Guidelines for Assessing and Managing Risks Associated with Dams

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February 2019

Dam Rehabilitation & Improvement Project

Central Water Commission
Ministry of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Front Cover Photograph: Bhakra Dam, Himachal Pradesh

सत्यमेव जयते

Government of India
Central Water Commission
Central Dam Safety Organization

Guidelines for Assessing and Managing Risks Associated with Dams

February 2019

Dam Safety Rehabilitation Directorate
3rd Floor, New Library Building
R. K. Puram
New Delhi - 110066

Government of India
Central Water Commission
Central Dam Safety Organisation

Guidelines for Assessing and Managing Risks Associated with Dams is one of the several dam safety guidelines being developed under the Dam Rehabilitation and Improvement Project (DRIP)

<u>Disclaimer</u>

Guidelines for Assessing and Managing Risks Associated with Dams in no way restricts the dam owner in digressing from it. The Central Dam Safety Organization or the Central Water Commission cannot be held responsible for the efficacy of the manuals developed by various dam owners based on these guidelines. Dam owners and operators should exercise appropriate discretion when preparing an operation and maintenance manual for their dams.

For any information, please contact:
The Director
Dam Safety Rehabilitation Directorate
Central Dam Safety Organisation
Central Water Commission
3rd Floor, CWC New Library Building (Near Sewa Bhawan)
R. K. Puram, New Delhi – 110066.
Email: dir-drip-cwc@nic.in

MESSAGE

The Central Water Commission under the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India has taken up the Dam Rehabilitation and Improvement Project (DRIP) with funding assistance from the World Bank to improve the safety conditions of some of the existing dams in the country. Along with the implementation of a host of measures for improving the performance of dams of varying ages, it also envisages to prepare a set of guidelines that will extend further help to the dam safety professionals. One of them is the *Guidelines for Assessing and Managing Risks Associated with Dams* that proposes a risk-informed dam safety program for India, covering the existing methods and tools for qualitative and quantitative risk assessments applied to dam safety.

The risk-informed dam safety program proposed in these Guidelines is aligned with the requirements of the Dam Safety Bill (2018), which requires to carry out risk assessment studies for all large dams within the next five years. In order to achieve this goal, the capacity and experience in performing risk assessment studies is required to be developed within various institutions in India, both in the Central and State Governments.

I hope the present Guidelines published by Central Water Commission will be the first step in building the required capacity in India. The Guidelines are very descriptive and include detailed examples and valuable references. I am sure that knowing and assessing the existing dam risks will allow us to make better decisions for our dam safety management.

(S Masood Husain)
Chairman
Central Water Commission

New Delhi
February 2019

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FOREWORD

Currently, India ranks third globally having 5254 large dams in operation and 457 under construction. Aspects such as climate change, ageing of the existing dams and high population growth may increment dam risks in the future. In addition, the high number of dams and the system complexity makes the decision making process more difficult.

For this reason, there is an international trend towards using risk analysis tools for taking decisions to ensure better dam safety management. In order to promote risk-informed dam safety management in India, Central Water Commission (CWC) has developed the *Guidelines for Assessing and Managing Risks Associated with Dams*. In these Guidelines, international best practices on risk analysis tools are explained and tailored to the Indian context. These tools integrate the dam's design, construction and operation in a framework of risk management, including aspects such as dam monitoring and surveillance, and emergency management, addressed in previous Guidelines. The integration of all these aspects in risk estimations allows for a more transparent and justified decision making process for potential investments on remediation measures and new studies or instrumentation.

Finally, I compliment all the individuals and organizations involved in the preparation of these Guidelines. I hope that dam owners make use of these guidelines for making risk assessment studies and developing risk management programs. I also put on record the support extended by the World Bank in accomplishing these objectives and especially thank Dr. C Rajgopal Singh, Task Team Leader, DRIP and their team for extending excellent support all the time.

(N.K. Mathur)
Member (Design & Research)
Central Water Commission

New Delhi
February 2019

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PREFACE

Today, society demands an increase in the safety and reliability levels of essential infrastructures, like large dams. It is globally recognized that there is always a probability associated with dam failure, even if it might be very low, and there exists a possibility for adverse consequences to occur. Consequently, there is an associated risk that should be estimated, managed and minimized.

In these *Guidelines for Assessing and Managing Risks Associated with Dams*, the main structure and lessons learned of risk-informed dam safety programs from countries like USA, Australia, UK and Spain are reviewed. These experiences are used to develop a risk-informed dam safety program which can be adapted by India. This program includes the main phases of a risk assessment process: Identification of Failure Modes and Semi-Quantitative and Quantitative Risk Assessments. Risk estimations are finally used to support decision making on allocating resources for rehabilitation actions and new studies or instrumentation.

In this sense, these guidelines propose a risk assessment methodology where all aspects related with dam safety to improve decision making are integrated. Available dam information is reviewed during the identification of failure modes process and it is used as input data in the quantitative risk model. In this sense, Risk Management does not replace traditional dam safety management but is based on its outcomes to improve decision-making processes and provides useful information to improve it. For this reason, all dam safety aspects described in the Guidelines and Manuals elaborated by Central Water Commission are directly and indirectly related with the Risk Assessment and Management process described in this document.

In these Guidelines, the best practices on methods and tools for risk assessment are explained in 8 chapters and 4 appendices, providing around 100 international references. In addition, it includes a template for risk assessment reports and two complete and illustrative case studies, which show how risk results are used to support decisions on real dams.

Central Water Commission acknowledge the contribution of Mr. Eric C Halpin, Former expert US Army Corps of Engineers and President Halpin Consultants L.L.C, USA for reviewing this guidelines and assisting us in bringing latest state-of-art of knowledge in this guidelines. We also thank to all members of Reviewing Committee who contributed in publication of this guidelines as well as other team members for sending technical support directly or indirectly for this document.

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Review Committee

Chairman	S K Sibal	Chief Engineer, Designs (N&M), CWC, New Delhi
Member Secretary	Pramod Narayan	Director, Dam Safety Rehabilitation Directorate and Project Director DRIP, CWC, New Delhi

Committee Members

Gulshan Raj	Chief Engineer, Dam Safety Organization, CWC, New Delhi
T K Sivarajan	Chief Engineer, Designs (E&NE), CWC, New Delhi
N N Rai	Hydrologist, CWC, New Delhi
Dr. M L Sharma	Professor, Department of Earthquake Engineering, IIT Roorkee
Dr. N K Goel	Professor, Department of Hydrology, IIT Roorkee
Vivek Tripathi	Director, CMDD (E&NE), CWC, New Delhi

Team Involved in Preparing this Guideline

Dr Ignacio Escuder Bueno	Team Leader, CPMU Consultant, DRIP and Professor UPV, Spain and President SPANCOLD
Dr Adrián Morales-Torres	Risk Specialist, CPMU Consultant, DRIP
Pramod Narayan	Director, Dam Safety Rehabilitation Directorate and Project Director, DRIP, CWC, New Delhi
Manoj Kumar	Deputy Director, Dam Safety Rehabilitation Directorate, CWC, New Delhi
Saurabh Sharan	Deputy Director, Dam Safety Rehabilitation Directorate, CWC, New Delhi
Bikram Kesharee Patra	Deputy Director, Dam Safety Rehabilitation Directorate, CWC, New Delhi

Independent International Reviewer

Eric Halpin	President Halpin Consultants LLC and Former expert US Army Corps of Engineers (USACE), Virginia, USA

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Abbreviations

Acronyms used in this publication are as follows:	
AEP	Annual Exceedance Probability
ALARP	As Low As Reasonably Practicable
ANCOLD	Australian National Committee on Large Dams
CWC	Central Water Commission of India
CDSO	Central Dam Safety Organization of India
DRIP	Dam Rehabilitation and Improvement Project
DSO	Dam Safety Organization
EAP	Emergency Action Plan
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission of United States
HSE	United Kingdom Health and Safety Executive
ICOLD	International Commission on Large Dams
IFM	Identification of Failure Modes
ISO	International Organization for Standardization
KaWRD	Karnataka Water Resources Department
MAGRAMA	Spanish Ministry of Agriculture, Food and Environment
m.a.s.l.	Meters Above Sea Level
MCE	Maximum Credible Earthquake
PAR	Population At Risk
PMF	Probable Maximum Flood
PST	Project Screening Templates
QRA	Quantitative Risk Analysis
SPANCOLD	Spanish National Committee on Large Dams
QRA	Semi-Quantitative Risk Analysis
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation

Chapter 1. OVERVIEW OF DAMS RISK ASSESSMENT AND MANAGEMENT

1.1 What is Risk in the Dam Safety field?

Risk is the combination of three concepts: what can happen, how likely it is to happen and what are the consequences in the case that it happens (Kaplan 1997). This combination of probability of events and consequences is the key to define risk across different fields and industries (ISO 2009).

In Risk Assessment applied to dam safety, *what can happen* refers to dam failure, *how likely* it is to happen is related to failure probability of the dam and the *consequences* are the facts resulting from the failure of the dam, including economic consequences and loss of life. Numerically, risk is estimated combining the likelihood of occurrence of loads (e.g., flood, earthquake, etc.), the likelihood of dam failure due to these loads and the failure consequences. There is always a probability associated with dam failure, even if it might be very low, and there are always possibilities for adverse consequences to occur. Consequently, there is always an associated risk that should be managed and minimized.

In this sense, Risk Analysis is a useful methodology to characterize this risk and establish priorities in critical infrastructure safety management since it allows the integration of all existing information on threats, vulnerability and consequences (Moteff 2005). Several entities in the dam safety industry have been using risk to inform decisions since the 1990s. Notably, the U.S. Bureau of Reclamation (USBR) and the U.S. Corp of Engineers (USACE) adopted risk management strategies to assess and manage risks for their dams. In addition, the Australian National Committee on Large Dams (ANCOLD) and the Spanish National Committee on Large Dams (SPANCOLD), even though neither are dam owners nor regulators, have developed guidelines to promote risk-informed dam safety management.

Using risk to inform decisions involves four distinct components. These components (summarized in **Figure 1-1**) are (ICOLD 2005; FEMA 2015):

- **Risk Analysis:** It is the first component of risk management and includes the process followed to estimate risk. Typically, it has a qualitative part and a quantitative (or semi-quantitative) part. First, the qualitative part (Identification of Failure Modes) identifies potential modes of failure and the conditions and events that must take place for failure to occur. Second, the quantitative (or semi-quantitative) part yields a numerical estimate of the failure probability and dam failure consequences. In a quantitative analysis, this estimation is made with a risk model that combines the probability of loads, the probability of dam failure (system response) and the magnitude of adverse consequence given dam failure.

- **Risk Assessment:** The process of deciding whether existing risks are tolerable and if not, what risk reduction measures are recommended. It incorporates the risk analysis and risk evaluation phases, where risk is to be compared against risk tolerability recommendations.

- **Risk Management:** It builds on risk analysis and risk assessment phases. Risk management encompasses activities related to making risk-informed decisions by prioritizing new studies and instrumentation, prioritizing risk reduction actions (structural and non-structural), and making program decisions associated with managing a portfolio of dams. Risk management includes evaluating the environmental, social, cultural, ethical, administrative, political, and legal considerations during every part of the process.

- **Risk Governance:** It includes the totality of actors, policies, roles, and procedures concerned with how relevant risk information is collected, analysed and communicated; thereafter, management decisions are taken. It defines how Risk Assessment and Management procedures are implemented within dam management and regulation organisms.

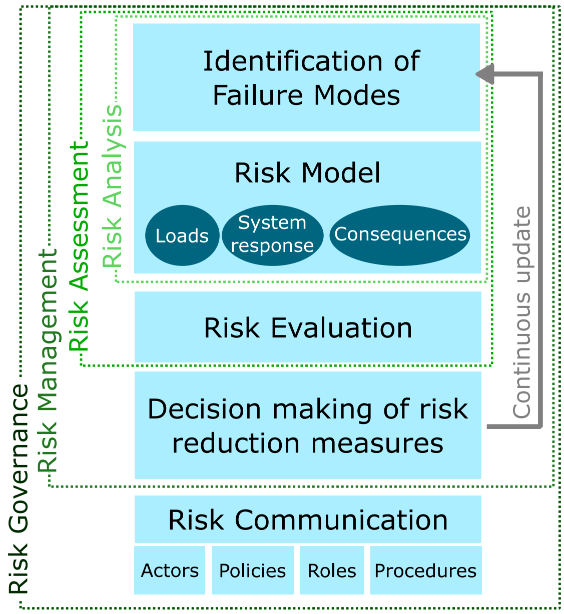

Figure 1-1. Relation between Risk Analysis, Risk Assessment, Risk Management and Risk Governance

In these guidelines, the experiences of some of the main dam safety management programs worldwide are used to design a **Risk-Informed Dam Safety Management Program** tailored for India and explained in Section 2.4.

The structure of this Program is used as a roadmap to explain the main steps of Risk Assessment and Management, like identification of failure modes (Chapter 4), steps of a semi-quantitative risk analysis (Chapter 5), elaboration of quantitative risk models and risk evaluation (Chapter 6) and, decision making and risk management (Chapter 7).

Even though the focus of these guidelines is Risk Assessment and Management, Chapter 8 provides general recommendations on key aspects to develop a dam Risk Governance Framework based on the designed Dam Safety Management Program.

Finally, to assist the application of these Guidelines, Appendix A provides a template to be used as a basis for Dam Safety Risk Assessment reports and Appendixes B and C detail how the explained methodologies have been applied in two cases studies.

1.2 Why is Risk Assessment and Management useful?

Today, society demands an increase in the safety and reliability levels of such infrastructures considered as essential (SPANCOLD 2012). The only way to respond positively to these expectations is to integrate the dam's design, construction and operation in a framework of risk management that ensures effective mitigations of natural and anthropic threats. Consequently, global strategies of risk management have gained great importance during the last years. Efforts carried out to implement them systematically include aspects such as sustainability, resilience and public participation.

In this context, Risk Assessment and Management provide a rational, transparent and systematic process to inform dam safety decision making. The benefits of risk-informed decision making for dam safety management institutions are (ANCOLD 2003; Kumar, Narayan, and Reddy 2018):

- Encouraging proactive management, establishing a reliable basis for decision making and planning.
- Promoting compliance with relevant legal and regulatory requirements.
- Efficient use of available resources, providing optimum risk reduction path-

ways.

- Greatly improved and comprehensive understanding of the safety of the dam.

- Engagement and integration of the different stakeholders (dam operators, dam regulators, civil protection, administrations, etc.) in the management process.

- Analysis and assessment of risks in areas where no traditional standards have been established.

- Considerably increasing of risk reduction cost effectiveness from traditional approaches.

- Improving organizational learning and organizational resilience.

- Improving dam safety and dam risk communication.

Risk Assessment and Management also provides benefits in the operation and surveillance of exiting dams:

- Promoting periodic reviews of existing information and data.

- Improving operation and maintenance procedures.

- Better understanding of potential failures in the dam, providing valuable information for dam surveillance and inspections (Narayan, Patra, and Singh 2018).

- Improving downstream loss prevention, emergency management and urban planning.

Finally, Risk Assessment and Management also provide benefits during the planning and design of new dams:

- Detecting research and study-needs to complete the design, identifying possible gaps in the available information.

- Better understanding on the dam's physics and its relationship with the foundation, providing in some cases, recommendations to improve the design. Changes during the design will be more economical and efficient than future rehabilitation works.

- Identifying and mitigating other potential risks during the dam's construction process (USSD 2017).

- Better design of dam instrumentation to detect potential failure modes.

- Quantifying downstream flood risk before and after the dam's construction allows highlighting risk reduction benefits provided by the dam.

- Promoting urban planning instruments to avoid encroachment into the flood plains and risk increasing.

1.3 Relation with other CWC Guidelines

Central Water Commission (CWC) is a public national organization that promotes integrated and sustainable development and management of Indian water resources by using state-of-the-art technology, and competency, and coordinating coordination of all stakeholders and water security for the nation.

Among others, one of CWC's main missions is providing expert services to State Dam Safety Organisations, dam owners, dam operating agencies and others concerned with ensuring the safe functioning of dams with a view to protect human life, property and the environment.

Following this mission, CWC is currently elaborating 16 Guidelines and Manuals to strengthen dam safety technical management in the country. Each one is related to a different aspect of dam safety, one of them being *Guidelines for Assessing and Managing Risks Associated with Dams*.

These guidelines are being developed under the Dam Rehabilitation and Improvement

Project (DRIP), a program funded by the World Bank for rehabilitation and improvement of about 223 dams, also including Dam Safety Institutional Strengthening in participating States and CWC.

As explained in the previous sections, Risk Assessment and Management provides a global framework where all aspects related with dam safety are integrated to improve decision making. Available dam information is reviewed during the identification of failure modes process and it is used as input data in the quantitative risk model. In this sense, Risk Management does not replace traditional dam safety management but is based on its outcomes to improve decision-making processes and provides useful information to improve it.

For this reason, all dam safety aspects described in the Guidelines and Manuals elaborated by CWC within the DRIP program are directly and indirectly related with the Risk Assessment and Management process, as shown in Figure 1-2. As can be observed, they are integrated in the results through failure modes and risk model input data (in its three parts: loading, system response and consequences). In addition, as explained in the previous section, Risk Management provides valuable outcomes for improving dam operation, surveillance and emergency planning.

This two-way relation between risk model input data and dam safety aspects (described in the DRIP Guidelines and Manuals) are explained in more detail in the following chapters. Below are some illustrative examples of this relationship:

- Monitoring data and conducting technical field inspections are central for identification of failure modes, while its outcomes are very useful for improving instrumentation and inspection procedures (Narayan, Patra, and Singh 2018).

- The current state and maintenance of gates are analysed to estimate reliability during flood events, while risk results are helpful to identify the most critical gates in the system, where maintenance and control should be higher.

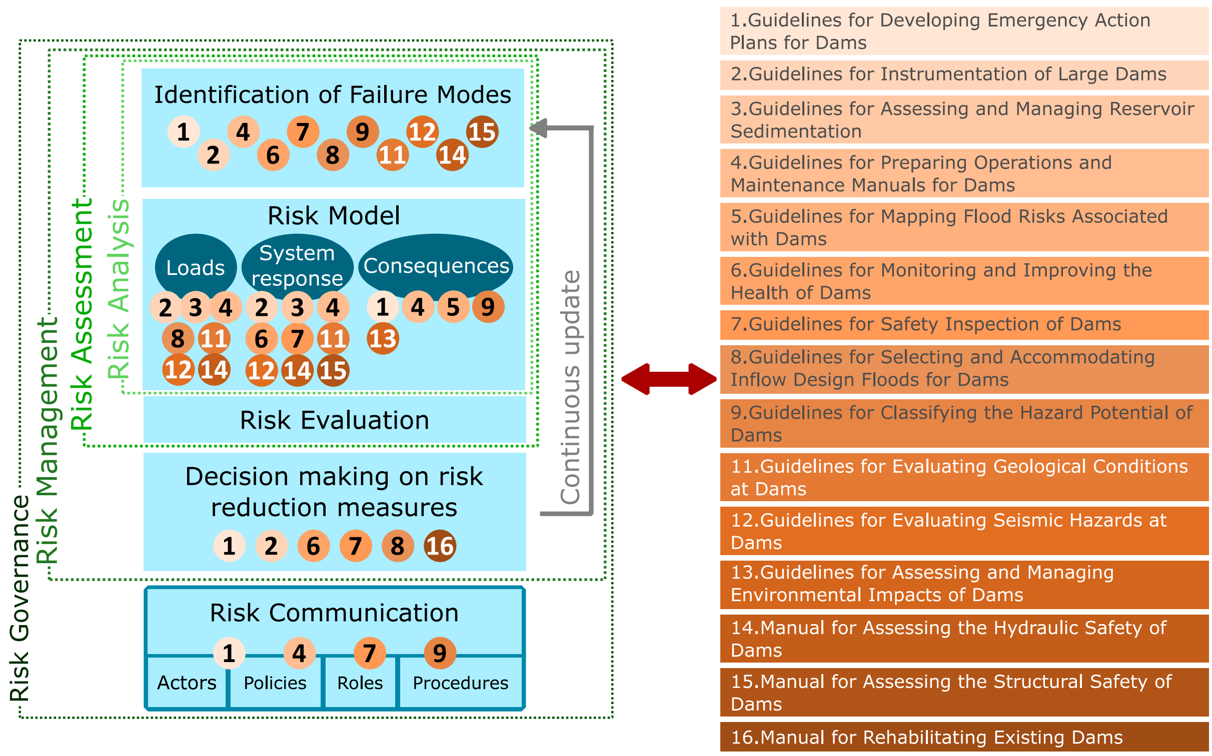

Figure 1-2. Relation between DRIP Guidelines and Manuals and Risk Assessment and Management process

- On one hand, existing hydrological studies are used to analyse overtopping and other hydrologic failure modes. On the other hand, risk assessment can evaluate the effect of hydrological data uncertainty on dam safety.

- Emergency Action Plans and dam failure hydraulic models are very useful to estimate loss of life and economic consequences. Results that show where higher fatalities could be expected are very useful to optimize emergency management procedures and actions.

1.4 Publication and Contact Information

This document is available on the CWC website

http://www.cwc.gov.in

and the Dam Rehabilitation and Improvement Project (DRIP) website

http://www.damsafety.in

For any further information contact:

Director
Dam Safety Rehabilitation Directorate
Central Dam Safety Organization
Central Water Commission
3rd Floor, New Library Building
R. K. Puram, New Delhi – 110066
Ph: +91-11-29583480
Email: dir-drip-cwc@nic.in

1.5 Acknowledgments

In preparing this manual, work of others from India, the United States, Australia, Spain and elsewhere has been drawn from liberally. Grateful appreciation is extended to the following organizations whose publications and websites have given valuable information on various aspects of dam risk assessment and management:

- International Commission on Large Dams (ICOLD).
- United States Army Corps of Engineers (USACE).
- United States Bureau of Reclamation (USBR).
- Spanish National Committee on Large Dams (SPANCOLD).
- Australian National Committee on Large Dams (ANCOLD).
- United States Society on Dams (USSD).
- United Kingdom Health and Safety Executive (HSE).
- Federal Energy Regulatory Commission of United States (FERC).
- Federal Emergency Management Agency of United States (FEMA).
- United Kingdom Environment Agency.

In addition, data with regard to practical applications included in the Appendixes B and C have been kindly shared by Karnataka Water Resources Department (KaWRD) and General Directorate of Water (Government of Spain, MAPAMA).

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Chapter 2. Basis for a Risk-Informed Dam Safety Management Program for India

2.1 Dam failure risks world-wide

Dams are critical infrastructures for economic development and flood protection worldwide. Dam failures in the past have produced high economic losses and social consequences.

The worst disaster caused by dam failure occurred in China in 1975. During one chain-reaction event triggered by a typhoon, 62 interrelated dams failed, the largest of which was Banquio Dam. These failures resulted in 26,000 direct fatalities due to flooding and 100,000 – 150,000 fatalities due to disease and exposure. Major dam disasters have also occurred in Italy (1961), India (1979), Ukraine (1961) the United States (1928, 1889), Indonesia (2009) and England (1864). The total number of fatalities produced by dam disasters in the twentieth century, excluding China, was approximately 13,500 (Coppola 2015).

According to ICOLD (ICOLD 2017), from the approximate 36, 000 large dams listed in the World Register of Dams, there have been around 300 reported accidents. It makes the overall accident rate of dams to be around 1 %. A time-related analysis shows that this has been reduced by a factor of four or more over the last forty years, mainly due to the improvements in dam design engineering, investigation techniques and dam safety management.

As explained in ICOLD Bulletin 99 (ICOLD 1995), the highest historical failure rates are produced in embankments, followed by buttress dams.

In embankments, the most common cause of failure is overtopping (31% as primary cause), followed by internal erosion in the dam body (15% as primary cause) and in the foundation (12% as primary cause).

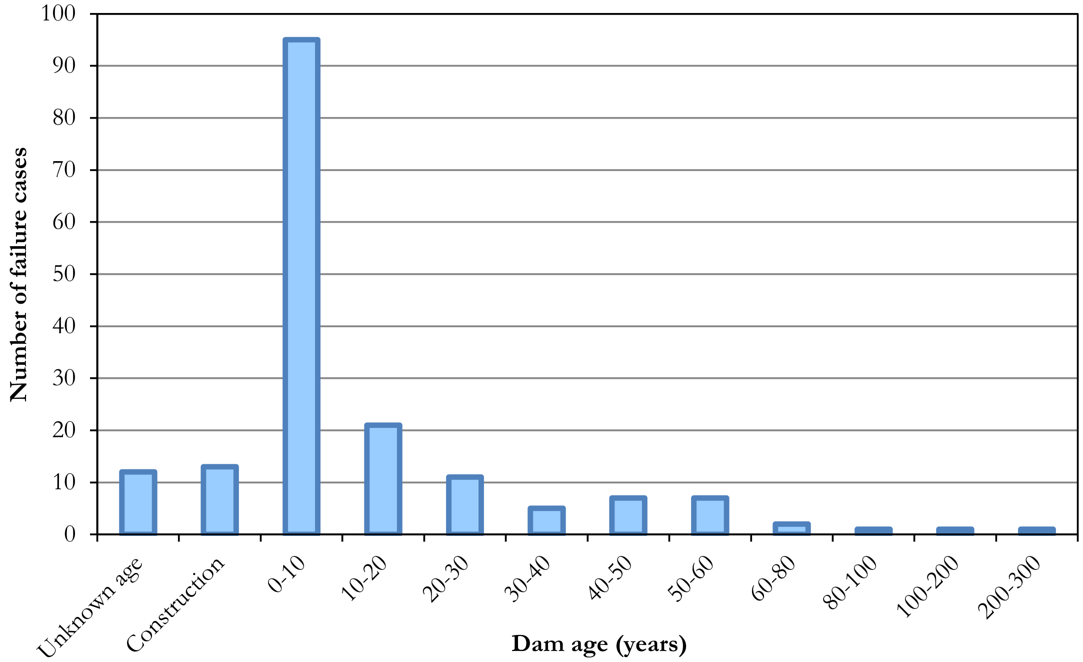


Figure 2-1. Failures by age of failed dams. Adapted from (ICOLD, 1995)

In concrete dams, foundation problems are the most common cause of failure, especially internal erosion (20%) and insufficient shear strength (26%), followed by overtopping (20%).

In masonry dams, the most common cause is overtopping (43%) followed by internal erosion in the foundation (29%).

As shown in Figure 2-1, a great number of failures have occurred in very young dams (0-10 years), especially during the first year, due to foundation or dam problems that were not detected during the design or the construction.

2.2 Dam failure risks in India

According to (CWC 2017), there are 5254 complete large dams in India, while 447 are being constructed, being the third country in the world by number of dams. So far, 36 dam accidents have been recorded in the country, where the overall accident rate is 0.685%, which is slightly lower than the world average (1%). In any case, due to the high population density in India, some of these dam failures have had very high consequences downstream. Some examples of major dam failures which have happened in India were compiled at ICOLD technical Bulletin 99 (ICOLD 1995), included 21 failure cases between 1954 and 1983, and have not been the last failures to have occurred.

Climate threats, such as those related to monsoons as well as some of the overall portfolio features where embankment dams are clearly predominant, make Indian dams particularly vulnerable to overtopping and internal erosion type of failure modes, which together with foundation related causes are the three prevalent worldwide causes of dam failure according to ICOLD (ICOLD 1995).

These past failure cases show the importance of proper dam safety management in India. In this sense, risk-informed dam safety management is recommended for India based on the following reasons:

- The ageing of the existing dams (most of the structures are over 50 years old), and, current engineering knowledge versus the knowledge at the time when they were designed and built has improved.
- The need to prioritize corrective actions in a high number of dams to achieve the greatest and optimal risk reduction possible.
- The need to evaluate available information in each dam and prioritize new studies and instrumentation.
- Water availability is crucial for human development in India. For this reason, water resources system management should be optimized and increased in their regulatory capacity to respond to important challenges such as Climate Change and its manifestation for severe droughts or severe floods.
- The complications of building new large dams mainly due to social and environmental reasons, that will predictably make it necessary to extend the operational phase of the existing structures beyond their originally planned lifespan.
- The increasing social demand for higher safety levels and justification for the use of public funds.
- India is a country with a high urban density, so first priority funding must be dedicated to improving the resilience of communities via more effective evacuation plans and exercises.

2.3 Lessons learnt from Risk Assessment and Management worldwide

2.3.1 United States

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 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.

According to USBR experience (Snorteland and Dinneen 2007), the most difficult aspect of risk management and risk analysis is the transition from standards-based and analysis-oriented philosophies to risk-based thought processes. However, over time, the technical staffs have become more comfortable with the risk processes, partly because the processes have led to reasonable conclusions. Due to the support of both the technical staff and senior managers, the risk management concept is certain to remain a fixture of the dam safety program at USBR.

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 (USACE, 2014 and FERC, 2016), collaborating with USBR.

As explained in (Ignacio Escuder-Bueno and Halpin 2016), USACE, which operates and maintains approximately 700 dams, has followed an adaptive learning process to implementing risk governance which acknowledged a set of skills, policies, and procedures that were not perfect, but sufficient to begin a journey. Ten years later, this bench of professionals has grown to several hundred engineers and scientists, policies and technologies are state of the art, and risk-informed decisions have reshaped the very culture of the agency.

In more detail, USACE Portfolio Management Process consists of two main components:

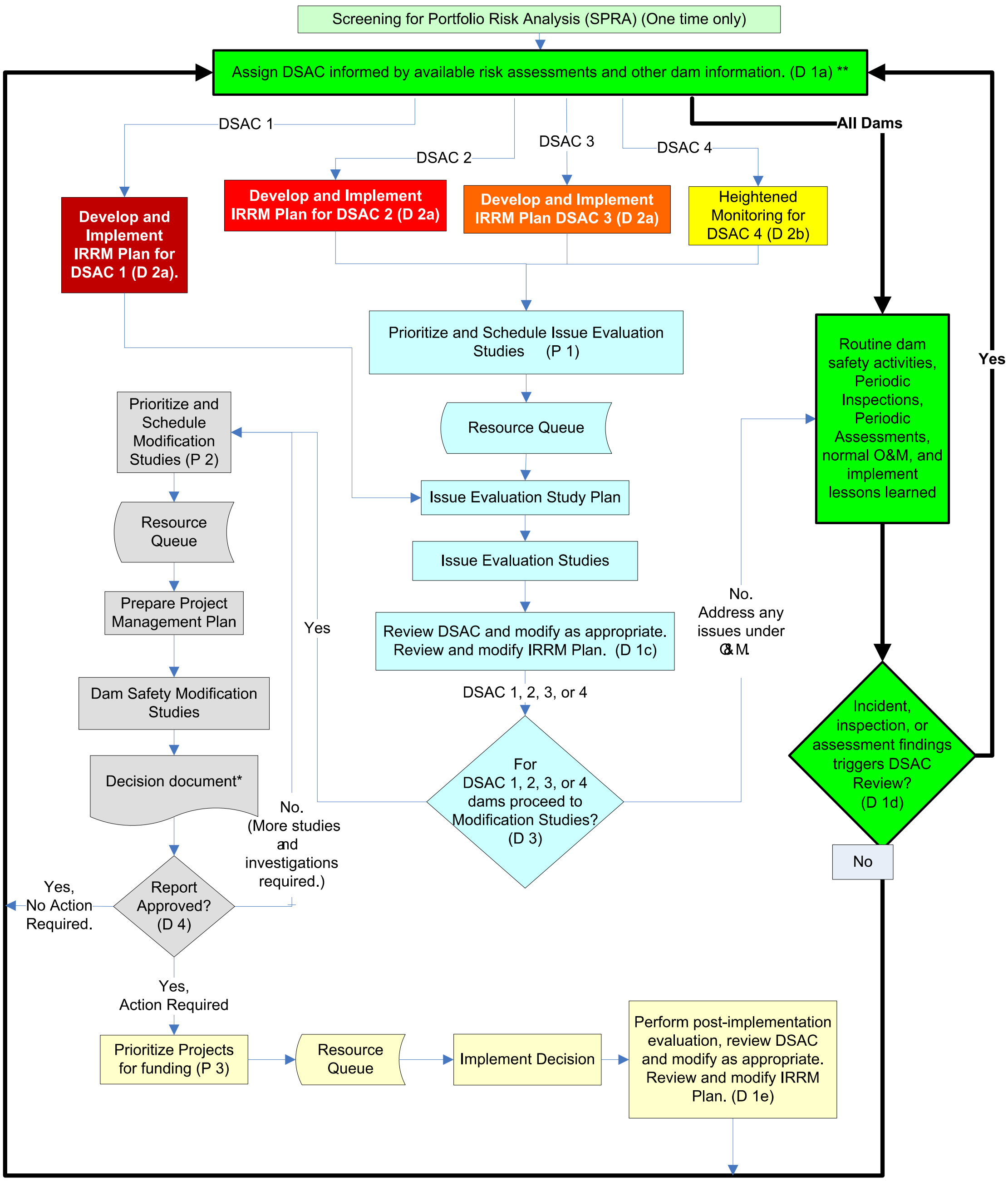
- Routine and regularly recurring dam and levee safety activities that are necessarily distributed to the project locations where decisions are made on a day-to-day basis. Examples include inspections, instrumentation, operations, and reporting.
- Non-routine decisions involving the investments of hundreds of millions of dollars for infrastructure modifications are handled with a more intensive level of data, assessment, and senior staff involvement that is commensurate with the importance of the decision.

It is also worth mentioning the creation of a new decision body called the Senior Oversight Group – a collection of agency wide experts in engineering disciplines, science, planning, management and **policy – meets 8-10 times per year to make decisions on key policies, infrastructure risk characterizations, investment priorities, and** selected repair alternatives. Figure 3 summarizes the overall processes very briefly described above (See (USACE 2014)) for a full explanation of the acronyms).

Main challenges and difficulties of this process have been found in risk uncertainty communication and socialization. It has also been a challenge to combine the prioritization of major rehabilitations with fulfilling gaps in existing information. However, risk governance has not only been achievable but also economically, socially and environmentally worthwhile to the USACE infrastructure management.

2.3.2 Australia

In 2003, the Australian Committee on Large Dams published its *Guidelines on Risk Assessment* (ANCOLD 2003). These guidelines explain the risk management stages (identifi-



Decision Points are label as (D 1a), Prioritization Points are labeled as (P 1), and the details for each point is explained in Chapter 3.
* Independent External Peer Review requirements are to be addressed per guidance in Chapter 9.
** Regardless of DSAC classification, dams with insignificant or no consequences should they fail are considered exceptions; will be so tagged, and are exempt from the dam safety portfolio management process depicted here in Figure 3.1

Figure 2-2. USACE Dam Safety Portfolio Risk Management Process. Source: (USACE, 2014).

cation of failure modes, risk analysis, risk evaluation) and explains how these results can be used to prioritize risk reduction actions in a Portfolio. The general framework proposed for Risk Assessment is shown in Figure 2-3.

These guidelines highlight the importance of combining Risk Assessment with traditional dam safety approaches, since ideally, both the traditional standards and tolerable risk policies and criteria would be satisfied. The Australian experience shows that Risk Assessment enables examination of such aspects as reliability of spillway gates and human factors, which the traditional approach does not treat well. Also, it helps where there is no clear guidance from traditional practice.

Since the publication of the Guidelines, the application of risk assessment techniques has evolved and some of the States within Australia have accepted the use of both the traditional and risk assessment techniques for the safety regulation of dams (in Australia, dam safety is regulated by States). There is considerable support provided to the ongoing development of risk assessment by professionals from all States and from both the government and private sector (Barker 2011). Considerable emphasis is now being placed on applying them in dam design. Fur-

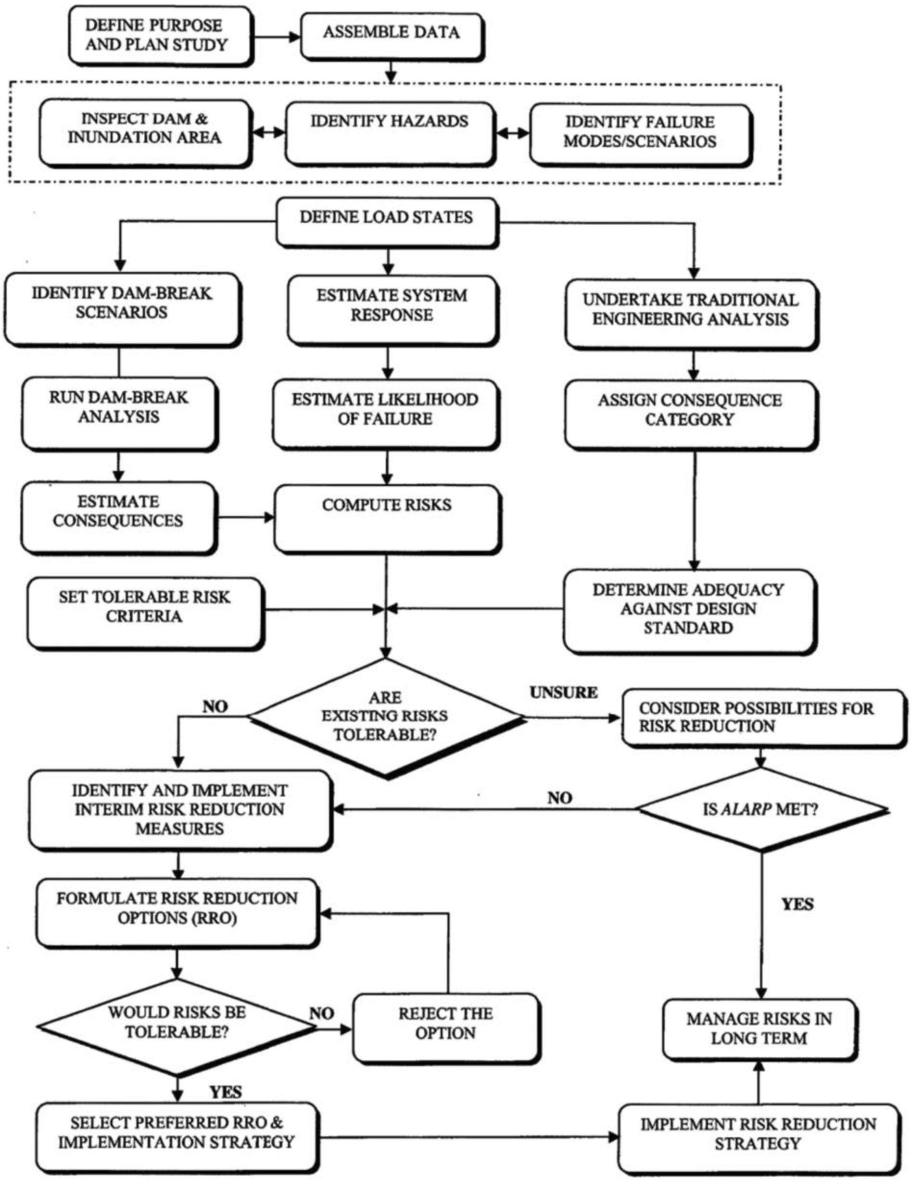


Figure 2-3. Risk Assessment Process for a Dam. Source: (ANCOLD, 2003).

thermore, risk assessment practices are routinely being followed in the design and ongoing operation and maintenance of tailings dams.

2.3.3 Spain

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 portfolio, 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. Specifically, Risk Assessment was applied 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 (Galán Martín, Escuder-Bueno, and Morales-Torres 2017; Setrakian-Melgonian et al. 2017; Ignacio Escuder-Bueno et al. 2016) and it is the key manual for capacity building on the matter in Spain (Ignacio Escuder-Bueno and Halpin 2016).

As shown in Figure 2-4, SPANCOLD Guidelines enforces Quantitative Risk Assessment to prioritize risk reduction actions. These risk models are defined based on the existing documents in the Dam Safety File (Safety reviews, Operation rules and Emergency Action Plans among the most important). In Spain, after the Tous dam failure in 1982 and subsequence legislation updates in 1996 and 2008, there was a high develop-

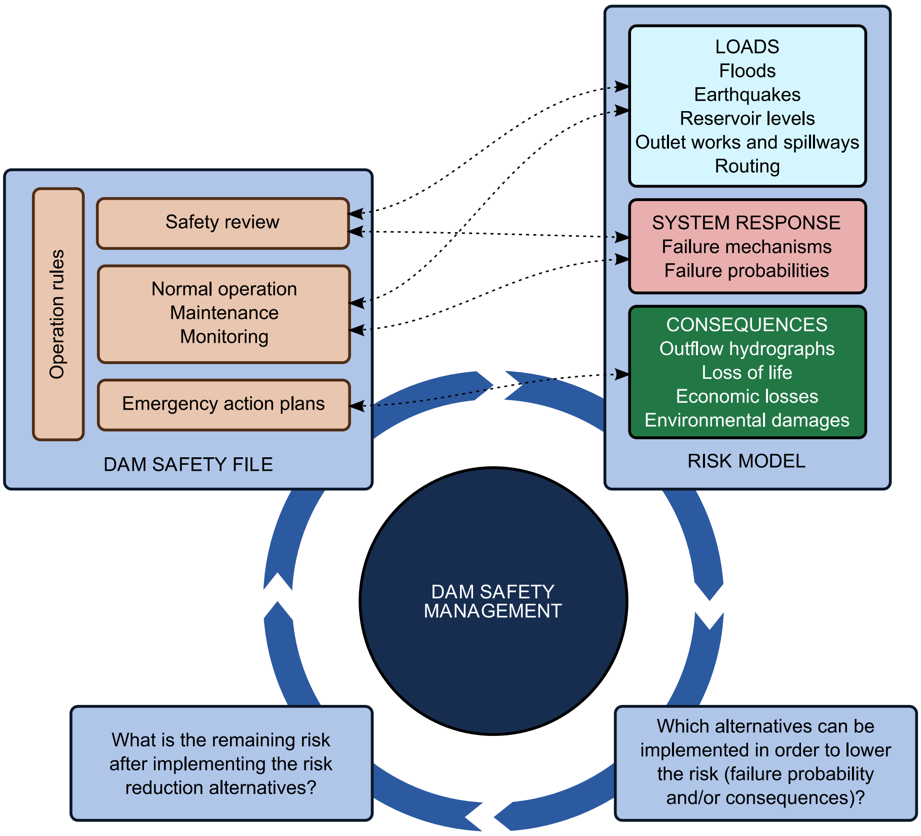


Figure 2-4. Risk-informed management of dams. Source: (SPANCOLD, 2012)

ment of dam safety documentation, therefore, these documents were elaborated for many of the Spanish large dams. For this reason, the use of quantitative risk models has been more direct since most of the needed information had already been elaborated.

Some of the main challenges in applying these techniques in the country are related with capacity building and personal engagement within the organizations. It should also be noted the importance on beginning with detailed pilot cases to develop a minimum but reasonable consensus on the procedures, simplifications, etc. (Ignacio Escuder-Bueno and Halpin 2016).

2.3.4 Other countries

In recent years, there are also other entities and countries that have developed specific recommendations on Risk Assessment and Management to inform dam safety management. Most of them are based on the stages and concepts described previously: identification of failure modes, quantitative (and/or semi-quantitative risk analysis), risk evaluation and risk reduction measures prioritization. Some examples are:

- **United Kingdom:** *Guide to risk assessment for reservoir safety management* elaborated by the Environmental Agency (EA 2013).
- **Canada:** In *Dam Safety Guidelines of the Canadian Dam Association* (CDA 2013), a risk-informed approach to dam safety assessment is encouraged.
- **New Zealand:** As explained in *New Zealand Dam Safety Guidelines* (NZSOLD 2015).
- **France:** Since 2007, France has developed specific legislation to implement dam risk management on a national level. The proposed approach is based on identification of failure modes and a combination of semi-quantitative and quantitative risk assessment, as explained in (MEDDE 2012).
- **China:** The Chinese *Dam Risk Assessment Guidelines* propose a risk classification for Chinese dams, as explained in (Zhou et al. 2015).
- **Brazil:** Currently, all Brazilian dams are being classified according to a risk-based screening methodology developed by the Brazilian Water Resources Council in 2012 (CNRH 2012).
- **South Africa:** The Department of Water Affairs (DWA), a national governmental department that owns a large number of dams, uses a risk-based approach to inform dam safety decisions (Reynolds and Barnardo-Viljoen 2014).
- **Argentina:** Since 2017, the Regulatory National Dam Safety Argentinian Authority (ORSEP) is developing a risk management approach for dam safety management (Dalmati et al. 2018).
- **Panama:** *National Dam Safety Norms* (ANSP 2010) introduce main risk concepts for dam classification and management.
- **Mexico:** New Norms being developed in the country (CNA 2015) introduce QRA and risk tolerability guidelines for dam safety management.
- **Korea:** New research is being made to develop a risk framework for dam safety management in the country (Heo 2016).

