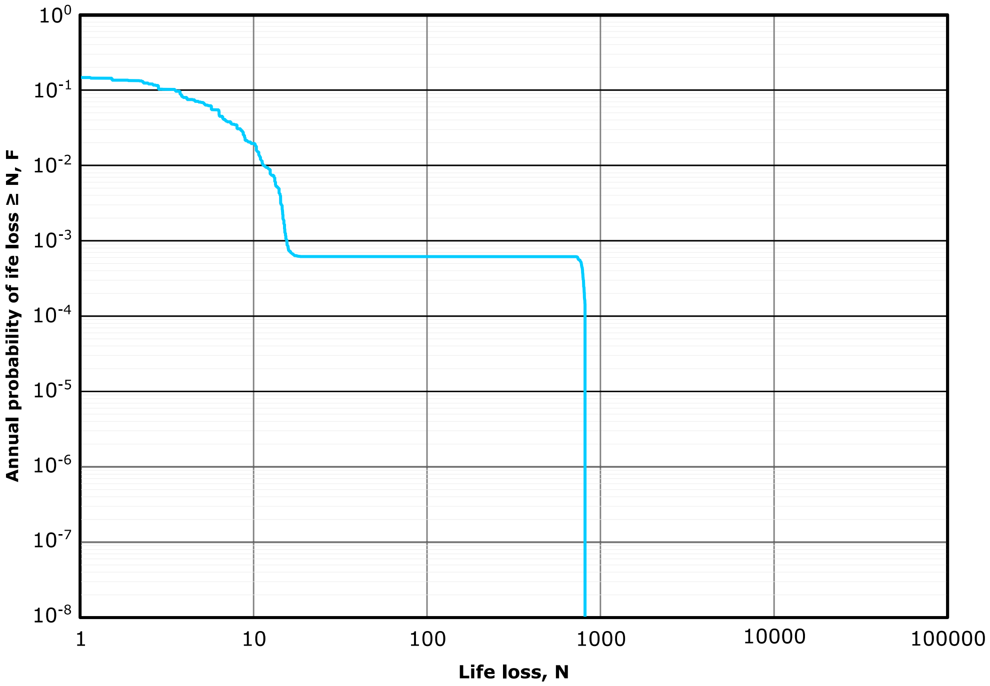


Figure 5.27. FN Graph with total risk results in current situation.

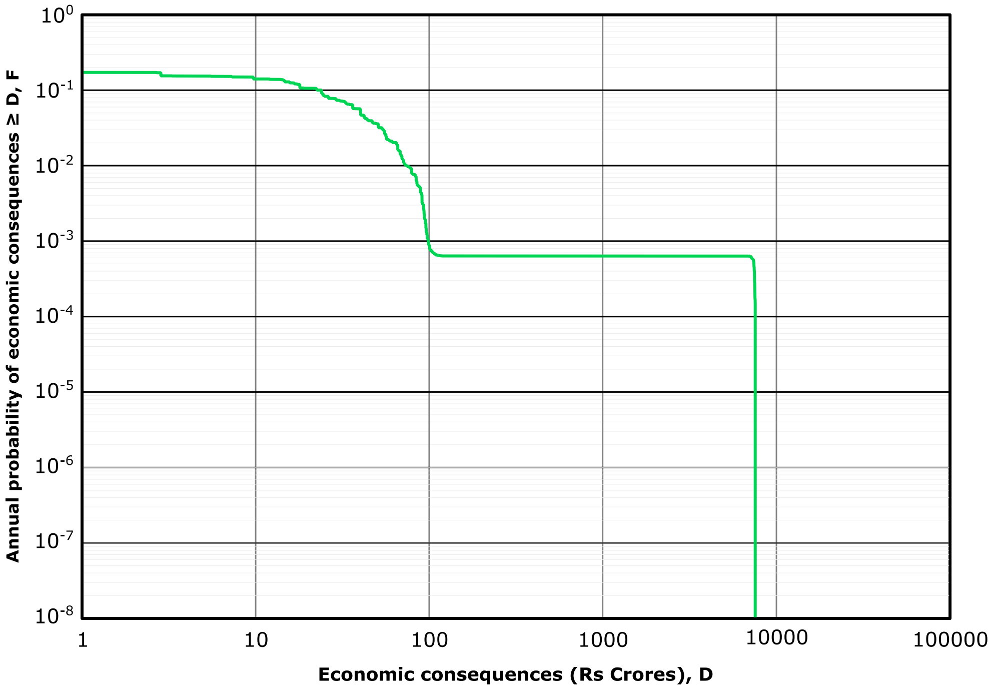


Figure 5.28. FD Graph with total risk results in current situation.

In these FN and FD graphs, the two parts of total risk can be clearly observed: failure risk (with higher consequences but lower probabilities) and non-failure risk (with lower consequences but higher probabilities).

5.5. Risk evaluation

Risk evaluation is the process of evaluating the importance of the risk associated with the failure of a dam. The phase of risk evaluation is the point where judgments and values are (implicitly or explicitly) introduced in decision-making by including the notion of risk importance. In this case, individual and societal risks are evaluated following international tolerability recommendations proposed by the USBR and the USACE (USBR 2011). Risk evaluation results are shown in Figure 5.29.

These results show that risks of overtopping and sliding are not aligned with international tolerability recommendations. In overtopping failure mode, these results are directly influenced by existing uncertainty on the need for improved hydrologic data, since very different flood results have been obtained in different reports depending on the data used. As shown in the following section, a detailed probabilistic flood analysis is needed (with more accurate rainfall data) in order to analyse more in detail overtopping risk and need for remedial measures. In dam-foundation sliding failure mode, actions could be recommended to reduce its probability like improvement of drainage and/or monitoring systems. Finally, FM5 (sliding in the dam body) is clearly located in the tolerability area.

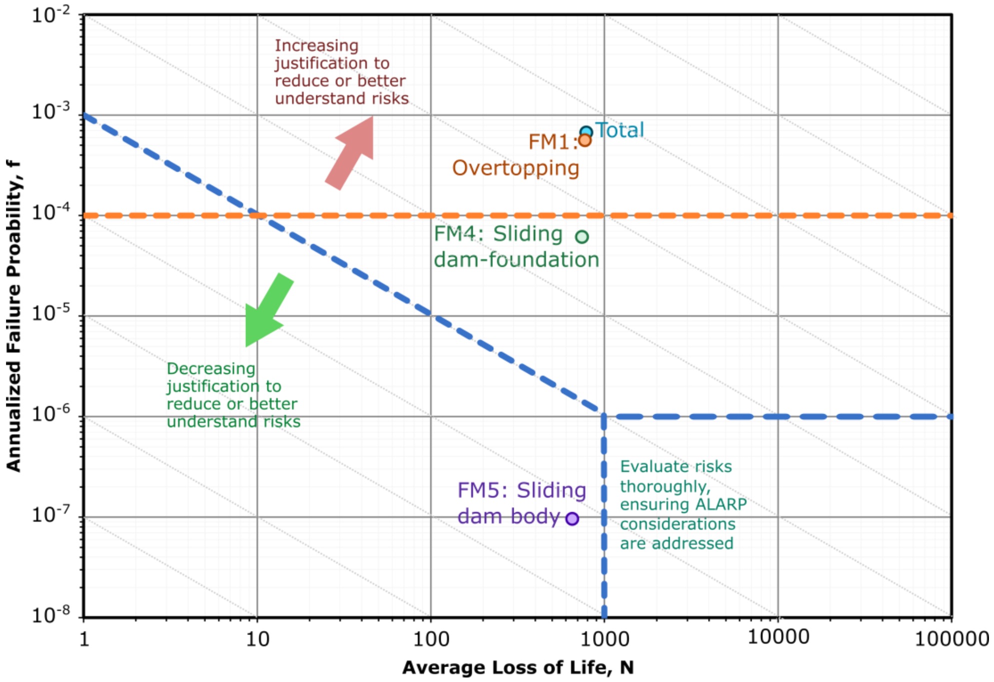


Figure 5.29. Individual and societal risk evaluation for current situation.

5.6. Uncertainty analysis

The objective of performing sensitivity and uncertainty analyses is assessing if existing input data uncertainty could change the conclusions of risk evaluation. With the purpose, the following analyses were made:

- **Hydrologic hazards:** The objective relied on analysing the impact of hydrologic data on flood routing results and consequently on failure probabilities.
- **Sliding physical model parameters:** The objective was to evaluate the impact of uncertainty on soil parameters and the corresponding effect on risk outcomes regarding failure modes due to sliding of the main dam.
- **Probabilities estimated by expert judgment:** An uncertainty analysis was made to assess the effect of the uncertainty in the expert judgment probabilities elicitation process.
- **Warning times and evacuation procedures to estimate loss of life:** The aim was to analyse the effect of available warning times on potential consequences and evaluate the impact of evacuation and emergency management effectiveness on societal risk.

5.6.1. Hydrologic hazards

As explained above, overtopping risk results are not aligned with international tolerability recommendations but extreme floods from this first probabilities hydrology analysis are higher than last estimated PMF (which by definition is the maximum probable flood in the catchment). These discordances in hydrologic studies are mainly due to the rainfall data used to estimate these floods.

For this reason, a sensitivity analysis was made on rainfall data. In this analysis, rainfall data from Chickmagalur station is used for the entire river basin catchment. This station data is in concordance with rainfall data used to compute PMF (359 mm for a 2-day rainfall event). Compared with the hypothesis made for the Base Case, this scenario includes lower rainfall rates thus flood volumes and peak discharges decrease. The table below shows the rainfall values used for the Base Case for each sub-catchment (SC) and values estimated for Chickmagalur station for each return period.

	Precipitation (mm) for a 2-day rainfall event									
T (years)	**2.33**	**5**	**10**	**25**	**50**	**100**	**500**	**1000**	**5000**	**10000**
Base Case - Subcatchment SC1	160.2	201.8	235.0	277.6	309.0	339.9	412.1	443.4	515.1	546.3
Base Case - Subcatchment SC2	141.6	179.3	209.5	248.2	276.6	304.6	370.3	398.7	463.7	492.1
Base Case - Subcatchment SC3	123.2	153.9	178.3	209.6	232.6	255.4	308.7	331.6	384.3	407.3
Chickmagalur station	90	112	129	151	167	183	221	237	274	290

Table 5.22. Rainfall rates at each subcatchment and for Chickmagalur station.

As can be observed in Figure 5.30, the overtopping failure probability for the Bhadra Dam moves from clearly non-tolerable area to tolerable are when rainfall data from Chickmagalur station is used, decreasing about three orders of magnitude. These results highlight the high uncertainty on rainfall data for this catchment and the need for detailed probabilistic hydrologic studies for the Bhadra River basin catchment. These studies will aim at reducing uncertainty on expected rainfall events and their corresponding probabilities of occurrence. This study should be done before implementing important risk reduction measures to reduce overtopping risk.

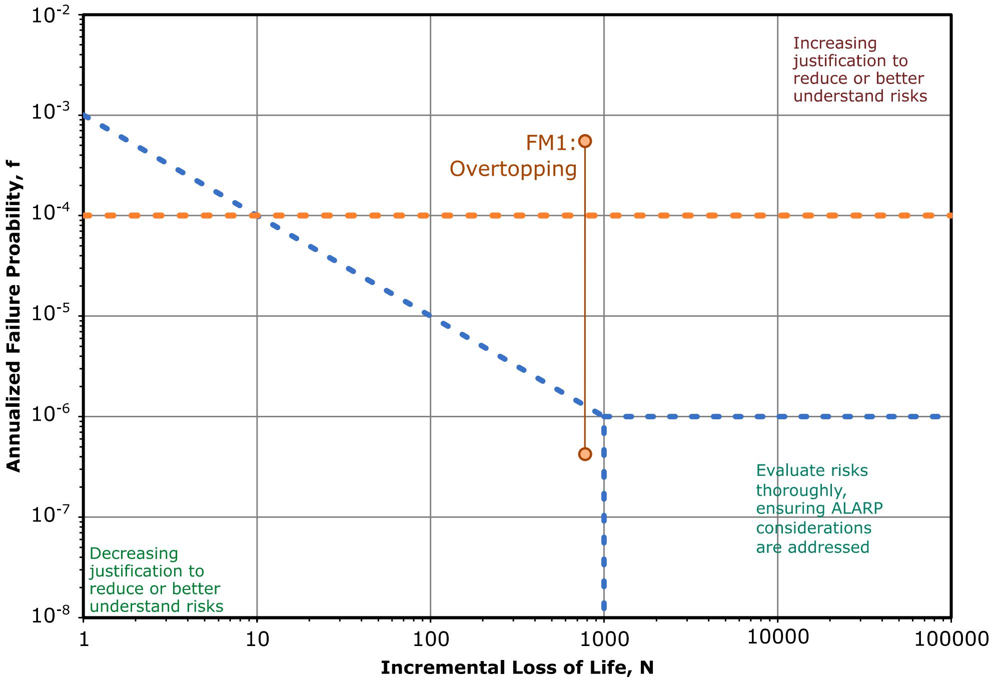


Figure 5.30. fN graph for uncertainty analysis on hydrologic hazards.

Consequently, actions conducted within the DAMSAFE project on improving flood forecasting and hydrologic modelling for Bhadra dam-reservoir system will help to reduce uncertainty on hydrologic loads and to better characterize potential flood events into the reservoir. In addition, in the long term, data gathering from the installed weather station will support updating and upgrading of rainfall data for the upstream river catchment.

5.6.2. Sliding physical model parameters

As explained above, there is uncertainty on foundation properties and resistance parameters, since no recent geotechnical tests or studies have been made. Although some initial values for resistance parameters were used to compute sliding failure mode, there is still uncertainty in the values used. In order to measure it, a sensitivity analysis was made on cohesion in the dam-foundation interface. Mean value of the probabilistic distribution used in the Monte Carlo analysis was changed from 0.35 MPa to 0.2 MPa and 0.5 MPa. Results of this analysis are shown in Figure 5.31. As can be observed, there is a high variation in the sliding failure probability from $3 \cdot 10^{-3}$ (cohesion 0.2 MPa) to $2 \cdot 10^{-6}$ (cohesion 0.5 MPa).

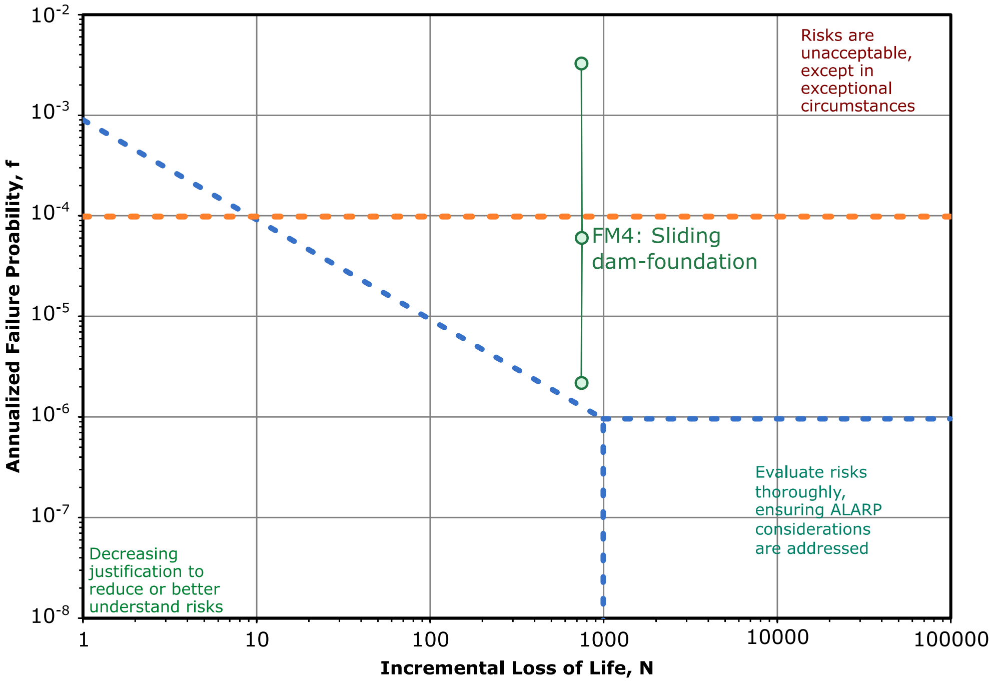


Figure 5.31. fN graph for uncertainty analysis on sliding physical model parameters.