2.4 Risk-Informed Dam Safety Management Program for India

In 1999, CWC published the first Guidelines for the management of dam safety risks (BC Hydro 1999). These guidelines are mainly focused on dam safety traditional activities like emergency preparedness, operation and maintenance, dam classification and dam inspections. However, they also introduce the main concepts of risk analysis and management, like identification of failure modes.

After 18 years, the experience gained in dam safety in India and the outcomes of some of the main Risk-Informed Dam Safety Management Programs worldwide have been a key input to build the herein presented **Risk-Informed Dam Safety Management Program for India**.

To create a program tailored to the Indian context, gathering of new studies and data is explicitly addressed and different levels of risk assessment are combined for decision making. As recommended by (Kumar, Narayan, and Reddy 2018; ISO 2009) this risk management program protects the value of dams, explicitly addresses uncertainty, is based on the best available information, facilitates continual improvement and enhancement of the organization and provides a structured, transparent, dynamic and iterative framework to inform decision making.

Figure 2-5 defines the **general framework** of the proposed Dam Safety Management Program. As can be observed in this figure, the designed program is directly related with the three identified **Dam Safety Management Pillars**. Namely, these pillars are comprised of the following:

- **Maintenance and operation:** It includes maintenance activities at the dam (vegetation control, outlet works, accesses…) and dam operation rules during normal operation and during floods. The details about this pillar are explained in the *Guidelines for Preparing Operations and Maintenance Manuals for Dams.*

- **Instrumentation, surveillance and inspections:** This pillar deals with surveillance and regular safety inspections of the dam, including reading and maintenance of data instrumentation and analysis of the data gathered. Recommendations for dam instrumentation are found in the *Guidelines for Instrumentation of Large Dams.* Furthermore, the *Guidelines for Safety Inspection of Dams* provide information on how to make these inspections to detect dam safety problems.

- **Emergency Action Planning:** It deals with the implementation of an Emer-

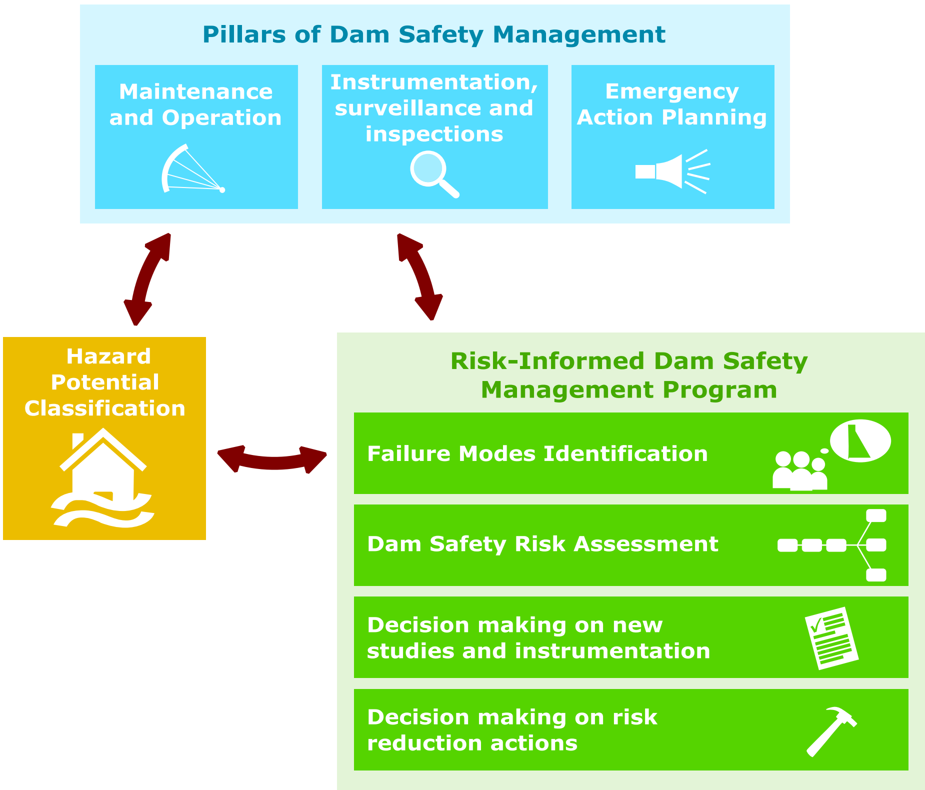


Figure 2-5. General framework of the designed Dam Safety Management Program.

gency Action Plan, including the development and update of emergency response procedures and warning systems. This pillar is explained within the *Guidelines for Developing Emergency Action Plans for Dams*.

The documents and outcomes of these three pillars of the dam safety fundamental activities provide useful information to improve dam safety risk management and vice versa.

The extent and periodicity of the three pillars documents and inspections is defined according to the **Hazard Potential Classification** of each dam, as explained in the *Guidelines for Classifying the Hazard Potential of Dams.*

Following the framework depicted in Figure 2-5, a **Risk-Informed Dam Safety Management Program** has been built as a reference for dam safety agencies in India. This program is summarized in Figure 2-6.

Firstly, this program begins with an **Initial Risk-based Screening Tool**. This screening tool serves to preliminarily identify the dams that could have more risk, so it indicates which ones should be the first to begin with the Dam Safety Risk Assessment process. As explained in Chapter 3, this screening is made based on the outcomes of those dam safety pillars or fundamental activities that are currently in the process of being uploaded to DHARMA (the selected tool by CWC to support dam asset management at a national level), as well as from the dam hazard potential.

Secondly, the **Dam Safety Risk Assessment** begins with a **Failure Mode Identification** process in each dam, which includes a review of the available information, a technical visit to the dam and multidisciplinary group working sessions, as explained in Chapter 4. Based on the information available and the credibility of each failure mode, they are classified in four categories:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and 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 Class A in very exceptional cases when failure seems imminent in the short term.

- **Class B:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class B failure modes are introduced within a quantitative risk model to compute risk in the dam. This risk model combines the probability of load, the probability of dam failure (system response) and the magnitude of adverse consequence given dam failure This risk is evaluated and if needed, potential risk reductions are proposed and prioritized. This assessment is explained in detail in Chapter 6.

- **Class C:** There is uncertainty about this failure mode, 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. As explained in Chapter 5, semi-quantitative risk results (failure probability and consequences) are directly estimated based on available information, without using a numerical risk model.

- **Class D:** Failure mode is not credible, or its consequences are very low. This failure mode should be documented and reviewed in the following updates of the Risk Assessment process.

For each dam, this Dam Safety Risk Assessment process is explained within a **Report** that details 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. Appendix A provides a template for this report. An example of this report for an Indian dam can be found in Appendix B and for an international case in Appendix C.

Next, prioritized risk reduction actions of each dam are combined to create a prioritized list of proposed actions in the whole Portfolio of dams. Similarly, the prioritized lists of new studies of each dam are combined to create a prioritized list of new studies and/or instrumentation in the Portfolio.

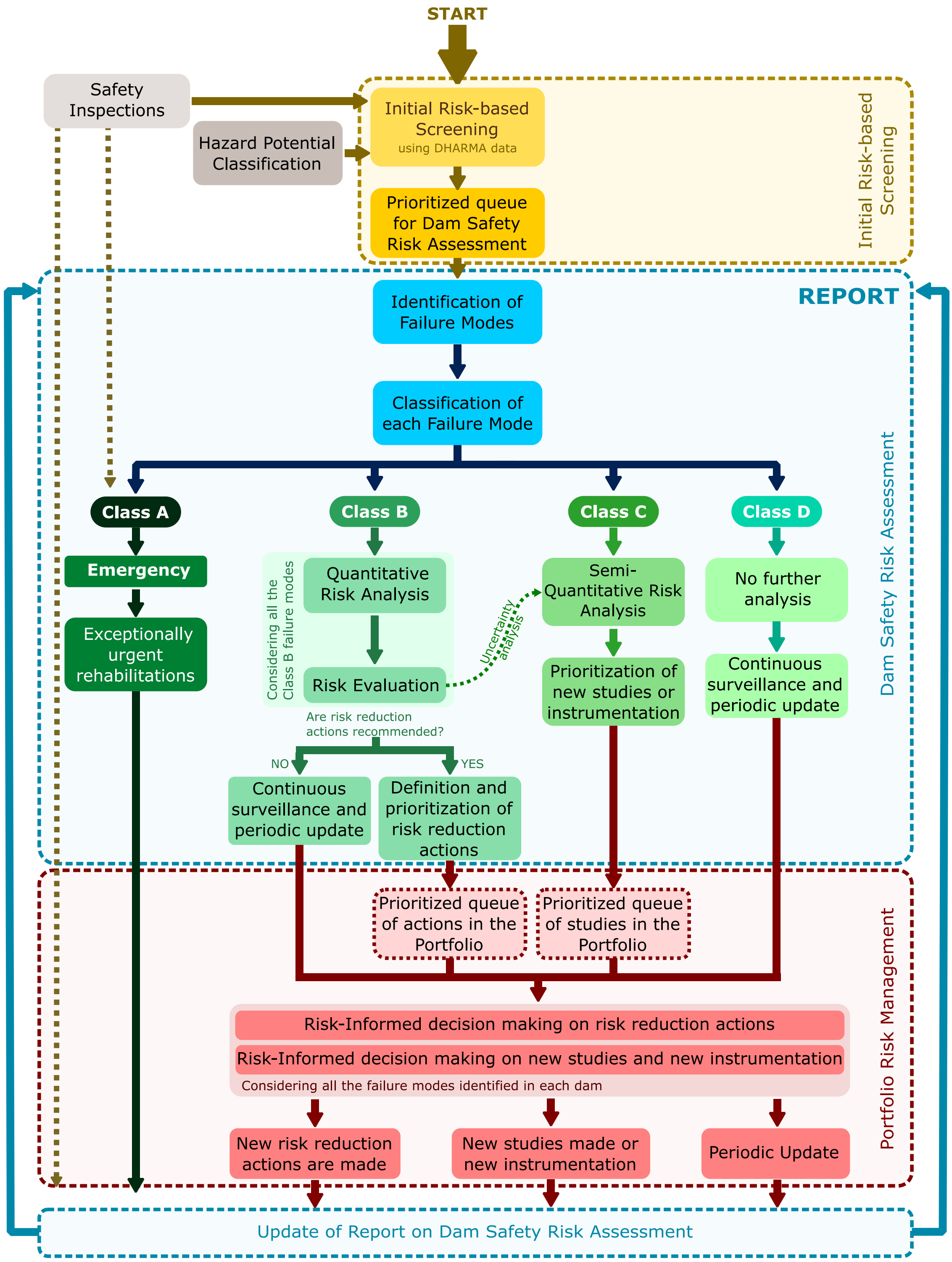


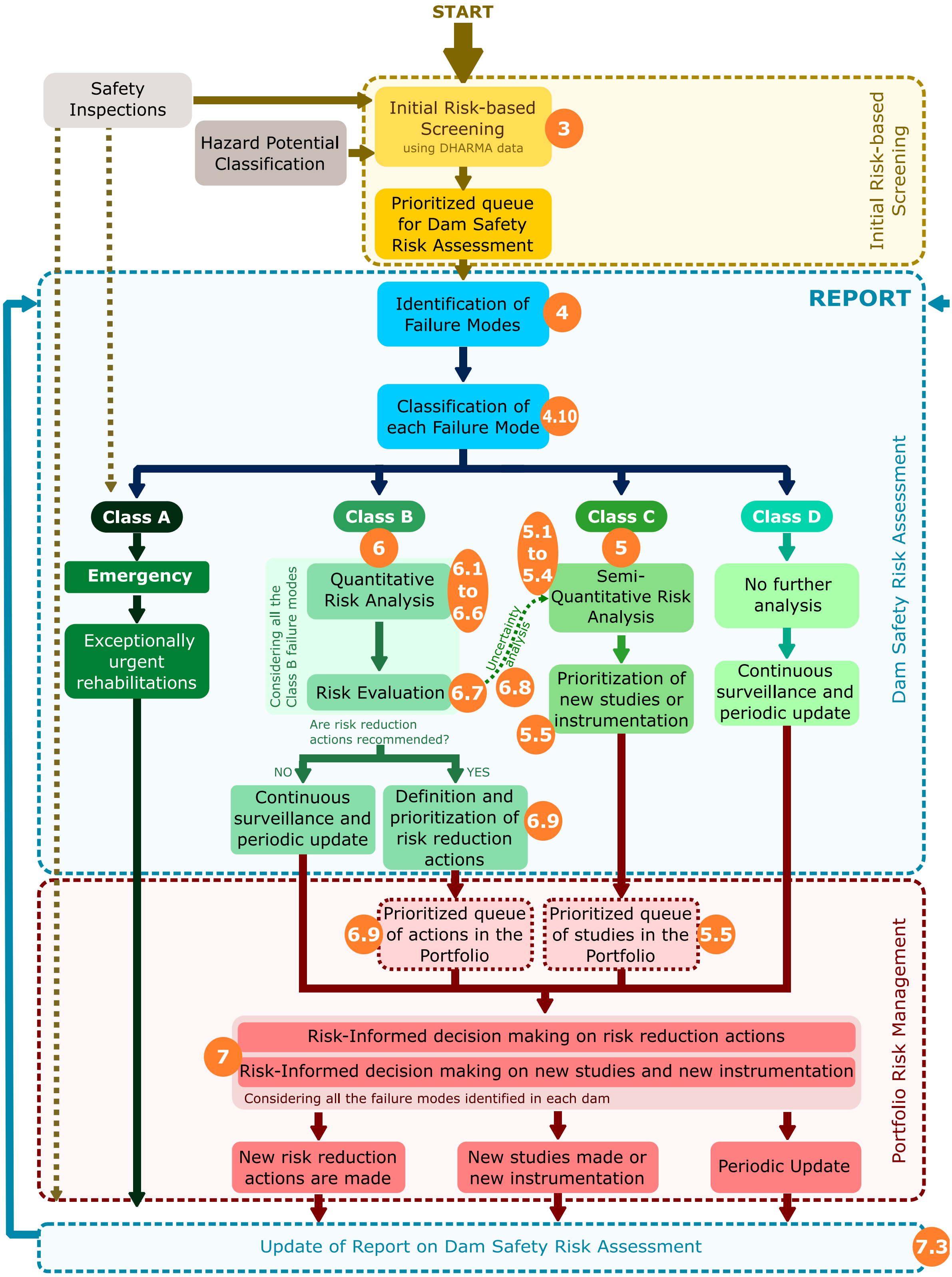
Figure 2-6. Proposed Risk-Informed Dam Safety Management Program.

Hence, new actions and studies are planned considering administrative, legal or societal issues and analysing all the failure modes identified in each dam. This Portfolio Risk Management process is explained in detail in Chapter 7.

Finally, the Report on Dam Safety Risk Assessment should be periodically updated. It should also be updated if new measures are implemented or new studies are available. In addition, it can also be updated if new problems or symptoms are detected during technical inspections.

The different steps of this program should be made by working teams with proved experience on risk assessment techniques, including identification of failure modes, elaboration of quantitative risk models and input data estimation for these models. In this sense, the proposed analysis must be coordinated by a multi-discipline professional who leads and oversees the estimation of risks. The most important aspect of this position is the demonstrated experience in quantitative risk analysis for dam safety.

As the program depicted in Figure 2-6 includes all the stages of Risk Assessment and Management, the same structure has been used to structure these guidelines. The different parts of this program are explained in detail in the following chapters of these guidelines, as shown in Figure 2-7. In these sections, the relation with the CWC Guidelines and Manuals is explained.



Note: Numbers in orange circles indicate the section of these Guidelines where each part of the Program is addressed.

Figure 2-7. Relation between the chapters of these Guidelines and the structure of the proposed Risk-Informed Dam Safety Management Program.

Chapter 3. Initial Risk-Based Screening

The purpose of the Risk-Based Screening is to develop the order to be followed in the Dam Safety Risk Assessment framework. This queue should be taken just as an indication on the urgency to perform a Dam Safety Risk Assessment for a dam, as shown in Figure 3-1.

The starting efforts of systematic collection of dam safety information in India was undertaken by the Central Water Commission issuing a procedure for "standardized data book format, sample checklist and proforma for periodical inspection of dams" in 1998 (CWC 1998).

Renewed efforts to gather dam key information regarding safety are dated later in 2012 under the DRIP umbrella, where data from a sample of more than 200 dams has been consolidated by means of fulfilling the "Project Screening Templates" (PST).

In addition, data for all Indian large dams are in the process of being collected and processed making use of a web-based asset management tool (DHARMA) officially adopted by CWC in January 2018. DHARMA has been designed and developed to enhance the capacity of individuals and organisations throughout India to manage their dam assets scientifically and professionally so as to sustain advantages of dams (irrigation and water supply, flood control, hydropower etc.) and prevent disasters. A general view of this tool is shown in **Figure 3-2**.

This will provide further opportunities to define indexes that can order the priorities that cannot be prescribed at this moment from this Guideline. Meanwhile, some of the over-arching principles that should be in the basis of a large portfolio screening tool are listed and explained in this chapter.

These key factors are:

- Population at Risk (PAR): This can be easily estimated from the dam break analysis that is to be performed as part of the supporting information for Emergency Action Plans as well as the studies for Hazard Classification, as explained in the corresponding guidelines.
- Main dam and reservoir features, emergency preparedness and present distress conditions: This information can be easily accessed via TSP for the DRIP projects and may need a different effort of elaboration for other projects nationwide.
- Hydrological and Seismic adequacy: This information can also be easily accessed via PST for the DRIP projects but may need a different effort of elaboration for other projects nationwide.

These three main factors can be exhaustively collected and scored in the future, following examples available worldwide such as the "Risk Based Profiling System" (USBR 2001) or the "Risk Category Classification Criteria" issued by the Brazilian Water Resources Council in 2012 (CNRH 2012).

While this screening systematic procedure is not in place, hazard classification may be considered as a first level index for prioritization together with a qualitative review of the known information in terms of features of the project, emergency preparedness, signs of distress conditions and hydrological and seismic design adequacy.

While one of the weakest points of implementing any screening tool is the potential for serious inconsistencies, one of the main benefits is serving as the ignition point for shifting towards a risk paradigm in any organization. For instance, adopting USBR screening procedure to the Duero River Basin portfolio of dams with very minor adjustments, served to provide a decently accurate and fast picture of the relative risks levels among 20 dams and prioritized efforts while motivating all actors involved in the whole portfolio management (Escuder et al. 2008).

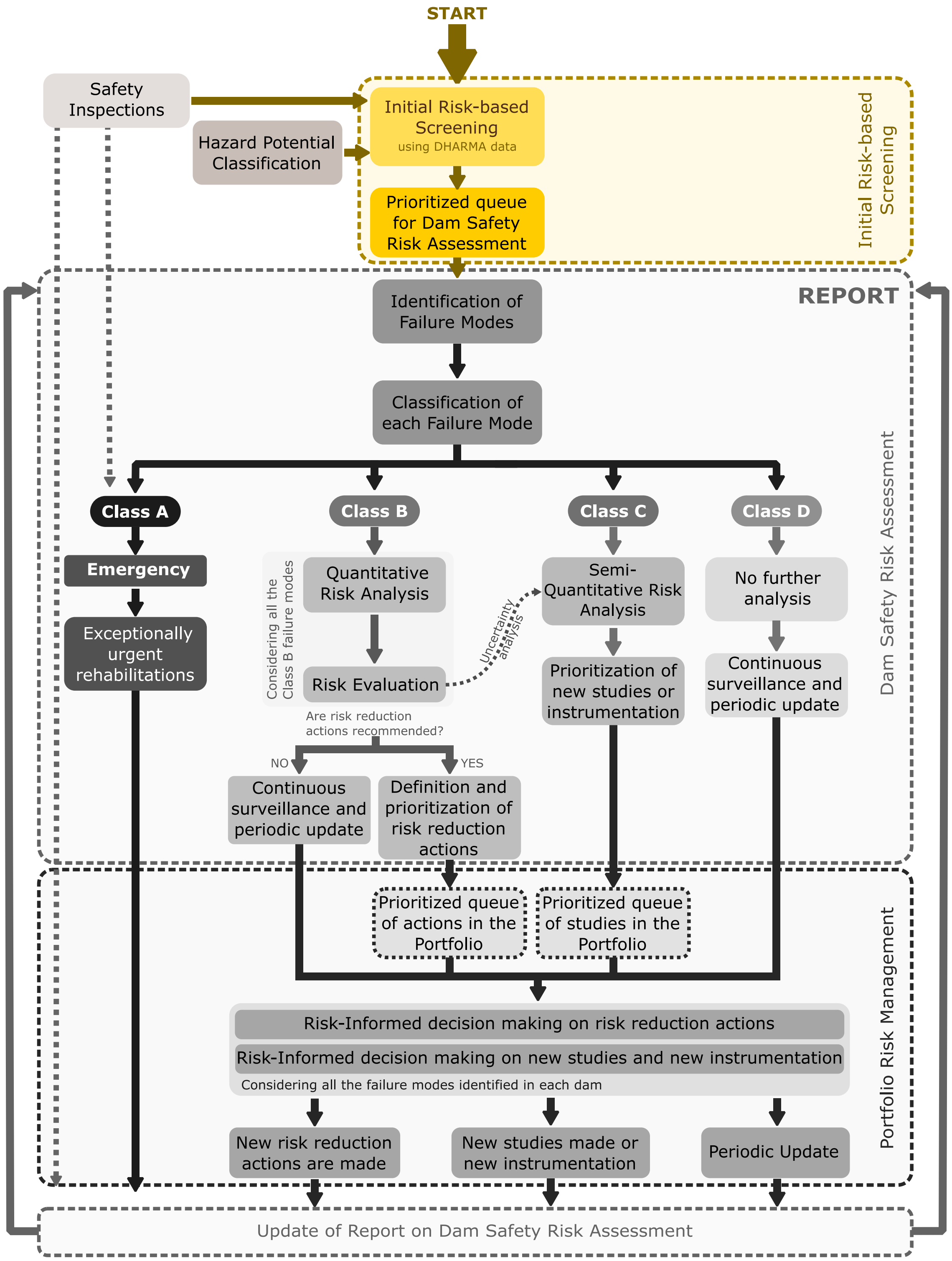


Figure 3-1. Initial Risk-based Screening (in color) within the Risk-Informed Dam Safety Management Program

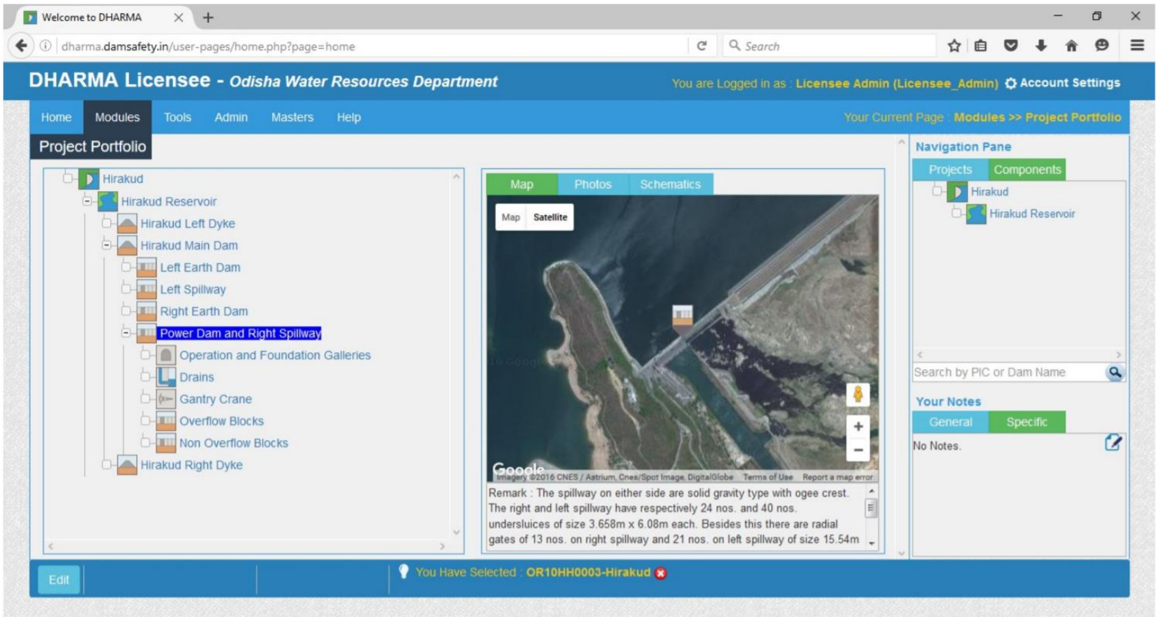


Figure 3-2. General view of DHARMA web-based tool

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Chapter 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, as shown in Figure 4-1.

In general, any failure mode with the potential to produce adverse social consequences (loss of life, displacements, flooding of urban areas, etc.) or economic loss should be analysed. However, focus is generally points to the failure modes that could produce an uncontrolled release of water downstream hence a potential loss of life or economic damages. The identification is not limited to the dam structure and it may include any feature or component of the dam-reservoir system.

Lessons learnt from Oroville incident in 2017 (France et al. 2018) show the importance of considering identification of how operational, organizational, human and cultural aspects could contribute to failure, especially in complex systems.

To structure a risk calculation and analysis, it is a common practice to link the failure modes with several **loading scenarios**, according to the loading event that triggers the failure mode. The three most common loading scenarios are:

- **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 identification of failure modes is paramount to all risk-based approaches and thus not surprising it has been used for such a long time. Aerospace -along with the nuclear industry- pioneered the application of methodologies based on risk, and during the 1960's developed a systematic process known as Failure Modes and Effects Analysis (IEC 2006).

In the Risk-Informed Dam Safety Management Program presented in Chapter 2, the Identification of Failure Modes (IFM) is the first step of the Dam Safety Risk Assessment, as shown in Figure 4-2. Identification of Failure Modes is very important in the Risk Assessment process since it links engineering judgment with risk calculations. Indeed, if a relevant failure mode is missed in the identification sessions, it will not be included in the model. Moreover, IFM is where all the knowledge and engineering judgment of the dam is consolidated, structured and presented.

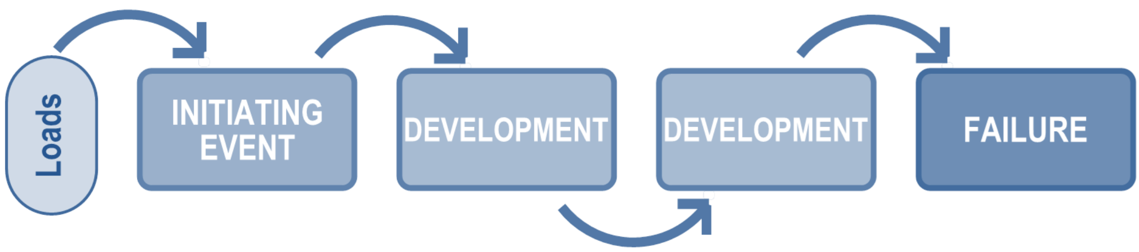


Figure 4-1. Generic structure of a failure mode.

The whole IFM process and its outcomes should be described in the Report on Dam Safety Risk Assessment as shown in Figure 4-2. Appendix A provides a template for this report. As an example, in Appendix B and C an IFM process for two cases are reported, including several different types of failure modes.

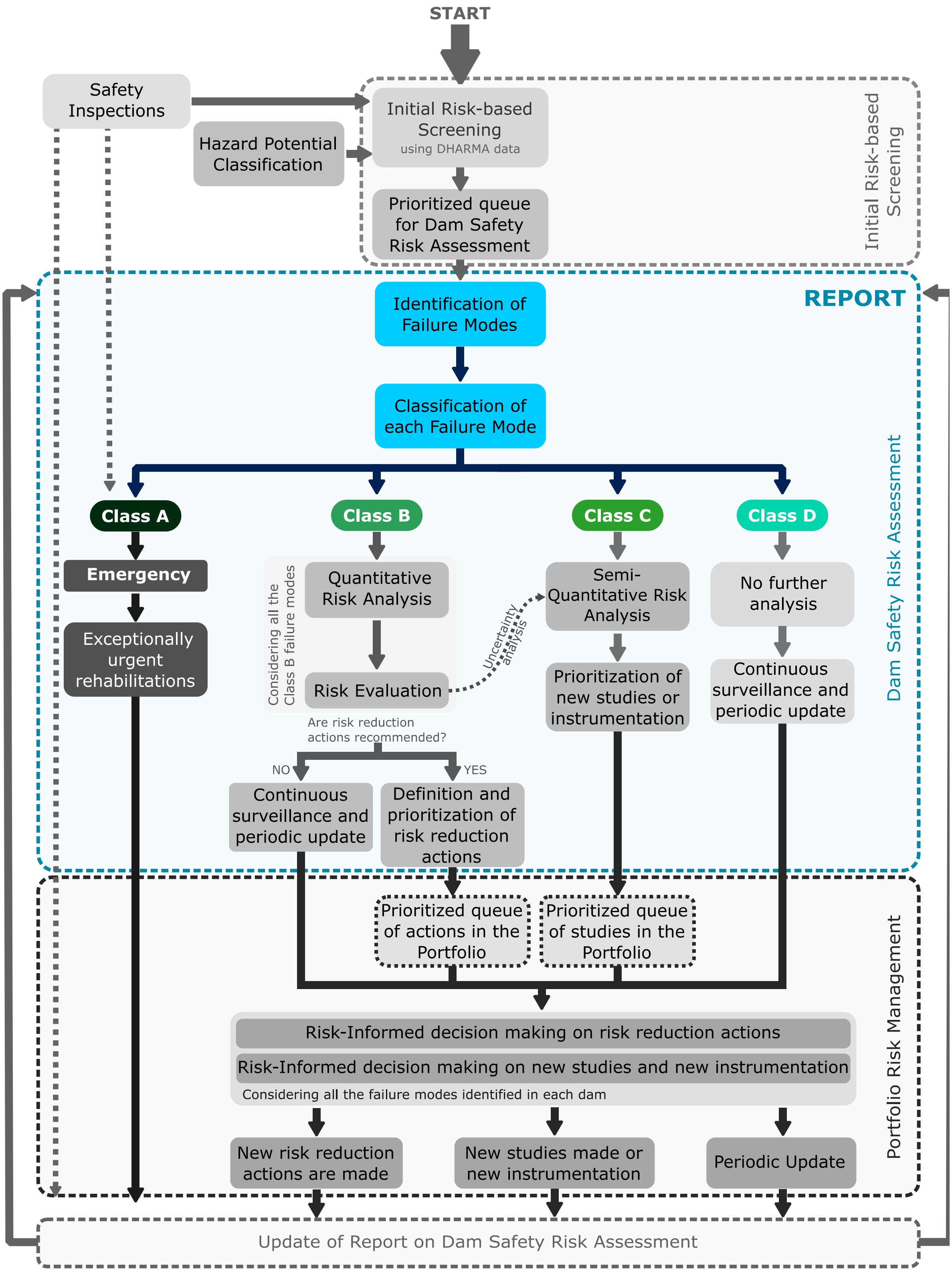


Figure 4-2. Identification of Failure Modes (in color) within the Risk-Informed Dam Safety Management Program

4.2 The process of Identification of Failure Modes

The recommended process for Identification of Failure Modes is summarized in Figure 4-3. This process is typically made through a collaborative work of several engineers and technicians, including a comprehensive review of available information, a technical visit to the dam and group comprehensive evaluation about the current state of the dam. Failure modes are identified in two phases: individual (where each participant makes a first identification) and group phase (where all the failure modes identified by the participants are put in common). Finally, identified failure modes are analysed in detail and classified, proposing potential actions for uncertainty and risk reduction.

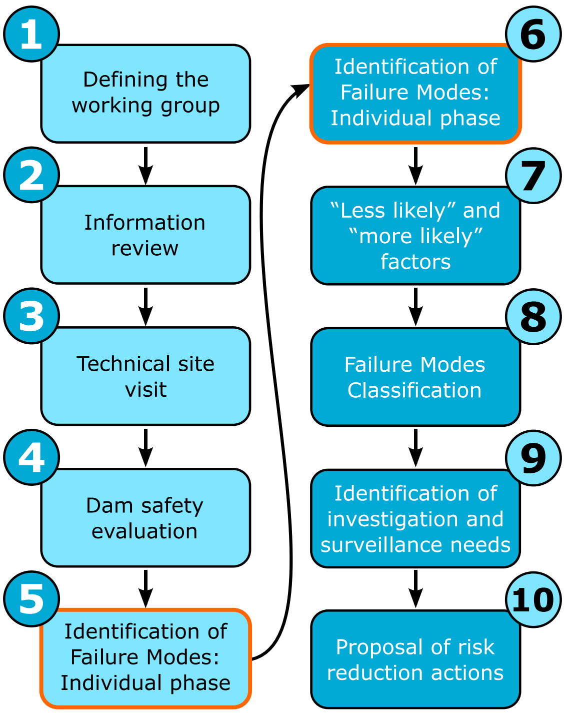


Figure 4-3. Recommended steps for Identification of Failure Modes

All the steps of this process are explained in detail in the following sections of this chapter. To complete all of them, normally between 3 and 5 days are needed in each dam for the first IFM whole process (including the report). Subsequently, updates of IFM could require less time.

In this process, the use of the individual booklets is strongly recommended to promote the contribution of all the participants and to document the whole process. An example of these booklets can be found in (iPresas 2014).

4.3 Defining the working group

Building a proper working group to make the Identification of Failure Modes is one of the keys to complete a comprehensive analysis of potential failure modes. It should be a multidisciplinary group that includes engineers and technicians in charge of the daily operation of the dam and regional/national experts in some of the topics addressed. Typically, the following professionals are part of the **working group**:

- Local technicians and engineers in charge of dam safety, maintenance and daily operation.
- Key staff in charge of dam data collection and analysis.
- Engineers in charge of dam periodical safety inspections.
- If possible, people involved in the construction of the dam.
- Decision makers for dam safety investments in the entity.
- Representatives of public bodies related with dam safety management and regulation.
- Regional/national dam safety experts in some of the topics that will be discussed during the sessions (hydrology, seismicity, geotechnics, structural stability, emergency management, etc.).

Normally, the recommended number of people in these sessions is between 10 and 20 people, in order to allow all the participants to interact. In capacity building processes within an organization, more people can be invited to the sessions, although more time will be needed for participants interaction.

It is recommended that the whole working group participates in every step of the process, to facilitate it and to make possible a group consensus approach of the potential failure modes of the dam.

All the IFM steps are done with the help of a **facilitator** who acts as a guide during the working sessions. He or she is responsible for structuring and facilitating the discussions and interactions among the participants. He or she must ensure these interactions take place and that there exists equity in the exposed information and opinions. He or she is the one responsible for structuring the failure modes identified by each expert and for creating the proper conditions for a direct aggregation of opinions. In general, the facilitator should compile the following requirements:

- A good professional record, recognition and level of competence, based on his/her academic education and experience.
- Experience on facilitating IFM sessions and elaborating quantitative risk models, including gathering the data needed for these models.
- Good interpersonal and communicative skills, flexibility, impartiality and analysis and synthesis skills.
- Leading and consensus forming skills. The facilitator does not need to be an expert in each failure mode process that is being studied but must possess a sound knowledge of all of them.

4.4 Information review

IFM working sessions usually begin with an exhaustive review of all the existing information about dam safety. The process of reviewing the available information is of relevance to Risk Assessment.

This process cannot be limited to a simple gathering of information, but this information should be discussed thoroughly in group sessions, where participants can provide useful information that is not included within the dam documents. It usually takes one day or more to review in detail all the available information.

This comprehensive review is also useful for making the first identification of additional needs in terms of studies, which should be defined lately in the process, as explained in Section 4.11. In this sense, the rest of *DRIP Guidelines and Manuals* explain best practices to address all dam safety topics, including the level of detail expected in these studies depending on dam characteristics.

The enhancement, structuration and review of the dam information provide some of the immediate benefits of making a Risk Assessment. For this reason, main conclusions and outcomes of this part of the session should be described within the Report on Dam Safety Risk Assessment.

Typically, this review is made through a presentation prepared by the facilitator and the coordinators of the working sessions, allowing some time to discuss in detail each topic. This presentation can be divided into different topics related with dam safety, providing for each topic the main information available and its source. Of course, outcomes from past **dam safety inspections** should also be reviewed. Topics to be reviewed in this part are listed in Section 4.6.

4.5 Technical site visit

Once the information has been reviewed by the whole group, an inspection of the dam must be done to check its current condition and to identify potential problems. Visiting the dam is needed to completely understand the potential failure processes.

This site visit should be made with enough time to exhaustively inspect all the part of the dam(s). If necessary, potential landslide areas in the reservoir may also be visited. Special attention should be paid to the main problems identified during the information review. Recommendations on how to make this type of visits and what type of problems could be detected can be found in the *Guidelines for Safety Inspection of Dams*.

Main findings of the technical visit should also be included within the Report on Dam Safety Risk Assessment.

4.6 Dam safety evaluation

After the field visit and the information review, a comprehensive evaluation of dam safety should be made as a basis for the identification of failure modes. Based on group discussions during the sessions, the following aspects should at least be addressed:

- Flood hazard and hydrological adequacy.
- Gates operation and hydraulic behaviour of the system.
- Gates and electromechanical equipment condition.
- Current state of spillway and stilling basin. Erosion in downstream areas.
- Foundation and abutments.
- Monitoring data and state of monitoring system.
- Dam body condition.
- Condition of the drainage system.
- Dam stability in normal loading conditions.
- Seismic hazard and dam stability during seismic events.
- Landslide in the reservoir.
- Emergency action planning and urban areas downstream.

The information available and conclusions about each topic must be included in the Report on Dam Safety Risk Assessment.

Therefore, the information review and site visit should end with a group discussion that summarizes the impression of the participants about these aspects. The analysed aspects related with the safety of the dam are globally assessed to detect the weakest points and to guide the identification of the failure modes processes.

A useful starting point for this discussion is using **engineering assessment** (Bowles et al. 2003). It consists in asking the participants to individually assess whether the dam meets established good international engineering practice. In this process, different aspects related to dam safety (dam body and foundation conditions, hydrological adequacy, gates state, monitoring and instrumentation, etc.) are evaluated. According to his/her understating of international best practices on each dam safety aspect, each participant should rate it as *pass/apparent pass/ apparent no pass/no pass /not applicable*.

Finally, every participant's ratings are shared to facilitate the group discussion. The results of this assessment are a good summary of the group's understanding of the status of the dam safety and where the main doubts are. An example of this assessment process in an Indian dam can be found in Appendix B and in an international case in Appendix C.

4.7 Identification of Failure Modes: Individual phase

In the first phase of the identification of failure modes, each participant in the session individually makes a preliminary identification of failure modes in the dam, using the provided booklet.

For each failure mode identified, a written description and a sketch should be elaborated. This identification should be made with enough time to allow all the participants to describe each failure mode that they could identify.

This description should be clear and detailed to be understood by others even years later. Hence, it should describe the whole failure process for each failure mode, from the initiation event to the type of dam failure. A failure mode description usually begins defining the loading scenario (hydrologic, seismic or normal) and it generally includes:

- The Initiator: e.g. Reservoir load, Deterioration/aging, Operation malfunction, Earthquake, etc.
- The Failure Mechanism (including location and/or path): Step-by-step progression.
- The Resulting Impact on the Structure: e.g. Rapidity of failure, Breach characteristics.

An example of this description is shown in Figure 4-4.

During the identification of failure modes, the participants should consider further than traditional dam safety approaches.

In recent years, more specific tools have been developed to aid in this identification of failure modes (iPresas 2014). These tools present a preliminary collection of failure modes for concrete and embankment dams that:

- Help to identify typical failure modes so they cannot be ignored.
- Help to structure the definitions so they are coherent, consistent, auditable and more easily quantifiable in the following steps of the process.
- Help to relate failure modes to dam monitoring and instrumentation.

A summary of these tools is included in Table 4-1 and Table 4-2. These tables may be useful to give some ideas about general failure modes at the beginning of the individual IFM process.

4.8 Identification of Failure Modes: Group Phase

Once each participant finishes the individual identification of failure modes, all of them are put in common and combined into group sessions. In this stage of the process,

Name: Embankment overtopping

Description: In a Hydrologic scenario, due to a severe flood and/or inadequate spillway capacity and/or inability to open the gates of the spillways, water level raises over the crest of the dam. Flow over the crest washes out the concrete slab in the downstream slope of the embankment and causes massive erosion that progresses leading to slope instability, breach and dam failure.

Sketch:

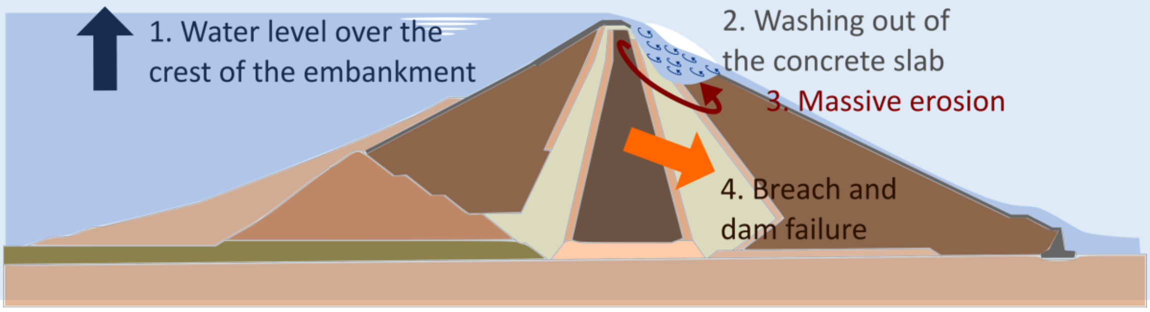


Figure 4-4. Example of overtopping failure mode description

failure modes considered less credible are not discarded since it is always advisable documenting all the failure modes identified and reviewing them in subsequent Risk Assessment updates. These failure modes are excluded from quantitative (or semi-quantitative) risk analysis after its classification.

In this phase, all the failure modes should be discussed with enough time, to include the contributions from all the participants. The objective of this stage is to build a consensus around the potential failure modes identified by the whole group.