This result indicates the need for geotechnical tests to reduce existing uncertainty on foundation conditions and further studies on this failure mode with more complex numerical models. However, all the sensitivity results are not aligned with international tolerability recommendations, so simple risk reduction actions could also be implemented while these studies and tests are being made. For instance, rehabilitating the drainage system or installing piezometers to make a better control of uplift pressures.

Actions conducted within the DAMSAFE project on dam monitoring, in terms of uplift pressures (based on equipment installed by Royal Eijkelkamp) and movements (analysed by SkyGeo from satellite images) will help to reduce uncertainty on system response and to better characterize this failure mode in the long term.

5.6.3. Warning times and evacuation procedures to estimate loss of life

Since there are very important populations living downstream of the Bhadra Dam, a sensitivity analysis was done to analyse how loss of life could change if the time of initiation of warning to the population downstream is made some time after the failure of the dam. Results from sensitivity analysis regarding the impact of warning times on reducing societal risk are included below. Different situations have been considered, including a decrease of 15 and 30 minutes and an increase of 15, 30 and 60 minutes on available warning times for the Base Case. The following table shows the results from consequence estimation for these three situations, compared with outcomes for the Base Case.

Failure event	Base Case	WT - 30 min	WT - 15 min	WT + 15 min	WT + 30 min	WT + 60 min
Maximum reservoir level at MOL	737	1602	1138	396	256	73
Maximum reservoir level at dam crest level	755	1988	1162	408	261	74
Maximum reservoir level 1 m above crest level	817	2087	1258	441	283	81

Table 5.23. Results from life-loss estimation for different available warning times.

The results obtained are shown in Figure 5.32. As can be observed, there is a high variation on loss of life results, of more than one order of magnitude. These results indicate the importance of warning procedures and population awareness to avoid loss of life in case of dam failure.

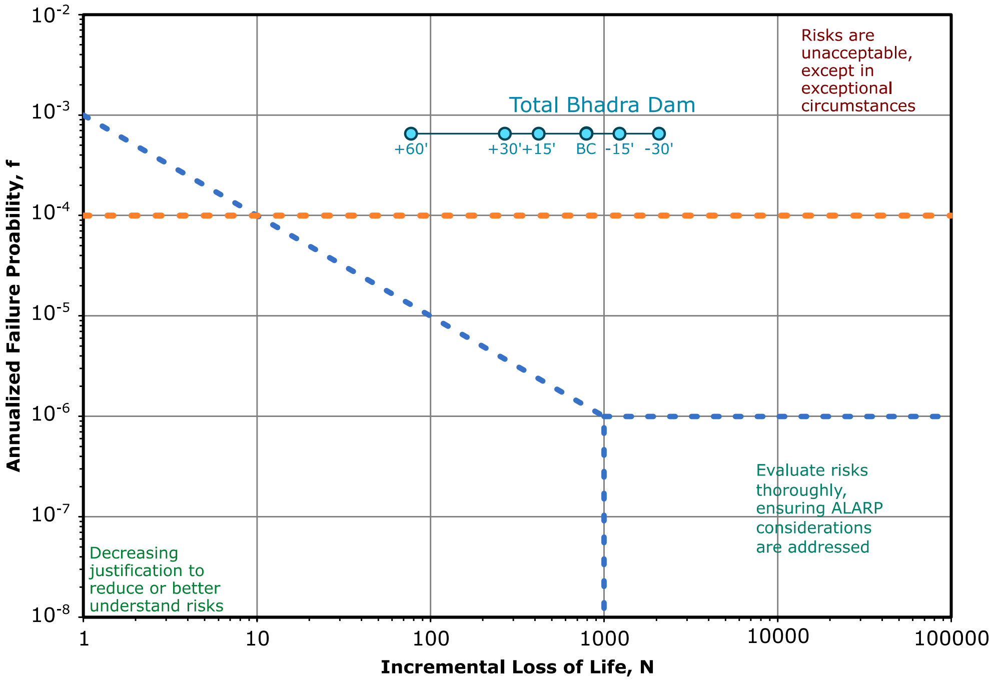


Figure 5.32. fN graph for uncertainty analysis of different warning times.

Due to the importance on reducing uncertainty on warning procedures and effectiveness of warning and evacuation actios, the work conducted within the DAMSAFE project on improving flood forecasting and hydrologic modelling for Bhadra dam-reservoir system will support future updates and upgrades on consequence estimations in case of dam failure or uncontrolled releases. Outcomes from improved flood forecasting will reduce uncertainty on available warning time in case of emergency.

5.7. Prioritization of risk reduction actions

5.7.1. Proposed risk reduction actions

The final stage in a Quantitative Risk Assessment is the study of potential risk reduction measures. Five measures have been selected from recommendations derived from failure mode identification and risk analysis conducted for the Base Case, along with technical inspections and, in general, expected measures planned for the dam.

The proposed risk reduction actions are shown in the following summary sheets.

Measure 1	Emergency Action Plan		
Introduction cost (Rs Crores)	0.8	Maintenance cost (Rs Crores/year)	0.04
Lifespan (years)	20	Failure Modes	All Failure Modes

Description

Implementation of the Emergency Action Plan (EAP), including improved flood forecasting and analysis systems, results in better procedures in case of emergency, improved communication, warning issues and response for conducting evacuation of population downstream. Consequently, potential fatalities in case of dam failure decrease due to larger available warning times and better emergency procedures. This plan is currently being developed but it is still not implemented.

Effect on risk model

This type of measure does not influence system response but reduces potential consequences in case of failure or uncontrolled releases. Category C4 of the SUFRI methodology is used for estimating fatality rates and available warning times are increased 30 minutes compared, since it is assumed that EAP implementation results in an increase on expected warning times for the Base Case. With this change, life-loss methodology assumed lower fatality rates due to improved communication and emergency management procedures. Potential consequences in terms of loss of life were recalculated and are shown in the table below. These new values were introduced in Nodes 18 and 20 to analyse this measure.

Failure event	Base Case	Emergency Action Plan
Maximum reservoir level at MOL	737	160
Maximum reservoir level at dam crest level	755	163
Maximum reservoir level 1 m above dam crest level	817	176

Measure 2	Improved gate reliability		
Introduction cost (Rs Crores)	1.33	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	30	Failure Modes	FM1

Description

This measure analyses the effect of the refurbishment made on spillway gates during 2017 to improve its reliability. The following repair actions have been taken up under the DRIP project, as stated in TN2017: “repairs to spillway crest gates and all its embedded parts, repairs to skin plate assembly, reconditioning of end box plate with rollers and painting to the rollers, lubrication of guide rollers, alignment of bottom seal stopper, replacements of all seals, cover plates, CSK bolts, fixing ladders for various levels on downstream face, bridge painting, calibration of gate position indicator dial for crest gates, construction of centralized control room for operation near spillway block and repairs to approach ladder”.

Effect on risk model

This measure includes the improvement of gate maintenance and more frequent gate operation tests to ensure a higher gate performance level. To include this change in the risk model, it was assumed a value of 95% of individual gate reliability, instead of 85% used for the Base Case, modifying the values introduced in Node 3 as shown in the following table:

Scenario	Gate reliability (0 gates)	Gate reliability (1 gate)	Gate reliability (2 gates)	Gate reliability (3 gates)	Gate reliability (4 gates)
Base Case	0.00051	0.01148	0.09754	0.36848	0.52201
Measure 2	0.00001	0.00048	0.01354	0.17148	0.81451

Measure 3	Dam grouting		
Introduction cost (Rs Crores)	0.57	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	40	Failure Modes	FM5

Description

This measure analyse the effect of the dam grouting made during 2017 to improve the dam body state and reduce its leakage. According to available documentation, the planned action is treating the upstream face of the dam through deep raking of joints and filling with epoxy formulations. The analysed measure is focused on improving the dam body state.

Effect on risk model

This measure includes grouting actions using cement to improve dam performance and reduce leakage, reducing the probability of the FM5 (sliding along the dam body) are then modified to capture the effect of this new situation after repair actions at the main dam. The changes made in the risk model are focused in the first node of this failure mode (Node 11: Leakage in the dam body and degradation) whose probability was reduced one order of magnitude, from 18% to 1.8%.

Measure 4	Installation of piezometers		
Introduction cost (Rs Crores)	0.05	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	25	Failure Modes	FM4

Description

This measure includes the installation of piezometers for data acquisition in terms of uplift pressures at the main dam foundation, distributed along the dam base. This data will help to detect a situation of high uplift pressures in the foundation, so if they are detected, remedial actions could be made to reduce probability of sliding failure mode along the dam-foundation interface.

These piezometers will also provide better data to be considered in the sliding failure mode study.

Effect on risk model

Conditional probabilities for failure mode FM4 are then modified to capture the effect of monitoring data on the masonry dam foundation. This measure reduces the probability or not detecting the situation of high uplift pressures in the foundation (Node 8), which has been modified from 90% to 10% to consider the effect of improving foundation monitoring in the risk model.

Measure 5	Drain rehabilitation and foundation grouting		
Introduction cost (Rs Crores)	1.45	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	25	Failure Modes	FM4

Description

During previous safety reviews, evidences of inoperative drainage foundation holes were found. Different actions were carried out some years ago at Bhadra Dam to reduce clogging of drainage holes. However, the present condition still indicates clogging of some drainage holes that might induce high uplift pressures at the base of the dam.

This measure analyses the effect of the rehabilitation of the foundation drainage holes located in the main dam gallery to ensure a proper dissipation of uplift pressures in the foundation. In addition, this measure also considers the grouting that has been recently made in the dam foundation within the DRIP project to increase its imperviousness.

Effect on risk model

This measure includes variations on conditional probabilities for failure modes FM4, since it reduces the probability of uplift pressures in the dam-foundation contact and the probability of sliding failure along the dam-foundation interface. The probability of high uplift pressures (Node 7) were modified from 70% to 5% to consider the effect of a better uplift pressures dissipation in the foundation.

5.7.2. Effect on incremental risk results

After defining these measures, the next step was recalculating risk by incorporating the effect of each measure into the risk model using incremental risks.

The results obtained for each measure are shown below. In this table, the results in green show the measures that produce a decrease with respect to the Base Case, while the results in red show an increase. The results include the effect of jointly implementing all risk measures.

	Base Case		
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	5.700E-04	4.470E-01	4.217E+00
FM4: Sliding dam-foundation	6.031E-05	4.457E-02	4.321E-01
FM5: Sliding dam body	9.519E-08	6.325E-05	6.338E-04
Total	6.304E-04	4.916E-01	4.650E+00

	Measure 1: Emergency Action Plan		
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	5.700E-04	9.653E-02	4.217E+00
FM4: Sliding dam-foundation	6.031E-05	9.642E-03	4.321E-01
FM5: Sliding dam body	9.519E-08	1.370E-05	6.338E-04
Total	6.304E-04	1.062E-01	4.650E+00

	Measure 2: Improved gate reliability		
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	3.609E-04	2.818E-01	2.662E+00
FM4: Sliding dam-foundation	5.666E-05	4.179E-02	4.052E-01
FM5: Sliding dam body	9.516E-08	6.321E-05	6.335E-04
Total	4.176E-04	3.237E-01	3.068E+00

	Measure 3: Dam grouting		
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	5.700E-04	4.470E-01	4.217E+00
FM4: Sliding dam-foundation	6.031E-05	4.457E-02	4.321E-01
FM5: Sliding dam body	9.486E-09	6.303E-06	6.317E-05
Total	6.303E-04	4.916E-01	4.649E+00

Failure mode	Measure 4: Installation of piezometers		
	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	5.706E-04	4.475E-01	4.222E+00
FM4: Sliding dam-foundation	6.702E-06	4.953E-03	4.801E-02
FM5: Sliding dam body	9.540E-08	6.339E-05	6.353E-04
Total	5.774E-04	4.526E-01	4.271E+00

Failure mode	Measure 5: Drain rehabilitation		
	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	5.707E-04	4.476E-01	4.222E+00
FM4: Sliding dam-foundation	4.304E-06	3.181E-03	3.084E-02
FM5: Sliding dam body	1.001E-07	6.658E-05	6.668E-04
Total	5.751E-04	4.508E-01	4.254E+00

Failure mode	All measures		
	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
FM1: Overtopping	3.613E-04	6.093E-02	2.666E+00
FM4: Sliding dam-foundation	4.494E-07	7.171E-05	3.214E-03
FM5: Sliding dam body	9.924E-09	1.430E-06	6.611E-05
Total	3.618E-04	6.100E-02	2.669E+00

As can be observed in this table, Measure 1 (Emergency Action Plan) has an effect on the three failure modes, reducing loss of life and moving the fN point towards the left. Measure 2 (improving gates reliability) mainly reduces failure probability of overtopping (FM1). Since this is the predominant failure mode, this measure is the one that has the highest effect on total failure probability. Measure 3 (dam grouting) reduces only probability of FM5 (sliding along the dam body) and Measures 4 (new piezometers) and 5 (drain rehabilitation) reduces the probability of sliding along the dam-foundation interface (FM4).

These effects on failure modes can also be represented in an fN graph as shown in Figure 5.33.

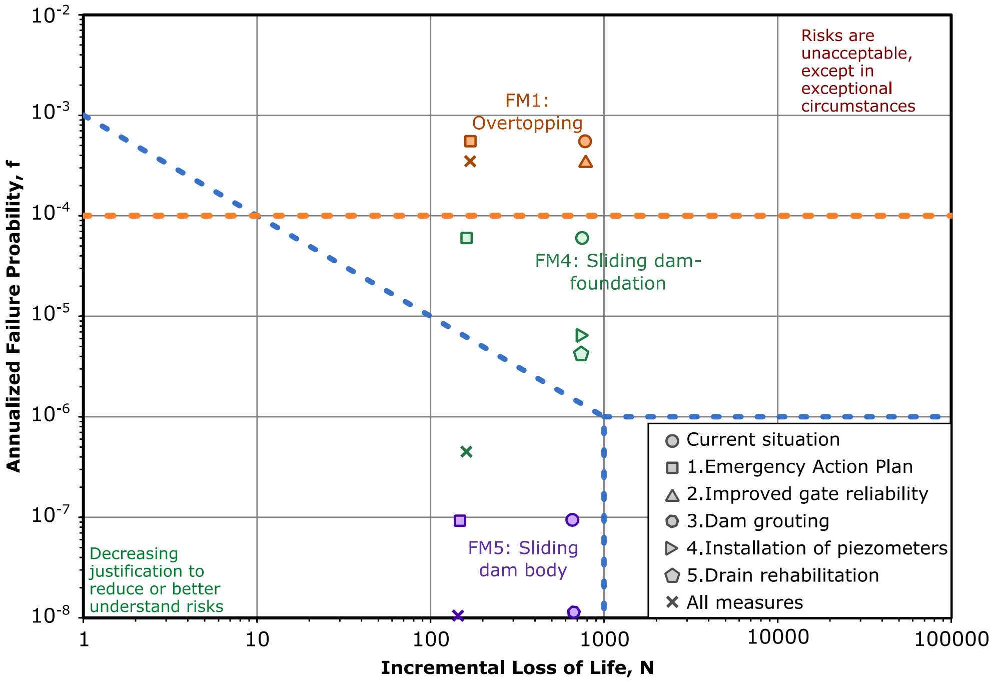


Figure 5.33. Individual and societal risk evaluation for proposed risk reduction actions.