Table 4-1. Summary of aid tool for concrete dams to support Identification of Failure Modes. Adapted from (iPresas, 2014)

1 SCENARIO	2 RESERVOIR - DAM SYSTEM COMPONENTS	RESERVOIR - DAM SYSTEM SUB-COMPONENTS	3 EVENTS OCCURING AT THE BEGINNING OR DURING FM PROGRESS
	FOUNDATION (including abutments)	*FOUNDATION*	1. Internal erosion 2. Tensile cracks 3. Liquefaction 4. Displacements (vert. and hor.)
HYDROLOGIC 1. Pool water level 2. Uplift pressures increment 3. Uncontrolled release			
		ABUTMENTS	1. Internal erosion 2. Tensile cracks 3. Liquefaction 4. Displacements (vert. and hor.)
SEISMIC 1. Earthquake acceleration 2. Pore pressures increment 3. Water pressures increment	**STRUCTURES**	*DAM BODY*	1. Cracking 2. Internal degradation of concrete 3. Concrete weathering 4. Alkali aggregate reaction (AAR) 5. Degradation of sealing elements 6. Displacements (vert. and hor.)
		IMPERVIOUS CUTOFF WALL	1. Cutoff wall malfunction
NORMAL OPERATION 1. Pool water level variation 2. Temperature variations 3. Normal exploitation 4. Maintenance works		*DRAINAGE SYSTEM*	1. Drains siltation
	OUTLET WORKS AND INTAKES	*CIVIL WORK*	1. Overcoming erosion at dam toe 2. Overtopping in spillway walls 3. Dam crest overtopping 4. Material degradation 5. Degradation of sealing elements
OTHERS 1. Natural hazards (volcanos, fires, etc.) 2. Manmade threats		*ELECTROMECHANICAL EQUIPMENT*	1. Loss of gate functionality 2. Collapse of gate 3. Loss of electrical generation 4. Operational error
	RESERVOIR BASIN	*HILLSIDE*	1. Landslide 2. Creep

4 ULTIMATE FAILURE MECHANISM	MECHANISM DEFINITION
I. SLIDING	Failure of a dam due to the movement of one of its structural monoliths over a surface, produced by the hydrostatic load and the uplift pressure.
II. SUBSIDENCE	Vertical movement of the dam produced by the foundation due to its high deformability or its discontinuities and cavities.
III. CRACKING	Failure in concrete resistance produced by cracking.
IV. OTHERS	Any other failure mechanism, including mechanisms that do not result in dam collapse, but generate important damages downstream or economical losses due loss of function or mission disruption.

Table 4-2. Summary of aid tool for embankments to support Identification of Failure Modes. Adapted from (iPresas, 2014).

1 SCENARIO
HYDROLOGIC 1. Pool water level 2. Pore pressures increment 3. Uncontrolled release
SEISMIC 1. Earthquake acceleration 2. Pore pressures increment 3. Water pressures increment
NORMAL OPERATION 1. Pool water level variation 2. Temperature variations 3. Normal exploitation 4. Maintenance works
OTHERS 1. Natural hazards (volcanos, fires, etc.) 2. Manmade threats

2 RESERVOIR - DAM SYSTEM COMPONENTS	RESERVOIR - DAM SYSTEM SUB-COMPONENTS	3 EVENTS OCCURING AT THE BEGINNING OR DURING FM PROGRESS
FOUNDATION (including abutments)	*FOUNDATION*	1. Internal erosion 2. Displacements (vert. and hor.) 3. Liquefaction
	ABUTMENTS	1. Internal erosion 2. Displacements (vert. and hor.) 3. Liquefaction
STRUCTURES	*DAM BODY**	1. Cracking 2. Liquefaction 3. Displacements (vert. and hor.) 4. Internal erosion 5. Hydraulic fracturing
	IMPERVIOUS CUTOFF LAYER	1. Cracking 2. Displacements (vert. and hor.) 3. Material degradation
	*CONCRETE WORKS IN DAM BODY***	1. Deformations 2. Degradation of sealing elements
OUTLET WORKS AND INTAKES	*CIVIL WORK*	1. Overcoming erosion at dam toe 2. Overtopping in spillway walls 3. Dam crest overtopping 4. Material degradation 5. Degradation of sealing elements
	ELECTROMECHANICAL EQUIPMENT	1. Loss of gate functionality 2. Collapse of gate 3. Loss of electrical generation 4. Operational error
RESERVOIR BASIN	*HILLSIDE*	1. Landslide 2. Creep

*It is only referred to elements of natural origin in dam body (rocks and soils, crest walls, filters and drains).

** Tunnels, galleries and all civil works with a different stiffness than the dam body (excluding outlet works).

4 ULTIMATE FAILURE MECHANISM	MECHANISM DEFINITION
I. EROSION	**a) Overtopping:** Produced when the pool water level gets too high and overtops dam crest level, scouring dam body and reaching dam structural failure.
	b) Internal: Flow through the dam body, with significant loss of constituent material, resulting in an instability and structural collapse.
II. SLIDING	Movement of an important part of the dam over a surface, located only in the dam body or including the foundation, produced by the hydrostatic load and high uplift pressures.
III. OTHERS	Any other failure mechanism, including mechanisms that do not result in dam collapse, but generate important damages downstream or economical losses due loss of function or mission disruption.

4.9 "Less likely" and "more likely" factors

After identifying the failure modes, the factors that make them likely are discussed. This group discussion is key for the classification of failure modes which will be made in the next step. In addition, these factors are very useful to estimate failure probability of failure modes within the quantitative risk model.

"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 certain failure mode. Factors that could increase (or decrease) the consequences if the failure mode occurs may also be defined. In Table 4-3, an example is shown of "less likely" and "more likely" factors for an overtopping failure mode of an embankment. More examples can be found in the study cases in Appendixes B and C.

4.10 Failure Modes Classification

After discussing the "less likely" and "more likely" factors of each failure mode, they should be classified to decide the type of Risk Assessment that should be made in further steps. The classification system proposed in this section is shown in Table 4-4 and it is based on the recommendations by (FERC 2005).

Hence, failures modes are classified according to the **Failure Mode Credibility.** The participants of the session evaluate if the failure mode is credible or not. They should also consider the existing uncertainty and if there is enough information to make a quantitative risk analysis.

This assessment of the available information depends on each failure mode and it is based on the doubts raised and recommendations made in the sessions. It should be evaluated if uncertainty about key failure mode mechanisms is very high and if gathering extra information or adding new instrumentation is possible and reasonable. As a preliminary guide, Table 4-5 shows the key studies needed to make a quantitative risk analysis of the most common failure modes.

Hence, available information should be evaluated in detail during the sessions since it determines the following steps of the process (quantitative risk assessment and risk reduction actions or Semi-Quantitative Risk Analysis and new studies or instrumentation). In this sense, it is recommended that engineers with experience in elaborating quantitative risk models participate in the sessions.

Therefore, as shown in Table 4-4, all the failure modes are classified during the working sessions in four categories:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation

Table 4-3. Example of "less likely" and "more likely" factors for an overtopping failure mode

Adverse or "more likely" factors	Favorable or "less likely" factors
• Late decisions trying to protect population. • Lacking of hydrological information in advance. • Possible combination of seismicity activating landslide in the reservoir. • Late decisions trying to avoid damages in the downstream power house. • Some doubts about reliability of spillway gates.	• The dam safety culture being developed leading to better decisions. • Institutional support. • Large drainage area with high time of concentration and high warning times. • High reservoir capacity and freeboards. • Concrete slab in the downstream face.

and 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 B:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class B 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. This assessment is explained in detail in Chapter 6.

- **Class C:** These potential failure modes, have to some degree inadequate 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 instrumenta-

Table 4-4. Classification of Failure Modes

Failure Mode Classification
CLASS A **Failure is in progress or imminent. Exceptionally urgent rehabilitation measures and/or emergency actions are needed**
CLASS B **Failure mode is credible and there is enough information to analyze its probability of occurrence through a quantitative risk analysis**
CLASS C **Insufficient information to determine credibility of failure mode. More studies and/or instrumentation are needed to analyze its probability trough a quantitative risk analysis**
CLASS D **Failure mode is not credible or its consequences are very low, and hence do not need to be carried forward for risk estimates. It must be re-evaluated in future reviews.**

Table 4-5. Key information for quantitative risk analysis of the most common failure modes

Failure Mode	Commonly critical information
Overtopping	Probabilistic hydrological analysis Stage-volume curve and operation rules
Concrete dam sliding	Dam stability analysis Information on foundation characteristics
Internal erosion through embankment	Embankment drawings Properties of embankment materials
Internal erosion through foundation	Properties of foundation materials
Seismic-induced failure modes	Seismic hazard analysis Dam stability analysis for seismic events

tion needed to reduce the uncertainty on these failure modes, as explained in Chapter 5.

- **Class D:** 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 extremely remote. They should be documented and reviewed in the following updates of the Risk Assessment process.

The outcomes of the whole IFM process and especially of this classification shall be reviewed by a group of experts at a Portfolio scale, to ensure coherence and quality in the results, as explained in Section 8.4.

4.11 Identification of investigation and surveillance needs

Once failure modes have been identified and classified, potential investigation and monitoring measures are defined. In general, these measures are mainly focused in reducing uncertainty of modes **classified as C**, to define the new studies and instrumentation required. New studies and/or new instrumentation should be recommended for all the failure modes classified as C, since this classification means that more efforts can be made to gather more knowledge about them. The recommendations made in this stage are the basis for the prioritization of new studies and instrumentation with a semi-quantitative analysis, as explained in Chapter 5.

In addition, surveillance and monitoring needs can also be identified to support the detection of failure modes **classified as B.** 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 prioritized with the rest of risk reduction measures using quantitative risk results as explained in Chapter 6.

The need for new studies in failure modes classified as B can also be assessed from uncertainty analysis results (Section 6.8). In this sense, participants can propose analysis, tests and uncertainty analysis to be made using the quantitative risk model to improve the knowledge about the dam-reservoir system. Some examples of this could be an uncertainty analysis on hydrological data or testing new freeboard requirements or new gates operation rules. Of course, these tests can further lead to proposals of risk reduction actions.

To encourage the discussion and participation in this stage, the following questions can be made:

- What additional variables could be measured in the dam to gather more knowledge about the occurrence of these failure modes?

- What additional studies/analysis/tests could be useful to know more about these failure modes?

- What uncertainty analysis and tests can be made using the quantitative risk analysis?

4.12 Proposal of risk reduction actions

The proposal to implement risk reduction actions is generally linked with failure modes classified as A or B.

As explained above, actions proposed to solve **Class A failure modes** are recommended to be made as soon as possible and they should be clearly highlighted in this part.

Actions proposed to reduce risk in **Class B failure modes**, are the basis for the prioritization of risk reduction actions using quantitative risk results as explained in Chapter 6.

Figure 4-5 provides a comprehensive (though not complete) list of potential risk reduction actions that can be used during the first brainstorming session. As can be observed in this figure, the list of proposed risk reduction action should also include the monitoring needs proposed in the previous stage that help to detect Class B failure modes.

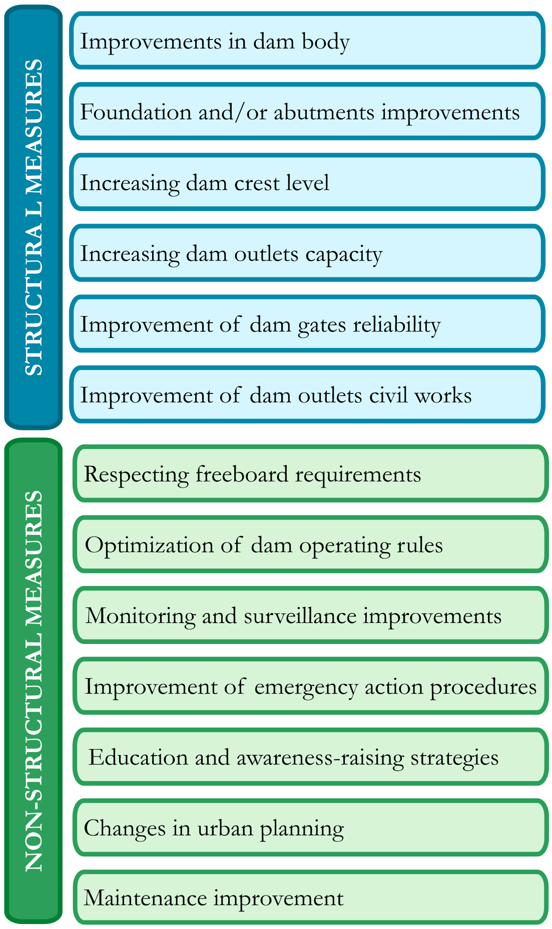


Figure 4-5. Summary of potential risk reduction actions

In this stage, the following questions can be made to encourage the discussion:

- What structural fixes could be made in the dam to avoid the occurrence of these failure modes?
- What non-structural measures (emergency action plans, coordination procedures…) could be implemented to reduce dam risk?
- What improvements could be made in dam operation?
- What additional variables could be measured in the dam to detect the occurrence of these failure modes?
- What improvements could be made in the surveillance and maintenance procedures?
- What uncertainty analyses and tests can be made using the quantitative risk analysis?

In summary, from this stage and the previous one, the participants should define the main outcomes expected from the quantitative risk analysis, from prioritization of risk reduction actions to different uncertainty analysis and tests on dam-reservoir system performance.

Chapter 5. SEMI-QUANTITATIVE RISK ANALYSIS

5.1 Introduction

In a Semi-Quantitative Risk Analysis, risk is preliminarily estimated based on available information. This estimation is made by 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 failures and consequences. This type of method is sometimes called Qualitative Analysis and it is very common as a first step for classifying dams and obtaining preliminary risk results. Some examples of their use can be found in (USACE 2014) and (MEDDE 2012).

In the herein designed Risk-Informed Dam Safety Management Program (Figure 5-1), a Semi-Quantitative Risk Analysis is recommended for **Class C Failure Modes** to prioritize new studies and new instrumentation in a Portfolio of dams. This information will serve as a foundation to make a complete Quantitative Risk Analysis in further steps to inform decisions about major rehabilitations and other risk reduction actions if that is the case, as explained in Chapter 6.

In addition, Class B Failure Modes can also be included in this Semi-Quantitative analysis if new studies are recommended after quantitative risk evaluation and uncertainty analysis (as shown in Figure 5-1 and explained in Section 6.8). In this case, results from the Quantitative Risk Analysis of these failure modes are very useful for Semi-Quantitative analysis.

This analysis should be made by a group of dam engineers with knowledge about the dam and risk concepts, including some of the participants in the Identification of Failure Modes sessions. In addition, the outcomes of this analysis shall be reviewed by a group of experts at a Portfolio scale, to ensure coherence and quality of the results, as explained in Section 8.4.

This Risk Analysis process and its outcomes should be described in the Report on Dam Safety Risk Assessment. Appendix A provides a template for this report. In Appendix B, the example of an analysis made for an Indian dam is shown. In addition, Appendix C shows an example of application for an international case.

5.2 Failure probability category

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 loading is high. However, for floods or earthquakes, the probability of loading could be very small. Based, on recommendations by (USBR and USACE 2015; USACE 2014), the following categories are proposed for failure probability:

- **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.

- **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 weighed more heavily toward "less likely" than "more likely."

- **High:** The annual failure probability is between 10^{-3} (1/1,000) and 10^{-4}

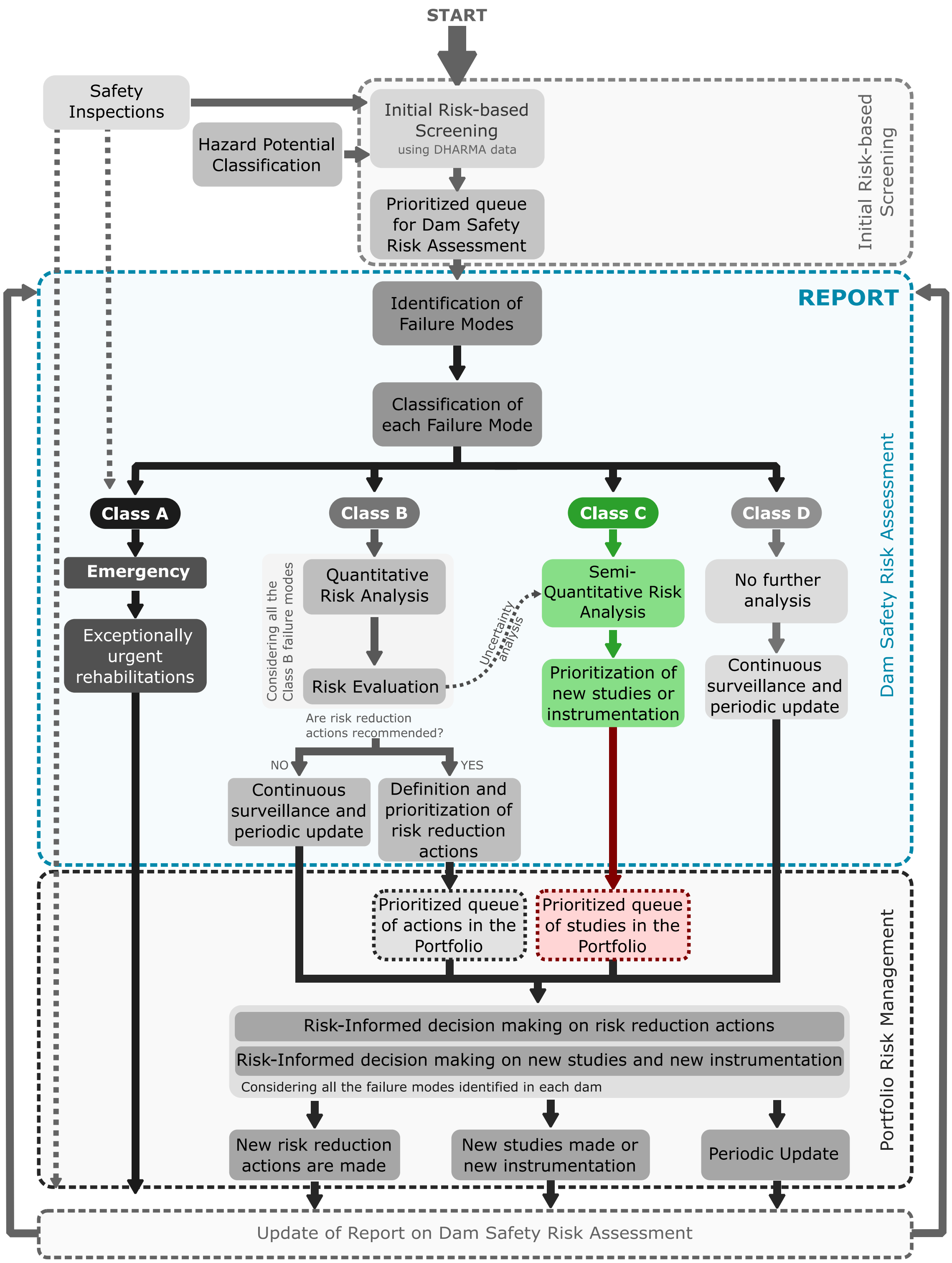


Figure 5-1. Semi-Quantitative Risk Analysis (in color) within the Risk-Informed Dam Safety Management Program

(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 towards "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.

As can be observed, to assign the failure probability category of each failure mode, "less likely" and "more likely" factors detected during the IFM process are considered. Among these factors, the potential for detection and intervention to reduce the probability of failure must be considered when assigning the failure probability category.

To assign this probability, a similar procedure to the one used in the IFM is recommended. After reviewing and completing "less likely" and "more likely, each team member is asked to make their individual estimate of the failure probability category prior to further discussion. Hereafter, these estimations are compared and discussed within the group to reach a "consensus" failure probability category.

Failure probability can be assessed between two categories (e.g. High/Very high or Low /Moderate) if needed.

The following recommendations can be followed to assign a category depending on the loading scenario:

- **In normal operation scenario**, a basis to evaluate the probability of a failure mode is the worldwide rate of dam failures during operation, which is around 10-4 (USBR and USACE 2015). This probability can be increased or decreased depending on the less likely" and "more likely" factors of each failure mode.
- **In hydrological scenario,** return period of design flood can provide a first guess of overtopping probability. With this objective, a simplification could be made for this semi-quantitative analysis assimilating the Probable Maximum Flood (PMF) with a 10,000-year flood (10^{-4} probability of exceedance). A preliminary flood routing analysis of the reservoir may also be needed to assign this category. In addition, it should be considered that concrete dams have more resistance to overtopping failures than embankments.
- **In seismic scenario,** seismic hazard maps can provide useful information if a detailed probabilistic seismic study is not available for a site. Regarding the failure probability due to the seismic event, it should be noticed that dams have generally performed well during past seismic events (USSD 2014). Main problems are detected in older embankments built on sandy materials.

5.3 Consequences category

The other component of risk is the magnitude of the consequence that each failure mode could produce. For semi-quantitative evaluations, the focus is typically on the potential for life loss. Based on the recommendations by (USBR and USACE 2015; USACE 2014), the following categories are proposed to define consequences in India:

- **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, 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 sufficient 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 this step, a preliminary potential loss of life estimation may be appropriate to assign the consequences category based on existing flood risks maps. Methods to estimate loss of life produced by dam failure are explained in Section 6.4.8.

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, consequences category can be assigned as the higher value of the previous scale and the following scale (based on recommendations by (USBR and USACE 2015):

- **Category 1:** Estimated economic loss is less than Rs 50 Crores.

- **Category 2:** Estimated economic loss is in the range of Rs 50 to 500 Crores.

- **Category 3:** Estimated economic loss is in the range of Rs 500 to 5,000 Crores.

- **Category 4:** Estimated economic loss is in the range of Rs 5,000 to 50,000 Crores.

- **Category 5:** Estimated economic loss is in the range of Rs 50,000 to 5,00,000 Crores.

- **Category 6:** Estimated economic loss is greater than Rs 5,00,000 Crores.

Methods to estimate the economic consequences of dam failure explained in Section 6.4.9 will provide valuable information to assign this category.

It is recommended to assign failure probability category, a two-stage process (individual and group) and may be repeated to arrive at a consequence category for each potential failure mode. Consequences can also be assessed between two categories if needed.

It is especially important during this process to note differences between likely breach flows associated with a potential failure mode, and what has been assumed in the breach inundation studies. In many cases, the breach outflow associated with a potential failure mode may be considerably less than assumed in the inundation studies.

5.4 Semi-Quantitative Risk Analysis Matrix

Once the categories for failure probability and the consequences have been assigned for each Class C Failure Mode, they are represented in a Risk Matrix. This matrix represents a failure probability category in the vertical axis (using cell divisions corresponding to the failure probability categories) and the associated incremental consequences on the horizontal axis (using cell divisions corresponding to the consequences categories) similar to the f-N diagram used to represent risk as explained in Section 6.6.

Figure 5-2 shows this matrix with some failure modes represented as example. As can be observed, when a failure mode is assessed between two categories (in failure probability or in consequences) it is represented in the division line between these categories.

5.5 Prioritization of new studies or instrumentation

Once the risk of each Class C failure mode 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 should be defined based on the IFM process recommendations (Section 4.11). Since a Class C 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 B Failure Modes can also be introduced in this prioritization if they are recommended after quantitative risk evaluation and uncertainty analysis (as shown in Figure 5-1 and explained in Section 6.8). In this case, results from the Quantitative Risk Analysis of these failure modes are very useful to select their failure probability and consequences category.

Second, based on the priority level of each failure mode, new studies and instrumentation are prioritized. The priority level of failure modes depends on their cell in the SQRA matrix, as shown in Figure 5-3. As can be observed in this matrix, failure modes closer to the upper-right corner (higher failure probability and higher consequences) have a higher priority level.

If a failure mode is categorized between two (or more) cells, its priority level is the average of these cells. For instance, the prioritization of the studies for the example failure modes represented in Figure 5-2 is:

1. Overtopping: Its priority level is 5.
2. Internal erosion: Priority level is 16.
3. Gate collapse: Priority level is 19.5.
4. Seismic instability: Priority level is 24.

If the proposed new studies or new instrumentation are directly related with several failure modes, the failure mode with the highest priority level should be considered for prioritization purposes.

Following this procedure, all the proposed new studies and new instruments can be prioritized within a dam and at the Portfolio scale. Therefore, this prioritization sequence of new studies will be the basis for decision making on new studies and new instrumentation at the Portfolio Scale, as explained in Chapter 7.

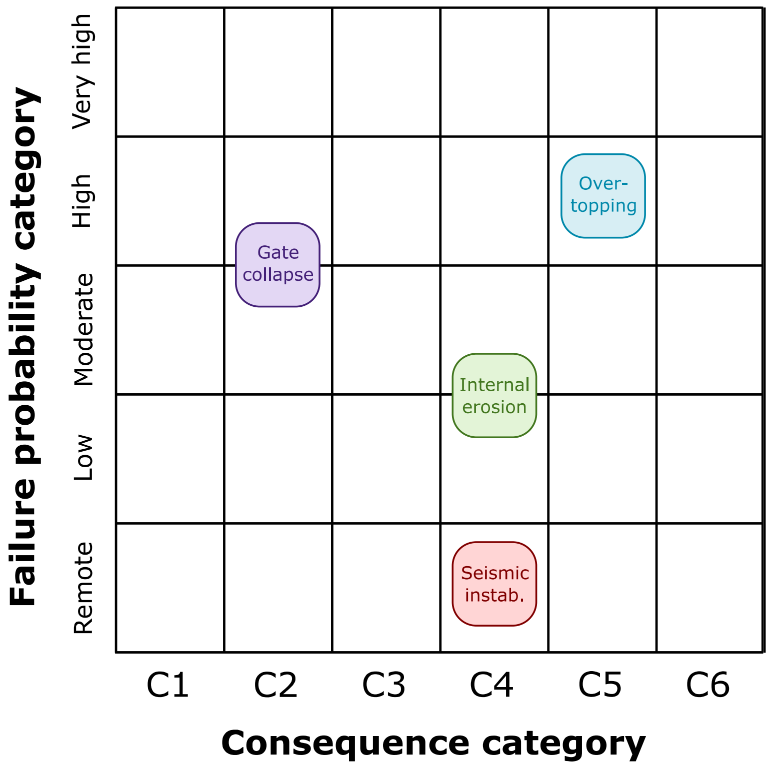


Figure 5-2. Matrix for Semi-Quantitative Risk Analysis with some example failure modes represented.

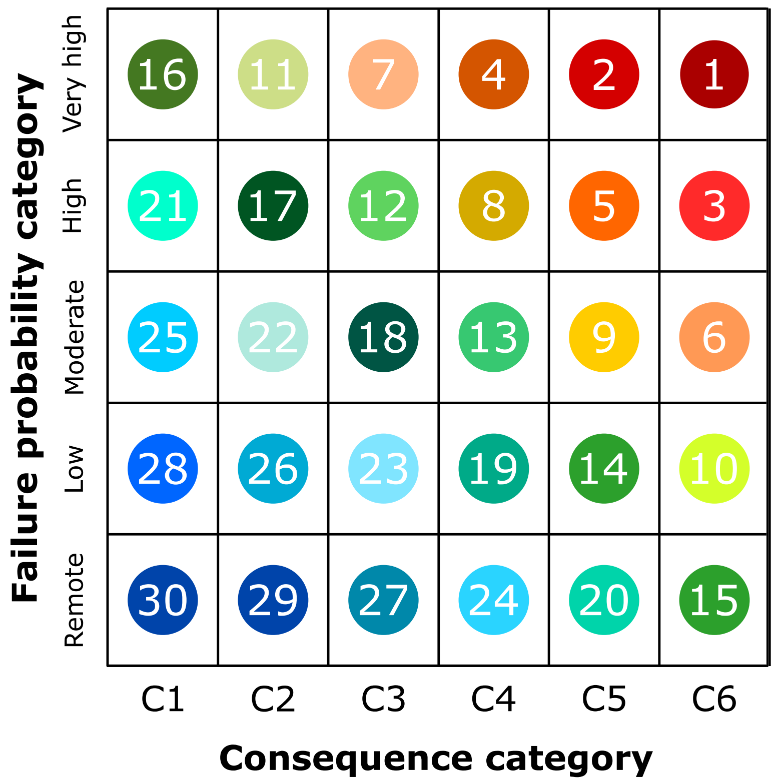


Figure 5-3. Priority Level in Matrix for Semi-Quantitative Risk Analysis.

Chapter 6. QUANTITATIVE RISK ASSESSMENT

6.1 Introduction

Fully quantitative risk assessment seeks to enumerate the risks in terms of probability and consequences in quantitative terms. As shown in Figure 6-1, this quantitative assessment is recommended for Class B Failure Modes, which are failure modes that are considered credible and with enough available information for this type of analysis.

The Quantitative Risk Assessment has three main steps:

1. **Quantitative Risk Analysis (QRA):** Risk is calculated through a risk model.
2. **Risk evaluation:** Risk is compared with tolerability guidelines to assess the need for risk reduction actions.
3. **Prioritization of risk reduction measures:** Risk results are used to define prioritized sequences of the proposed risk reduction actions.

Quantitative Risk Assessment should be made by a working team with proved experience in elaborating risk models and estimating risk model input data. Experience of working team in these techniques is key to achieve defendable and consistent results. In addition, some of the team members should have participated in the IFM working sessions. In this sense, the proposed analysis must be coordinated by a multi-discipline professional who leads and oversees the estimation of risks. The most important aspect of this position is the demonstrated experience in quantitative risk analysis for dam safety.

This Quantitative Risk Assessment process and its outcomes must be described in the Report on Dam Safety Risk Assessment. Appendix A provides a template for this report. In Appendixes B and C, two examples of this report are shown.

In a QRA, risk is estimated combining the probability of occurrence of loads (e.g., flood, earthquake, etc.), the probability of dam failure due to these loads and the failure consequences, as observed in the following equation:

$$\boldsymbol{Risk} = \int \boldsymbol{P(l)} \cdot \boldsymbol{P(f|l)} \cdot \boldsymbol{C(l,f)}$$

Where the integral is defined over all the events under study, $P(l)$ is the probability of the different load events, $P(f|l)$ is the conditional failure probability for each load event and $C(l, f)$ are the consequences of the dam failure for each loading event.

These three terms in the equation define the three main parts in the risk model: loads, system response and consequences.

From this general equation, different risk results can be computed (Morales-Torres, Serrano-Lombillo, et al. 2016):

- **Failure probability:** It is obtained with the two first terms of the previous equation, as shown in:

  $$\boldsymbol{P_F} = \int \boldsymbol{P(l)} \cdot \boldsymbol{P(f|l)}$$

  Where P_F is the dam failure probability. It is normally treated as an annual probability, that is, as the probability that in any given year the dam fails. This is due to the common use of annualized loads ($P(l)$ has units of 1/year) and to the fact that the rest of the probabilities are non-dimensional.
  This failure probability can be computed for each failure mode, which later can be properly added to obtain the dam failure probability.

- **Individual risk:** The increment of risk imposed on a particular individual by the existence of a dam. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the dam did not exist. It is usually estimated through the probability of death of the most exposed person downstream due to dam failure. Therefore, it is measured in probability terms (units of 1/year).
- In most of the large dams in India, it can be assumed that a major dam failure would produce at least one fatality, which means that individual risk can be equivalent to these cases, individual risk made equivalent to failure probability.

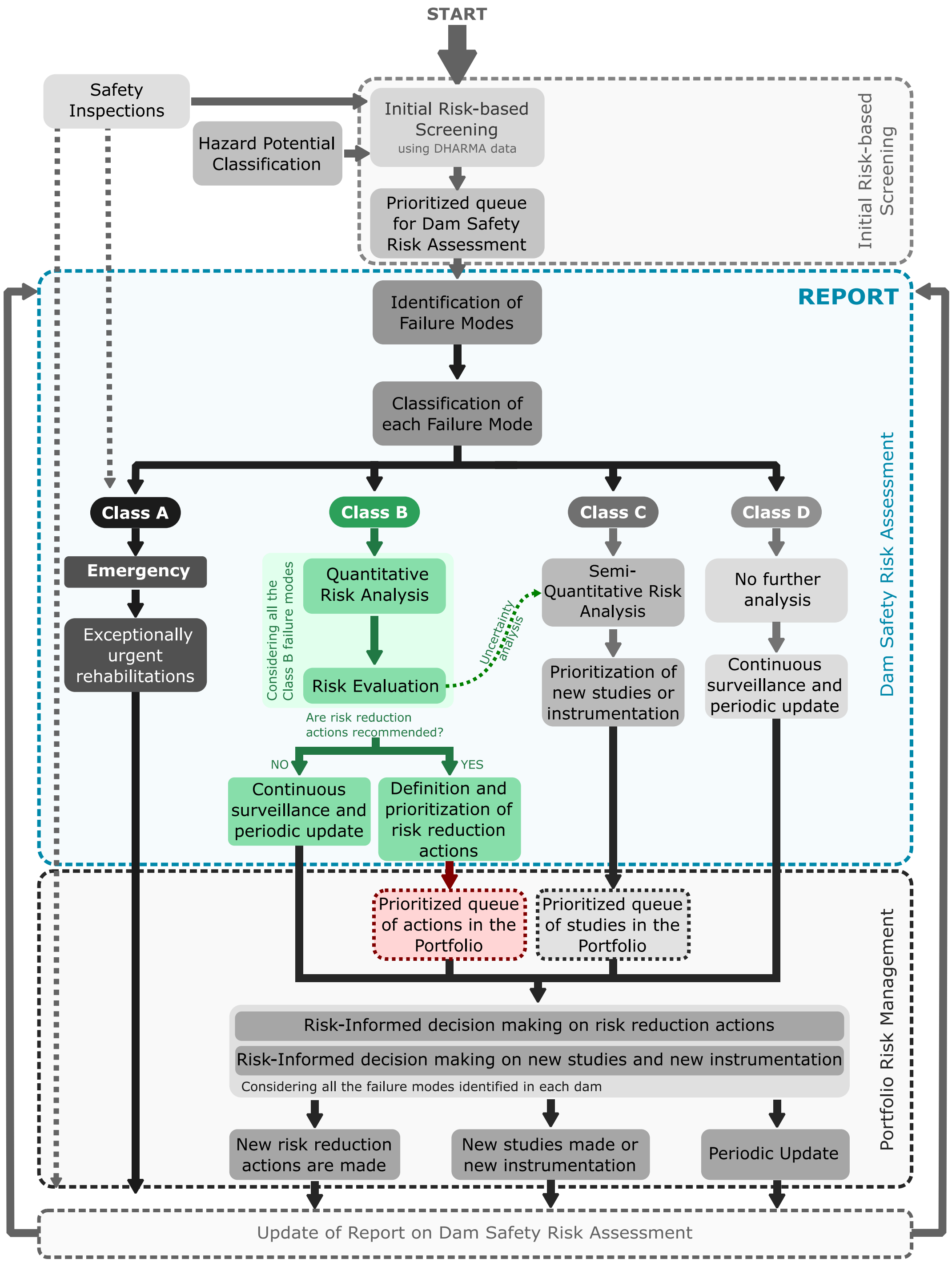


Figure 6-1. Quantitative Risk Assessment (in color) within the Risk-Informed Dam Safety Management Program.

- **Societal risk:** It is obtained by combining failure probabilities and the harmful consequences suffered by the population as a result of that failure (Jones 1985). Mathematically, it is obtained through the following formula:

$$\boldsymbol{R_S = \int P(l) \cdot P(f|l) \cdot C_S(l,f)}$$

  Where $C_S(l, f)$ are the societal consequences of the dam failure for each loading event which are generally expressed in terms of loss of life. R_S is the societal risk with units of lives per year and it is also known as estimated annualized loss of life (Bowles 2004).

- **Economic risk:** It is obtained by combining failure probability and the economic consequences of that failure (Jonkman, van Gelder, and Vrijling 2003), as shown in the following formula:

$$\boldsymbol{R_E = \int P(l) \cdot P(f|l) \cdot C_E(l,f)}$$

  Where $C_E(l, f)$ are the economic consequences of the dam failure for each loading event and are expressed in monetary units. R_E is the economic risk with units of monetary units per year and it is also known as expected annualized economic damage (Bowles 2004).

From these general definitions, two types of risks are combined in dam safety management:

- **Incremental risk:** It is the part of risk exclusively produced by the dam failure. Societal and economic incremental risks are obtained with the previous equations using incremental consequences:

$$\boldsymbol{R_\Delta = \int P(l) \cdot P(f|l) \cdot C_\Delta =}$$
$$\boldsymbol{= \int P(l) \cdot P(f|l) \cdot (C(l,f) - C(l,nf))}$$

  Where R_Δ is the incremental risk (which can be societal or economic depending on the type of consequences) and C_Δ are the incremental consequences. As can be observed, these consequences are obtained by subtracting from the consequences of the dam failure the ones that would have happened anyway, that is, even if the dam had not failed. For instance, in a hydrologic scenario, consequences produced by the flood itself without the dam failure are subtracted from dam failure consequences.

  This type of risk is generally used in tolerability guidelines to evaluate risk. It is recommended to use this type of risk in order to prioritize potential risk reduction actions.

- **Total risk:** Is the total risk of flooding downstream of the dam. It is produced by both cases in which the dam fails and from when it does not. Conceptually, it can be apprehended as:

$$\boldsymbol{R_T = \int P(l) \cdot P(f|l) \cdot C(l,f) +}$$
$$\boldsymbol{+ (1 - P(l) \cdot P(f|l)) \cdot C(l,nf)}$$

  Where $C(l, nf)$ are the consequences of non-failure cases and R_T is the total flooding risk downstream. It can also be economic or societal, depending on the consequences units.

  This type of risk should be computed for all the proposed risk reduction actions, to ensure that they are not incrementing flood risk downstream (for instance, in some cases flood risks can increase due to higher discharges with a new spillway). This type of risk is especially important to analyse the gates operating rules.
  In addition, this type of risk should also be analysed when a new dam is designed.

6.2 The quantitative risk models

Risk models are mathematical tools used to compute risks by defining the variables affecting dam safety and the relations between them. Once a risk model is set up, it is then possible to estimate failure probability, consequences and risks.

Event trees are the most common mathematical tool used to build risk models. An event tree is a representation of a logical model that includes all the possible chains of events resulting from an initiating event. As its name indicates it is based on the mathematical structure known as tree, which is widely used in many other contexts. Figure 6-2 shows an example of tree along with the notation used to refer to its parts.

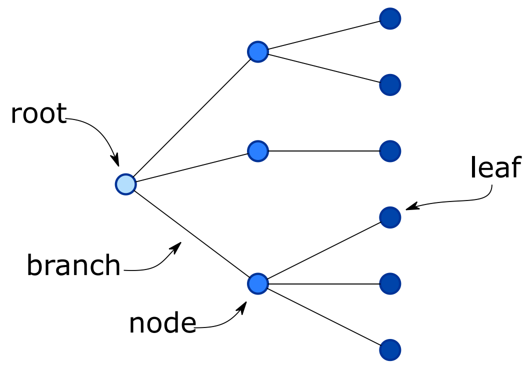


Figure 6-2. Generic example of an event tree. Adapted from (SPANCOLD 2012)**.**

Each node of the tree represents an event. The root node is called the initiating event. The branches that grow from an event represent the possible outcomes from their event of origin. The branches must represent mutually exclusive and collectively exhaustive events, so an event will always be reflected in one and only one branch. In this way, if a probability is assigned to each branch, the sum of all the probabilities arising whichever node will be 1.

Probabilities in event trees, except for the initiating event, are always conditional, that is, for any intermediate node it is assumed that all preceding events (parent nodes) have already happened.

Any path between the initiating node and each of the leaves of the tree represent one of the possible outcomes that might result from the original event. Thus, each of these chains will be unique and defined by the results of all the events that will have occurred in the tree (defined by the values that certain representative variables will have adopted). All these values compose the fingerprint or signature that identifies each of the paths.

To calculate the probability of occurrence of one of the chains of events, the conditional probabilities in the branch must be multiplied, as shown in Section 6.5.

As explained in the following sections, some of the variables appearing in risk models, such as the water level in the reservoir or the return period of a flood, are continuous. When they are to be modelled through event trees, these variables are discretized in several branches. Each of these branches represents a range of values which this variable can adopt. Therefore, for later calculations, a representative value of this branch is taken, usually the average value of the interval.

Influence diagrams are compact conceptual representations of the logic of a system. On its most generic form, an influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and its consequences.

An influence diagram offers a visual representation of the risk model event tree. Each variable of the system is represented as a node and each relation as a connector or arc. Therefore, it is possible to build an event tree from an influence diagram to perform a calculation at a later stage.

Figure 6-3 shows an example of influence diagram.

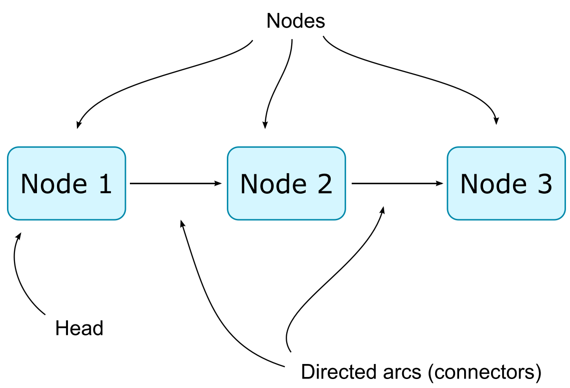
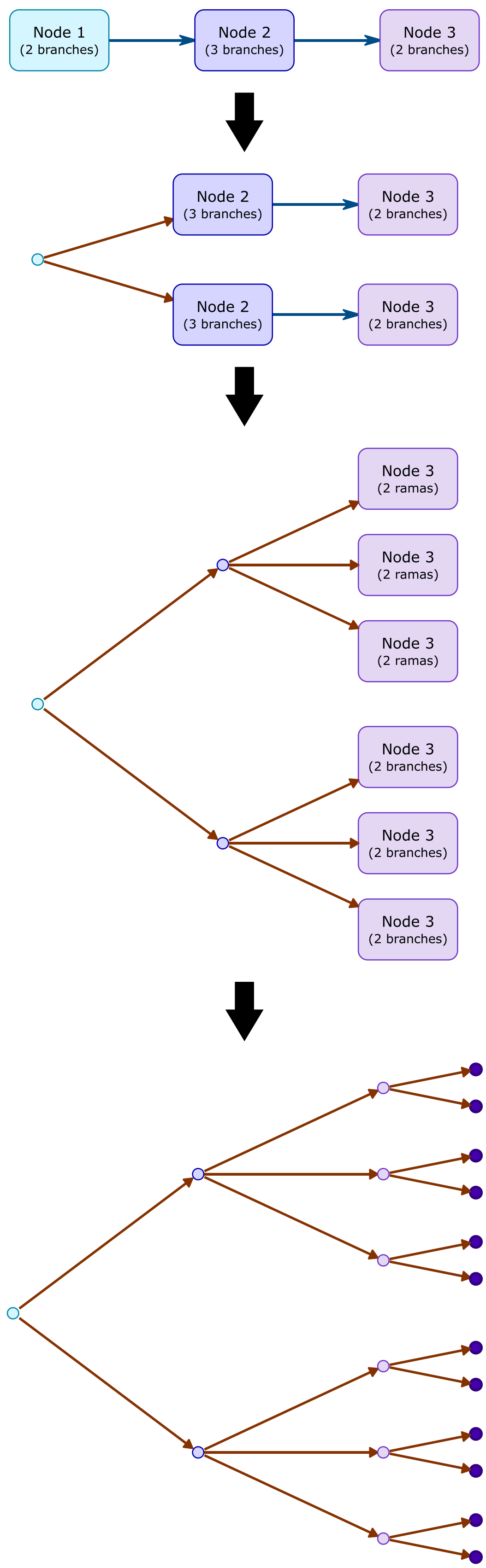


Figure 6-3. Generic example of an influence diagram.

As it can be observed, the direction of the connectors indicates that the variable represented in Node 2 depends on the variable in Node 1 and the variable in Node 3 depends on the variable in Node 2.

Finally, Figure 6-4 shows how a diagram of influence can be converted in its equivalent event tree to compute risk.



6.3 Building the risk model architecture

6.3.1 Introduction

The first step in the development of a risk model is defining its architecture. When setting the architecture, the variables that are included in the model and the relations between them are defined.

Risk model architecture is built based on the loading scenarios and the failure modes identified. These risk models should include all the Class B Failure modes.

If failure modes are related to different loading scenarios, they can be computed in a different risk model (each one with different architecture) or they can be combined in a single risk model. For instance, normal operation and hydrological scenarios can be combined in the same risk model by including the full range of floods, see Section 6.4.1 for details.

6.3.2 Normal operation scenario

Error! Reference source not found. outlines the structure of a standard risk model for a normal scenario. Figure 6-6 summarizes further analyses that will be required to develop risk model input data discussed in Section 6.4.

The analyses are usually divided into three groups that correspond with the three terms of the risk equation: loads (blue nodes), system response (red nodes) and consequences (green nodes). Coloured nodes can be seen in **Error! Reference source not found.**.

Figure 6-4. Relation between an influence diagram and its equivalent event tree.

The first node of the diagram corresponds to the action represented by the water level in the reservoir. The starting information is usually the exceedance probability curve for the water levels of the reservoir. This curve can be obtained in many cases by adjusting an empirical curve to the historic registers. For this it is necessary to count with a register that is sufficiently long and representative of the current operating situation. Whenever this condition is not met or when it is intended to analyse a potential future situation (for example, freeboard requirements in the reservoir), simulation proves a helpful tool. These subjects are detailed in section 6.4.3.

The following nodes, in red, contain the information of the failure modes. There should be a branch in the diagram for each failure mode. It is possible to model the failure probability of each mode in the diagram through one or more nodes. Section 6.4.6 deals with the way of estimating probabilities for each of the steps of a failure mode.

A node estimating the failure hydrograph follows each failure mode. Concerning the event tree, it is usual to characterize the failure hydrograph with a significant variable (usually the peak discharge), so for these nodes it suffices to obtain a curve relating the pool level of the reservoir with this variable. In any case, it will always be necessary to have a series of complete failure hydrographs to do the ulterior flooding simulations in the following step. Different methods for doing these studies are discussed in Section 6.4.7.

Finally, there are the nodes of estimation of consequences where the relations between the consequences and the failure hydrographs are introduced. In the normal scenario, the consequences of the non-failure case are null, so it is not necessary to evaluate them to obtain the incremental consequences. The case shown in **Error! Reference ource not found.** is the simplest one, but the calculation could be sharpened if the consequences were disaggregated as a function of other variables such as the time of the day, the week or the year, the moment the warning took place or the failure mode. The different types of consequences that can be found and the existing methodologies for studying them are discussed in Sections 6.4.8, 6.4.9 and 6.4.10.

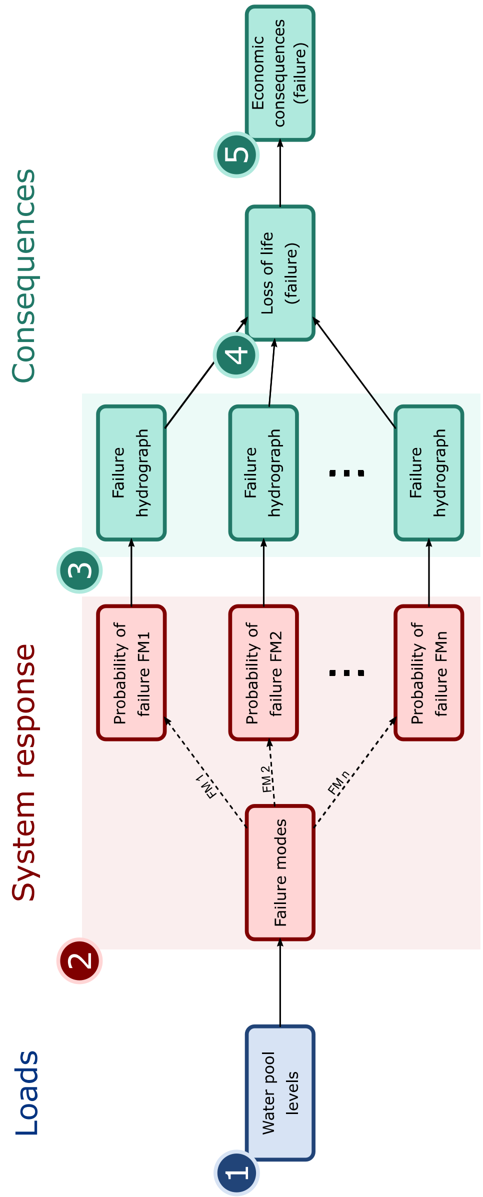


Figure 6-5. Influence diagram of a generic risk model for normal operation scenario. Adapted from (SPANCOLD 2012)**.**

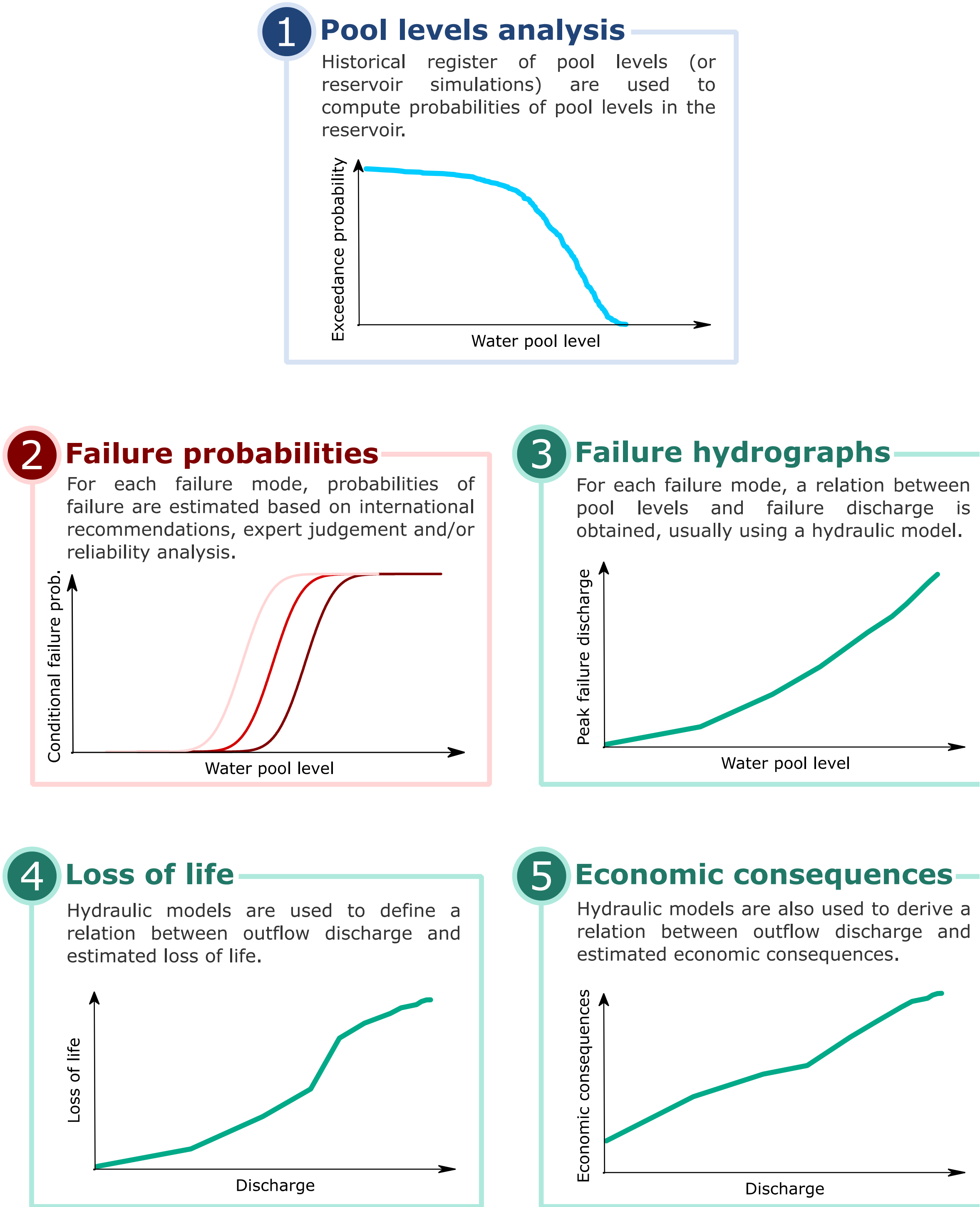


Figure 6-6. Common input data needed to populate a risk model for normal operation scenario.

6.3.3 Hydrologic scenario

Figure 6-7 outlines the structure of a standard risk model for a hydrologic scenario. Figure 6-8 summarizes the further analyses that will be required to develop risk model input data discussed in Section 6.4.

The analyses are usually divided into three groups that correspond with the three terms of the risk equation: loads (blue nodes), system response (red nodes) and consequences (green nodes). Coloured nodes can be seen in Figure 6-7.

The first node introduces the flood entering the reservoir. A probabilistic hydrologic analysis is necessary to obtain the annual exceedance probability of the possible floods. Although it does not appear in the figure, it is possible to incorporate seasonal hydrologic studies. Section 6.4.1 deals with hydrologic studies.

The next node (previous pool level) is very similar to the node of pool level of reservoir in the normal scenario. However, there is a conceptual difference between the previous pool level in a normal and a hydrologic scenario: whereas the former represents the pool level of the reservoir any day of the year, the latter represents the pool level in the reservoir at the moment preceding the arrival of the largest flood of the year. The computation of pool levels probabilities is explained in Section 6.4.3

The availability of outlet works, and spillways gates is the probability of these devices functioning properly (or not) when a flood arrives. This aspect is very difficult to introduce into a traditional calculation based on safety factors but fits naturally into a risk-based analysis. The different reasons to discard an outlet works or spillway (e.g., consider it does not work) are discussed in Section 6.4.4 and it also explains how to do other estimations from operation registers, expert judgment and fault trees.

The following node includes the results of the flood routing study (see section 6.4.5). In this study, maximum pool levels and peak outflows are computed for each possible combination of previous pool level, inflow flood and availability of the gates. Depending on the failure modes to be studied, some additional variables, such as time of overtopping are needed in certain cases.

Regarding failure modes and failure hydrographs, the same comments as for the normal scenario, are generally valid.

Concerning flood consequences, the only difference, with respect to the normal scenario, is that the consequences of the non-failure case are also calculated to obtain incremental consequences (and incremental risks).

6.3.4 Seismic scenario

Figure 6-9 outlines the structure of a standard risk model for a seismic scenario. Figure 6-10 summarizes the further analyses that will be required to develop risk model input data and that are discussed in Section 6.4.

The analyses are divided into three groups that correspond with the three terms of the risk equation: loads (blue nodes), system response (red nodes) and consequences (red nodes). Coloured nodes can be seen in Figure 6-9.

The first node models the probability of occurrence of the earthquake through a representative variable, usually the basic seismic acceleration. This relation must be obtained from a seismic study (see section 6.4.2). In the failure mode classification, it should be decided if in the case where seismicity is low it is possible to disregard this scenario entirely as the risk it will introduce will be negligible in comparison with the ones provided by the other two scenarios.

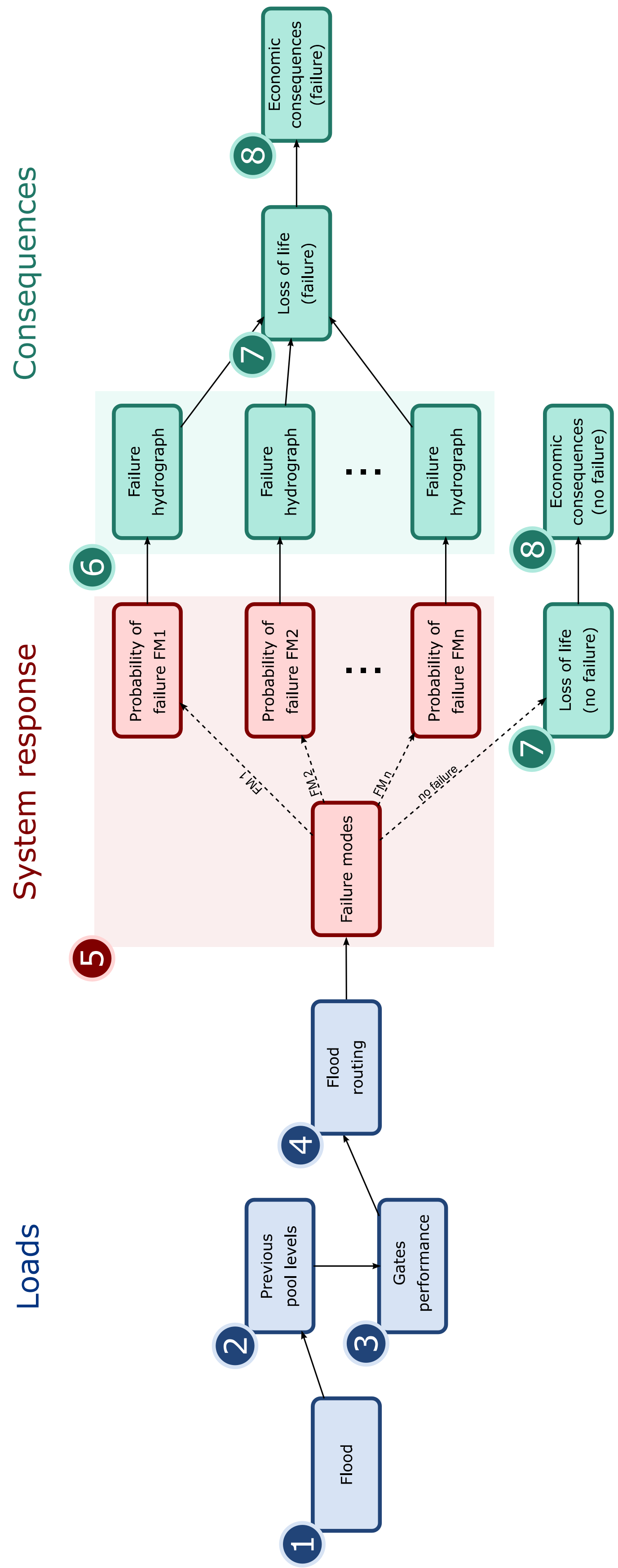


Figure 6-7. Influence diagram of a generic risk model for hydrologic scenario. Adapted from (SPANCOLD 2012)**.**

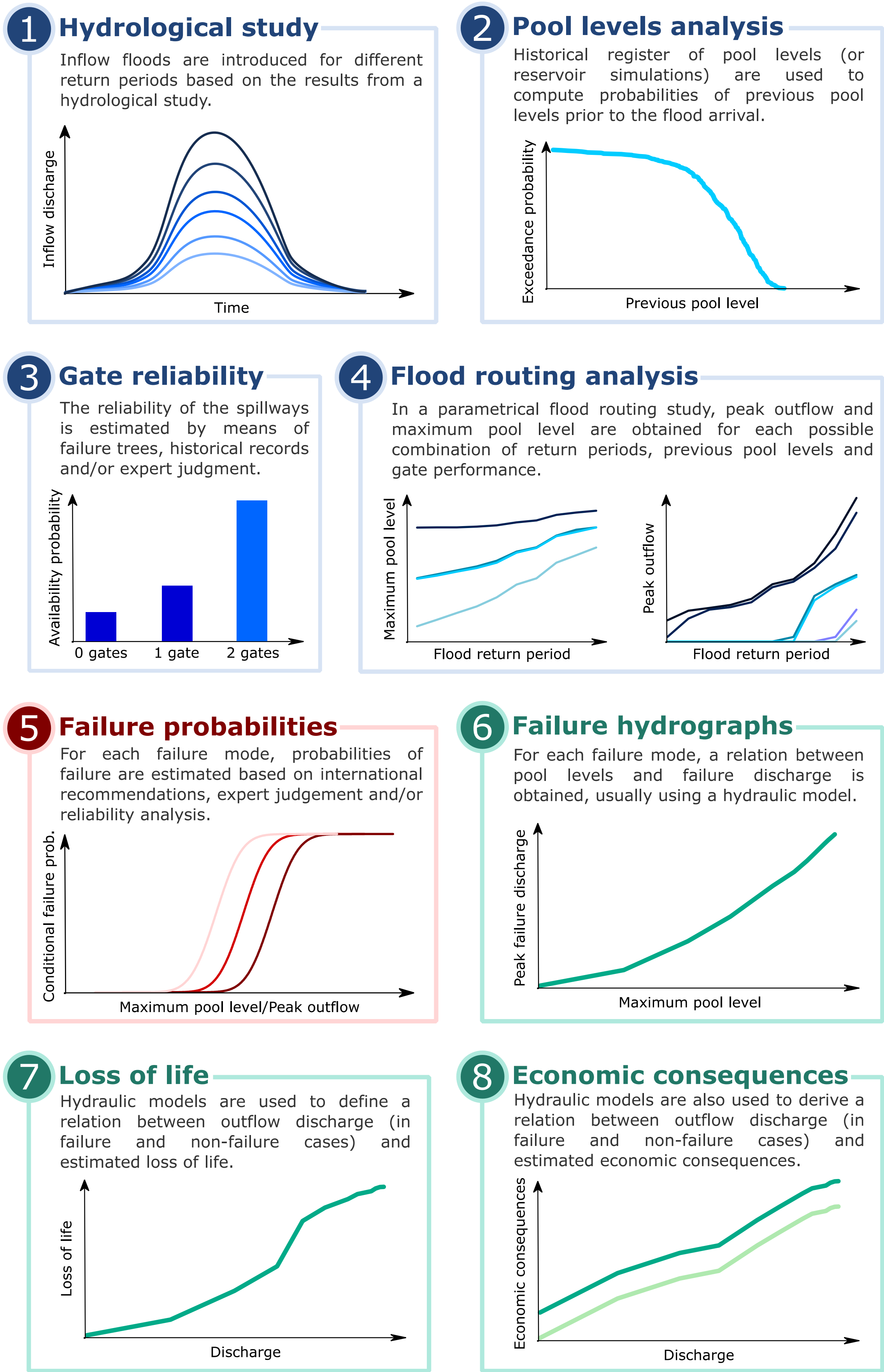


Figure 6-8. Common input data needed to populate a risk model for hydrologic scenario.

As in the two previous situations, it is also necessary to model the water level of the reservoir when the earthquake takes place. The failure modes presented in this scenario are equivalent to those found in previous scenarios and can be considered in a similar way. The same can be said of the nodes of the failure hydrograph.

Finally, the consequences usually depend only on the failure hydrograph and, as it was the case in the normal scenario, it is generally not necessary to evaluate the consequences for the non-failure case (because there is no flood in such a case). A more accurate analysis could consider the combined consequences of an earthquake and a flood in a breakage case and the consequences of an earthquake with no flood in the non-failure case.

6.3.5 Failure modes structure

When failure modes are included within risk models, they are usually disaggregated into **failure mechanisms** to facilitate the failure probabilities estimation and to clearly identify the full sequence of steps required to reach failure. Therefore, each failure mechanism is represented with a different node in the risk model. This ensures that due diligent consideration is given to each event in the failure sequence. It also supports the identification of key issues contributing to the risk.

An example of nodes structure for an internal erosion potential failure mode is illustrated in Figure 6-11. A challenge with estimating probabilities for detailed event trees is to bear in mind that each branch is conditional on predecessor branches. For the typical internal erosion event tree, this means that the probability estimation for the continuation branch should assume that the initiation has already occurred even if the probabilities for initiation are very small.

The number of nodes to define each failure mode depends on the failure mode description, which indicates the mechanisms that should occur to produce the failure. Additional advise on how to structure different types of failure modes can be found in (USBR and USACE 2015).

In some cases, when failure mode structures are defined, it can be advisable to include the possibility of non-failure branches resulting in high risk for damage or economic loss. For instance, this could happen with partial failure of a dam with high economic consequences, prior to a complete failure.

In many cases, the structure of failure modes should also include one or several **"No detection/No intervention"** nodes. This node evaluates those actions that can lead to detecting and preventing a failure from occurring. Hence, a higher probability on these nodes indicates that these failure mechanisms would be hard to be detected or avoided, and it would continue developing. Successful intervention requires taking actions to not only detecting a developing failure mode but also taking actions to stop further development of the failure mode. For instance, these nodes could evaluate the probability of detecting the initiation of an internal erosion problem and the probability of implementing successful actions to stop it.

Two phases of detection/intervention are typically considered for possible inclusion in the event tree, although the number of nodes depends on each failure mode and existing surveillance and monitoring system. The first phase of detection and intervention includes routine and non-routine actions such as surveillance, inspection, monitoring and instrumentation. These actions occur during the early stages of failure mode development. Actions to prevent breach during the first phase of intervention generally have a higher likelihood of success.

The second phase of intervention includes emergency actions that are taken as a last-ditch effort to prevent failure. These emergency actions occur during the later stages of failure mode development when the failure is virtually certain and imminent (hours to days). Actions to prevent a breach during the second phase of intervention generally have a lower likelihood of success.

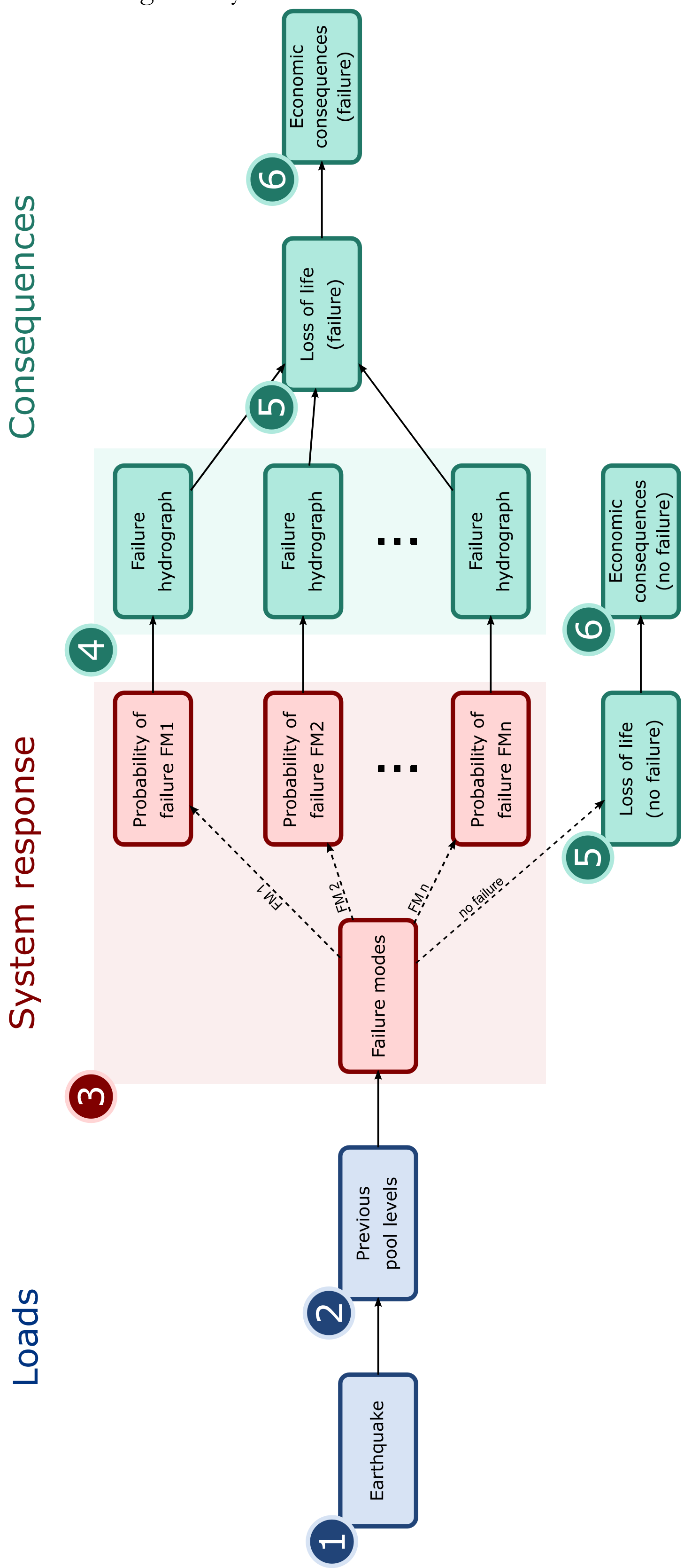


Figure 6-9. Influence diagram of a generic risk model for seismic scenario. Adapted from (SPANCOLD 2012)**.**

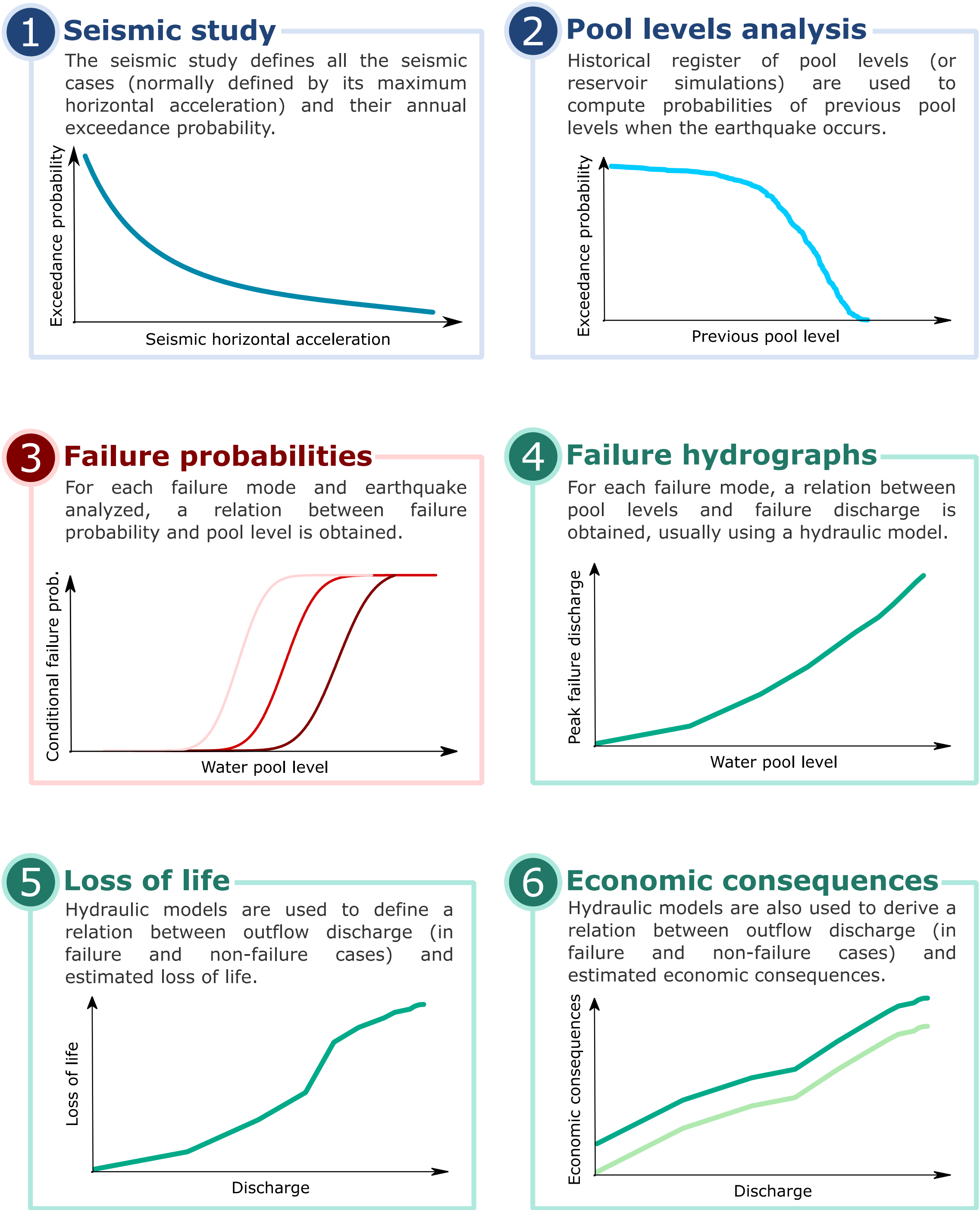


Figure 6-10. Common input data needed to populate a risk model for seismic scenario.

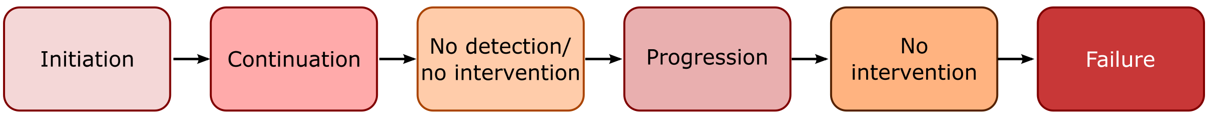


Figure 6-11. Example of structure for internal erosion failure mode.

6.3.6 System of dams

When building the risk model architecture in a cascade system of dams, it can be necessary to build a single risk model that encompasses the entire system.

On one hand, these types of models have a more complex architecture and their computation times are much higher. As an example, if there are two dams *a* and *b* with their event trees of n_a and n_b branches respectively, and if they are analysed separately, between the two trees it will be necessary to calculate $n_a + n_b$ branches. Contrary, if they are analysed as a system, the event tree can have as many as $n_a \cdot n_b$ branches (admitting they do not share any node). As n_a and n_b are usually large numbers, their multiplication is much larger than their mere addition.

On the other hand, they allow analysing cross effects in complex dam systems and combined risk reduction actions like emergency procedures or new operation rules.

In general, it is recommended to create a risk model for the whole dam system in the following two cases:

- When both reservoirs have a similar size, so the failure of the upstream dam could produce (or not) the failure of the downstream dam.
- When the gates operation of the dam system is managed globally, and downstream water pool levels greatly influences the gate operations in the upstream dam.

In these combined models, dam risk models are put in order, one after the other. Hence, downstream dam models include the effect of upstream dams in failure and non-failure cases. An example of this type of model for three dams is shown in Figure 6-12. In addition Appendix 3 provides a complete case study of a Risk Assessment for a system of two dams.

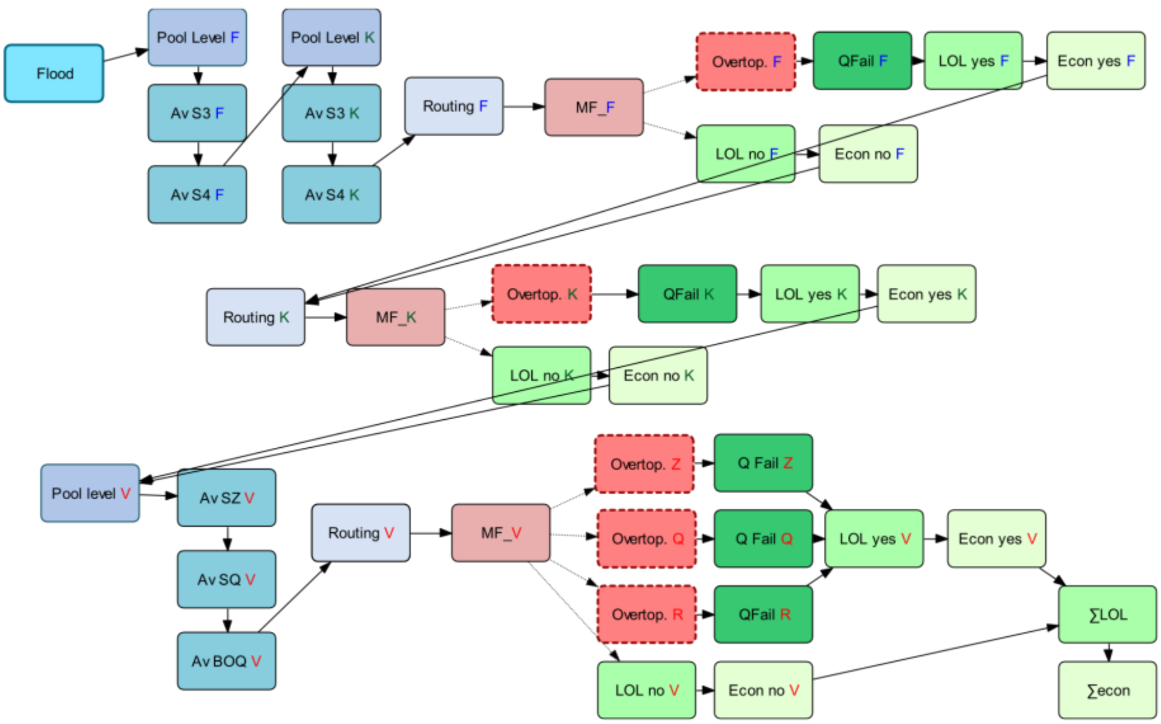


Figure 6-12. Example of risk model for a system of three dams in Albania. Source: (Ignacio Escuder-Bueno et al. 2016).

6.4 Risk model input data

6.4.1 Hydrological analysis

In the hydrologic scenario, floods are the phenomena under study and usually the initiating event of the risk model. Historically in India, dam design and analysis methods have focused on selecting a level of protection based on spillway evaluation flood loads. Traditionally, the protection level is based on the Probable Maximum Flood (PMF).

However, risk analysis, from a hydrologic perspective, requires an evaluation of a full range (frequency of occurrence) of hydrologic loading conditions and possible dam failure mechanisms. This risk approach contrasts with the traditional approach in India of using a single upper bound. In the context of probabilistic hydrologic loadings, a deterministic maximum event such as the PMF is just one flood outcome amongst a collection of flood peaks, volumes and hydrograph shapes.

The typical outcome from this type of analysis is a relation between flood peak discharge (or flood volume) and its Annual Exceedance Probability is shown in Figure 6-13. Typically, different flood durations are tested with the risk model through a sensitivity analysis to check the most critical one for the reservoir.

In general, the data used to build hydrographs are based on registers less than 100 years old, though they can be lengthened up to 150 years by using historical information. There are different sources of information used to set the extrapolation to small enough AEPs (Swain et al. 1998):

- Discharge data.
- Climatological data.
- Historical data.
- Paleoflood data.

When it comes to predicting severe floods in a reliable way the better results can be obtained by combining regional data of different sources. Thus, the analysis based on rainfall, discharges and regional paleofloods information should offer the most accurate results in the definition of floods with low AEPs. More information about how to make a probabilistic hydrologic analysis will be found in the *Guidelines for Selecting and Accom-*

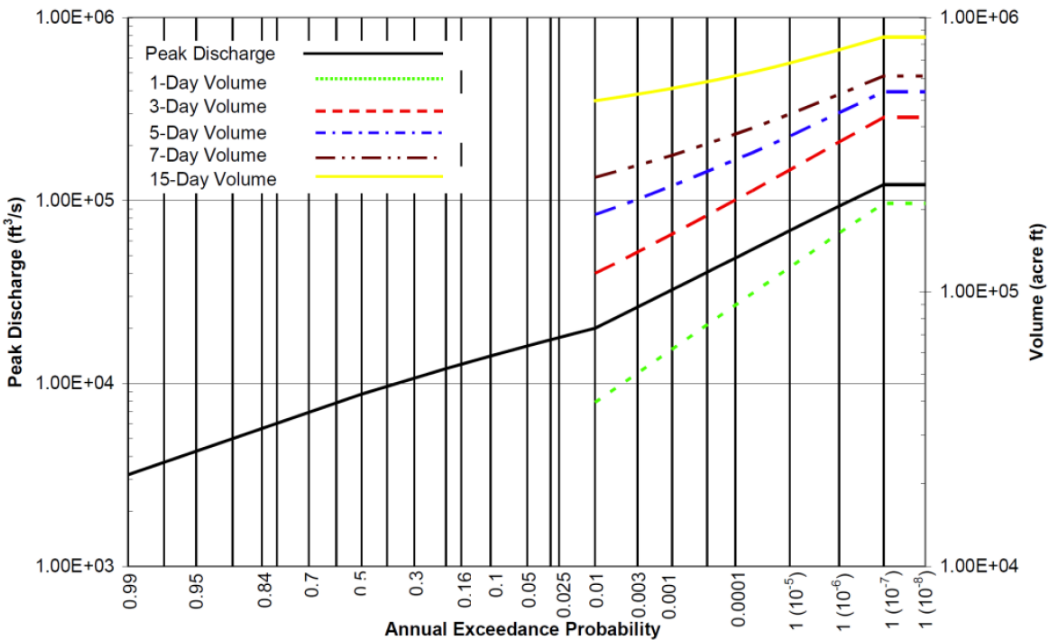


Figure 6-13. Example of hydrologic hazard curves showing peak flow and volume probability relationships. Source: (FERC, 2016).

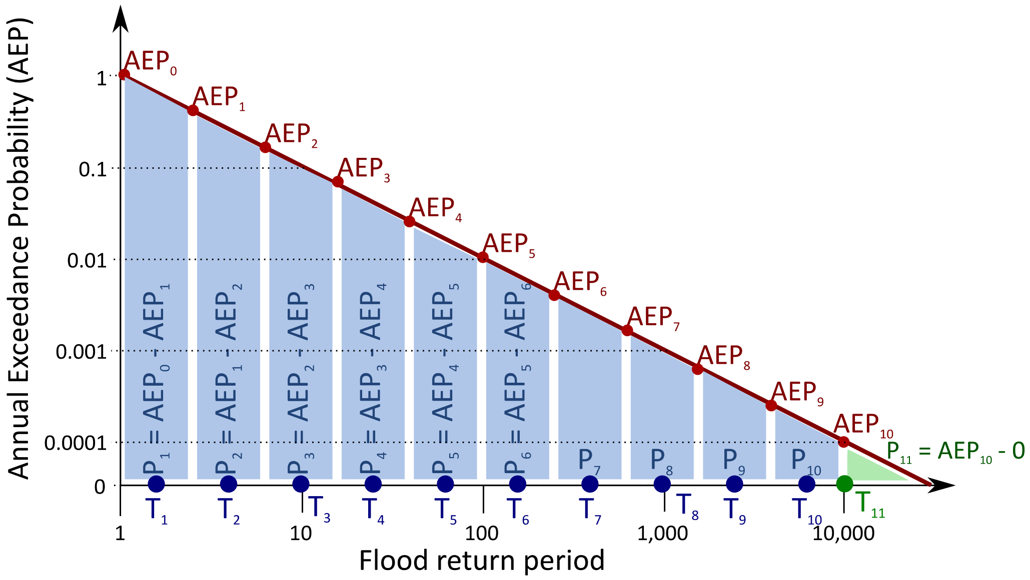


Figure 6-14. Example of discretization of the flood range to be introduced in the event tree.

modating Inflow Design Floods for Dams and the *Manual for Assessing the Hydraulic Safety of Dams.*

In a **basic analysis**, when a probabilistic hydrologic analysis is not available, a first risk computation can be made using the PMF and relating it with an exceedance probability of 10^{-4} (10,000 years return period). In addition, another flood will be needed with a lower return period (for instance 100 years return period) to define the AEP-Discharge relation.

Instead, in **more complex** hydrological analysis, season variations of floods can be analysed. This type of analysis is very useful to define seasonal freeboards in the reservoir.

More complex analysis can be made deriving a large number of families of hydrographs through a Monte Carlo simulation framework (Bianucci et al. 2013).

Once inflow hydrographs have been obtained with their associated probability, they must be introduced in the risk model event tree. With this purpose, the complete range of flood probabilities analysed should be **discretized** to create the different branches of the event tree. This discretization can be made on the Peak discharge-AEP relation or directly in a Return period (T)-AEP relation, since each flood is also defined by its return period.

Figure 6-14 shows how the relation between Return period-AEP is discretized in 11 intervals in a logarithmic scale to create this number of branches in the event tree. Each branch will have a flood hydrograph associated from the probabilistic hydrologic analysis.

When this relation is discretized in intervals, accuracy increases as the numbers of intervals increase. Consequently, this leads to a higher number of branches in the event tree. If the event tree was about to be calculated manually, the number of intervals should be necessarily small. With the employment of software to automatize the calculations this ceases to be a problem. In general, using several intervals greater than 50 in the Floods node does not change the results considerably.

Discretizing the whole range of flood from 1-year return period (case without flood) to a high return period flood (typically 10,000 or even up to 100,000 years in some cases) allows combining hydrologic and normal operation scenario into a single risk model, since both types of failure modes are considered in the event tree.

6.4.2 Seismic analysis

In seismic analysis, the traditional standards-based approach is typically performed by selecting an earthquake scenario that can reasonably be expected to produce the largest seismic demand (ground motion) on the dam, referred to as the Maximum Credible Earthquake (MCE). The deterministic analysis considers one source, one magnitude and one distance at a time. The ground motion obtained from deterministic method is typically considered independent of time with the earthquake recurrence assumed to be the same for all seismic sources.

In contrast, for risk analysis a probability seismic analysis is required. This type of analysis involves an element of time and uses all possible earthquake scenarios and probability levels as inputs to the seismic load for the dam. The probabilistic approach also incorporates the uncertainties in earthquake locations, earthquake size and ground motion models. The procedure for a probabilistic approach includes the following steps (FERC 2016):

1. Define the earthquake source seismicity.
2. Estimate the maximum magnitude for each source and earthquake occurrence rates.
3. Calculate the ground motion parameters using one or more ground motion models appropriate for the seismic sources, seism-tectonic setting and site conditions. Develop the uncertainty associated with each step.
4. Develop the seismic hazard curves and uniform hazard spectrum/ conditional mean spectrum.

These steps are summarized in Figure 6-15.

The process followed to make this kind of analysis will be explained in detail in the *Guidelines for Evaluating Seismic Hazards at Dams.*

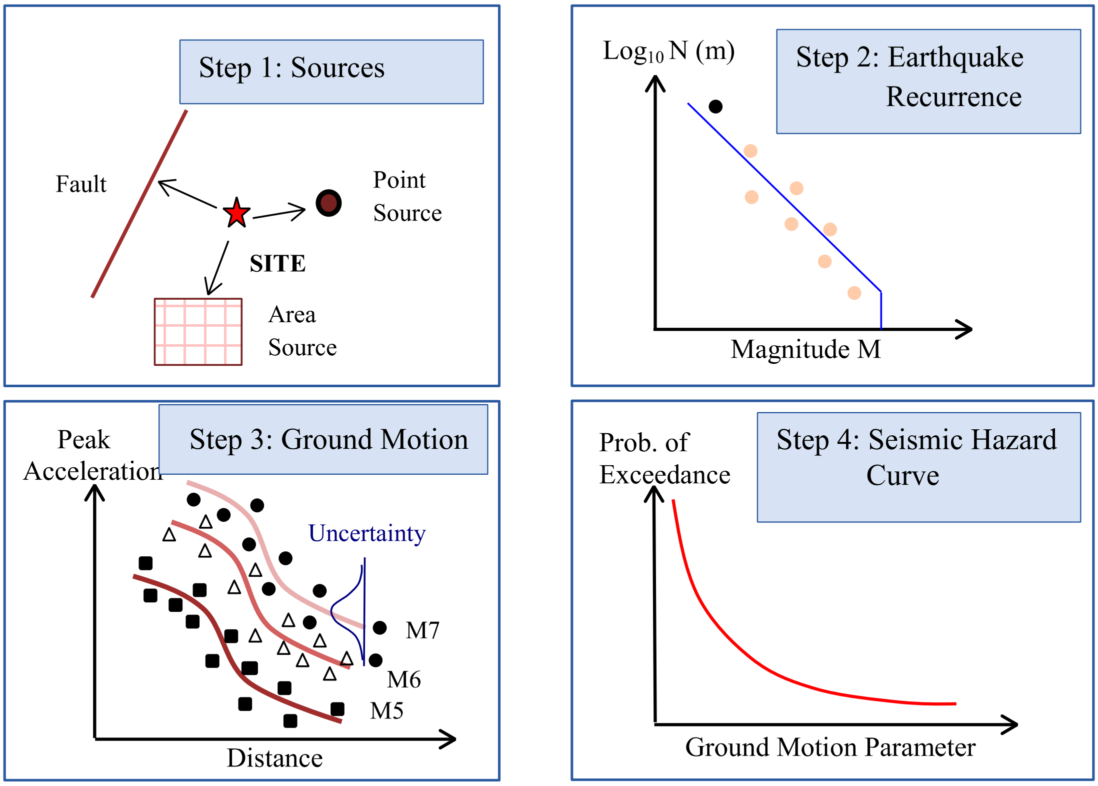


Figure 6-15. Steps for probabilistic seismic analysis. Source: (FERC, 2016).

In a first risk computation, when a probabilistic seismic analysis is not available, dam risk response for seismic can be preliminarily assessed from existing seismic hazards maps with expected ground accelerations.

Finally, the considered range of the earthquake's return period should also be discretized to be included in the event tree, following the same approach that the discretization made for flood hazards.