This graph shows how Failure Mode 4 (sliding dam-foundation) would move from a non-tolerable to a tolerable area after implementing measures 1, 3 and 4, even though the results of this failure mode have a high degree of uncertainty as explained in the Section 5.6. Failure Mode 1 would still remain in the non-tolerable region, so a detailed probabilistic hydrology analysis is recommended to check these results, and if they are confirmed, new measures should be implemented in the dam to reduce overtopping probability.

5.7.3. Effect on total risk results

Total risks were also recalculated including the effect of each risk reduction action. Results obtained for each measure are shown in the following table:

Measure	Societal risk (lives/year)	Economic risk (Rs Crores/year)
Current situation	1.34	10.04
Measure 1: Emergency Action Plan	0.29	10.04
Measure 2: Improved gate reliability	1.30	9.22
Measure 3: Dam grouting	1.34	10.04
Measure 4: Installation of piezometers	1.30	9.66
Measure 5: Drain rehabilitation	1.30	9.64
All measures	0.27	8.83

Table 5.24.Participants on Risk Assessment process for Bhadra Dam.

As can be observed in this table, all the measures reduce total flood risk downstream, especially Measures 1 and 2, which reduce the risk of the predominant failure mode (overtopping).

Effect of risks reduction measures was also represented in an FN graph for total risk. In this graph, the only measures that modify risk of the predominant failure mode are represented (Measure 1 and 2), since they are the only ones whose effect can be clearly observed in the total risk FN graph. The FN graph for the other measures is very similar to the current situation graph.

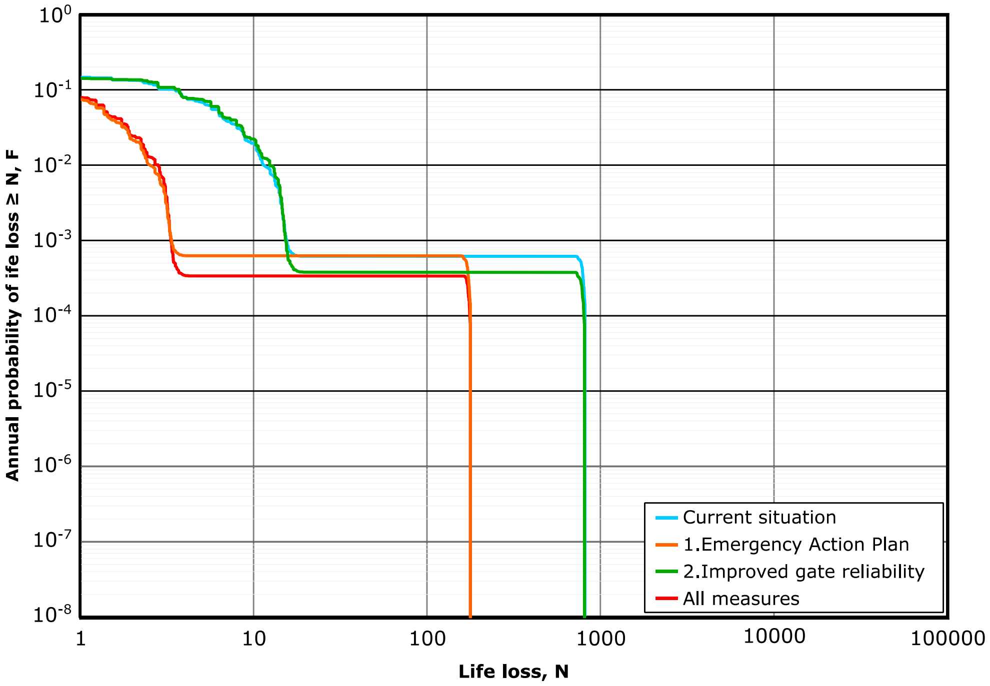


Figure 5.34. FN Graph with total risk results for proposed risk reduction actions.

In these graphs, it can be observed how Measure 1 (Emergency Action Plan) reduces risk in failure and non-failure cases, moving the curve towards the left. In contrast, improving gates reliability only reduces failure risk moving this part of the curve downwards.

5.7.4. Prioritization of risk reduction actions

Finally, proposed risk reduction actions were prioritized according to incremental risk and the EWACSLS indicator, which combines equity and efficiency criteria. This indicator was computed using a discount rate of 6.25% (following Indian Central Bank recommendations for 2017). The results obtained for this indicator are summarized in the following table:

Measure	Annualized cost (Rs Crores /year)	ACSLS (Rs Crores /life)	EWACSLS (Rs Crores /life)
Measure 1: Emergency Action Plan	0.107	0.2775	0.2775
Measure 2: Improved gate reliability	0.09339	< 0	< 0
Measure 3: Dam grouting	0.03678	638.5	638.4
Measure 4: Installation of piezometers	0.00377	< 0	< 0
Measure 5: Drain rehabilitation	0.1093	< 0	< 0

Table 5.25. Results of annualized cost and ACSLS results for each measure.

ACSLS and EWACSLS of Measures 2, 4 and 5 are negative, which indicate that these measures are directly compensated by the economic risk that it reduces, since the upper part of the equation (annualized cost minus economic risk reduction benefits) is negative. These results indicate that all the proposed measures are very efficient but dam body grouting, which is related with the failure mod with lower probability (FM5).

These results are used in an iterative process to obtain a sequence of risk reduction actions. The steps of the obtained sequence are shown in Table 5.26.

Step	Measure	Societal risk (lives/year)	Economic risk (Rs Crores /year)	ACSLS (Rs Crores/life)	EWACSLS (Rs Crores/life)
1	Measure 2: Improved gate reliability	4.916E-01	4.650E+00	< 0	< 0
2	Measure 4: Installation of piezometers	3.237E-01	3.068E+00	< 0	< 0
3	Measure 1: Emergency Action Plan	2.868E-01	2.711E+00	0.48	0.48
4	Measure 5: Drain rehabilitation	6.194E-02	2.711E+00	73.53	72.37
5	Measure 3: Dam grouting	6.102E-02	2.670E+00	2611.90	2611.21

Table 5.26. Results of societal and economic risk, and ACSLS values for each step of the sequence.

As can be observed in this table, when all the proposed measures are implemented, societal risk is reduced in 0.43 lives/year and economic risk is reduced in 1.98 Rs Crores/year. The total introduction cost of these measures is 4.2 Rs Crores and the total annualized (including implementation and maintenance) is 0.32 Rs Crores/year.

Results of ACSLS show the three steps of the proposed sequence of measures are very efficient since they are not very expensive and they have a notable effect on reducing dam risk. Drain rehabilitation is also efficient, although at a lower degree.

This itinerary can also be represented using an fN graph for the three failure modes as shown in Figure 5.35.