6.4.3 Estimation of pool levels probabilities

The study of previous pool levels aims to analysing the probability of finding a certain pool level in the reservoir at the arrival of a flood or a seismic event occurring. The relation between probability and pool levels can be obtained by using the register of historical pool levels. It is necessary to count with a register that is long enough and sufficiently representative of the current situation. When this is not possible or when a potential future situation is being assessed, it becomes necessary to resort to simulation.

The relation between previous pool levels and its probability of occurrence is usually included in the model through the exceedance probability graph of the reservoir. This graph is obtained from a series of data that can come from historic registers or reservoir simulations.

Data from **historical registers** of measurements of the pool level in the reservoir can be usually used to obtain a relation between previous water pool level and probability. Yet, those data must satisfy certain conditions to be valid for the risk model purpose.

First, data must be consistent and reliable, for which the utilized series must be filtered so that erroneous data can be discarded.

If these data are to be used in the model, it is necessary to ensure they represent properly the distribution of the pool levels in the reservoir. Therefore, the series must be lengthy enough to guarantee that the pool level's variability is properly represented.

When this curve is obtained, data corresponding to exceptional situations must be removed for the analysis to avoid the introduction of events that do not represent the normal situation of the reservoir. This is the case for:

- The filling-up of the reservoir.
- The emptying of the reservoir for rehabilitation works.
- Other situations which are unusual from the normal operation of the reservoir.

To obtain a correct definition of the current situation of the pool levels in the reservoir, it is also important to remove the data corresponding to the occurrence of any event that has modified substantially the variation of the pool levels, such as it might be the construction of a dam upstream or the rising of the crest of the dam.

Additionally, when analysing the hydrologic scenario, it is necessary to remove the flood situations in the register because, the increase of the pool level produced by the flood is introduced independently in the risk model through the flood routing study.

In general, it suffices to truncate the curve of exceedance probability obtained in the MOL (Maximum Operating Level), admitting this way that whenever the level in the reservoir is over the MOL is due to a flood situation. In a more detailed study, the year's pool levels obtained during the maximum annual flood can be removed.

On the contrary, data corresponding to other unusual situations in the reservoir (e.g., draught periods) must be included in the analysis of the register of historic pool levels

Whenever the register of pool levels does not satisfy the mentioned conditions or in case a potential future situation (e.g., a restriction of the operation pool levels) is to be assessed, it is necessary to resort to simulation to obtain the level data.

The objective of a **simulation model** of the water resources management is to estimate the functions of distribution of a variable by analysing its behaviour. In this case, the simulation reproduces the work of a reservoir according to the current or suggested management rules of the system. In general, the simulation of a reservoir is done within the frame of a more complex simulation that concerns the planning of the system of water resources and that can include several reservoirs. The model consists of a sequential calculation of the location and use of the water resources. For this, the equation of mass balance is used considering the physical restrictions of water and the rules of infrastructure management. There are several software tools for the planning of basins, such as, HEC-ResSim (Klipsch and Hurst 2013) that could make these types of calculations easier.

Once data of pool levels is obtained (from the historical register or from simulation) the empiric **exceedance probability curve** of the pool levels of a reservoir is obtained by ordering all the data in an increasing order. In this way, the probability of exceedance of each pool level is given by the following formula (SPANCOLD 2012):

$$PE_n = 1 - \frac{i_n - 1}{N - 1}$$

Where PE_n is the probability of exceedance for a pool level n, i_n, is the number of order of pool level n within the series of ordered pool levels and N is the length of the series.

When the pool levels of the reservoir and their exceedance probabilities are represented, a curve like the one shown in Figure 6-16 is obtained.

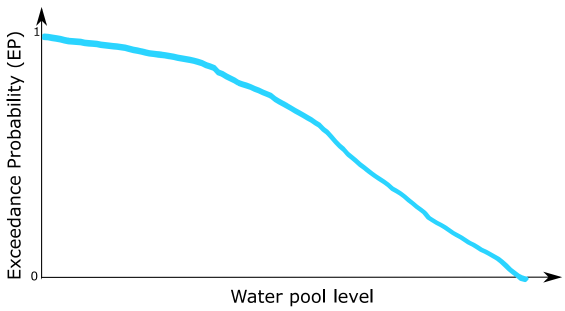


Figure 6-16. Example of pool level - exceedance probability curve.

In a **simplified approach**, it is possible not to incorporate pool level probability by admitting the dam is always at its Maximum Operating Level (MOL). This falls on the safe side, that is, it will produce higher probabilities of failure. In dry climates with severe floods (such as the case of some areas in India) where it is normal to find a pool level much lower than the MOL, this simplification can be excessively distant from reality and offer extremely conservative results, not suitable for comparison with the results of other dams where the calculation considers the real fluctuation of pool levels.

Finally, this curve should be discretized in different intervals to be included within the risk model event tree. Therefore, for ulterior calculations, a representative value of each interval is taken, usually the average value of the interval. In the event tree, the probability of each branch is then the probability of falling within any of the values of the interval, which is computed as shown in Figure 6-17.

Additionally, the intervals do not require being equidistant, and with the same number of intervals, a proper distribution can be very important in the consecution of useful and accurate results.

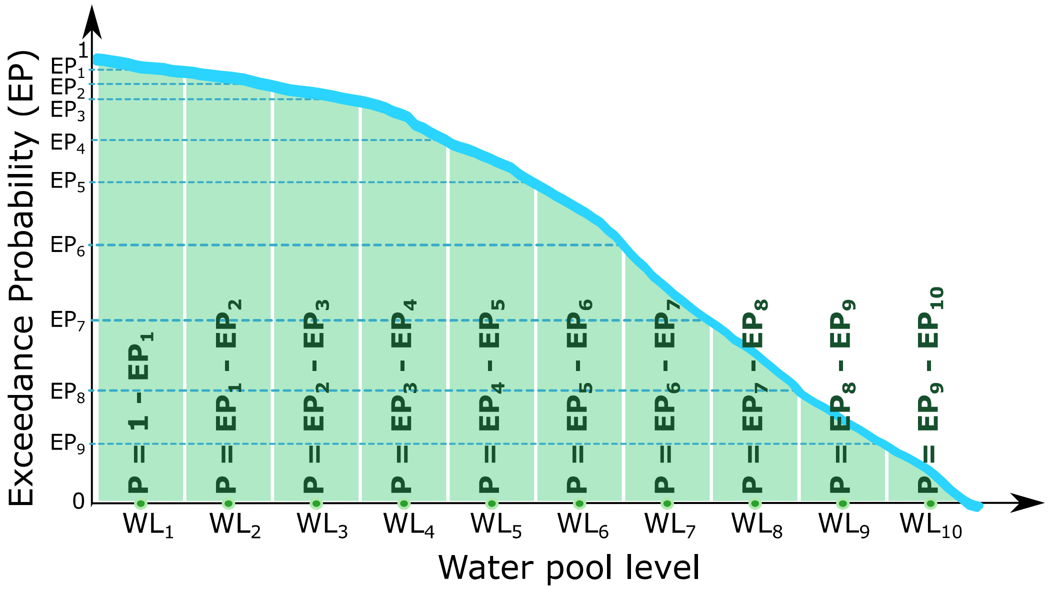


Figure 6-17. Discretization of water pool level-exceedance probability curve.

6.4.4 Gates performance evaluation

Outlet works and spillway reliability is of great relevance to dam safety and has played a fundamental role in many catastrophic failures. Despite its manifest importance, gate reliability has remained an aspect of difficult integration into traditional hydrologic adequate analysis and thereby, has been usually treated separately. In the context of Risk Analysis, this aspect gets integrated in the risk model and its impact on safety becomes quantifiable.

Therefore, the information these nodes should include is the probability that every outlet works and spillway behaves properly, that is, that in the moment of the arrival of the flood, the outlet works or spillway are available. It is usual (and most of the times sufficient) to make the hypothesis that each outlet works and spillway (each gate of a spillway, each conduit of a bottom outlet) works perfectly or does not work at all. In principle, it would be possible to study intermediate scenarios of partial dysfunction though it would be necessary to determine whether the improvement of the results would be meaningful.

Outlet works and spillway reliability should not be mistaken for the possibility they undergo a collapse or opening that creates an artificial flood downstream (such as Flosn gate failure in USA). This aspect must be equally analysed but not as a component of the gates availability but as a potential failure mode. In conclusion, this section does not deal with the possibility of the gates opening at an undesired time but with only the issue of them not opening when desired.

When performance is evaluated, the analysis of the causes that must lead to gates failure cannot be limited to a mechanical failure, as experience shows, failures can be due to very disparate reasons. When the whole system is analysed it becomes apparent there are several causes that might induce failure:

- Human failure (either because the need of opening a gate is not identified or because the order is not transmitted or because the person in charge of operating a gate makes a mistake, etc.).
- Lack of access to the manoeuvre chamber (e.g., due to snow).
- Mechanical failure (breakage of a piece, blockage, etc.).
- Mechanical failure of the civil works (that could render the outlet works or

spillway useless).

- Electrical failure (either in the supply or in the components of the outlet works or spillway themselves).
- Blockage of the outlet works or spillway (e.g., due to the presence of logs and debris).
- Failure in the software controlling the gate or the valve (in case it exists).
- Other.

Therefore, all these assumptions must be considered in order to estimate the gate failure probability.

In a **basic analysis**, individual reliability of gates can be estimated directly for each gate after analysing these aspects. (Altarejos García et al. 2014) provides guidance for this individual reliability estimation:

- **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 has never been used.

In this type of basic analysis, gates can be considered independent. So, the probability of each availability gates case can be estimated with a binomial distribution and the following formula:

$$\boldsymbol{P(x) = \frac{n!}{x! \cdot (n-x)!} \cdot p^x \cdot (1-p)^{n-x}}$$

Where *P(x)* is the probability that *x* number of gates work properly, *n* is the total number of gates and *p* is the individual reliability of gates. If, for instance, a spillway has three gates, the probabilities of four cases are estimated with this formula: 0 gates available, 1 gate available, 2 gates available and 3 gates available for flood routing.

In a **more detailed analysis**, it is recommended to use **fault trees**, which are the most common tool to study gates reliability. A fault tree is a deductive logical tool in which a major undesired event -failure- is postulated and from which all the possible manners are deducted systematically. Hence, all the predecessor events that could lead to a gate failure are analysed.

Each node of a fault tree represents a binary event (it can happen or not). For example: a gate works or does not, there is electrical supply or not, a piston breaks or does not, etc. In other words, it is always a binary relation.

Events are interrelated throughout logic gates. The simplest ones are the AND / OR gates. If a top event A relates throughout an AND gate with the lower elements B and C, it means that in order for event A to happen, events B and C should both take place. On the contrary, if a top event A is related to lower events B and C by means of an OR gate, it means that for event A to happen, either event B or event C should happen (or both can occur).

It is usual to employ a fault tree as a mere tool for aiding in the understanding process of a system or for rationalizing a discussion, without doing any numerical evaluation. Even in these cases, the knowledge provided by the tree will prove to be very helpful in the assignment of reliability probabilities.

A fault tree can be made as exhaustive as desired, modelling even the different mechanical, electrical supply and chain of command components. The probabilities of the disaggregated elements are estimated and then the global one is obtained through the fault tree. For that reason, it is a flexible tool to address different levels of detail. The level of detail for each analysis is defined considering the relative importance of the analysed gate for flood routing: For instance, spillway gates are usually more important for flood routing than other outlets gates. Figure 6-18 shows an example of a fault tree for an intermediate level of analysis.

Fault trees typically distinguish two types of failures: individual failure (only one gate fails) or group failure (when all the gates fail at the same time, for instance due to lack of energy supply). These two types of failures can be combined in the same fault tree or they can be computed separately and combined in a third fault tree.

Once the logic of the system has been modelled through fault trees, individual probabilities of fault tree components must be estimated. For this, there exist mainly three tools:

- **Analysis of historical registers:** It consists of estimating the reliability of the system or of any of its components based on past failure frequencies. On some occasions, the operators of the dam can access the registers of all the manoeuvres that have been done in the outlet works or spillway and that specify if the operation was carried out successfully or if any problems were encountered. These registers must be long enough to be statistically significant.

  When an outlet works or spillway comprises several gates, it must be considered that failure probability might differ from one to another (e.g., from exterior spans to interior ones). In this respect, a disaggregation of the registers by gate can be helpful.

  However, not all operators have this kind of register since the reliability of outlet works and spillways have not always received the same level of attention in the past. In every case, the values contained in the historic register do not have to be adopted directly as the reliability values introduced in the risk model but can rather act as a starting point for discussion.
- **Assignment of probabilities by expert judgment:** The process of probabilities assignment by expert judgment during group sessions is the same as the one followed to assign failure probabilities to the different failure modes. Thus, this process is described in Section 6.4.6.
- **Dormant-Weibull Formula:** This formula is useful to estimate individual mechanical and electrical components reliability. For each component, reliability is estimated depending on the type of failure, the number of uses and frequency and expected characteristic life. Recommendations on parameter to be used within the formula have been developed by USACE based on its experience and databases (Patev et al. 2013).

Once all the probabilities are introduced within the fault tree, it can be computed. There are several programs to compute fault trees, some of them free like (Auvation n.d.).

More information on creating fault trees and using them to evaluate gates performance can be found in (SPANCOLD 2012; USBR and USACE 2015).

Finally, it should be highlighted that fault trees are recommended to estimate failure probabilities of spillway gates (providing data for this node) but not to elaborate the whole dam risk model.

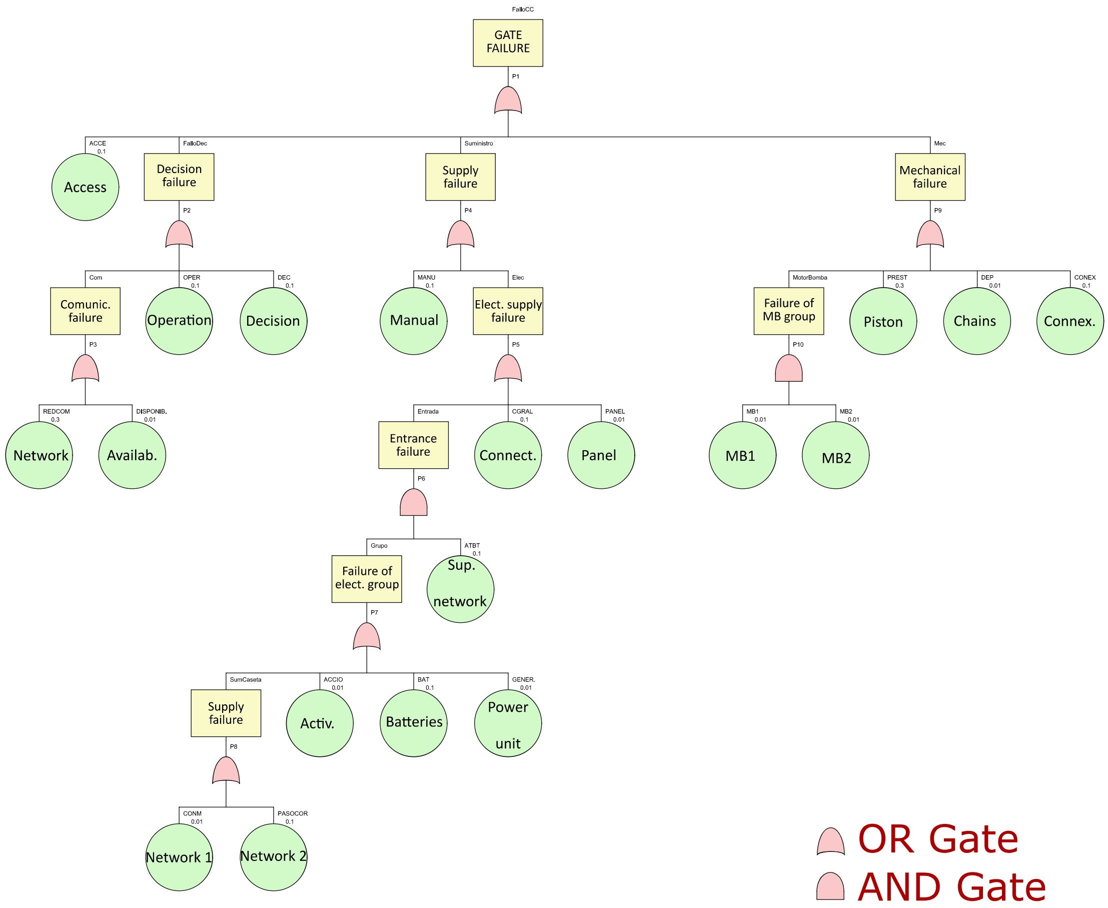


Figure 6-18. Example of fault tree for a dam gate. Source: (Setrakian-Melgonian et al. 2017).

6.4.5 Flood routing analysis

When analysing a hydrologic scenario, it is necessary to carry out a flood routing study with the objective of estimating the response of the dam-reservoir system when confronted by hydrologic loads. This is obtained through the calculation of the function that relates the evacuated discharges downstream of the dam and the pool levels reached in the reservoir along time. This curve provides the data necessary to estimate:

- The probabilities of reaching certain pool levels of loading (maximum pool level in the reservoir, potential overtopping, duration of the overtopping situation, etc.), that serves to quantify the probabilities of dam failure.
- The consequences downstream of the dam resulting from the spills released in case of non-break of the dam.

Flood routing analysis is typically defined by the inflow *I(t)*, the outflow *Q(t)* and the reservoir storage *S (t)*, which are related by the continuity equation:

$$\frac{\partial S}{\partial t} = I(t) - Q(t)$$

In a flood routing analysis, this equation must be solved numerically, either through a simple direct discretization or using more sophisticated techniques such as the modified Puls method and the method of Runge-Kutta.

In general, the entries to the reservoir will depend on time and will be represented by the input or inflow hydrographs. In the case of a very large reservoir, the movement of the flood wave will depend on the dimensions of the reservoir too, and at its arrival to the dam it will do a backwater curve from the tail of the reservoir. Thus, since what are looked for are the pool levels in the dam, I will be a function of time, of the surface of water in the reservoir and of its dimensions. In most reservoirs this distinction is not needed as it can be considered that the entries to the reservoir depend exclusively on time; this means that the surface of water in the reservoir is supposed to be horizontal during the whole process, that there are no effects of backwater in the tail and that at any instant the discharge that arrives in the reservoir affects directly the water levels in the dam. The main data required to carry out a flood routing calculation are:

- Hydrograph entering the reservoir (inflow hydrograph).
- Previous pool level.
- Characteristic curve of the reservoir.
- Discharge curves of the outlet works and spillways.
- Gates operation rules.

With these data, flood routing is computed following the general procedure shown in Figure 6-19.

In the risk models, flood routing results should be introduced for each combination of:

- Flood, including all the floods obtained and their return period obtained from the probabilistic hydrology analysis, as explained in Section 6.4.1.
- Previous pool level, including all the pool levels in which the exceedance curve has been discretized, as explained in Section 6.4.3.
- Gates availability case, as explained in Section 6.4.4.

For each case, outflow from the reservoir and water pool levels are obtained as shown in Figure 6-20. Typically, results introduced in the risk model from these flood routing calculations are:

- Maximum water level reached in the reservoir.
- Maximum overtopping height.
- Peak discharge outflow release by the dam.
- Time of overtopping.

Other results can also be useful depending on the identified failure modes.

In addition, it should be remarked that risk analysis contemplates, for each action, both possibilities of the dam breaking and resisting. Therefore, to properly model the cases in which important loads are acting and the dam does not fail, it will be required to model the **overtopping process** and to integrate it as part of the capacity of response of the system when facing hydrologic loading. In this case it is considered in the flood routing that an uncontrolled spill takes place, like the one produced by a gateless spillway, with a length of spillway approximately equal to the length of the crest of the dam (or, when it is possible, to the length the spill is forecasted to take place along).

The existence or absence of a parapet (small protection wall built all along the crest of the dam to protect the passage and avoid falls) can impact the calculation of the flood routing, if water reaches the crest. Parapets can be continuous walls of a certain height in the crest of the dam or include openings. If the parapet is closed, continuous and resistant enough to support a certain hydraulic load on its upstream side, it could be considered as an additional height added to the one of the dam for flood routing.

Finally, when modelling a **system of dams**, flood routing is made considering the working of the whole system. Hence, inflows and outflow from each reservoir should be analysed with the system operation rules. Furthermore, additional cases should be analysed to consider the effect of upstream dam failure discharges in downstream dams.

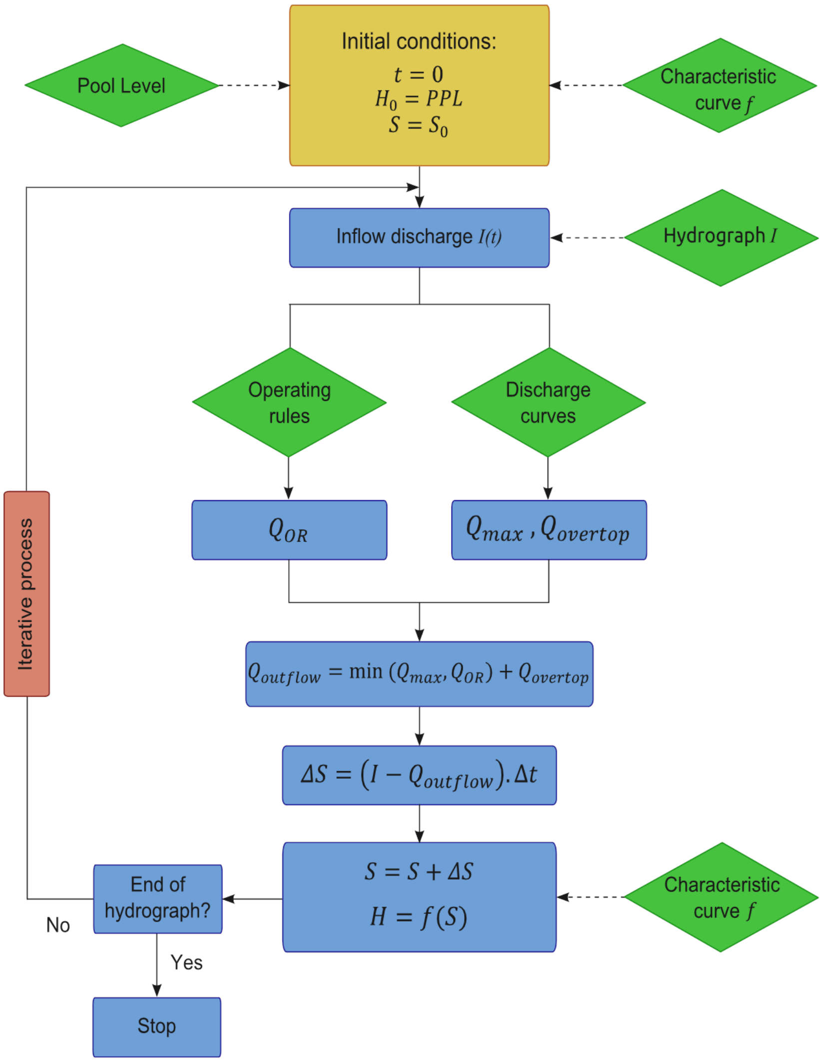


Figure 6-19. Generic scheme of flood routing process. Source: (A. Serrano-Lombillo, Fluixá-Sanmartín, and Espert-Canet 2012)**.**

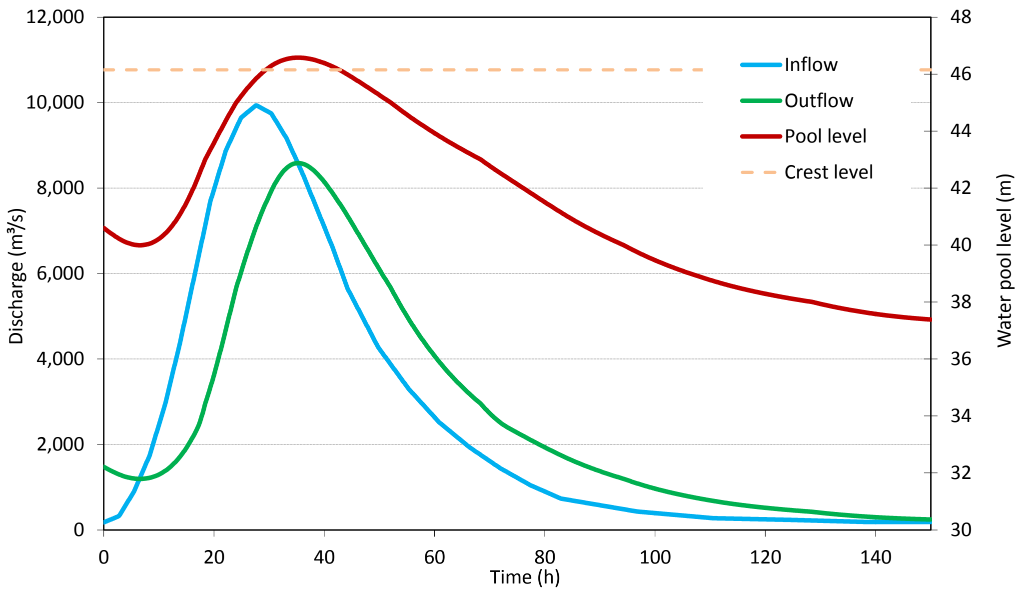


Figure 6-20. Example of flood routing results.

6.4.6 Failure probabilities estimation

Introduction

Once failure modes have been divided in well-defined failure mechanisms, the probability of each node is estimated. The study of failure probabilities is one of the key elements of the risk model and it is directly based on the identification of failure modes' outcomes.

Probabilities introduced in these nodes of the event tree are conditional on predecessor branches. This means that the probability estimated for one node, considers that the events described in the previous nodes (including loading cases) have already occurred.

The main tools to estimate these probabilities are reliability tools, expert judgment and specific methodologies to estimate failure probabilities for some types of failure modes like internal erosion or overtopping.

In practical cases, the former classification is not composed by hermetic cases. For example, it is valid to study some probabilities of the same failure mode through expert judgment and others through reliability techniques. It is also possible to employ both methods in the estimation of the same probability, as reliability techniques require data that can be estimated through expert judgment.

Reliability techniques

Any probability of a failure mode that can be modelled by a deterministic **numerical model** is a potential candidate to be numerically assessed throughout reliability techniques. Reliability techniques consist of propagating the uncertainties of the input of a model until reaching a result, in such a way that a probability is obtained instead of a deterministic value (like a safety factor). Therefore, a fragility curve is obtained that provides failure probability for each loading case, as shown **in Figure 6-21.**

Typical failure modes that can be assessed through these techniques are **sliding** in concrete dams, **instability** in embankments and other **structural failures** due to seismic events.

Usually, the results of reliability techniques are combined in the failure mode structure with other nodes (whose probability is estimated with expert judgement) that defines the probability of the model hypothesis.

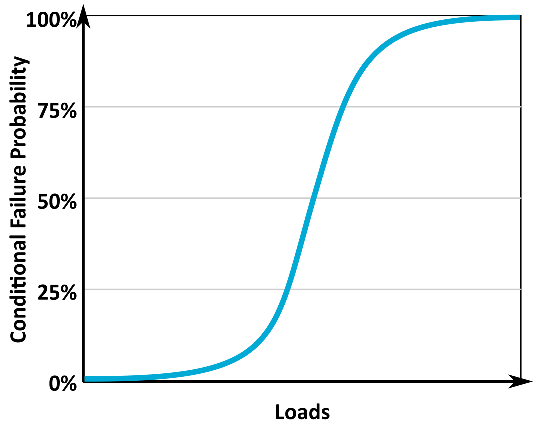


Figure 6-21. Typical shape of fragility curves obtained through reliability techniques

In this type of analysis, numerical models are usually related to Monte Carlo techniques. The uncertainties they must incorporate include: the scenario (levels of water, earthquakes to be considered, etc.), the way in which the loads act (uplift pressure, effective pressure, etc.) and the properties of the materials and model parameters. Other common difficulties lay in the definition of failure itself when the seismic scenario is under study. Therefore, though the model is built on a deterministic basis, at least, part of its input parameters has a stochastic structure, causing the output of the model to be also of stochastic nature.

The level of detail in this estimation is directly related to the level of complexity of the numerical model used and the epistemic analysis made. However, the number of necessary executions required for reaching an acceptable level of accuracy combined with the long times of execution of the usual models, can make the problem impossible to tackle in a direct way. A technique to overcome this obstacle is to deduce an analytic failure function (limit surface) from a few runs of the model and with the help of expert engineering judgment. Simplified analysis techniques as First Order Second Moment (FOSM) are also acceptable. Finally, it is worth mentioning that apart from studying the relevant failure probability it is convenient to correlate it to safety factors.

Some example on how this analysis can be made for different levels of detail and with different levels of treatment of uncertainty can be found in (Altarejos-García et al. 2014; Morales-Torres, Escuder-Bueno, et al. 2016; Altarejos-García et al. 2012).

Expert judgement

The estimation of probabilities by expert judgment consists of recording the opinion a subject has about the plausibility of an event. To provide solidity, the average of the estimations of several individuals is always recommended.

When probabilities are estimated through expert judgment, numerical models usually play a relevant role too. Although a numerical model could not provide directly failure probability, it can contribute to the understanding of the problem through the different parts composing the process. It can also delimit the boundaries of the debate, demonstrating a failure mode is plausible or quantifying the effect of some characteristic on which there exists some uncertainty through sensitivity studies. The process of estimating failure probabilities throughout expert judgment has an information role in which deterministic models are as valid as statistic or hybrid ones.

Moreover, there is a series of good practice rules that must be followed when doing expert judgment. Minimal conditions for this process according to (ANCOLD 2003) are:

- The estimations must be done by professionals with an extensive experience in dam engineering and a broad knowledge of dam failures, though it can also be beneficial to include some generalists as well as specialist in some subjects relevant to the process.

- Before estimating the probabilities, the logic of the failure must have been defined (see section 6.3.5), usually through an event tree, in such a way that the failure probability estimations are focused exclusively in the estimation of those probabilities.

- All the reasoning processes leading to the estimation of probabilities must be documented.

- The values and the process of its estimation must be reviewed externally.

In these sessions, firstly the relevant information to support probability elicitation for each failure mode and mechanism is reviewed in detail.

Secondly, the different factors that make each mechanism more of less likely, based on the factors defined in the identification of failure modes sessions, as explained in section 4.9, and identifying new factors for each node.

Thirdly, opinions are emitted by each expert individually. If the failure modes were not sufficiently disaggregated, the experts could be forced to express very low probabilities. This is problematic because when probabilities fall outside the range 0.1-0.9, the capacity of understanding disappears so it becomes difficult to emit impartial judgments. This is the reason why the disaggregation done in the definition of a failure mode is very important and if it is sufficiently detailed it will make this step easier (see section 6.3.5).

The tables of verbal descriptors are very helpful to guide the process of expression of probabilities. The descriptors relate terms such as "implausible", "possible" or "very probable" with numerical values. The use of this kind of table has been broadly cited in the scientific literature (Ayyub 2001). Despite their limitations they present several advantages: they help to overcome the initial resistance to express probabilities by people not accustomed to it, they speed up the process, the make easier to reach a consensus and they make the results more repeatable. Additionally, using the same table for all failure modes and in different dams helps the comparison and consistency of the results. Table 6-1 is recommended to support this elicitation process for probabilities of failure modes mechanisms.

Table 6-1. Verbal descriptors to support expert judgement. Source: (Ayyub 2001)**.**

Expression	Single-number probability, % (median of responses)	Specified range, % (median upper and lower bounds)
Almost impossible	2	0-5
Very improbable	5	1-15
Very unlikely	10	2-15
Unlikely	10	5-15
Low chance	15	5-20
Medium chance	15	10-25
Possible	20	10-20
Very low chance	40	40-70
Improbable	50	40-60
Probable	50	45-55
Likely	70	60-75
Very probable	70	65-85
Even chance	80	70-87.5
Very possible	80	75-92
High chance	80	80-92
Very likely	85	75-90
Very high chance	90	85-99
Almost certain	90	90-99.5

Table 6-2. Verbal descriptors to support expert judgement. Source: (USBR and USACE 2015)**.**

Verbal descriptor	Associated probability (%)
Virtually certain	99.9
Very likely	99
Likely	90
Neutral	50
Unlikely	10
Very unlikely	1
Virtually impossible	0.1

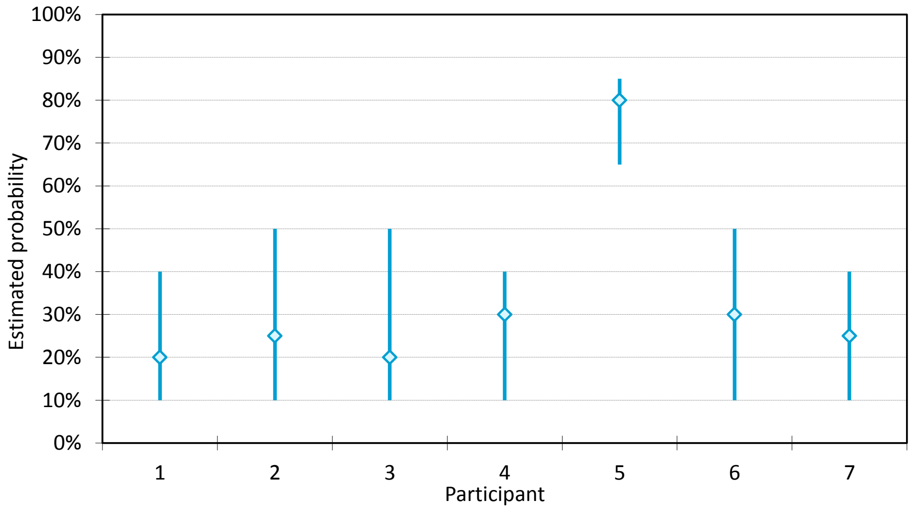


Figure 6-22. Example of presentation of expert judgment results for one node.

Verbal descriptors proposed by USBR (Table 6-2) are recommended to estimate failure probabilities of components in a fault tree.

Within the process of providing probabilities, it is a good practice not to give a single value but three: lower limit, best estimation and upper limit. In this way, each expert assesses the confidence they have on their own probability. Moreover, this makes the comparison with the results easier and facilitates uncertainty analysis on these probabilities.

All the information used in the session should be prepared in advance in a format that enables its review. To speed up the gathering of information, it is convenient to prepare forms that will be distributed to each participant.

Fourthly, once the individual probability estimations have been gathered, these must be shared and discussed within the group. For this, it is very useful to show this comparison in a quick and simple graph as shown in Figure 6-22.

At the sight of the comparison, if an expert has expressed a probability that falls out of the range of the group, he or she must argue his/her reasons. It is perfectly admissible to use different points of view which must be documented as they are a positive reflection of the diversity in the group. It is important to create an atmosphere in which the person who sustains a different opinion from the predominant in the group does not feel uncomfortable at expressing and defending his/her opinion. After the discussion, all the experts have the possibility to change their assignments.

Finally, results from all the experts are aggregated to obtain failure probabilities in each node. This aggregation can be made through arithmetic or a geometric mean.

More recommendations for this process can be found in (SPANCOLD 2012; ANCOLD 2003; Ayyub 2001; Budnitz et al. 1997).

Recommendations for specific failure modes

Overtopping is the most common failure mode in dams, especially in embankments whose resistant capacity to overtopping is generally lower.

In (Altarejos García et al. 2014), reference fragility curves for overtopping failure are recommended according to the dam typology. These curves are shown in Figure 6-23. These curves can be used as a first guide in a basic analysis and they can be adapted to each dam considering the following aspects:

- Dam foundation and abutments properties.
- In embankments, downstream face materials and type of protection.
- Existence of parapet walls in the crest of the dam.
- In heterogeneous embankments, upper limit of the impervious core, since core overflow could begin before the water level reaches the dam crest.
- Duration of the overtopping event, according to flood routing results.

Regarding **internal erosion** in embankments, several methodologies have been developed in recent years to estimate the probability of these types of processes, as shown in (Fell and Wan 2005; Fell, Wan, and Foster 2004; USBR and USACE 2015; FERC 2016).

According to these methodologies, internal erosion is analysed through a first initiation event. Internal erosion initiation probability is based on historical rates and embankment factors shown in Figure 6-24.

Hence, probability of internal erosion continuation and progression is based on embankment materials capacity to create pipes and filter efficiency. Then, detection and intervention probability before the failure occurs is evaluated, based on existing surveillance and monitoring procedures and intervention possibilities. Finally, dam breach probability is estimated according to dam geometry and foreseen intervention actions.

Finally, detailed recommendations to estimate failure probability for **other failure modes** can be found in (USBR and USACE 2015).

6.4.7 Dam failure hydrographs data

In risk models, failure hydrographs are usually characterized throughout a significant variable (usually the peak discharge). This makes the required works to be split into two parts:

- Estimation of the complete failure hydrographs (not just their peak discharge). These hydrographs are not introduced directly in the risk model but serve in the

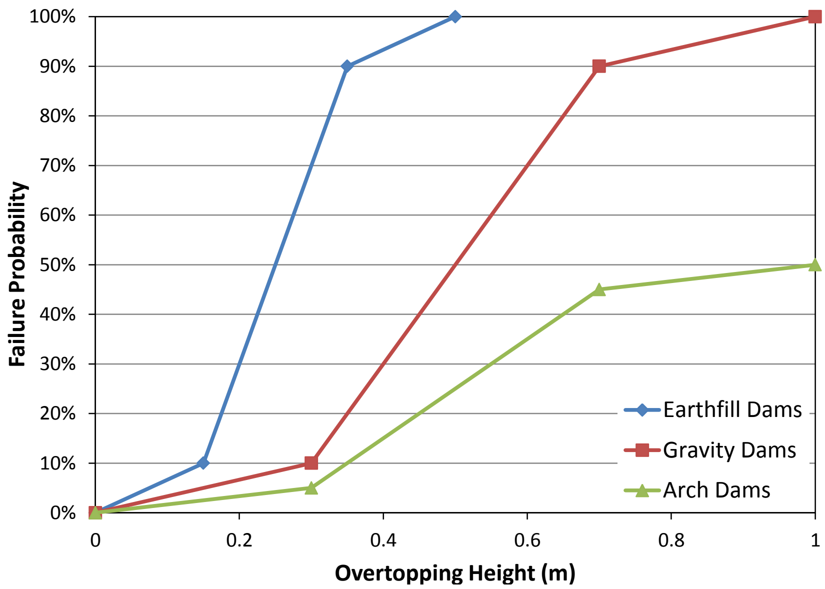


Figure 6-23. Fragility curves recommended for the overtopping failure mode. Source: (Altarejos García et al. 2014).

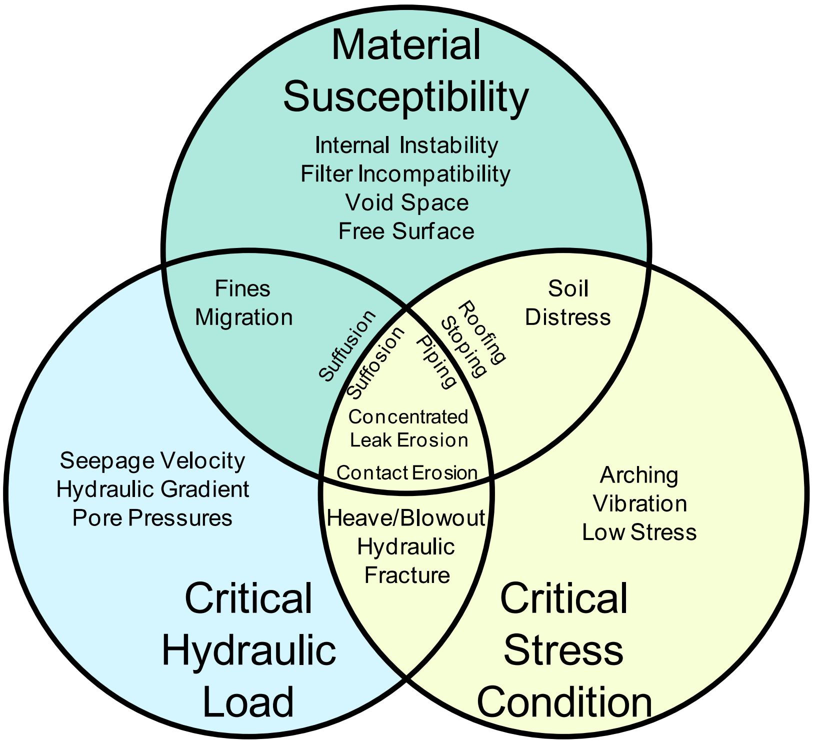


Figure 6-24. Factors affecting the initiation of internal erosion. Source: (USBR and USACE 2015)**.**

calculation of the curves of consequences in case of peak discharge (as shown in the following sections), which are the ones introduced in the model.

- Estimation of a curve relating the maximum pool level with any representative variable of the failure diagram (typically breakage peak discharge) for each failure mode. These curves are introduced in the *Failure hydrograph* node of the risk model.

In both cases, the first step in the estimation of failure hydrographs is to estimate the dam failure breach. This breach may be different for different failure modes and its progression will also vary as the water level in the reservoir changes. Consequently, as opposed to the studies usually developed for an Emergency Action Plan, in which only a few failure scenarios are studied (e.g., breakage with the reservoir at its crest level), Risk Analysis contemplates the failure hydrographs corresponding to the whole range of possible pool levels in the reservoir and to each of its failure modes.

In the *Guidelines for Mapping Flood Risks Associated with Dams,* it is described in detail different hypothesis that can be used to define the dam breach parameters and to obtain the **complete failure hydrographs** that will be used to estimate dam failure consequences. As explained above, these hypotheses should be adapted to each case based on the expected failure mechanism for each failure mode.

In general, the **relation between maximum pool level and breakage peak discharge hydrographs** are usually obtained trying different pool levels in the hydraulic model used to estimate dam failure consequences and flood risks maps. Hence, with these models, the curve of peak discharge vs. pool level is obtained by correlating the peak discharges of the hydrographs with the maximum pool levels to which they correspond.

In a **less detailed analysis**, a single failure hydrograph is obtained and then, it is escalated for smaller and larger peak discharges. Hence, the dam break peak discharge curve vs. pool level could be obtained from empirical relations. The basic level of detail can be particularly advantageous when there are already one or several available failure hydrographs, for example, the ones contained in the Emergency Action Plan, but the hydraulic model is not available. In this case, the proposed methodology provides the required results with little effort. On the contrary, if it is necessary to calculate the failure hydrograph, the additional effort required to develop the explained methodology is relatively small.

To define these empirical relationships, some researchers have used past dam failures to develop empirical equations that relate peak discharges at failure with one or several parameters of the dam or the reservoir (height of the dam, storage volume, water level at the moment of failure, etc.). Most of these relationships are discussed in the *Guidelines for Mapping Flood Risks Associated with Dams.*

Among all the aforementioned methods, Froehlich's method (Froehlich 1995; Wahl 1998), is briefly explained hereafter. Froehlich developed a simple regression equation in 1995 to estimate the peak discharge as a function of the reservoir volume and its height, from the data of peak discharge for 22 cases:

$$\boldsymbol{Q_p = 0.607 \cdot V_w^{0.295} \cdot h_w^{1.24}}$$

Where Q_p is the predicted peak discharge in m^3/s, V_w is the volume of stored water at the moment of failure in m^3 and h_w is the pool level in the reservoir calculated from the lower point of the final breach where the water level is expressed in meters. Figure 6-25 compares the values of peak discharge calculated using Froehlich equation. As explained, this is recommended to adjust this relation using a single value of water pool level and peak discharge. This value can be obtained from the Emergency Action Plans

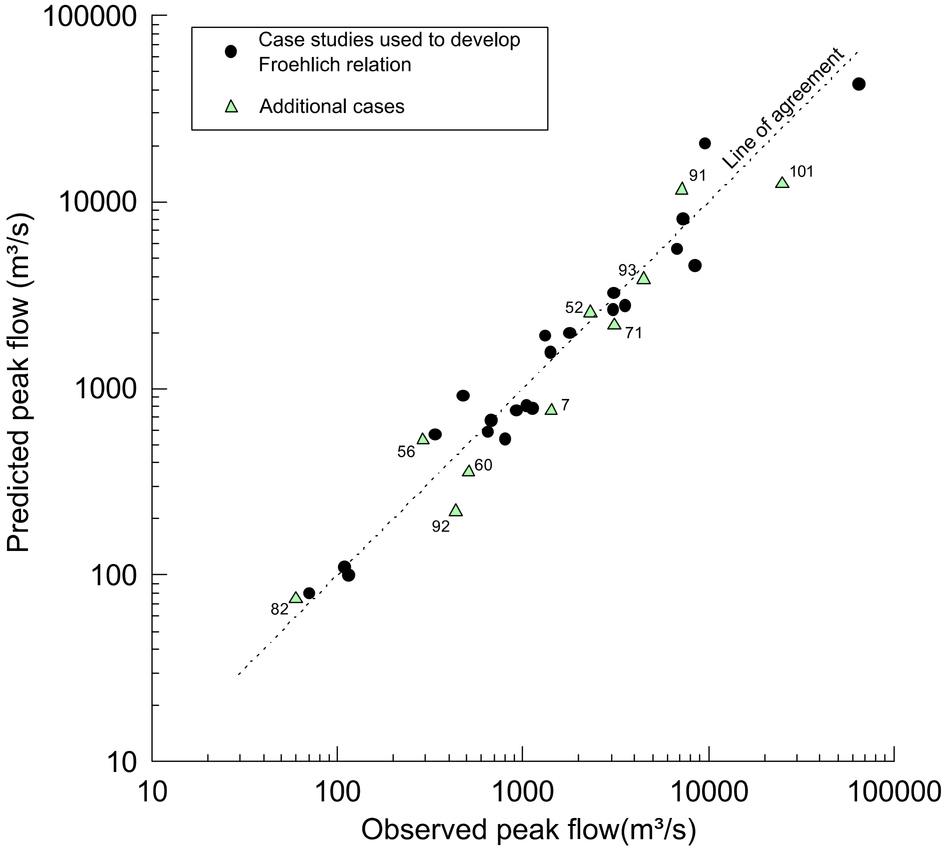


Figure 6-25. Observed peak discharges vs. predicted peak discharges using Froehlich equation. Source: (Wahl 1998)**.**

or the Dam Hazard Potential Classification.

6.4.8 Loss of life estimation

When a flood due to a dam failure results in loss of life, this is clearly the most serious consequence and the one that causes the biggest impact on the public perception of the disaster. Therefore, this consequence has been the object of most consequences studies and therefore, the one where more calculation methods are available.

Loss of life is generally produced directly by the flood wave. In some types of floods (especially in hydrologic scenarios in tropical areas), the indirect loss of life due to diseases or lack of drinkable water can reach important magnitudes and should also be studied.

The methods to estimate loss of life provide an indicative value of the magnitude of this parameter but cannot provide an accurate figure. This is due to the numerous variables involved in this process that are difficult to properly model (e.g., people's behaviour). In any case, they are very useful to compare the expected social impact of failure between different dams.

In general, most of the current methodologies follow the scheme described below (Graham 2009):

1. Identifying a scenario to be assessed, including the moment of the day or of the year and the failure mode of the dam since they can affect the results. If there are significant daily or seasonal variations in the downstream populations, different loss of life results can be obtained and introduced in the risk model (with the probability of each one).
2. Obtaining data of the characteristics of the flood such as water speed, depth, rapidity, duration, etc. from flood maps.
3. Determining for the evaluated scenario when and how the messages to the population are broadcast.
4. Determining, for the different downstream centres of population, the time elapsed since the warning message was received and the arrival of the flood wave. This is called the warning time and is one of the keys to estimating the loss of life. In this sense, it is necessary to think of warning procedures and estimating the time needed to initiate warnings once the dam begins to fail, as explained in the previous point.
5. Estimating the number of people in each of the zones where the floodable area is divided, according to the flood and the warning time. People remaining in the flooded areas will be there either because they were not warned, because they could not be evacuated or because they refused to move.
6. The loss of life is estimated from the exposed population in each area by using the fatality rates based on the characteristics of the flow and the availability of shelters (buildings, high areas, etc.).

This general procedure is summarized in Figure 6-26.

The most common method to estimate loss of life is the one proposed by (Graham 1999). Graham's method proposes fixed fatality rates that are applied to the population in the locations flooded due to a dam failure. These fatality rates are shown in Table 6-3 and they depend on:.

- **Severity of the flood**: It represents the degree of destruction of buildings and refuges, so it is a function of the depth of the flood. This severity is divided in three categories:
  - High severity: A destruction of the buildings and structures, killing most of the people inside. It is usually applied to areas near the dam.
  - Medium severity: Some buildings, such as houses, suffer serious damages, however trees and most of the

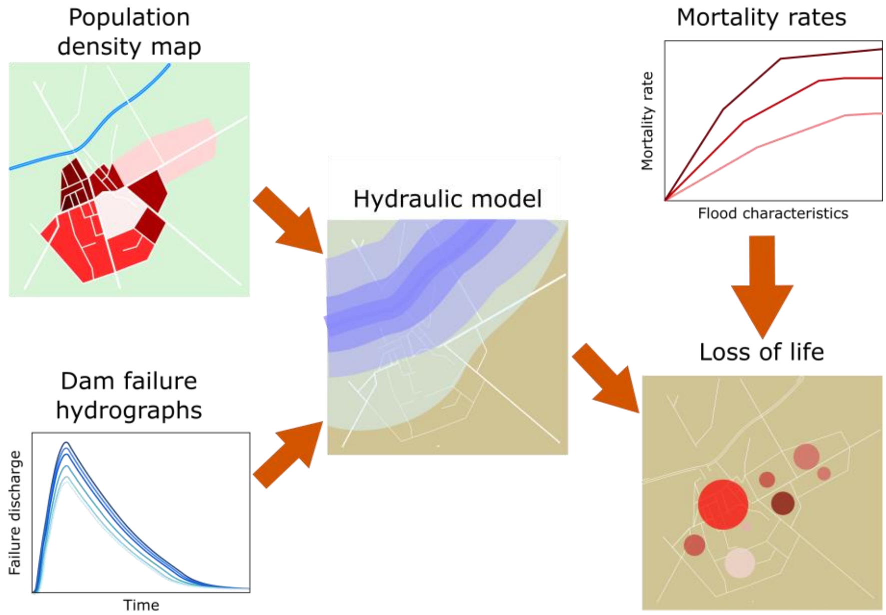


Figure 6-26. General procedure to estimate loss of life.

buildings remain for people to seek refuge.

- Low severity: No building is destroyed, and damages are superficial.

- **Warning time**: Time elapsed between the first warning is issued to the population and the moment of arrival of the flood to this population. As explained above, this is the one of the key parameters to estimate loss of life, since it is an indicator of the available time to evacuate or protect people. It is also grouped into three categories:
  - No warning: Warning time less than 15 minutes. The population is only warned when they see or listen to the in-coming flood.
  - Some warning: Warning time between 15 and 60 minutes. Official warnings circulated to some people through different communication channels; not everybody is warned properly.
  - Adequate warning: Warning time greater than 60 minutes. Proper warning disseminated; most people at risk know about the in-coming flood.

- **Understanding of the severity of the flood**: This parameter introduces the understanding by the population of the potential consequences and dangers to which they are exposed and their alertness regarding a possible flood. It is divided in two categories:
  - Vague understanding: Population receiving the warning has never seen a flood or does not comprehend the magnitude of the imminent flood.
  - Precise understanding: Population understands the warning messages properly and realises the flood's magnitude.

In this method, the population at risk is defined as the population within the flood zone when the dam fails, therefore, it does not consider explicitly the evacuation procedures. To estimate it, it is important to study the population located in each of the locations affected by the considered situation. It is possible to resort to census data and to population studies performed by public institutions that reflect seasonal variations. Other data, such as the number of working people in the commercial and industrial areas along with their origin are also important to estimate the daily variations of population.

The methodology proposed by the **SUFRI project** proposes a classification of ten categories for the studied population, according to the existence of warning systems, coordination between the emergency systems and the local authorities, mass media, training of the population, etc. Each category is related to some referential fatality rates (see Table 6-4), depending on the warning time and the degree of severity of the flood, which are based on the studies done by Graham in 1999. SUFRI has put a focus on the affected population, expected to act in a proper way to reduce possible consequences of flooding. In this context, an effective risk communication plays a major role to initiate, support, maintain and keep up the knowledge about flood reducing measures and adequate behaviour.

One method similar to Graham's is the method developed by Jonkman (Jonkman, van Gelder, and Vrijling 2003), which calculates loss of life from population at risk, estimating the different processes that happen during the flood.

In recent years, more **complex methods** have been developed to estimate loss of life, which can be appropriate for a higher level of detail. An example is the **Life Safety Model** (Lumbroso et al. 2011) which uses a two-dimensional model. It is a dynamic, model for estimating the flood risk to people in terms of loss of life and injuries. It also considers evacuation times and how improvements in emergency planning may help to reduce the loss. It allows for a dynamic interaction between people, vehicles, buildings and the flood wave. This model is based on the latest available physical equations rather than empirically deduced mortality rates and evacuation times.

It estimates the loss of life due to drowning,

Table 6-3. Proposed fatality rates for estimating life loss due to dam failure: Adapted from (Graham, 1999)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk that died)	
			Average	Range
HIGH	No warning	Not applicable	0.75	0.3 to 1.00
	15 to 60	Vague	The values shown above are to be used and applied to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		Precise		
	More than 60	Vague		
		Precise		
MEDIUM	No warning	Not applicable	0.15	0.03 - 0.35
	15 to 60	Vague	0.04	0.01 - 0.08
		Precise	0.02	0.005 - 0.04
	More than 60	Vague	0.03	0.005 - 0.06
		Precise	0.01	0.002 - 0.02
LOW	No warning	Not applicable	0.01	0.0 - 0.02
	15 to 60	Vague	0.007	0.0 – 0.015
		Precise	0.002	0.0 – 0.004
	More than 60	Vague	0.0003	0.0 – 0.0006
		Precise	0.0002	0.0 – 0.0004

exhaustion, building collapse and cars being swept away. It includes traffic and pedestrian models and the ability to simulate the effectiveness of the dissemination of flood warnings on the behaviour of the persons affected.

In all these methods, the impact of warning initiation and propagation hypothesis in loss of life results may be considerable. For this reason, uncertainty analysis of the judgements made is advisable, assessing its impact on risk results. This analysis provides also valuable information on the importance of warning procedures for each dam.

As explained in Section 6.3, the final goal of loss of life assessment is the **estimation of curves** relating the dam output hydrograph with the resulting loss of life so risks can be obtained (in failure and non-failure cases). The peak discharge used to define a flood is usually employed to correlate loss of life with hydrographs, since damage will depend in great measure on this value.

In non-failure cases, when these curves are defined, it is necessary to identify the discharge which could produce the first loss of life (usually when first households are flooded) to define the initial point of these curves.

Several floods with different maximum peak discharges must be studied to determine these curves. In this way, the estimated loss of life of each flood would define a point of the curve. Thus, the number of points will coincide with the number of studied floods. The larger the amount of studied points, the better defined the curve and the more accurate risk results will be. It can be concluded that the number of points depends on the desired level of detail intended in the Risk Analysis. In general, it is advisable to use at least 4 or 5 points to avoid an incomplete definition of the curve.

Loss of life estimation is explained in more detail in the *Guidelines for Mapping Flood Risks Associated with Dams*. More information can also be found in (USBR and USACE 2015; FERC 2016; SPANCOLD 2012).

Table 6-4. Fatality rates in case of river flooding. Adapted from (I. Escuder-Bueno et al., 2012).

ID	Category for the Case Study (C)	Warning Time TW(h)	Flood severity (Sv)		
			High (3)	Medium (2)	Low (1)
1	There is no public education on flood risk terms. No warning systems, no EAP. There is no coordination between emergency agencies and authorities. No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.9 0.7 - - -	0.3 0.3 0.08 0.06 0.0002 0.0002	0.02 0.02 0.015 0.0006 0.0002 0.0001
2	There is no public education on flood risk terms. There is no EAP, but there are other warning systems. There is no coordination between emergency agencies and authorities. No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.9 0.675 - - -	0.3 0.3 0.075 0.055 0.0002 0.0002	0.02 0.02 0.014 0.00055 0.0002 0.0001
3	There is no public education on flood risk terms. There is EAP, but it has not been applied yet. Some coordination between emergency agencies and authorities (but protocols are not established). No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.85 0.6 - - -	0.3 0.2 0.07 0.05 0.0002 0.0002	0.02 0.015 0.012 0.0005 0.0002 0.0001
4	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols established). No communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.75 0.5 - - -	0.3 0.15 0.04 0.03 0.0002 0.0002	0.02 0.01 0.007 0.0003 0.0002 0.0001
5	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public (not checked yet).	0 0.25 0.625 1 1.5 24	0.9 0.75 0.5 - - -	0.3 0.15 0.0375 0.0275 0.0002 0.0002	0.02 0.01 0.0065 0.000275 0.0002 0.0001
6	There is no public education on flood risk terms. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.75 0.475 - - -	0.3 0.15 0.035 0.025 0.0002 0.0002	0.02 0.01 0.006 0.00025 0.0002 0.0001
7	Public education. EAP is already applied. Coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public. Or Dam break with no hydrologic scenario.	0 0.25 0.625 1 1.5 24	0.9 0.65 0.4 - - -	0.3 0.1 0.02 0.01 0.0002 0.0002	0.02 0.0075 0.002 0.0002 0.0002 0.0001
8	Public education EAP is already applied. It has been proved or used previously. Coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.55 0.35 - - -	0.3 0.06 0.01 0.005 0.0002 0.0002	0.02 0.006 0.0015 0.00015 0.00015 0.0001
9	Public education. EAP is already applied. It has been proved or used previously. High coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.55 0.35 - - -	0.3 0.06 0.008 0.004 0.0002 0.0002	0.02 0.006 0.0015 0.000125 0.0001 0.0001
10	Regular activities and plans for public education. EAP is already applied. It has been proved or used previously. High coordination between emergency agencies and authorities (there are protocols established). Communication mechanisms to the public.	0 0.25 0.625 1 1.5 24	0.9 0.5 0.3 - - -	0.3 0.03 0.005 0.002 0.0002 0.0002	0.02 0.005 0.001 0.0001 0.0001 0.0001

6.4.9 Estimation of economic consequences

Large dam failures can produce very high economic consequences in downstream areas. These consequences are generally divided into two groups:

- Direct consequences: Damages produced directly by the flood wave.
- Indirect consequences: Due to the economic disruption that the flood produces in the downstream area and the losses created by the absence of the reservoir.

In general, current methods used to estimate **direct economic consequences** consist of two steps:

1. Estimating the total value of land use, that is, what would be the costs if every building and crop existing in the analysed land were destroyed because of the flood.
2. Applying those costs to the curve depth-damages, that relates the maximum depth of a flood with an associated value of destruction. In this way, by multiplying the degree of destruction by the economic cost of a maximal destruction, it is possible to estimate the economic consequences of the relevant flood.

Consequently, to apply this methodology, it is necessary to use, as a starting point, land-use maps and flood maps which show the depth of water at each location, as shown in Figure 6-27.

In (Huizinga, De Moel, and Szewczyk 2017), a compilation is made of depth-damage curves worldwide. Average curves for Asian countries are shown in Figure 6-28. In this document, recommendations are also provided to estimate land use value to estimate flood consequences. These values can be particularized for specific locations if more data is available of the land use value.

When a higher accuracy is intended these curves can be calibrated with data of degree of destruction caused by past floods, which will provide a better adjustment of the results to reality.

Indirect damage refers to the economic consequences that are not produced directly by the flood wave. That is, the effects the flood has on the area beyond the effect of water itself. Some clear examples of this kind of effects are the consequences due to the abrupt stoppage of economic activities in the area and the cost of accommodating the displace public whose homes have been affected by the flood.

The estimation of indirect damage is very complicated as there are myriad components involved and the processes implied are very complex. One factor of importance is time, since, as opposed to direct conditions, indirect damages appear prolonged in time.

It is obvious that if economic activity stops in a certain area, there will be a loss of production and decrease of the products offer. Other consequences can ensure this interruption and some of them can be particularly severe in certain industries related to intermediate products, commerce, and services such as electric supply, telecommunications supply and relations between firms. In addition, indirect damage will include other costs non-related to economic activity, such as the accommodation of the populations whose homes have been affected, the costs of rescue actions and/or of protection structures.

In general, it is possible to estimate indirect costs as a fix percentage of direct costs. The values of this percentage vary largely according to the area in which they are applied. (James and Lee 1970) recommend adopting indirect damages as 15% of direct damages in urban areas and as 10% in agricultural areas. Economical models can be used to estimate long term flood consequences in more complex studies.

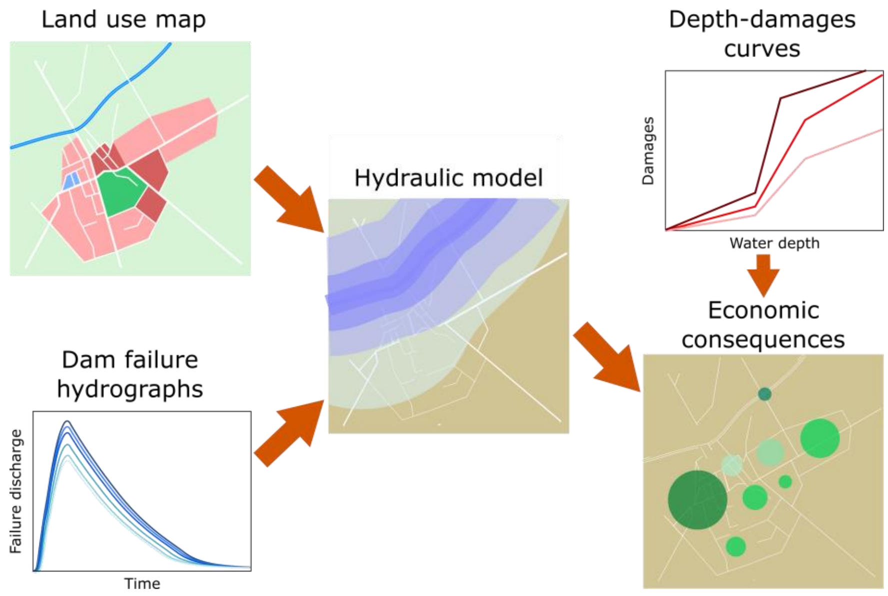


Figure 6-27. General procedure to estimate direct economic consequences.

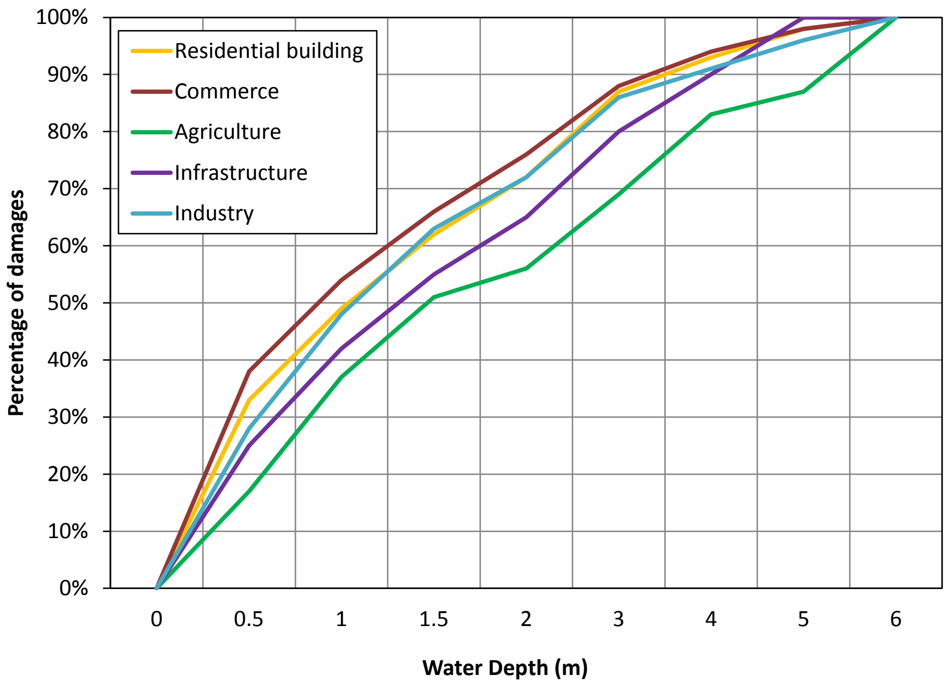


Figure 6-28. Average depth-damage curves for Asia. Adapted from: (Huizinga, De Moel, and Szewczyk 2017)**.**

Economic consequences produced by **the loss of the reservoir** should include the expected loss of benefits during the recovery period (typically 5-10 years). According to (Ekstrand 2000), the losses produced by the breakage of the dam on the water resources are:

- Loss of agricultural benefits: since water cannot be stored, its use for irrigation becomes difficult and affects cultivation of certain crops, resulting in additional economic losses.

- Loss of water supply: the loss of water storage can produce a lack of industrial production and economic costs resulting in extraordinary measures adopted to guarantee sustainable water supplies to the public.

- Loss of recreational use: the loss of the water storage makes its use for recreational activities in the reservoir impossible, which might induce significant economic losses depending on the usual number of visitors and existing businesses.

- Loss of benefits for flood control: the existence of the reservoir enables the routing of floods and the reduction of the flood consequences downstream; therefore, its destruction can imply future damages by uncontrolled flooding.

- Loss of electrical supply: if there is a hydroelectric plant in the dam, its destruction produces a loss of electrical supply that must be estimated. This loss is particularly important in dams with high power production.

In addition, if it is expected that the dam would be rebuilt after failure, an estimation of dam building costs should also be included. This cost can be estimated from similar construction projects in the country or using international references (A. Serrano-Lombillo, Morales-Torres, and García-Kabbabe 2012; Ekstrand 2000).

Estimating economic consequences are explained in more detail in the *Guidelines for Mapping Flood Risks Associated with Dams*. More information can also be found in (SPANCOLD 2012; USDHS 2011; Ekstrand 2000).

As explained in Section 6.3, the final goal of economic consequences assessment is the **estimation of curves** relating the dam output hydrograph with the resulting economic consequences, so risks can be calculated for failure and non-failure cases. The peak discharge used to define a flood is usually employed to associate consequences to hydrographs, since damage will depend in great measure on this value.

In non-failure cases, when these curves are defined, it is necessary to identify the discharge that produces the first economic consequences for defining the initial point of these curves. In addition, non-failure curves do not include the economic consequences produced by the loss of the reservoir.

Several floods with different maximum peak discharges must be studied to determine these curves. In this way, the estimated consequences of each flood would define a point of the curve. Thus, the number of points will coincide with the number of studied floods. The larger the amount of studied points, the better defined the curve and more accurate the risk results. It can be concluded that the number of points will depend on the desired level of detail intended in the Risk Analysis. In general, it is advisable to use at least 4 or 5 points to avoid an incomplete definition of the curve.

6.4.10 Other dam failure consequences

Dam failure can produce other types of consequences that cannot be easily quantified through loss of life or economic terms.

An example is the effects of dam failure on **health and social affairs.** These effects depend on the nature, location, and extent of the area affected by the dam failure, with regards to the distribution of the inhabitants. Human health could be affected by consumption of polluted drinking water/ food due to contamination of the source/ supply network. It could also be due to failure or shortage of the water, sewage and power supplies. Uncontrolled release of sewage, industrial or toxic waste because of a dam break may also lead to widespread contamination. Social impacts of dam break would depend on demographic characteristics, social and community values, needs and networks, the extent of community support services, the capacity of responding institutions as well as the degree of disaster preparedness and warning time available.

Regarding **environmental consequences**, damages are difficult to define numerically and therefore difficult to integrate in a quantitative analysis, but it is important to describe them and to take them into consideration for decision making, especially when important environmental protected areas are located downstream or when industrial or toxic waste is found in the reservoir. Some examples of potential environmental impacts of dam failure are (FEMA 2012):

- Contamination resulting from septic system failure, back-up of sewage systems, petroleum products, pesticides, herbicides or solvents.
- Pollution of the potable water supply or soils.
- Changes in land development patterns.
- Changes in the configuration of streams or the floodplain.
- Erosion, scour, and sedimentation.
- Changes in downstream hydro geomorphology.
- Loss of wildlife habitat or biodiversity.
- Degradation of wetlands.
- Loss of topsoil or vegetative cover.
- Loss of indigenous plants or animals.

More information on these consequences will also be found in the *Guidelines for Assessing and Managing Environmental Impacts of Dams*.

However, in recent years, methodologies are being developed to estimate economic benefits from ecosystem services provided by the environment (recreation, habitat, resources…). Hence, this can be the first step towards quantifying environmental impacts of dam failure in economic terms and including them in the risk models.

Other consequences that cannot be easily quantified but should be considered in decision making include **patrimonial and cultural losses**.

6.4.11 Summary of Levels of Detail

In the previous sections, different methods are proposed to obtain the data needed for the risk model from basic to more complex levels of detail. These methods are summarized in Table 6-5.

Depending on the depth of the analysis and the importance of the dam, it will be sensible to employ a higher or lower level of detail. In general, the level of detail must be reasonably consistent between the different parts of an analysis, putting more effort into the variables that will have a bigger impact on the result. A way of finding out which are the most influent variables is to start from a simple model and to do a sensitivity analysis of the different variables. The same reflection is valid regarding the level of detail in the analysis of a portfolio of several dams.

Therefore, it is not always advisable to do an analysis with a maximum level of detail. On some occasions, it can be more helpful to follow an iterative process in which the analysis is done with a low level of detail for the first time. Doing this at the first stage allows the identification of the issues and/or the dams that require a deeper study. The level of detail should also be influenced by the type of risk reduction actions that are being prioritized and their importance.

6.5 Risk Calculation

6.5.1 Event tree calculation

Once the risk model architecture is built and input data is introduced in each node, risk results can be obtained for computing the event tree.

As explained previously, probabilities in event trees, except for the initiating event, are always conditional, that is, for any intermediate node it is assumed that all preceding events (parent nodes) have already happened. For example, Figure 6-29 shows a simplified event tree with only two events: pool level and failure probability. As it can be seen, the probabilities assigned to the second event (failure probability) are conditional to the pool level and therefore different in each sub-tree.

Therefore, to calculate the probability of occurrence of one of the branch of events, the conditional probabilities in the branch must be multiplied. Since the rule requires the branches from a same node to be mutually exclusive and collectively exhaustive, the sum of the probabilities of all of them must be one.

Table 6-5. Summary of levels of detail in risk model input data.

Model Data	Tier 1 – Basic level	Tier 2 – Intermediate level	Tier 3 – Advanced level
Floods	Basic study with PMF	Hydrologic analysis with a broad range of return periods	Seasonal hydrology Complex uncertainty analysis
Earthquakes	Basic analysis with seismicity maps or MCE	Probabilistic seismic analysis	Complex seismic analysis including epistemic uncertainty
Previous pool levels	Pool level equal to Maximum Operation Level	Pool level probability based on registry or simulations	Pool levels simulations accounting for climate change
Gates availability	Recommended vales for gates reliability	Simple fault tree analysis	Complex fault tree analysis
Flood routing	Simple flood routing computation	Flood routing with existing operation rules	Flood routing with complex operating rules in systems of dams
Failure probabilities	International recommendations for overtopping	Expert judgment Simple reliability techniques	Complex numerical models and reliability techniques
Failure hydrographs	Directly from the Emergency Action Plan	Empirical methods and hydraulic models particularized for each failure mode	Complex uncertainty analysis on breach parameters and hydraulic models
Loss of life estimation	Graham or SUFRI Methods directly with data from the Emergency Action Plan	Graham or SUFRI Methods with new hydraulic simulations	Simulation methods like LSM
Economic consequences	Depth-damages curves with data from the Emergency Action Plan	Depth-damages curves with new hydraulic simulations	Economic models to evaluate long term flood consequences
Other consequences	Description of main consequences in protected areas	Qualitative analysis of environmental and cultural consequences	Economic estimation of environmental and cultural consequences

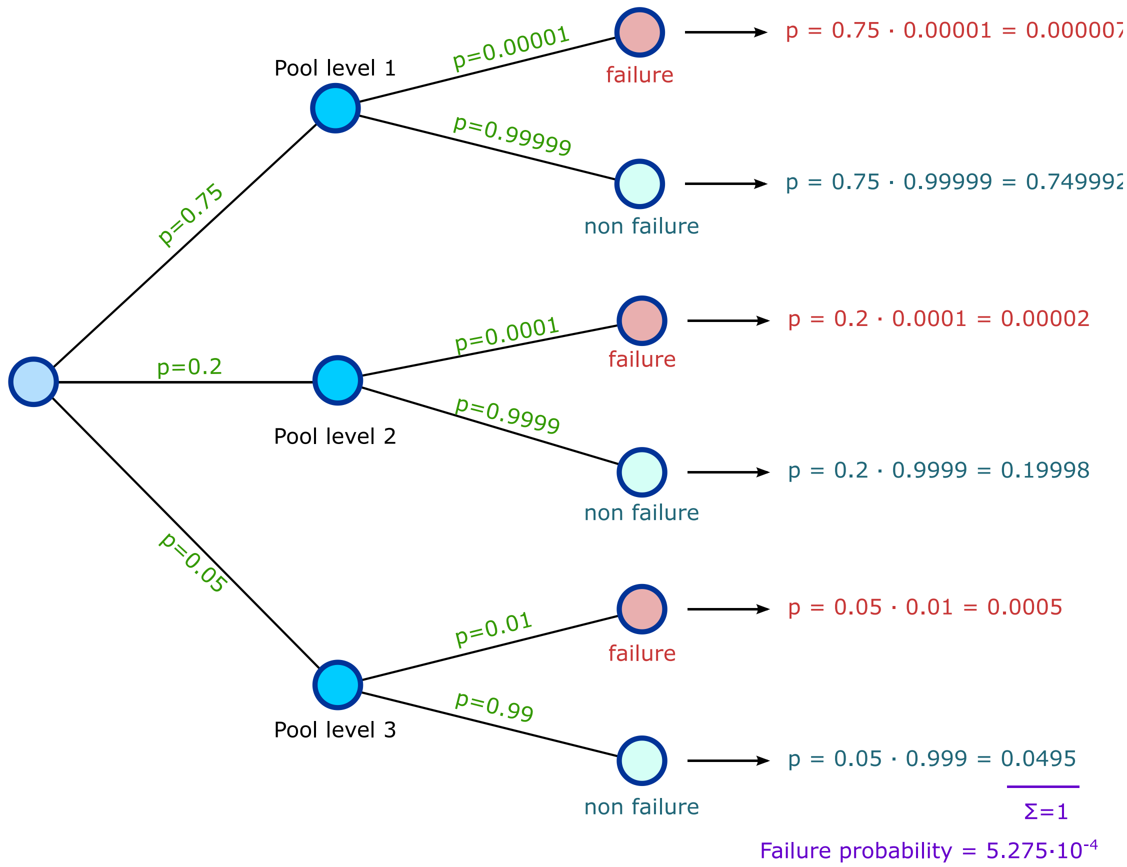


Figure 6-29. Example of failure probability calculation in a simplified event tree.

Figure 6-29 illustrates this calculation of probabilities for this simplified event tree. It can be checked that the global sum equals 1. As can be observed in this figure, when all the branches of the event tree are calculated, failure probability can be obtained by adding the probability of all the failure branches. Societal risk is obtained by multiplying in each branch its probability by its social consequences. The same computation with economic consequence is made to obtain economic risk. A more detailed event tree is shown in the example found in Appendix B.

As explained in Section 6.1, both types of risk (incremental and total) should be computed to inform dam safety decision making.

6.5.2 Common Cause Adjustment

When there are *k* non-mutually exclusive failure modes within a same load (each one with an individual probability p_i), the total probability of failure for this load (p_F) is found within the range fixed by the *Theorem of the unimodal limits* (Melchers 1999). This theorem is therefore one way of bounding the magnitude of the total failure probability in scenarios resulting from a common cause:

$$\max(p_i) \le p_F \le 1 - \prod_{i=1}^{k} 1 - p_i$$

For instance, if for a certain pool level, probability of failure mode 1 is 20%, probability of failure mode 2 is 60% and probability of failure mode 3 is 40%. The total dam failure probability for this pool level is between 60% (lower limit) and 80.8% (upper limit, obtained from: 1 - (1-0.2) · (1-0.6) · (1--0.4)).

If it is decided to do an adjustment from the lower limit, an option with physical meaning is to maintain without adjustment the probability of the most likely failure mode and to reduce the rest of the probabilities to 0. This corresponds to a dominance process and is equivalent to saying that if the dam fails, it

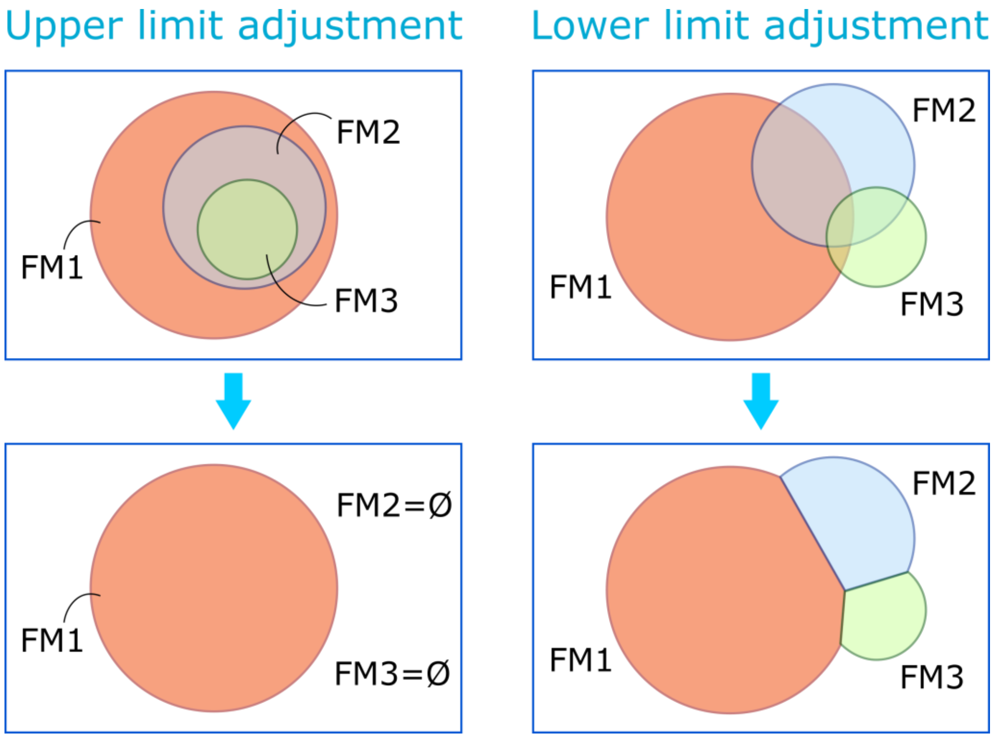


Figure 6-30. Conceptual representation of Common Cause Adjustment techniques. Adapted from (SPANCOLD, 2012).

will be due to the first failure mode, preventing other failure modes from happening. Figure 6-30 illustrates the situation.

If an adjustment from the higher limit is preferred, all the failure modes can be adjusted in the same manner, so the sum of the probabilities is equal to the one calculated through its higher limit. Figure 6-30 illustrates this situation.

It is also possible to perform intermediate types of adjustment between the two detailed ones. Many times, there is no firm reason to prefer one type of adjustment over another, both adjustments are calculated and the average between them is taken.

Finally, it should be highlighted that each failure mode may be made up by a combination of different events, as explained in Section 6.3.5.

6.5.3 Risk Calculation in dam systems

As explained in 6.3.5, in systems of dams in cascade, it can be recommended to create a risk model that encompasses the whole system of dams.

In these cases, direct incremental risk calculation of each dam from the event tree results is not so straightforward. In (A Serrano-Lombillo et al. 2011), a methodology is proposed to compute this type of incremental risks, being able to allocate the risk for each dam and of each failure mode. Conceptually, the proposed approach consists in obtaining the global risk of the system in its existing state (with the estimated probabilities of failure of each dam but including the risk corresponding to the branches of non-failure) and computing the risk of the system assuming that a specific dam is indestructible. The subtraction between these two values provides the incremental risk for this dam.

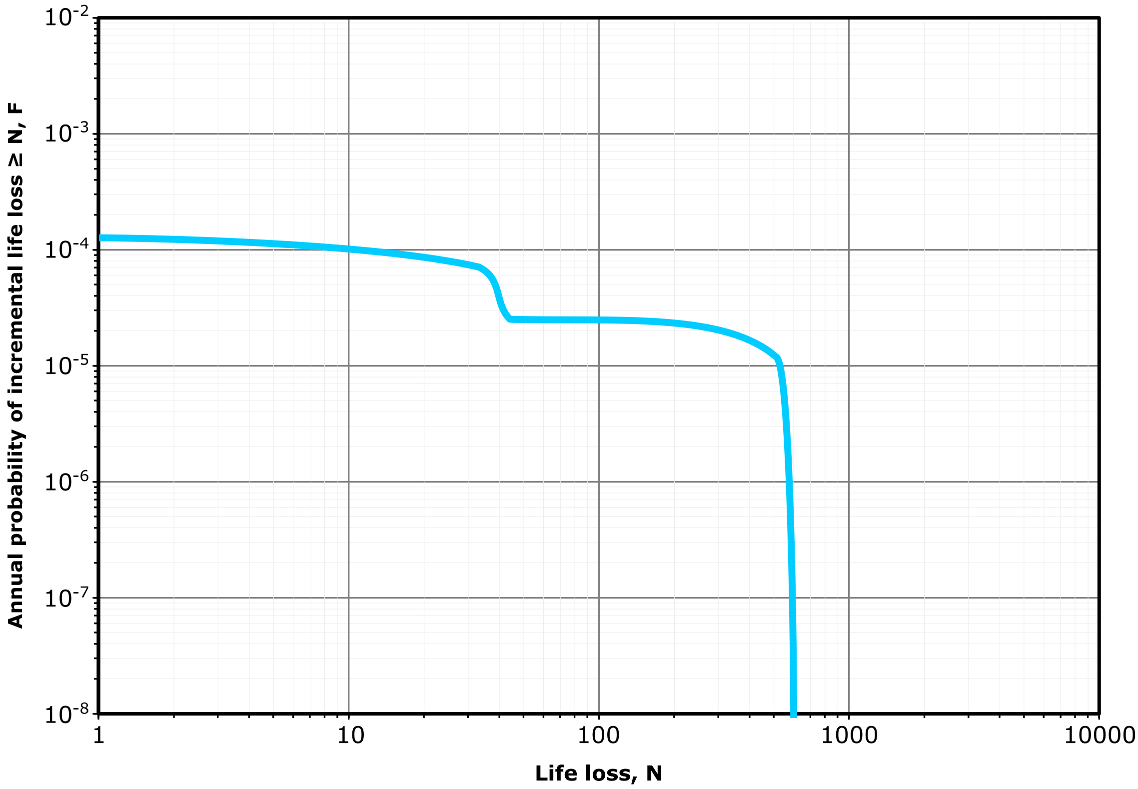


Figure 6-31. Example of FN graph. X and Y axis are represented in logarithmic scale.

Appendix 3 provides a complete case study of a Risk Assessment for a system of dams.

6.6 Risk Representation

6.6.1 FN and FD Graphs

One of the most extended representations of risk is the **FN graph**, where existing risk is represented by a curve. In this curve, the horizontal axis represents the consequences in terms of fatalities (N) and the vertical axis the probability that this number of fatalities (F) is exceeded. Figure 6-31 shows an example of an FN graph. The area located under an FN curve is equal to the societal risk.

As can be noticed, the curve decreases monotonically, since it is a cumulative distribution function. This type of graph is constructed through the event tree resulting by ordering the loss of life in all the branches and using them to create this cumulative probability curve. It is also usual to use double logarithmic scales when using theses graphs.

If economic damages are drawn in the X Axis instead of loss of life, it is called **FD graph** (Frequency-Damages). The area located under an FD curve is equal to the economic risk.

As explained in Section 6.7, this type of graph is used by ANCOLD and USACE to propose tolerability recommendations for incremental risk.

FN (and FD) graphs can be used to represent both types of risks: incremental and total, depending on the type of consequences drawn in the X Axis. In Figure 6-32, both types of risks are presented in an example. As can be observed, incremental risks and failure risks have a similar FN curve, but consequences are a bit lower for incremental risk since non-failure consequences have been subtracted from failure consequences. Non-failure risk represents the flooding downstream produced by expected dam releases during floods.

FN graphs are also very useful to represent the effect of a new dam in the risk profile, as can be observed in Figure 6-33. In this graph, it can be observed how the flood risk profile is modified from the natural regime (red line) to the protection achieved through structural measures like large dams (green line). The area under the red line is much larger than the area under the green line (since it is represented in a logarithmic scale), so these measures have a high impact for reducing flood risks. However, large dams also introduced a new part, with usually low probabilities but high consequences, (higher that these produced in natural regime) due to the possibility of dam breakage.

6.6.2 fN and fD Graphs

In Figure 6-34, the annualized probability of failure is represented by the vertical axis (f) and its consequences are represented in the horizontal one (N for fatalities or D for economic damages). Thus, risk will be the dimension that combines both axes and is smaller in the lower left corner and grows towards the upper right corner. Diagonal lines (from top-left to bottom-right) are equal-risk lines (lines made of combinations of equal risk value). Logarithmic scales are usually used in these kinds of graphs.

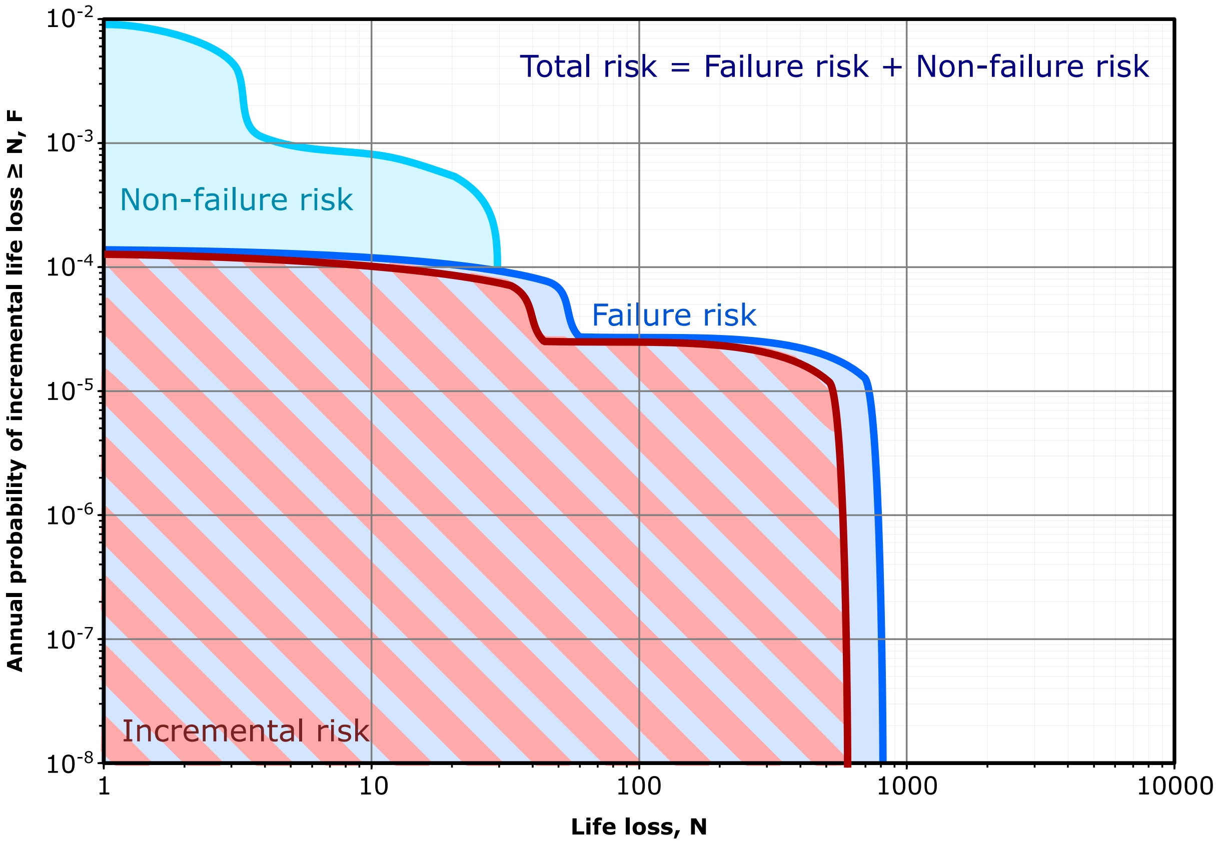


Figure 6-32. Example of incremental and total risks results in an FN graph.