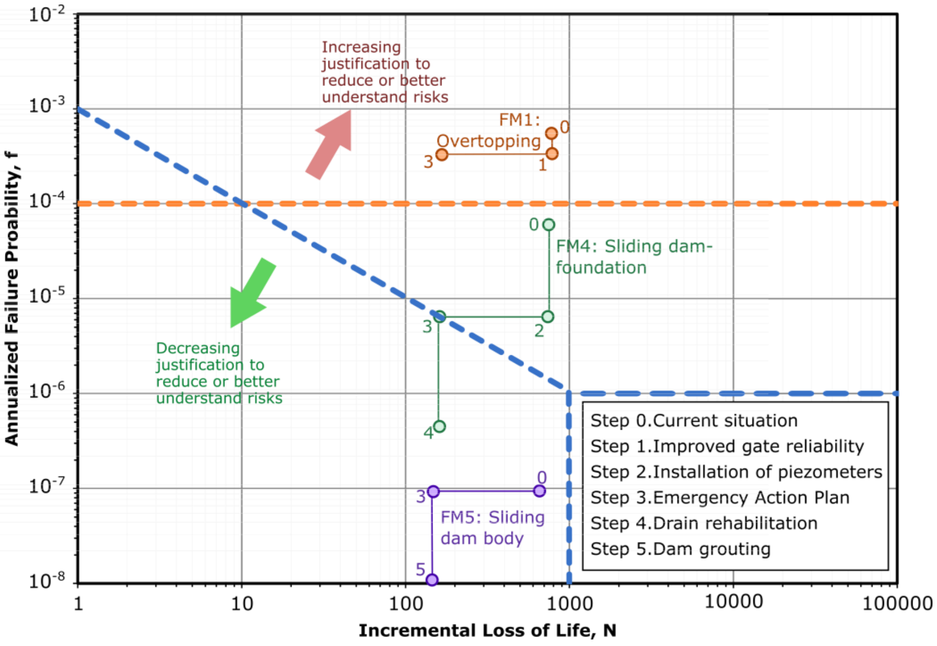


Figure 5.35. Itinerary followed by implementing the proposed sequence of actions in an fN graph.

Finally, the measures currently being implemented within the DRIP program (Measures 1, 2 and 3) are introduced jointly to analyze risk reduction achieved in the Bhadra Dam thanks to this program. When these measures are implemented, societal risk is reduced in 0.42 lives/year and economic risk is reduced in 1.58 Rs Crores/year. The total introduction cost of these measures is 2.7 Rs Crores and the total annualized (including implementation and maintenance) is 0.24 Rs Crores/year. Cost/Benefit ratio of these measures (obtained by dividing measures costs by risk reduction benefits) is 15%, which demonstrate its economic efficiency.

These results are shown in Figure 5.36.

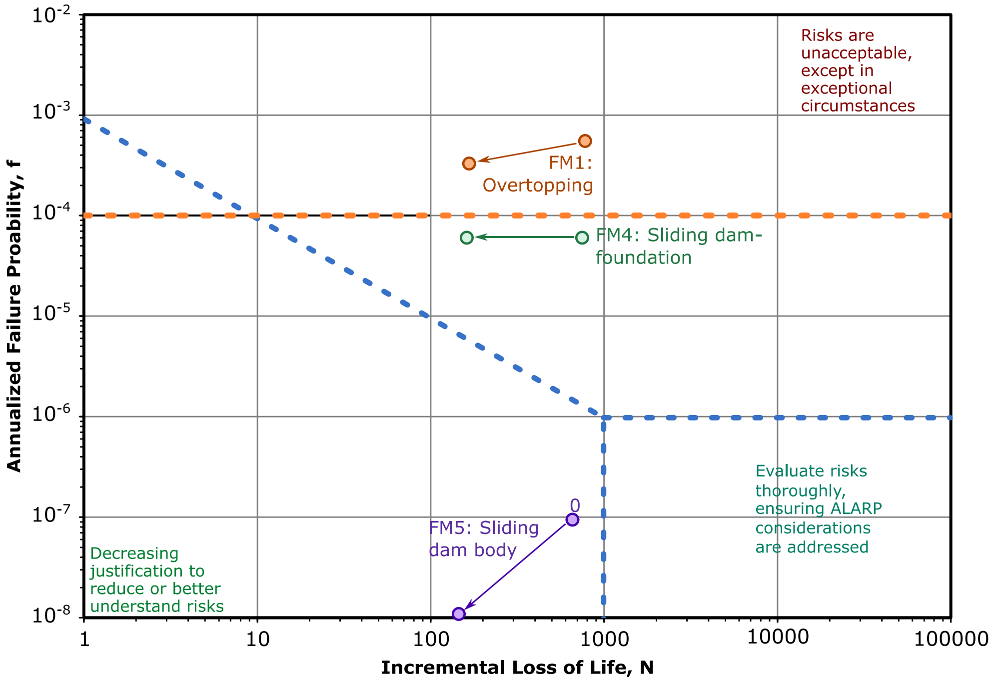


Figure 5.36. Risk reduction achieved in the Bhadra Dam thanks to DRIP program.

6. Semi-Quantitative Risk Analysis

6.1. Introduction

In a Semi-Quantitative Risk Analysis, a preliminary estimation of risk is made based on the available information. This estimation is made assigning a category to the failure probability (usually linked to a value of failure probability) and a category to the failure consequences (normally linked to a value of dam failure consequences). Therefore, risk values are represented in a Risk Matrix that combines both categories.

Semi-Quantitative Risk Analysis is made for **Class III Failure Modes** to prioritize new studies and new instrumentation in the Portfolio of dams. In addition, **Class II Failure Modes** can also be included in this Semi-Quantitative analysis if new studies are recommended after quantitative risk evaluation and uncertainty analysis.

In this case, the **Class III failure modes** included in this analysis were:

- FM6: Sliding in a seismic event in the main dam.
- FM7: Overtopping in a seismic event in saddle dams.
- FM8: Internal erosion in saddle dams.
- FM9: Failure due to settlement at upstream face in saddle dams.

In addition, the following **Class II Failure Modes** have been included in this analysis following uncertainty analysis recommendations:

- FM1: Overtopping failure in the main dam (to prioritize a new probabilistic hydrological study).
- FM4: Sliding in the main dam along the dam-foundation surface (to prioritize geotechnical test and detailed sliding failure analysis).

This Semi-Quantitative Risk Analysis was a collaborative process, made during different working sessions. The participants of this working group are summarized in the following table:

Name	Title (s)	Entity
Ignacio Escuder	Phd. Civil Engineer	iPresas Risk Analysis
Adrián Morales	Phd. Civil Engineer	iPresas Risk Analysis
Jessica Castillo	PhD Civil Engineer	iPresas Risk Analysis
Yevhen Zobal	Civil Engineer	iPresas Risk Analysis
Daniel Cervera	Civil Engineer	iPresas Risk Analysis
Ignacio Aranguren	Civil Engineer	iPresas Risk Analysis

Table 6.1. Participants during Semi-Quantitative Risk Analysis.

Semi-Quantitative Risk Analysis was coordinated and supervised by Adrián Morales (iPresas Risk Analysis) who has proven experience in this type of analysis applied to dam safety.

6.2. Semi-Quantitative risk results

In the Semi-Quantitative Risk Analysis, for each failure mode, a category was assigned to failure probability and consequences.

Failure probability is the first component that should be categorized. The category assigned to a probability of failure should consider both the probability of the loading condition and the probability of failure given the loading condition. For normal operating scenarios, the probability of the loading is high. However, for floods or earthquakes, the probability of the loading could be very small. The following categories were used:

- **Remote:** The annual failure probability is more remote than 10^{-6} (1/1,000,000). Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible probability such that the failure probability is negligible.
- **Low:** The annual failure probability is between 10^{-5} (1/100,000) and 10^{-6} (1/1,000,000). The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to initiation.
- **Moderate:** The annual failure probability is between 10^{-4} (1/10,000) and 10^{-5} (1/100,000). The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward “less likely” than “more likely.”
- **High:** The annual failure probability is between 10^{-3} (1/1,000) and 10^{-4} (1/10,000). The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward “more likely” than “less likely”.
- **Very High:** The annual failure probability is more frequent (greater) than 10^{-3} (1/1,000). There is direct evidence or substantial indirect evidence to suggest it has initiated or is likely to occur in near future.