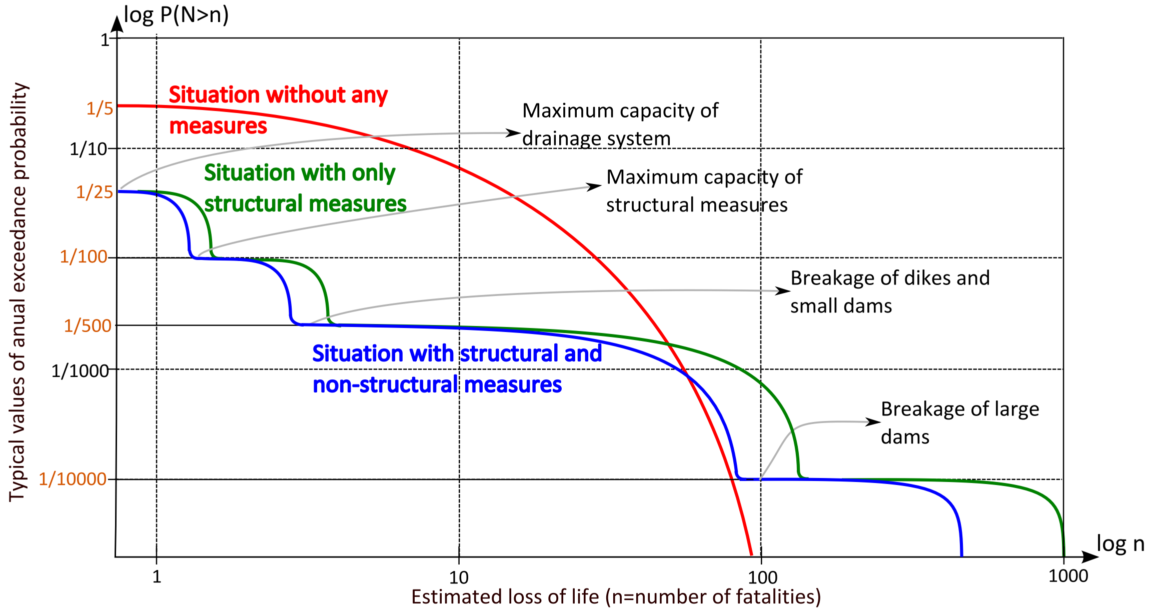


Figure 6-33. Expected changes produced by structural and non-structural measures in the flood profile of downstream urban areas. Source: (I Escuder-Bueno, Morales-Torres, Castillo-Rodríguez, & Perales-Momparler, 2011).

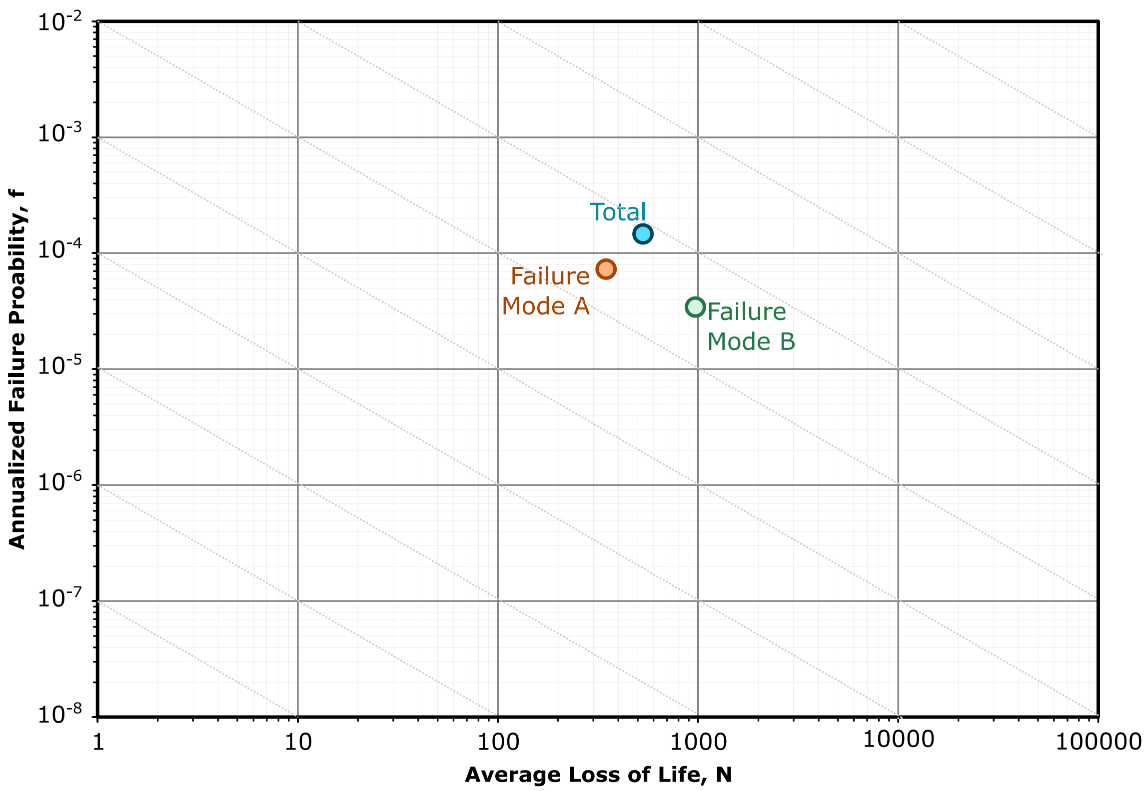


Figure 6-34. Example of fN graph for different failure modes. X and Y axis are represented in logarithmic scale. Diagonal lines are equal-risk lines (equal multiplication of probability and consequences).

In general, this type of graph aggregates dam risk results, where the sum of all probabilities is plotted on the vertical axis whereas on the horizontal axis, the weighted mean of the consequences is used. This second term can be easily obtained by dividing the total annual risk by the total annual probability. Hence, risk results can be plotted for each failure mode and for the whole dam, as shown in Figure 6-34.

As explained in Section 6.7, this type of graph is used by USBR to propose tolerability recommendations for incremental risk.

6.7 Risk Evaluation

6.7.1 Introduction

Risk evaluation is the process of examining and judging the significance of risk. Therefore, risk is compared with tolerability recommendations. The risk evaluation phase is the stage in which judgments are introduced into the decision process (implicitly or explicitly) by including the importance of estimated risks.

According to United Kingdom HSE (HSE 2001) recommendations, three tolerability ranges are generally defined:

- The first region is denoted as "unacceptable", where existing risk can only be justified under extraordinary circumstances.
- The second region is the "tolerable" region, where risk is aligned with the tolerability limit. In this region risk must be further analysed and controlled since it is only accepted by society if it complies with the ALARP considerations (As Low As Reasonably Possible). Therefore, risk is only tolerable if its reduction is impracticable or the costs are disproportionate. ALARP considerations can be analysed using risk reduction indicators, as explained in Section 6.9.4.
- The third region is the region of broad acceptance which refers to systems with risk that can be considered negligible or can be adequately controlled. Normally, large dams are not in this region, due to

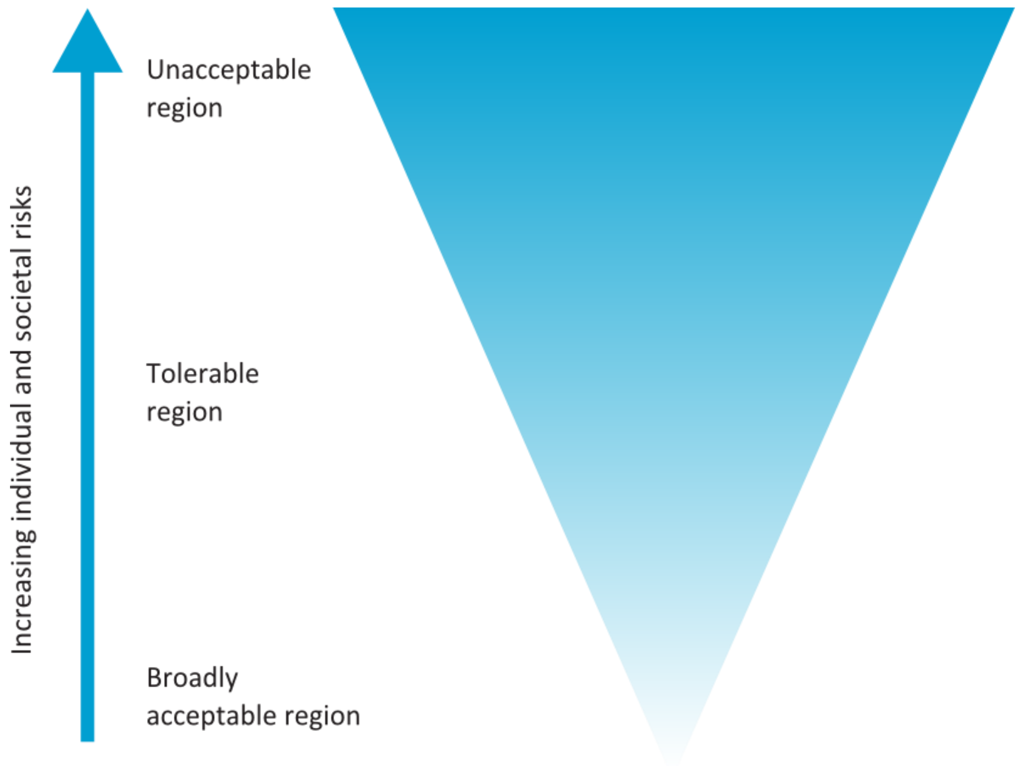


Figure 6-35. Graphical representation of tolerability regions. Adapted from (HSE; 2001).

the high consequences failures.

These three regions are shown in Figure 6-35.

According to (HSE 2001; ANCOLD 2003), the following principles should be considered to apply risk tolerability guidelines:

- Society is willing to live with the risk associated with the dam or levee to secure the benefits provided by the dam or living and working downstream or in the protected area.
- There is a continuation of recognition of dam or levee risk.
- The risks associated with the dam or levee system are being properly monitored and managed by those responsible for managing the risk.
- Those responsible for managing the risk associated with a dam or levee system continue to reduce the risk still further as practicable.

In this section, the main international tolerability guidelines for dam risk are reviewed. Finally, new tolerability guidelines for dam risk are proposed for India.

It should be noted that these recommendations should be applied on incremental risk results, since they evaluate the risk that the dam is introducing into the system.

6.7.2 Tolerability Guidelines proposed by ANCOLD

Risk tolerability guidelines recommended by ANCOLD are described in (ANCOLD 2003). Tolerability recommendations for **individual risk** adopted by ANCOLD limit the risk of the most exposed person is limited to 10^{-4} a year for existing dams and 10^{-5} for new dams or big increases of height of the existing ones (unacceptable risk). In practice, it is common to make this value

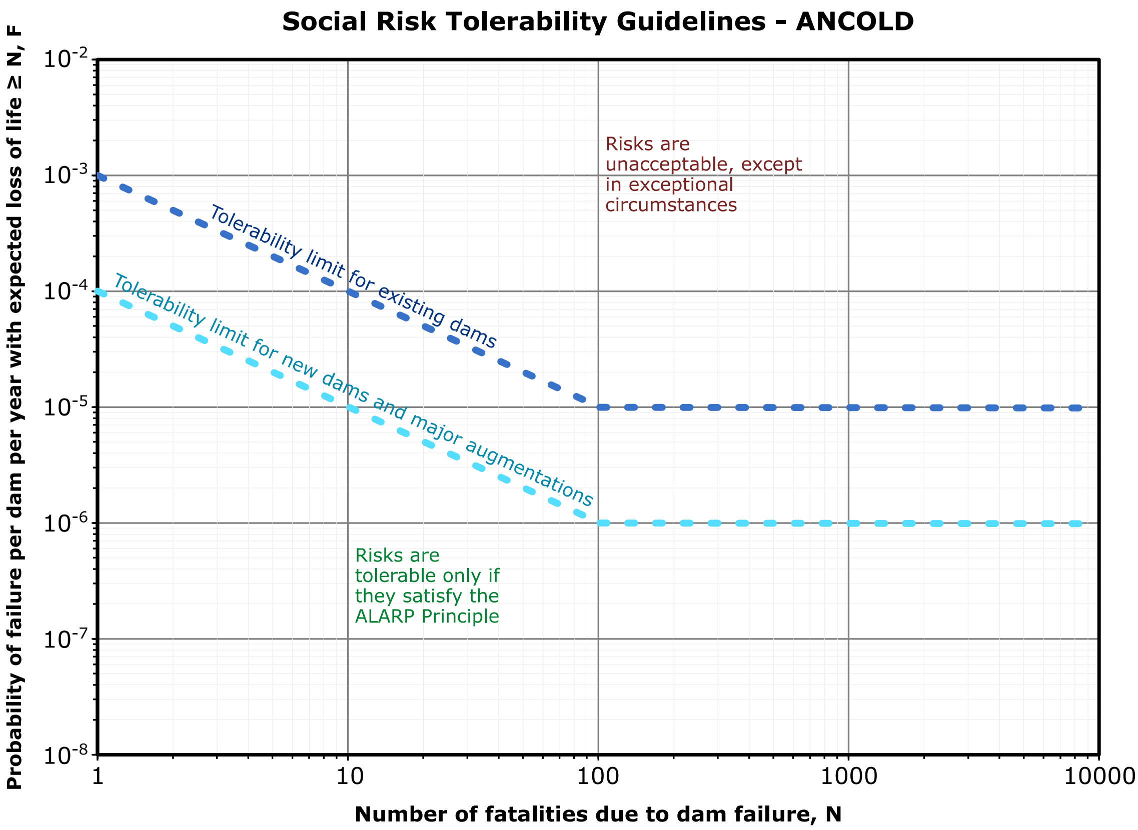


Figure 6-36. ANCOLD Tolerability Guidelines for societal risk. Adapted from (ANCOLD, 2003).

equal to the dam failure probability.

Tolerability recommendations for **societal risk** correspond to those adopted for risk tolerability in hazardous industries and are based on the FN curve (cumulative annual exceedance probability (F) of a certain value of potential consequences (N, in terms of loss of life)), rather than considering average risk.

These recommendations are represented in FN charts, where the situation of a dam is represented by a curve and not by a single point. Incremental life-loss is represented on the horizontal axis. ANCOLD tolerability recommendations are shown in Figure 6-36.

When risks are above the criterion, it is said that the risk in unacceptable except under exceptional circumstances. According to ANCOLD the decision on when these exceptional circumstances are met must not belong to the owner of the dam but to the government or organization operating the dams. For instance, high risks that would normally be unacceptable could be tolerable if they are necessary to ensure some exceptional benefits, but it is not up to the owner of the dam to do this judgment.

When the risk is below the criterion, it is tolerable only if it satisfies ALARP considerations.

Regarding economic risks (and intangible risks), it says they must be limited, though it does not specify any criterion and leaves it to the responsibility of each dam.

6.7.3 Tolerability Guidelines proposed by USBR

The tolerability recommendations proposed by the USBR (USBR 2011) are based on average risk values and are represented using fN graphs. As explained above, in these graphs, the failure probability (f) is represented on the vertical axis and incremental loss of life (N) on the horizontal axis.

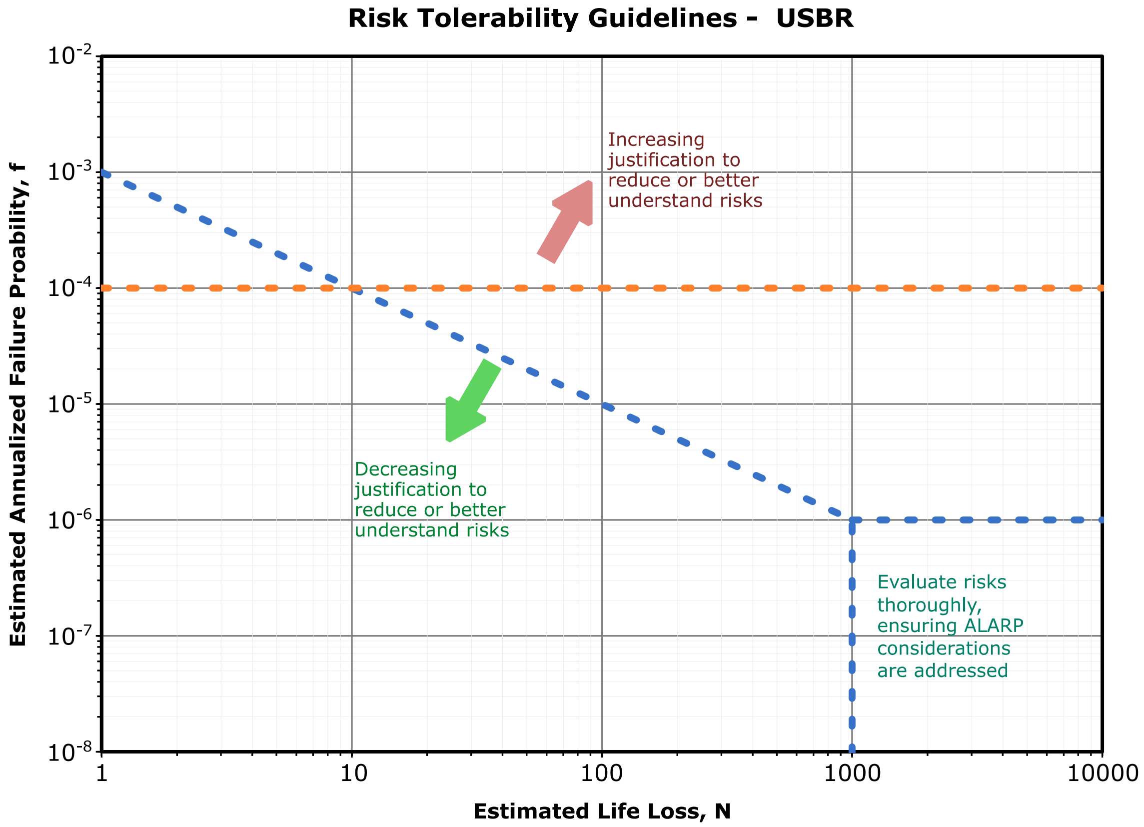


Figure 6-37. USBR Risk Tolerability Guidelines. Adapted from (USBR, 2011).

According to these recommendations, there is a first limitation on the annual **probability of failure** (that for practical purposes is considered equivalent to individual risk). This limit is defined for a value of 10^{-4} (orange line shown in Figure 6-37).

The second limitation is established in terms of **societal risk**, which should be limited to values lower than 10^{-3} lives/year (blue line shown in Figure 6-37). In addition, when estimated loss of life is higher than 1,000 people, recommendations are given to evaluate risk thoroughly and to ensure that ALARP considerations are met.

6.7.4 Tolerability Guidelines proposed by USACE

The US Army Corps of Engineers (USACE 2014) have developed a set of risk tolerability recommendations also on FN charts, incorporating ANCOLD recommendations and providing an additional limitation to maximum tolerable consequences. In this sense, when expected loss of life is greater than 1,000, the tolerability of risk must be based on an official review of the benefits and risks. These tolerability recommendations are shown in Figure 6-38.

In addition, the USACE has proposed a tolerability recommendation on individual risk, which should be lower than 10^{-4} as shown in Figure 6-39.

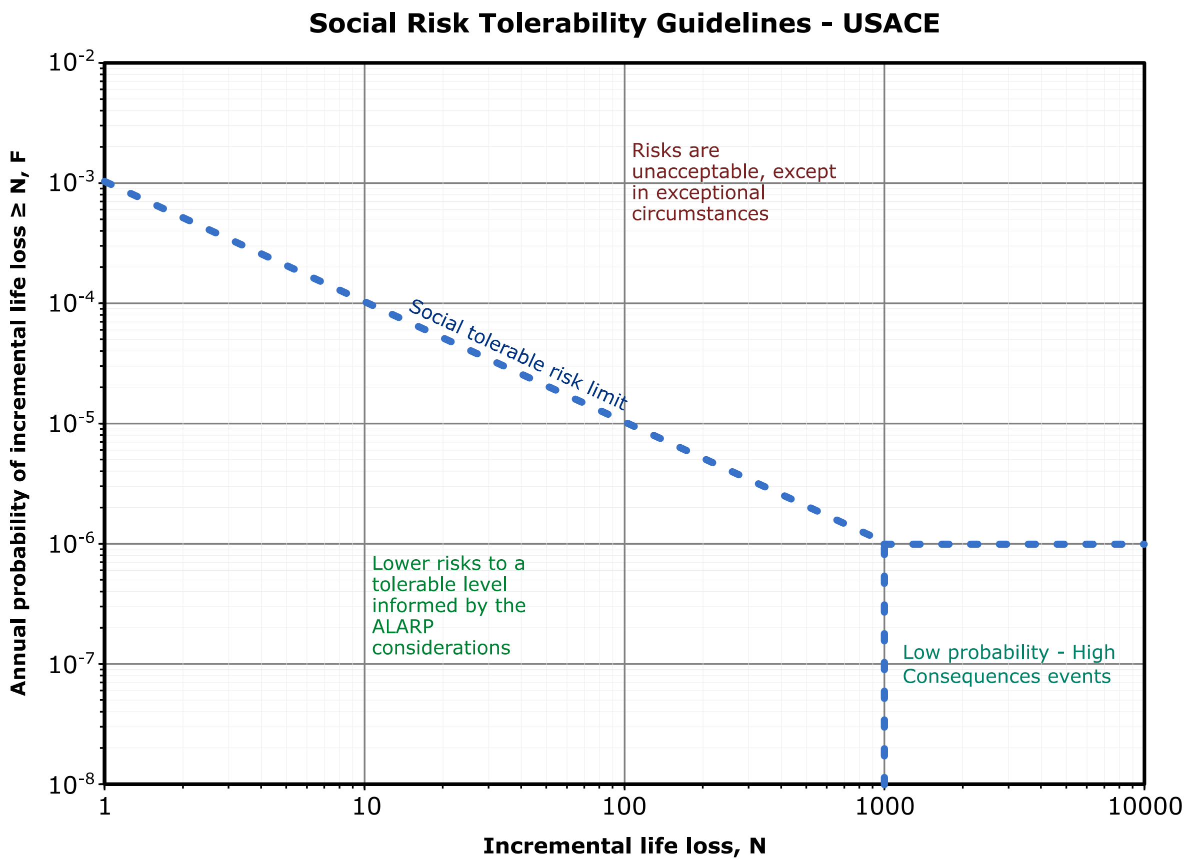


Figure 6-38. USACE Societal Risk Tolerability Guidelines. Adapted from (USACE, 2014).

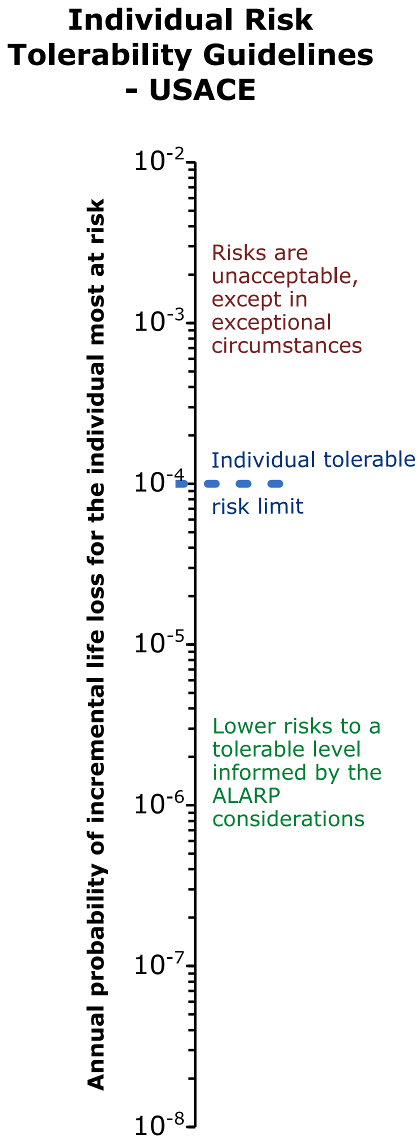


Figure 6-39. USACE Individual Risk Tolerability Guidelines. Adapted from (USACE, 2014).

6.7.5 Proposal of Tolerability Guidelines for India

To propose Tolerability Guidelines for dam risks in India, the previous recommendations from international organizations have been used. They have been adapted for India considering the higher potential of loss of life, due to higher population density.

First, tolerability recommendations are proposed for the **individual risk**. As defined above, individual risk is the probability that at least one person dies due to dam failure. In large dams, with a significant population downstream, individual risk can be assimilated to failure probability.

Following the ANCOLD recommendations, individual risk produced by dams should be clearly lower than the average death probability in the country at any age. Therefore, these death probabilities have been obtained from (OGD 2014) and are shown in Figure 6-40. As can be observed, a limit of 10^{-4} for individual risk is proposed to ensure that dam risks are not above probability of death.

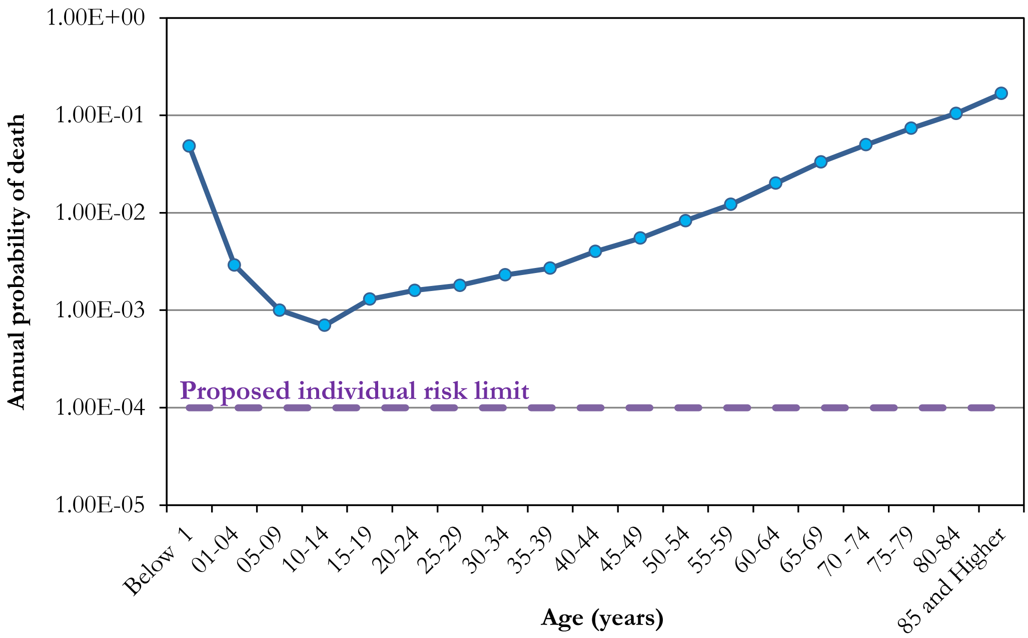


Figure 6-40. Average death probability per age and proposed individual risk limit.

This limit on individual risk (and consequently on dam failure probability) is closely related to the image and reliability of the dam owner.

Regarding **incremental societal risk**, tolerability limits are proposed based on fN graphs (following the USBR approach) as shown in Figure 6-41. This type of graph is chosen since it is more suitable to visualize the risk introduced by each failure mode and simpler for Portfolio management.

In this graph, each dam is represented by a single point that should include all the Class B Failure Modes that can produce loss of life (and therefore have an associated societal risk).

As can be observed in Figure 6-41, different tolerability regions are considered:

- **Non-tolerable region:** When dam risk is above the individual risk limit and/or the tolerability band, it is considered non-tolerable so risk reduction actions are recommended.
- **Tolerability band:** If dam risk is within this band, it is still considered non-tolerable, but depending on uncertainty analysis results, recommended actions could be more focused on understanding these risks better (with new studies or new instrumentation) than in new risk reduction actions. If after new studies, risks are still in this non-tolerable area, new risk reduction measures should be implemented.
- **High consequences – Low probability region:** When dam risk is below the tolerability band, but incremental loss of life could be higher than 1,000, risks should be analysed in detail and continued to be surveyed. This risk is only tolerable if project benefits are justified and the ALARP considerations are completely met. Therefore, risk reduction actions and/or new studies are typically recommended for these dams.
-
- **Tolerable region:** When risk is below the tolerability band, it is considered tolerable. In any case, ALARP considerations should be applied and potential risk reduction action can be recommended and prioritized. In addition, dam risk should be continuously monitored and risk results updated.

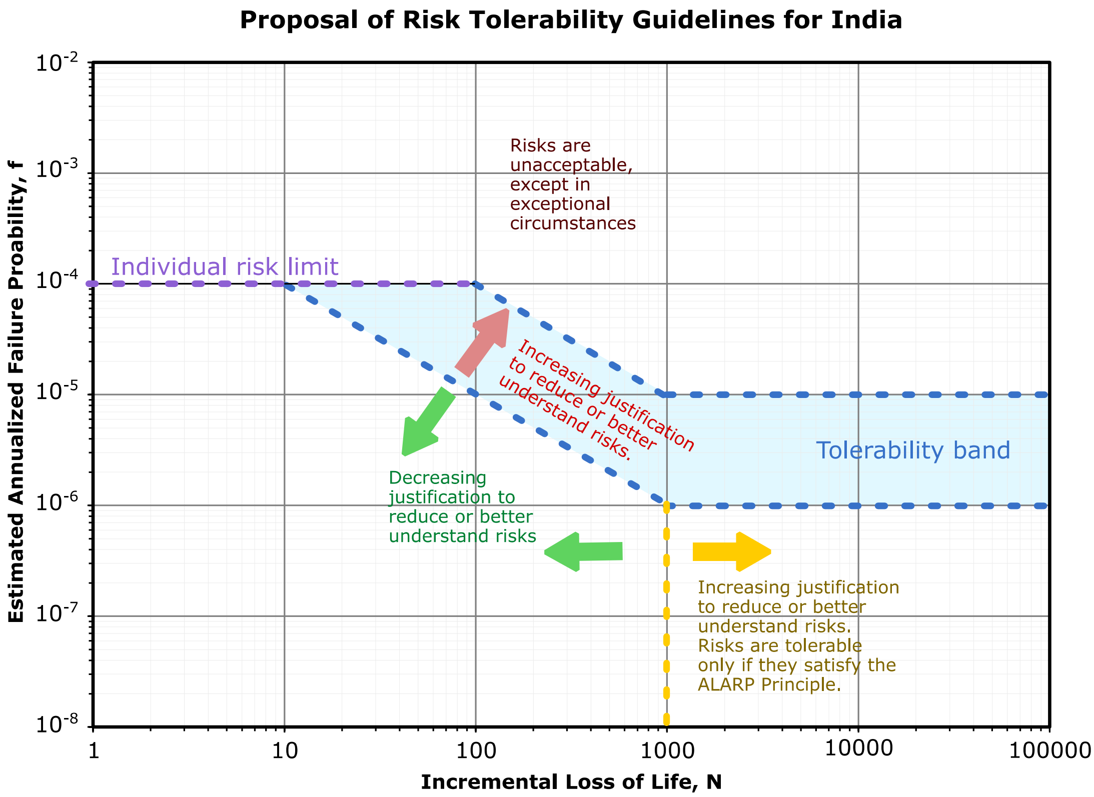


Figure 6-41. Proposal of Risk Tolerability Guidelines for India.

ALARP considerations can be analysed using risk reduction indicators, as explained in Section 6.9.4.

Finally, although tolerability recommendations for economic risk are not proposed, it is recommended to prioritize the proposed risk reduction actions, as explained in Section 6.9.

6.8 Uncertainty analysis

In dam safety, two general categories or sources of uncertainty are generally identified (Hoffman and Hammonds 1994; Ferson and Ginzburg 1996; Hartford and Baecher 2004):

- **Natural uncertainty or randomness:** Produced by the inherent variability in the natural processes. It includes the variability along time of phenomena that take place in a precise point of the space (temporal variability) or the variability across the space of phenomena that take place in different points but simultaneously (spatial variability).

  An example of this kind of uncertainty is the variability of the loads that the structure must withstand, for instance, the variability in the potential intensity of earthquakes. Another example is the strength's variability of the foundation where the structure stands. This type of uncertainty cannot be reduced, though it can be estimated.

- **Epistemic uncertainty:** Resulting from lack of knowledge or information about the analysed system. The more knowledge is available about a structure, the more this type of uncertainty can be reduced. In the rest of these guidelines, this type of uncertainty is simply called uncertainty.

  An example of this type of uncertainty can also be found in the strength of the foundation. The information about the foundations may be limited so the parameters used to characterize its resistance are estimated though probing and exploration. With more resources, the foundation can be better characterized, and the epistemic uncertainty is reduced, although the natural variability of the foundation may still be very significant.

In the dam safety context, natural uncertainty is usually related to the occurrence of events that can produce the structural failure and the randomness of the structure's resistant behaviour for the load produced by these events. Therefore, this type of uncertainty is addressed through risk models and it is included within the risk results.

In contrast, epistemic uncertainty is mainly focused on the lack of knowledge of the loading events, the failure mechanisms probabilities and the consequences produced by the failure. This type of uncertainty is addressed by making an uncertainty analysis and it is typically just called **uncertainty**.

A **sensitivity analysis** is the simplest type of uncertainty analysis. In this type of analysis, different values are selected for one (or several) of the variables introduced in the risk model and risk is recomputed modifying these variables. Hence, the expected range of variation in risk results due to this variable is obtained. An example of a sensitivity analysis for hydrological results in three dams is shown in Figure 6-43.

In some cases, it can be recommended to make a more complex **uncertainty analysis** (generally called uncertainty analysis). It can be accomplished by using probability distributions to define one or several event tree variables. Many samples of these variables are made with a Monte Carlo analysis and each sample of values is used to compute risk with the event tree. Therefore, a probability distribution should be defined for one (or several) variable(s) where the uncertainty analysis is focused and using the risk model, a risk result is obtained for each group of sampled values with the event tree (Altarejos-García et al. 2014; Chauhan and Bowles 2001). In both approaches, when risk results are ordered, a risk probability distribution is obtained as shown in Figure 6-42.

Hence, in this type of uncertainty analysis a risk probability distribution, a cloud of points in the fN graph and a family of FN curves are obtained instead of a single result and curve, as explained in (Paté-Cornell 2002; Chauhan and Bowles 2001). The spread of risk results represents the degree of uncertainty in the risk assessment. An example of the results of a detailed epistemic uncertainty in the dam foundation resistance capacity is shown in Figure 6-44. This figure shows how risk results change due to uncertainty in foundation resistance in the current situation and after implementing different risk reduction actions.

These types of analysis will help to identify the key areas of uncertainty in the risk model. Common sources of epistemic uncertainty within risk models are:

- Hydrologic hazards.
- Seismic hazards.
- Gates reliability.
- Probabilities estimated by expert judgment.
- Physical model parameters.
- Warning times and evacuation procedures to estimate loss of life.

Finally, the objective of performing an uncertainty analysis is assessing the cases where uncertainty could change the conclusions of risk evaluation. In these cases, where uncertainty variation in a failure mode could make that risks move from tolerable regions to clearly not tolerable regions, epistemic uncertainty is considered too significant. As shown in Figure 6-1, if it happens and more information can be gathered that reduce uncertainty, these new studies to reduce uncertainty should be prioritized based on a Semi-Quantitative Risk Analysis (together with Class C Failure Modes). These new studies should be made before implementing large rehabilitation actions.

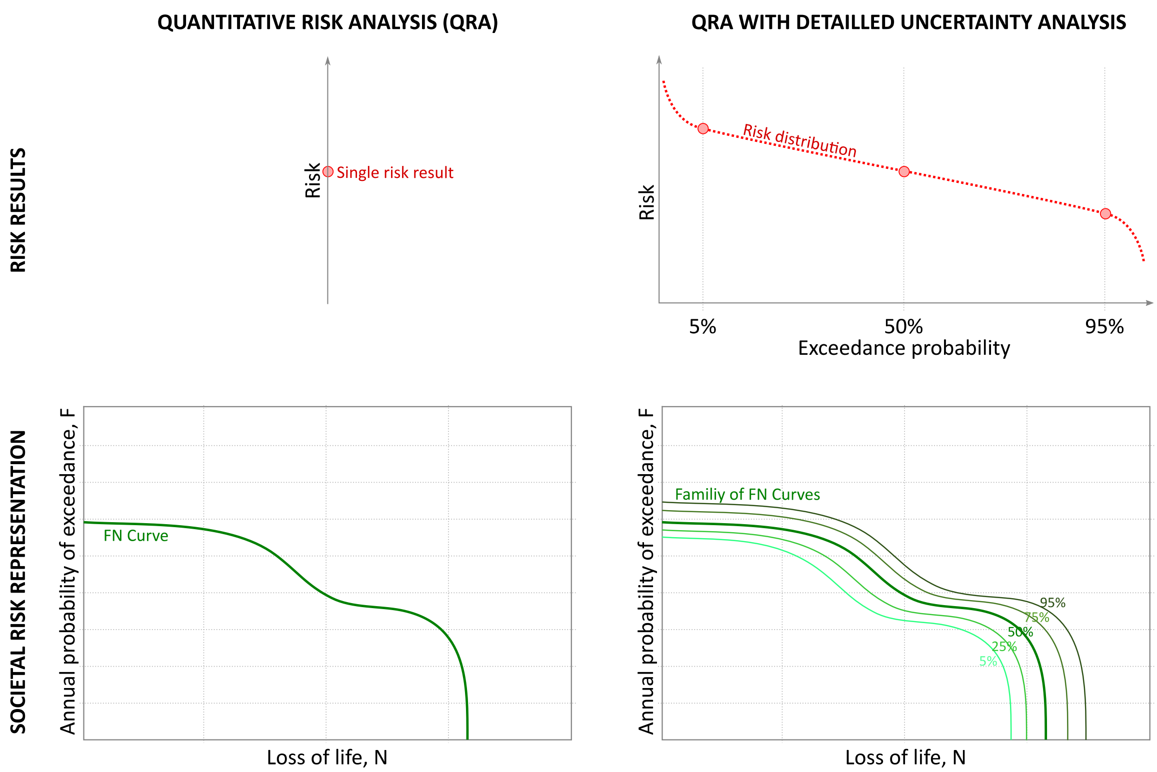


Figure 6-42. Comparison of risk results and risk representation between simple risk analysis and risk analysis with uncertainty analysis.

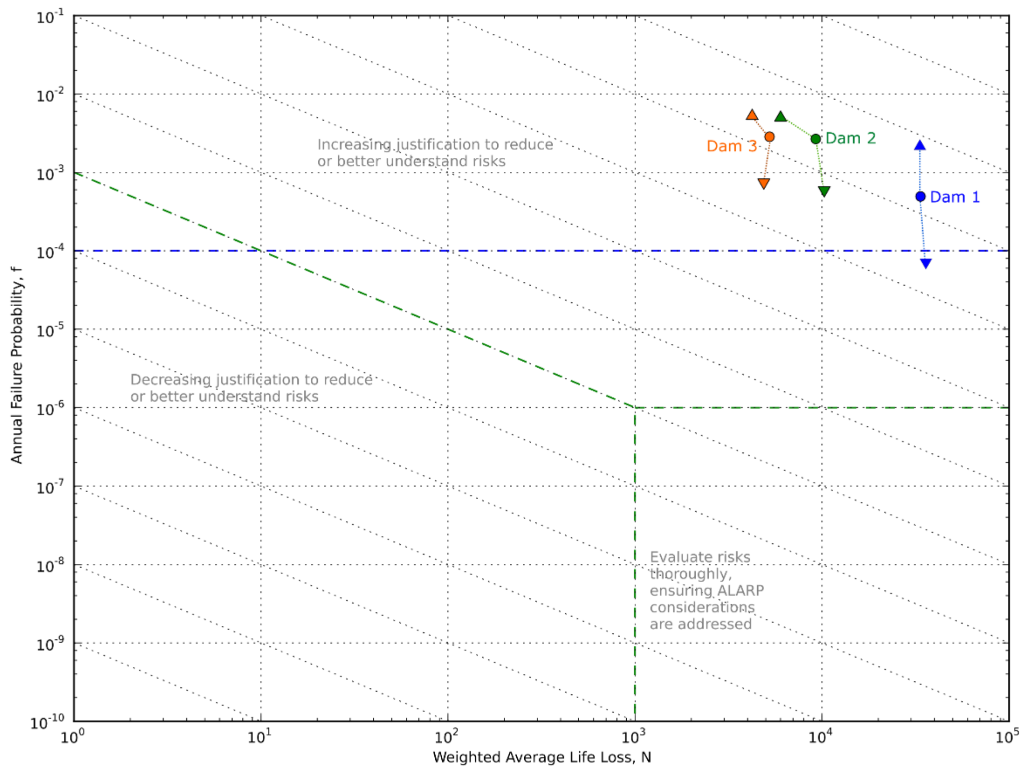


Figure 6-43. Results of sensitivity analysis for hydrologic data in three Albanian dams in an fN graph. Source: (Escuder-Bueno et al., 2016).

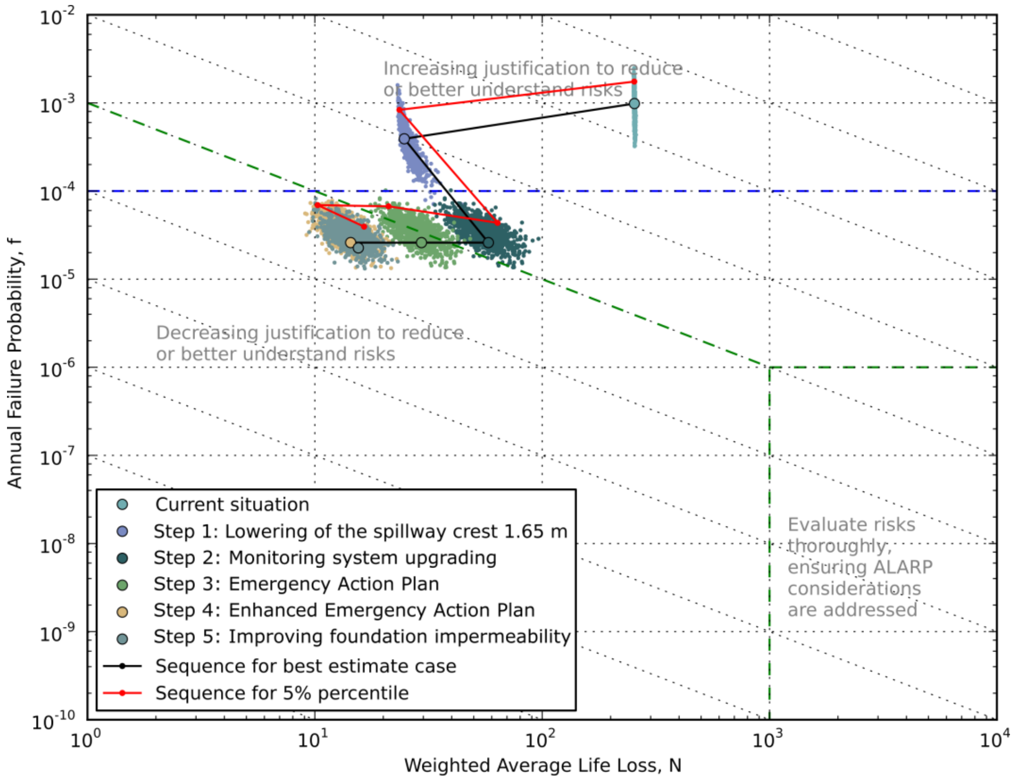


Figure 6-44. Results of uncertainty analysis for dam foundation data in a Spanish dam in an fN graph. Source: (Setrakian, Escuder-Bueno, Morales-Torres, Simarro Rey, & Simarro, 2015)

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6.9 Definition and prioritization of risk reduction actions

6.9.1 Risk reduction principles

The key part of the risk analysis process is decision-making for risk management. Decisions are made after considering possible alternatives and analysing their effect on infrastructure risk. Generally, two principles are recommended to guide this decision-making process (HSE 2001; ICOLD 2005; USACE 2014):

- **Equity:** In the context of critical infrastructure safety management, this principle arises from the premise that all individuals have unconditional rights to certain levels of protection (Le Guen 2010). This principle is applied through the individual risk.