The other risk component is the magnitude of the **consequences** that each failure mode could produce. For semi-quantitative evaluations, the focus is typically on the potential for life loss. The following categories were used:

- **Category 1:** Downstream discharge results in limited property and/or environmental damage. Although life-threatening releases could occur, direct loss of life is unlikely due to severity or location of the flooding, or effective detection and evacuation.
- **Category 2:** Downstream discharge results in moderate property and/or environmental damage. Some direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travellers and small population centres (estimated life loss in the range of 1 to 10).
- **Category 3:** Downstream discharge results in significant property and/or environmental damage. Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travellers and smaller population centres, or difficulties evacuating large population centres with significant warning time (estimated life loss in the range of 10 to 100).
- **Category 4:** Downstream discharge results in extensive property and/or environmental damage. Extensive direct loss of life can be expected due to limited warning for large population centres and/or limited evacuation routes (estimated life loss in the range of 100 to 1,000).
- **Category 5:** Downstream discharge results in very high property and/or environmental damage. Very high direct loss of life can be expected due to limited warning for very large population centres and/or limited evacuation routes (estimated life loss in the range of 1,000 to 10,000).

- **Category 6:** Downstream discharge results in extremely high property and/or environmental damage. Extremely high direct loss of life can be expected due to limited warning for very large population centres and/or limited evacuation routes (estimated life loss greater than 10,000).

In some cases, dam failure could not have a high impact on loss of life but could have a very high economic impact, due to the dam importance for the regional economy. In these cases, a consequences category can be assigned based on economic consequences.

The categories assigned to each failure mode are explained in the following tables:

<table>
<tr><th colspan="2">Failure Mode 6: Sliding in a seismic event in the main dam</th></tr>
<tr><td>Failure probability category</td><td>Low</td></tr>
<tr><td colspan="2">Justification</td></tr>
<tr><td colspan="2">This probability category was estimated according to the following factors:
• Zone 2 is classified as Low Damage Risk Zone (least active seismic zone). The maximum horizontal acceleration that it is estimated can be experienced by a structure in Zone 2 is 10% g.
• Seismic forces were not considered in the design.
• There are no studies to evaluate the potential and magnitude of a seismic scenario.
• These types of dams have historically behaved properly during seismic events.</td></tr>
<tr><td>Consequences category</td><td>4</td></tr>
<tr><td colspan="2">Justification</td></tr>
<tr><td colspan="2">This category was assigned following the results of consequences estimation made for the risk model. According to these results, complete failure of Bhadra Dam would produce an estimated loss of life between 100 and 1000.</td></tr>
</table>

<table>
<tr><th colspan="2">Failure Mode 7 : Overtopping in a seismic event in saddle dams</th></tr>
<tr><td>Failure probability category</td><td>Remote</td></tr>
<tr><td colspan="2">Justification</td></tr>
<tr><td colspan="2">This probability category was estimated according to the following factors:
• Zone 2 is classified as Low Damage Risk Zone (least active seismic zone). The maximum horizontal acceleration that it is estimated can be experienced by a structure in Zone 2 is 10% g.
• Reservoir level is 5 m below saddle dam crest level for MOL. Consequently, settlements should be very important to produce overtop-ping in the saddle dam.
• Seismic forces were not considered in the design.
• There are no studies to evaluate the potential and magnitude of a seismic scenario.
• This type of dams has historically behaved properly during seismic events.</td></tr>
<tr><td>Consequences category</td><td>3</td></tr>
<tr><td colspan="2">Justification</td></tr>
<tr><td colspan="2">The HEC-RAS model used to estimate consequences in the main Bhadra dam were used to make a preliminary computation of the flood produced by the failure of Saddle Dam. In this case, the flooded are will be much lower, with an estimated loss of life between 10 and 100.</td></tr>
</table>

Failure Mode 8: Internal erosion in saddle dams

Failure probability category	Low

Justification

This probability category was estimated according to the following factors:

- Embankments height is relatively low and reservoir levels are 5 m below saddle dam crest level for MOL, so hydraulic gradients are not high.
- No information is available on filtering materials (if any) nor is there information on properties of impervious layer.
- There are no signs of the initiation of this failure mode (material transport or increment of seepage).
- Detection through instrumentation and observations is not possible.
- There are evidences of settlements in the upstream face but causes are unknown.

Consequences category	3

Justification

The HEC-RAS model used to estimate consequences in the main Bhadra dam were used to make a preliminary computation of the flood produced by the failure of Saddle Dam. In this case, the flooded are will be much lower, with an estimated loss of life between 10 and 100.

Failure Mode 9: Failure due to settlement at upstream face in saddle dams

Failure probability category	Low

Justification

This probability category was estimated according to the following factors:

- Embankments height is relatively low and reservoir levels are 5 m below saddle dam crest level for MOL.
- Detection through instrumentation and observations is not possible.
- There are evidences of settlements in the upstream face but causes are unknown.
- Magnitude of sliding should be very large to produce an embankment failure.

Consequences category	3

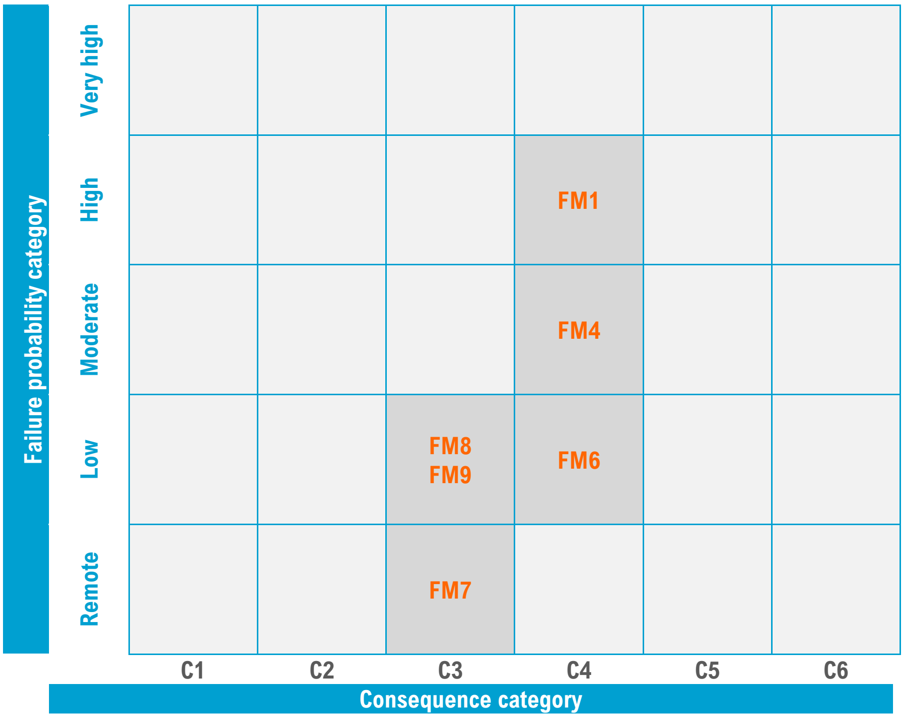
Justification

The HEC-RAS model used to estimate consequences in the main Bhadra dam were used to make a preliminary computation of the flood produced by the failure of Saddle Dam. In this case, the flooded are will be much lower, with an estimated loss of life between 10 and 100.

Failure Mode 1: Overtopping failure in the main dam	
Failure probability category	High
Justification	
Failure probability category was estimated based on the quantitative risk results for this failure mode.	
Consequences category	4
Justification	
This category was assigned following the results of consequences estimation. According to these results, complete failure of Bhadra Dam would produce an estimated loss of life between 100 and 1000.	

Failure Mode 4: Sliding in the main dam along the dam-foundation surface	
Failure probability category	Moderate
Justification	
Failure probability category was estimated based on the quantitative risk results for this failure mode.	
Consequences category	4
Justification	
This category was assigned following the results of consequences estimation. According to these results, complete failure of Bhadra Dam would produce an estimated loss of life between 100 and 1000.	

The results of this Semi-Quantitative Risk Analysis are represented for each failure mode in Figure 6.1.



Failure probability category	C1	C2	C3	C4	C5	C6
Very high						
High				FM1		
Moderate				FM4		
Low			FM8 FM9	FM6		
Remote			FM7			

Figure 6.1. Semi-Quantitative Risk Analysis results.

6.3. Prioritization of new studies or instrumentation

Once risk is represented in the matrix for Semi-Quantitative Risk Analysis (SQRA), potential new studies and/or new instrumentation should be prioritized.

First, new studies or instrumentation needed were defined based on IFM process recommendations. Since Class III classification assumes more information must be gathered for a QRA, all the failure modes should be directly linked to at least one of the proposed new studies or new instrumentation. In addition, new studies or instrumentation for Class II Failure Modes can also be introduced in this prioritization if they are recommended after quantitative risk evaluation and uncertainty analysis.

For Bhadra dam, four new studies and instrumentation are proposed and shown in Table 6.2.

<table>
<tr><td>Study 1</td><td>Probabilistic Hydrologic Analysis</td></tr>
<tr><td>Failure Modes</td><td>FM1</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Detailed probabilistic hydrologic study to analyse rainfall-runoff data on the Bhadra river basin and better characterize flood events and related probabilities of occurrence. Detailed analysis of the rainfall data used for this analysis, checking different sources for this information.</td></tr>
<tr><td>Study 2</td><td>Sliding analysis and geotechnical tests</td></tr>
<tr><td>Failure Modes</td><td>FM4</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Numerical analysis of sliding failure mode for the main dam. This analysis should be based on a geotechnical survey to gather information on soil characteristics at the foundation to gather more knowledge and to reduce uncertainty on geotechnical parameters at the foundation and the dam-foundation contact.</td></tr>
<tr><td>Study 3</td><td>Analysis of settlements in saddle dams</td></tr>
<tr><td>Failure Modes</td><td>FM8 and FM9</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Study to clarify the causes of exiting settlements in the saddle dams. This study can be accompanied with actions to monitor seepage conditions and control of movements in saddle dams to analyse feasibility of failure modes related to internal erosion or potential settlements.</td></tr>
<tr><td>Study 4</td><td>Seismic stability analysis</td></tr>
<tr><td>Failure Modes</td><td>FM6 and FM7</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Detailed seismic studies to gather data related with seismic hazard in this area and to analyse structural stability and feasibility of failure modes related to seismic events in main dam and saddle dams.</td></tr>
</table>

Table 6.2. Studies proposed for Bhadra dam-reservoir system.

Second, based on the results from the SQRA, these studies are prioritized. As can be observed in the SQRA matrix, failure modes closer to the upper-right corner (higher failure probability and higher consequences) should be implemented first. Steps within the proposed sequence of studies are shown in Table 6.3.

Studies	Step
Study 1: Probabilistic Hydrologic Analysis	1
Study 2: Sliding analysis and geotechnical tests	2
Study 3: Analysis of settlements in saddle dams	3
Study 4: Seismic stability analysis	4

Table 6.3. Prioritization sequence for proposed studies based on SQRA for Bhadra dam-reservoir system.

As expected, the first steps are defined for the two studies focused on reducing uncertainty in the two predominant failure modes of the risk model: overtopping (FM1) and dam-foundation sliding (FM4). In this sense, probabilistic hydrologic analysis is especially important since this data is influencing risk results and decision making in this dam.

7. Conclusions

The risk assessment process applied to the Bhadra Dam involved a number of positive effects derived from its own nature and structure, due to the participation of technical personnel from KaWRD and dam safety and risk analysis experts. Results obtained can be used to guide and define future activities of dam response reporting and actions to gather more information and to improve dam safety.

Regarding the direct results of this work, with the available level of information and the inherent limitations of the study, the following conclusions can be derived:

- The process for identification of failure modes allowed a comprehensive and collaborative safety review of the Bhadra main dam and existing saddle dams with a complete group of experts and it provided recommendations for risk reduction actions and new studies. These sessions were the key to develop the Risk Assessment process.
- Identified Failure Modes will be a better guide for future monitoring actions and technical inspections with the aim of detecting potential failures processes.
- Existing risk in this dam was reasonably characterized by a quantitative risk model with 3 failure modes (overtopping, dam-foundation sliding and dam body sliding) and a semi-quantitative risk analysis for 6 failure modes.
- The process for elaborating this quantitative risk model was useful to make a comprehensive review of available information in the dam-reservoir system and performing detailed analysis on key aspects like sliding failure and potential consequences downstream.
- In fact, results from consequences estimation show the high economic and societal impact of a potential dam failure, mainly due to the number of settlements affected by the resulting flood. In addition, potential life-loss results have a high dependency on available warning times, which makes relevant the importance of adequate training, coordination, warning and evacuation in case of emergency. This result highlights the importance of a proper Emergency Action Plan.
- Risk evaluation shows that the Bhadra Dam risks are not aligned with international tolerability recommendations for overtopping and dam-foundation sliding failure modes, then requiring actions for better understand the system, reduce uncertainty and risk.
- Uncertainty analysis shows a high variation on overtopping failure results depending on the rainfall used for hydrologic analysis. In this sense, a detailed probabilistic hydrology analysis is recommended to properly characterize hydrological hazard in this dam. This study should be made prior to large investments to reduce overtopping failure probability. However, while this study is made, an improvement of gates reliability is recommended to ensure that they work properly during flood events. In addition, outcomes from work conducted within the DAMSAFE project on improved flood forecasting and modelling for Bhadra dam will help to reduce uncertainty on hydrology.
- Regarding the dam-foundation sliding in the main dam, significant uncertainties are also found in the results due to the lack of knowledge on geotechnical parameters and foundation characteristics. In this sense, a geotechnical survey and stability analysis is recommended to reduce uncertainty in this failure mode. Nevertheless, in all the cases this failure mode is are not aligned with international tolerability recommendations, so reasonable actions are proposed to reduce its probability while this study is made. Namely, the proposed measures are improving the drainage system performance and installing new piezometers to measure uplift pressures in the foundation. Results from dam monitoring within the DAMSAFE project will contribute to reduce uncertainty on uplift pressures.

- It should be remarked that outcomes from DAMSAFE actions will help to collect data on key aspects for Bhadra dam in terms of flood forecasting and dam monitoring, and to reduce uncertainty of the two main risk drivers identified in the risk model (overtopping failure and sliding failure).
- Based on results of the risk model, five risk reduction measures were analysed based on actions undertaken under the DRIP project and proposals from IFM sessions. A prioritization sequence was obtained for these measures, combining efficiency and equity principles.
- As expected, the most efficient measures to reduce risk according to this sequence are improvement of gates reliability, piezometers installation, implementing the Emergency Action Plan and drainage rehabilitation. These prioritization results are useful to prioritize the proposed risk reduction actions within the Dams Portfolio management.
- In addition, estimates on risk reduction achievement and cost/benefit ration of actions being implemented by DRIP were quantified. These results show a high economic efficiency of these measures thanks to the risk reduction achieved.
- Semi-Quantitative Risk Assessment was used to prioritize new studies and instrumentation in both dams. Priority levels obtained for these studies are useful to prioritize new studies within the Dams Portfolio management.
- Higher priority levels are obtained for the two studies proposed to reduce uncertainty in the two predominant failure modes of the risk model (overtopping and dam-foundation sliding). In this sense, probabilistic hydrologic analysis is especially priority since this data is conditioning risk results and decision making in this dam.

In conclusion, risk results show important uncertainties in hydrological data and dam structural behaviour in this case. In this sense, proposed actions are focused on new studies about these two topics, since implementing major structural measures cannot be decided with the existing level of uncertainty, even though risk seems not to be aligned with international tolerability recommendations. Meanwhile these studies are made, other measures that require lower investments (improvement of gates reliability, piezometers installation, implementing the Emergency Action Plan) are recommended since they are very efficient in reducing risk.

Finally, it is worth mentioning that the process described in this document does not replace or exempt from compliance with current or future legislation and safety standards and/or best practices at national and/or international levels.

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