  Hence, individual risk tolerability recommendations seeking a certain level of protection for every individual of the population are related to the principle of equity. According to (HSE 2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability.

- **Efficiency:** This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first. This is usually the prevailing principle when risk is tolerable (HSE 2001). In these guidelines, a distinction between two types of efficiency is suggested, depending on the targeted risk:

  - **Societal efficiency:** When the target risk to be reduced is societal risk.

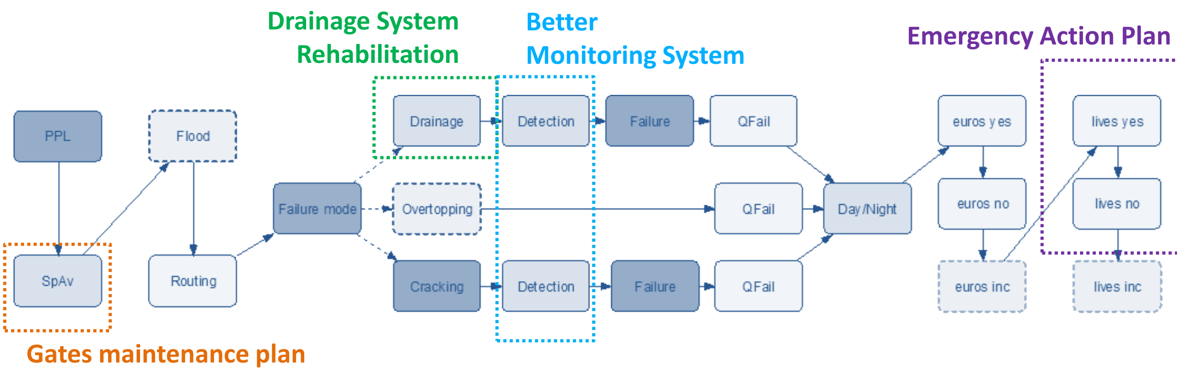

Figure 6-45. Example of effect of different risk reduction actions in a risk model.

- **Economic efficiency:** When what is analysed is economic risk reduction, that is, the searched strategy is the most advantageous from an economic point of view. According to some authors (Bowles 2001), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

These two principles can conflict since what can be an optimal measure from the equity point of view may not be so from the efficiency point of view and vice versa. This dilemma between efficiency and equity is not only restricted to risk analysis and safety management, but it also occurs in many other fields related with decision making in the public sector. In general, it is recommended to combine efficiency and equity principles in an integrated management of public resources.

Following the principles and procedures proposed in this section, all the proposed risk reduction actions within a dam and at the Portfolio scale can be prioritized. Therefore, this prioritization sequence of new risk reduction actions is the basis for decision making at Portfolio Scale, as explained in Chapter 7.

6.9.2 Defining risk reduction actions and measuring their effects

Risk reduction measures to be analysed and prioritized are typically selected from identification of failure mode recommendations, technical inspections and, in general, expected measures planned for each dam. Before including them in the quantitative risk analysis, the feasibility of the proposed measures should be analysed. *Manual for Rehabilitating Existing Dams* provides very useful information to propose and to design these measures.

In any case, risk results provide new information that can be used to propose to and define new risk reduction actions or to exclude some of the actions proposed previously.

In this sense, the proposed measures should be discussed by the team group, defining them in detail and deciding if it is necessary to group some of them for the risk analysis. The level of detail required for each measure should be balanced with its complexity and the investment needed.

Risk assessment results are essential to define these measures, and different trials can be made with the risk model to define the most efficient solution. For instance, risk model can be used to define the deep of a cut-off wall or the capacity of a new spillway. Therefore, a risk-informed approach is strongly recommended to design these measures in detail.

The first step to prioritize risk reduction actions is analysing how they change the risk results. It should be made by revaluating the input data of each node of the risk model considering that the analysed measures have been implemented.

Some examples of the effect of risk reduction measures in the risk model data are:

- New freeboard requirements would change probabilities of previous pool levels in the reservoir.
- Better maintenance of gates or replacement of some elements will improve gate reliability.
- New operating rules will modify flood routing results.
- Better surveillance or monitoring will reduce the probability of not detecting a failure mode.
- Major rehabilitations can be planned to reduce the failure probability of some of the failure modes. For instance, building an additional spillway to reduce overtopping probability.
- Better emergency procedures will reduce expected loss of life in failure and non-failure cases.

An example on how different risk reduction measures can modify different events of the risk model is shown in Figure 6-45.

Finally, it is highlighted that the effect of risk reductions actions should be measured in terms of **incremental risk and total risk,** to ensure that they are not increasing flood risk downstream. For instance, flood risks downstream could increase due to new gates operating rules or higher discharges with a new spillway.

In some cases, it can be recommended to prioritize risk reduction actions using total risk instead of incremental risk, especially when proposed actions are not only related to the dam failure but also with managing flood risks downstream.

6.9.3 Computation of prioritization sequences

When quantitative risk analysis is applied to inform safety management of portfolios of dams, a high number of results are obtained. In this context, **risk reduction indicators** are the most common tool to prioritize risk reduction measures (Bowles et al. 1999; ANCOLD 2003; SPANCOLD 2012; Morales-Torres, Serrano-Lombillo, et al. 2016). Risk reduction indicators are numeric values obtained for each potential measure based on its costs and the risk reduction it provides and are widely used to inform safety management in different fields, as explained in the following section.

In (Morales-Torres, Serrano-Lombillo, et al. 2016), a procedure is laid out to obtain prioritization sequences based on risk reduction indicators. In each step of the sequence, the measure with the lowest value of the indicator is chosen. Of course, the obtained prioritization sequence depends on the risk reduction indicator used to define it. Hence, this procedure does not intend to choose between different alternatives but to prioritize them, if with enough time and resources, all of them will be implemented.

As explained in the previous paper, prioritization sequences can be represented in variation curves (Figure 6-46), which represent the variation of the aggregated risk in the portfolio as measures are implemented. In the X axis, annualized costs or implementation steps can be displayed while in the Y axis aggregated individual risk, societal risk or economic risk can be shown. Depending on what is represented in each axis, the risk reduction indicator leading to the optimum sequence will be different.

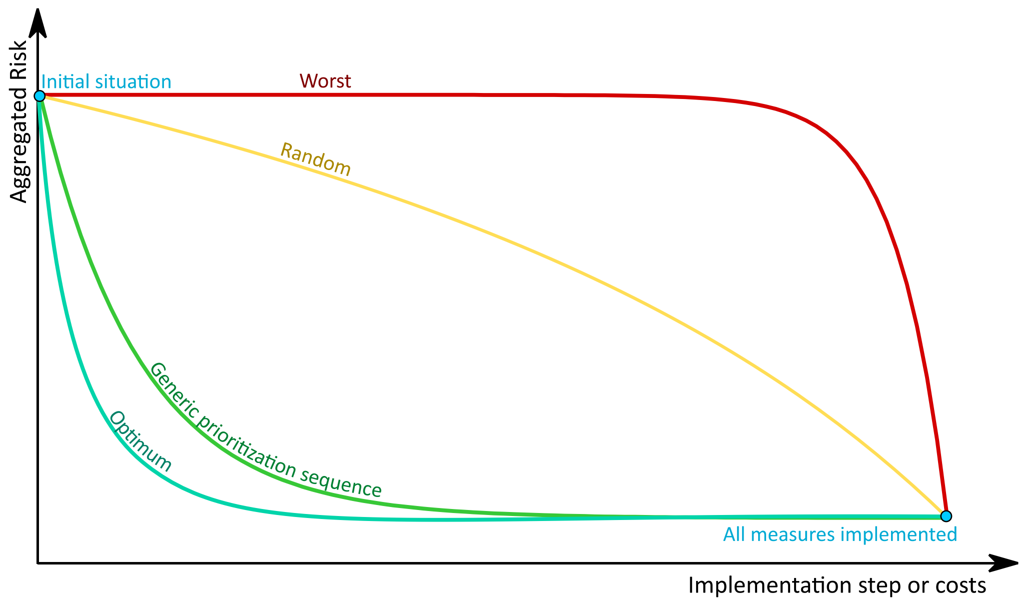

Figure 6-46. Generic representation of variation curves to define prioritization sequences. Source: (Morales-Torres, Serrano-Lombillo, et al. 2016)**.**

The optimum sequence of the variation curve, which represents aggregated societal risk versus costs, will be the optimum from the societal efficiency point of view, since it represents the sequence which reduces societal risk at the lowest costs.

6.9.4 Risk reduction indicators

In (Morales-Torres, Serrano-Lombillo, et al. 2016) existing risk reduction indicators for comparing different investment alternatives are reviewed, defining their relationship with risk reduction principles. In the dam safety field, three indicators are prevalent in the evaluation of risk reduction measures:

- **CSLS (Cost per Statistical Life Saved):** (HSE 2001; ANCOLD 2003) This indicator shows how much it costs to avoid each potential loss of life as a result of a dam. It is widely used to manage quantitative risk results in different fields. Its value is obtained through the following formula:

$$CSLS=\frac{C_a}{r_s(base)-r_s(mea)}$$

Where $r_s(base)$ is the societal risk expressed in loss of lives for the base case, $r_s\ (mea)$ is the societal risk in lives after the implementation of the measure and C_a is the annualized cost of the measure including its annualized implementation costs, annual maintenance costs and potential changes in operation costs produced by the adoption of the measure.
CSLS compares costs with societal risk reduction, so when considering several measures, the measure with a minimal value of this indicator will be the one that employs the resources in the most efficient way. Therefore, this indicator is based on the principle of societal efficiency.

- **ACSLS (Adjusted Cost per Statistical Life Saved):** (ANCOLD 2003; Bowles 2001) This indicator has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$ACSLS=\frac{C_a-(r_e(base)-r_e(mea))}{r_s(base)-r_s(mea)}$$

Where $r_e(base)$ is the economic risk of the infrastructure for the base case and $r_e(mea)$ is the economic risk after the implementation of the measure. As in the

previous case, it is based on the efficiency principle, though for adjusted costs, so it considers both societal and economic efficiency.
This indicator can also be used to analyse the ALARP Considerations when risk is in the tolerable areas. In this sense, the following values are recommended to justify new risk reduction actions based on international recommendations (ANCOLD 2003):

- **Very strong justification:** ACSLS is between Rs 0 and 25 Crores.
- **Strong justification:** ACSLS is between Rs 25 and 100 Crores.
- **Moderate justification:** ACSLS is between Rs 100 and 500 Crores.
- **Poor justification:** ACSLS is higher than 500 Crores.

It should be considered that these values are referred to 2018 Rs prices.

- **Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS):** (Armando Serrano-Lombillo et al. 2016) This indicator is computed with the following formula:

$$EWACSLS = \frac{ACSLS}{\left(\frac{max(r_i(base),IRL)}{max(r_i(mea),IRL)}\right)^n}$$

Where $r_i(base)$ is the individual risk for the base case expressed in years^{-1}, $r_i(mea)$ is the individual risk in years^{-1} after the implementation of the measure, *IRL* stands for Individual Risk Tolerability Limit (in India, a limit of 10^{-4} is recommended following international recommendations) and *n* is a parameter that allows assigning a higher weight to either efficiency or equity in the prioritization process. When applying this equation in large dams with significant population downstream, individual risk can be assimilated to failure probability as explained above.

As can be observed in this equation, if the individual risk (or failure probability) is lower than *IRL*, the only prevailing principle is efficiency (through ACSLS) since the denominator of the formula is then 1. Thus, the equity principle only modifies the value of the indicator in the cases where individual risk is above tolerability thresholds.

The *n* parameter can be used to provide flexibility to the EWACSLS. If the value of n is very high, the prevailing prioritization principle is equity whereas if it is very low, efficiency prevails. Hence, once a value of n is set, it can be used to consistently compare an array of measures. A value of n equal to 1 seems to be a reasonable compromise between both principles.

The EWACSLS indicator allows a smooth transition between equity and efficiency principles, since the closer the individual risk is to its limit, the less weight the equity principle has. This indicator is better aligned with risk analysis principles than simply establishing a binary threshold determining whether equity should prevail or not. If this kind of binary threshold is used, only equity is taken into consideration in the non-tolerable area and only efficiency in the tolerable area, so principles are used in separated domains. The results of this approach would be more sensible to existing uncertainties in risk estimation, since small changes in individual risk could produce changes in the prevailing principles. Risk evaluation and governance should not be about being above or under a threshold, but about informing decision making combining both principles to reduce risk as much as possible.

Other existing reduction indicators to prioritize risk reduction measures are:

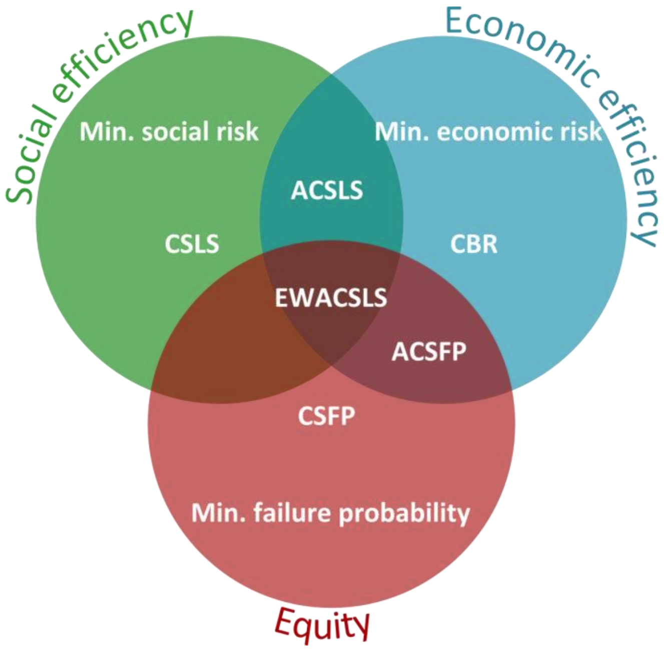

Figure 6-47. Venn diagram that shows the relationship between risk reduction indicators and efficiency and equity principles. Source: (Armando Serrano-Lombillo et al. 2016).

- **CBR (Cost-Benefit Ratio):** (Bowles 2003) This indicator arises from the comparison of the costs of a measure with the benefits on the economic risk reduction resulting from its implementation. Therefore, this ratio shows which measure is the most cost-effective. According to the following equation, the lower this indicator is, the better the measure is:

$$CBR = \frac{C_a}{r_e(base) - r_e(mea)}$$

- **CSFP (Cost per Statistical Failure Prevented**): (Morales-Torres, Serrano-Lombillo, et al. 2016) This indicator expresses how much it costs to avoid infrastructure failure for each measure. The lower this value, the more convenient the measure is. It is calculated as follows:

$$CSFP = \frac{C_a}{f_p(base) - f_p(mea)}$$

Where $f_p(base)$ is the annual failure probability for the base case and $f_p(mea)$ is the failure probability after the measure implementation. As for the rest of indicators, the lower this value, the better the measure is.
This indicator combines costs with failure probability, so it considers the principles of economic efficiency and equity, particularly the latter. When applying this indicator to decision-making the authors recommend considering a two-step process. When individual risk (or failure probability) is not tolerable, the CSFP is used. Once individual risk is below the tolerability level, then efficiency-based indicators such as CSLS or ACSLS may be more suited.

- **ACSFP (Adjusted Cost per Statistical Failure Prevented):** (Morales-Torres, Serrano-Lombillo, et al. 2016) This indicator presents the same form as CSFP but introduces an adjustment on the annualized cost to consider the reduction of economic risk produced by the implementation of the measure. It is calculated with the following formula:

$$ACSFP=\frac{C_a\text{-}(r_e(base)\ \text{-}\ r_e(mea))}{f_p(base)\ \text{-}\ f_p(mea)}$$

This indicator considers the principles of economic efficiency and equity, particularly the last one. A two-step approach like the one described for the CSFP is also recommended for the ACSFP.

Other options could be to choose, in each step of the prioritization process, the measure that minimizes the individual risk, the societal risk or the economic risk.

Figure 6-47 uses a Venn diagram to visualize the relationship between all the reviewed indicators and principles. As can be observed in this figure, EWACSLS is the only indicator that is related with the three risk reduction principles.

As explained above, these indicators can be computed using incremental risk or total risk, obtaining typically different prioritization sequences depending on the type of risk used.

In general, it is recommended to use the **EWACSLS with incremental risk results** to prioritize risk reduction actions**.** However, as explained in Section 6.9.2, the effect of risk reduction measures on total risk should be checked.

Finally, following the principles and the procedures proposed in this Section, all the proposed risk reduction actions within a dam and the dam Portfolio can be prioritized. Therefore, this prioritization sequence of new risk reduction actions will be the basis for decision making at Portfolio Scale, as explained in Chapter 7

6.9.5 Restrictions for prioritization

When prioritization sequences of risk reduction indicators are obtained, constraints can be necessary to modify the implementation sequence. They introduce conditions that must be met when managing a portfolio of infrastructures due to administrative, economic or social reasons, as explained in Chapter 7. Constraints typically used in this type of prioritization are:

- **Order constraint:** It can be used to force a measure to be implemented before another one. Hence, the measure will appear before in the implementation sequence. An example of this may be if an Emergency Action Plan is required before considering the implementation of an enhanced system for alerting and educating downstream inhabitants.

- **Mutually exclusive constraint:** It can be used for measures which are mutually exclusive, that is, implementation of one of them invalidates the possibility of implementing the other one. This condition is typically used for evaluating different alternatives. For instance, when several possible types of gates are considered to substitute old gates in a spillway: only one of them would be implemented.

- **Eliminative constraint**: It can be used when implementation of measure A precludes implementation of measure B but not the other way around. An example is when considering freeboard requirements or an increase in spillway capacity. If the spillway capacity is incremented, then freeboard requirements would not be necessary. But even if freeboard requirements are implemented, an increase in spillway capacity could be considered in a later stage.

- **Group constraint:** It can be used when two different measures will be implemented simultaneously. The effect and costs of both measures will be considered jointly when calculating risk indicators. This, for example of, could happen if budgetary constraints impose that Emergency Action Plans for several dams be implemented in the same contract. Another example is when a major rehabilitation is made in a dam; it can be more suitable administratively to make all the proposed measures in this dam while making this major rehabilitation.

- **Set implementation step:** It can be used to fix the implementation step in which a certain measure must be implemented. This can be used, for example to force a measure to be implemented in first place of the implementation sequence if the decision to go ahead with that measure has already been made.
- **Set measure relative position:** It can be used to fix the implementation step of a measure relative only to other measures in the same infrastructure. For example, this could be used to force a measure to be the first one to be implemented in a specific infrastructure.
- **Omit measure**: This can be used to exclude a measure from the analysis. An example of this could happen if a measure is found to be non-viable for any reason.

Figure 6-48 shows a chart that summarizes these constraints

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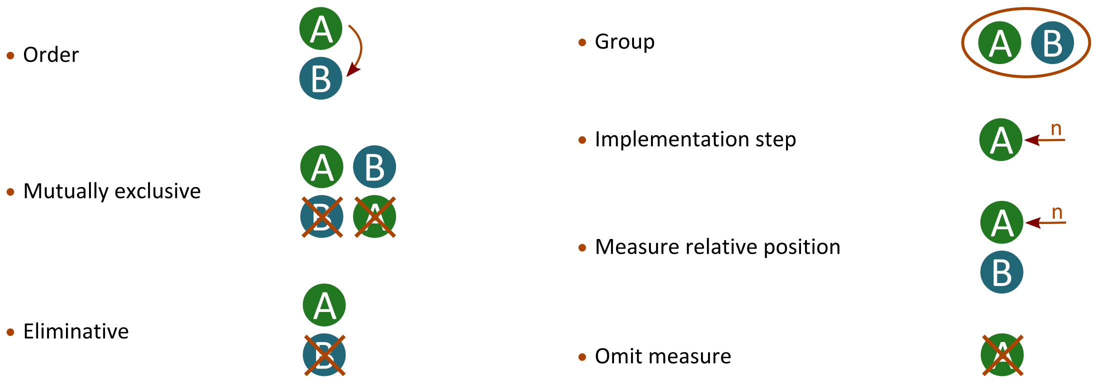

Figure 6-48. Summary of possible prioritization constraints.

6.10 Relation between quantitative risk models and DRIP Guidelines

In the previous sections, it has been described how the different Guidelines and Manuals being elaborated within the DRIP project are directly related with the input data introduced in the different nodes of the quantitative risk models.

Figure 4-3 shows a summary of the key relations between the Guidelines and Manuals and the risk models data. Of course, these Guidelines can be useful to obtain risk model data for other nodes other than the ones represented in this figure, but these are the clearest relations. As can be observed, risk models integrate all the aspects related to dam safety challenges represented by these guidelines; so, their results are a combination of all of them.

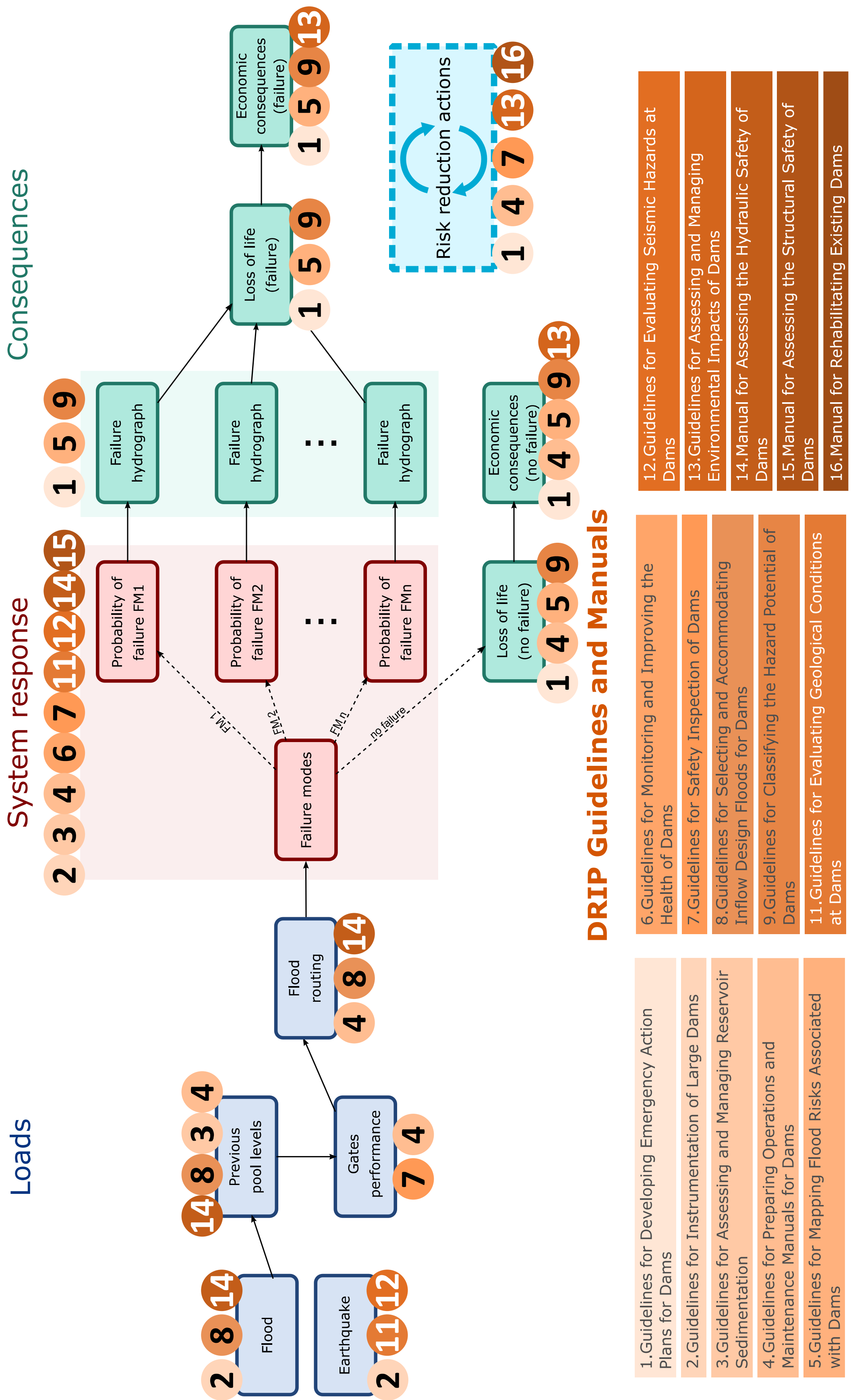

Figure 6-49. Relation between risk model input data and DRIP Guidelines and Manuals

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Chapter 7. PORTFOLIO RISK MANAGEMENT

7.1 Introduction

Risk Management encompasses activities related to making risk-informed decisions by prioritizing new studies and instrumentation, prioritizing risk reduction actions (structural and non-structural), and making program decisions associated with managing a portfolio of dams. Therefore, in this step incremental risk results are used to inform decision making in dam safety at a Portfolio scale.

As explained in Section 6.9.1, two main principles are generally considered for risk management and prioritization of risk reduction measures (HSE 2001; ICOLD 2005; USACE 2014):

- **Equity:** This principle arises from the premise that all individuals have unconditional rights to certain levels of protection. This principle is applied through individual risk.

- **Efficiency:** This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. According to this principle, when considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) is chosen first.

Therefore, in the Dam Safety Management Program developed in these guidelines, this chapter is directly linked to the decision-making process, which is the last part of the flowchart, as shown in Figure 7-1.

As can be observed, the main input for this decision-making process are the obtained sequences for prioritization of risk reduction actions and prioritization of new studies and dam instrumentation. As explained in the following sections, these outputs are combined with other technical, environmental, societal and regulatory aspects to decide on new dam safety investments.

Finally, Risk Management results may be used to develop a Risk Governance Framework for dam management, as explained in Chapter 8.

7.2 Risk-informed decision making

As shown in Figure 7-1, the two main inputs for risk-informed decision making are:

- Prioritization queue of potential risk reduction actions in the Portfolio, obtained from Quantitative Risk Assessment results explained in Section 6.9.

- Prioritization queue of new studies and instrumentation in the Portfolio, obtained from Semi-Quantitative Risk Analysis results explained in Section 5.5.

These prioritizations queues of potential investments provide an insight and key information to decision makers. However, other factors should be considered in decision making regarding new studies and new risk reduction actions. Some of the most common aspects conditioning the decision-making process are:

- When planning risk reduction actions or new studies, all dam failure modes should be considered, not only the failure modes included in the quantitative (or semi-quantitative) risk analysis. Failure mode interaction should be considered and improvements in these measures or studies can be helpful for other failure mode analyses. Hence, all failure modes should be considered in decision making as shown in Figure 7-1.

- In some cases, uncertainty analysis of Class B Failure Modes concludes that extra studies are needed to assess one or several failure modes, as explained in Section 6.8. These studies should be made before implementing large rehabilitation actions in the dam related with these failure modes.
- In some cases, an action may be included in both prioritization lists (queue for risk reduction actions and queue for new studies). It can happen with new instru-

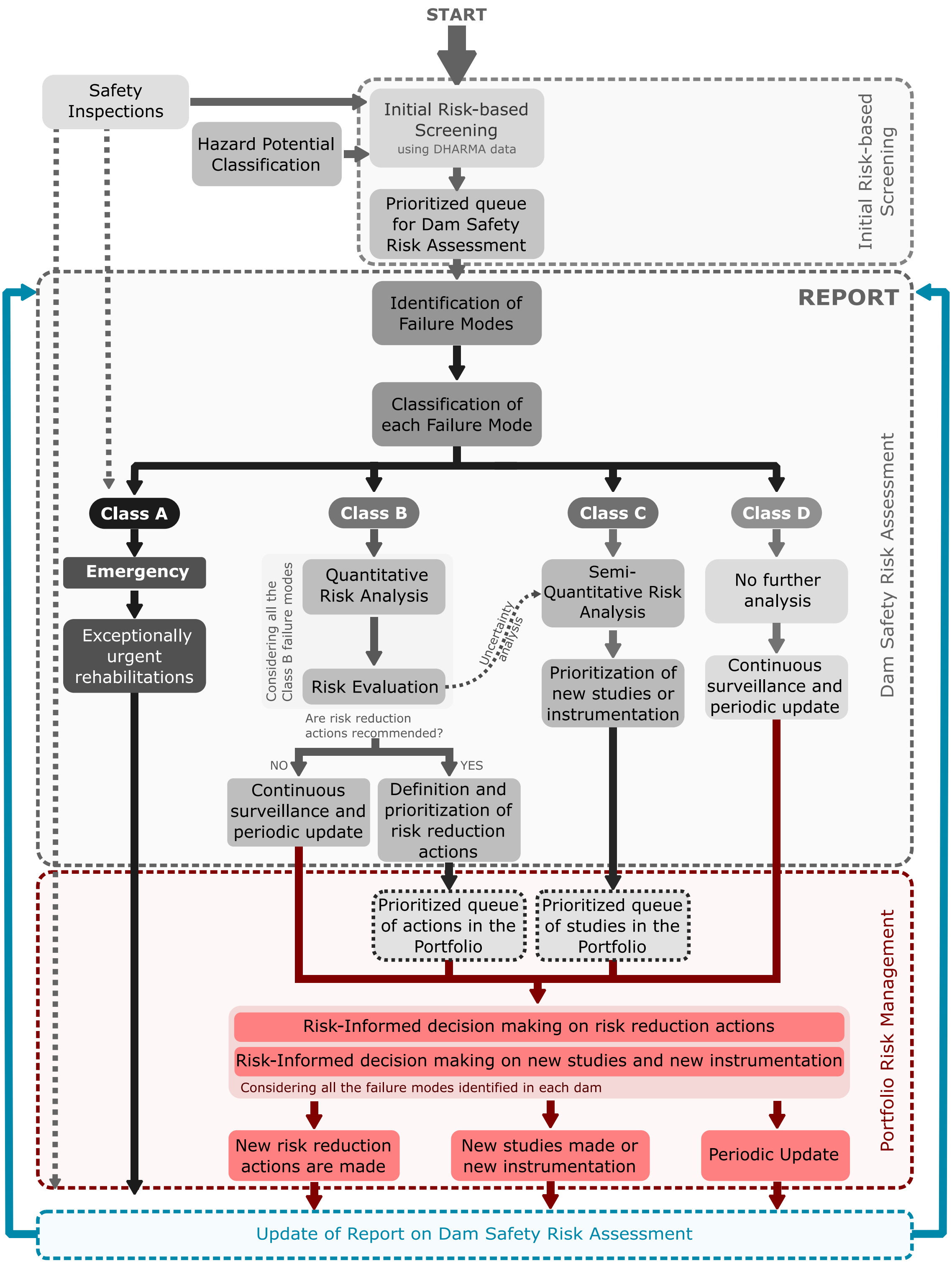

Figure 7-1. Portfolio Risk Management (in color) within the Risk-Informed Dam Safety Management Program.

mentation, which is useful to reduce uncertainty and to reduce probability of failure since failure modes can be more easily detected and avoided.

- As explained in Chapter 6, total and incremental risk results should be considered in decision making, checking that the proposed risk reduction actions do not increment total flood risk downstream.

- In some cases, when a major rehabilitation is being made in a dam, it can be suitable to implement at the same time other smaller risk reduction actions or dam instrumentation due to administrative or technical reasons. This can be introduced in the prioritization of measures through group restrictions, as explained in Section 6.9.5.

- Sometimes, environmental or cultural impacts of dam failure are very high, and they should be considered in decision making although they are not usually included in quantitative risk results.

In conclusion, dam safety decision making will be informed by risk results and prioritization of investments, but it must be aligned with the operator's mission, existing restrictions, objectives and general context. For this reason, it is a "Risk –informed decision making" process and not "Risk based decision-making". Figure 7-2 shows a summary of conditioning aspects in dam safety decision-making.

In this sense, decision making in the Portfolio should be explained in periodic reports. These reports should include prioritization ques obtained from risk outcomes and they should explain in detail the specific reasons and conditioning aspects for decision making of new risk reduction actions and new studies.

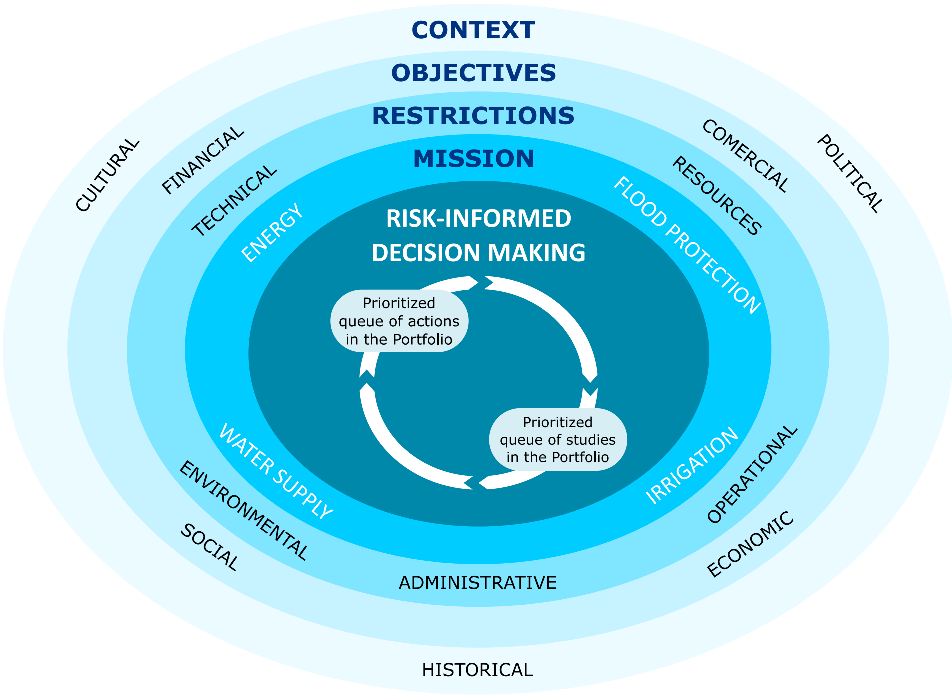

Figure 7-2. Conditioning aspects in dam safety decision making.

7.3 Update of Reports on Dam Safety Risk Assessment

Finally, within the process of Dams Portfolio Risk Management, periodic updates of Reports on Dam Safety Risk Assessment should be made to provide inputs in the decision-making process. In general, the following reasons should trigger a review of these reports:

- Periodical update of Reports on Dam Safety Risk Assessment, including new identification of failure modes sessions and a comprehensive review of risk results. It is recommended to make these complete updates every 4-10 years, depending on the dam Hazard Potential Classification. The following update periods are proposed:
    - Minor Hazard Class: 10 years.
    - Moderate Hazard Class: 8 years.
    - Significant Hazard Class: 6 years.
    - Major Hazard Class: 5 years.
    - Catastrophic Hazard Class: 4 years.
- When a new study is made, or new instrumentation is installed and data is gathered, a review of identification of failure modes and dam safety risk assessment should be made. This review will be directly related with the Class C failure mode(s) that has justified these new studies or instrumentations. New information available should be evaluated, and if possible, a quantitative risk assessment should be made including these failure modes.
- Depending on its importance, when a new risk reduction action is implemented in the dam, the report review can include only an update of risk results or also a complete review of identification of failure modes and classification.
- When proposing a new action to reduce risk in a dam that requires a significant investment and it has not been included in the Risk Assessment, it is recommended to update the risk model to analyse this action and include it in the list of prioritization of actions.
- If a new significant deficiency is detected during dam technical inspections, it can be recommended to make a new session for identification of failure modes and a new risk assessment to propose risk reduction actions. As shown in Figure 7-1, depending on the importance of this deficiency, recommendations can be made to update this report (if it could lead to a long-term failure process) or to directly implement exceptionally urgent rehabilitation measures (when the failure is in progress or imminent in the short term).

Chapter 8. RISK GOVERNANCE

8.1 Introduction

According to the International Risk Governance Council (IRGC 2006), risk governance includes the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed and communicated and how management decisions are made. Encompassing the combined risk-relevant decisions and actions of both governmental and private actors, risk governance is of importance in, but not restricted to, situations where there is no single authority to take a binding risk management decision but where, instead, the nature of the risk requires the collaboration of and coordination between a range of involved stakeholders.

However, risk governance not only includes a multifaceted, multi-actor risk process but also calls for the consideration of contextual factors such as institutional arrangements (e.g. the regulatory and legal framework that determines the relationship, roles and responsibilities of the actors and coordination mechanisms such as markets, incentives or self-imposed norms) and political culture, including different perceptions of risk.

Consequently, when the risk governance framework is applied to operation and safety of dams and reservoirs, the main challenge consists in **aligning people, processes and policies to support decision making**, and the factors that form the underlying basis to define the overall scope of this work: developing policies, implementing tools and training personnel to build the needed capabilities (Ignacio Escuder-Bueno and Halpin 2016).

In this sense, Risk Governance builds on Risk Assessment and Management results to develop a complete framework for dam safety management.

Even though these guidelines are focused on the Risk Assessment and Management process, this chapter provides general recommendations on key aspects to develop a dam **Risk Governance Framework** based on the designed **Dam Safety Management Program** (explained in the previous chapters). These three key aspects explained in the following sections are capacity-building, quality assurance and risk communication.

8.2 Capacity building

Risk Assessment and Management is a methodology that is continuously improved and completed while it is being used. New scientific developments and technologies will continue to improve dam safety management and data collection in the future. In this sense, it can be said that the analysis, evaluation and management of risk requires uninterrupted training and research.

Within a dam safety organization, capacity building on risk techniques and risk-informed decision making is needed at different levels (FEMA 2015):

- **Dam site personnel:** The dam tenders, inspectors, staff performing visual inspections and taking seepage readings and instruments, and plant operators responsible for gate operations provide a valuable source of information relative to risk analyses and need to be included. Dam operators often have detailed information and understanding of the dam history, past performance issues, and a good perspective on perceived changes at the dam.

  As explained above, it is important to include them in risk analysis activities to benefit from their knowledge of the dam, especially during sessions for identification of failure modes. In addition, it is very important for them to gain an understanding of potential failure modes at the dam, specific locations at the dam where potential failure modes might develop, and the initiating mechanisms for the potential failure modes. This will allow them to monitor the dam more effectively.

Likewise, the main concepts of the methodology and the outcomes of risk analyses and the decisions and rationale used in risk assessment and risk management need to be explained to the personnel so that they have a full understanding of the outcome of the risk process.

- **State level:** Supervision and management of the operation of a few numbers of projects and dams are usually the responsibility of an office within a dam safety organization. These offices are responsible for staffing personel for routine operation and maintenance of projects and dams under their purview, as well as for inspection and monitoring of their dams. In addition, they are often responsible for implementing structural and non-structural actions which may be specified as the outcome of the risk-informed decision analyses.

  Therefore, State office personnel also need to be trained and included in risk analyses relative to development of failure modes and dam performance. State offices are typically the key intermediary between the desired objectives of the organization's dam safety office and the field site that would be affected by the outcomes.

- **Technical staff in charge of risk analysis:** Detailed capacity-building and communication activities are required among the technical staff (including consultants and contractors) performing the risk analysis and the staff performing the studies that provide data for risk models (hydrological analysis, seismic analysis, estimation of consequences, numerical models…). At this level, capacity-building is more demanding and is more frequently needed since this team oversees risk analysis results and they should know the latest developments in risk assessment worldwide. In this sense, participation in international conferences and benchmarks are encouraged and strongly recommended.

- **Decision makers:** Decision makers need to have a general understanding of the potential failure modes at a dam, the results of studies and analyses performed, the risk analysis results, and the process for prioritization of risk reduction actions. Decision makers have the responsibility for formally accepting dam safety actions and must be convinced that the proposed actions are warranted and appropriate. Individuals who have the responsibility for setting priorities within an organization will also need to understand the basis and urgency of dam safety actions at a given dam.

Consequently, capacity-building should be implemented at every level of each organization, especially during the first years of implementation of a risk-informed dam safety program. However, it should be a long-term continuous process within the organizations to ensure proper risk-informed decision-making processes are sustainable.

As explained in (Halpin and Escuder-Bueno 2017), capacity-building is fundamental since changes happen with people and through people, not to people; hence leading people provides one of the necessary ways to overcome the challenges posed by risk informed governance.

Risk informed governance cannot primarily or solely be a top-down driven initiative due to the need to have those who do the work understand and become an advocate for the change itself. In other words, the best laid plans and policies of risk informed governance that come from within an organization will be like the farmers who seed that falls on rocky ground – it withers in the sun without a foundation to support growth. So, people and organizations need to be involved in the change to risk informed governance by helping lay the groundwork for approaches to decision processes, technologies, and policies. Secondly, the bench of professionals experienced in risk informed approaches must be grown through training and experience, experience being the most important of these.

Organizational competency is demonstrated when the governance to hold up good decisions is sustained over a period years and is consistent, credible, and defendable.

8.3 Risk Communication

Risk communication is a critical component of an effective risk informed decision process. In the proposed dam safety program, it is not identified as a separate component but rather as something that should be integrated into every aspect of the process, especially in the portfolio management process.

As explained in the previous section, risk capacity-building and communication is essential within an organization, but it is also necessary within other individuals or organizations that would be impacted by a dam failure. A goal for risk communication is to help people understand potential hazards to their person, property, or community.

In this sense, as explained in (USBR 2011), the key outcome of the risk analysis is to communicate the current understanding of risk (and its relation to the tolerability guidelines) to the decision-makers. Showing graphically the impact of risk reduction actions and the need for better characterization of some failure modes is very useful to convince existing stakeholders regarding the need of investments on these actions and studies. For this reason, risk assessment is a useful tool that helps to communicate risk to stakeholders.

As explained in (FEMA 2015), it may be helpful to include individuals from **water user stakeholders** as observers in the risk analysis, especially in the risk assessment and decision making meetings. This will allow those individuals to gain a better understanding of the basis of risk analysis estimates, the subsequent findings, and the rationale on which a decision is made. They will typically be interested in the reasoning behind proposed dam safety and will want to ensure that the chosen actions are appropriate and efficient. It will also be helpful to explain the overall dam safety process used and explain the risk guidelines that were used in the risk assessment.

Communication should be provided proactively for organizations and the **general public** that will be, could be, or consider themselves impacted by a dam failure or by dam safety actions that could restrict or modify the operations at the dam (FEMA 2015). These communications should be initiated at the planning or investigation stage to prevent erroneous information and rumours from developing. Such presentations need to be technically appropriated, conveying the technical information in a manner that collects the key issues and concerns at the dam, the potential impacts of a dam failure, the proposed actions to address the issues/concerns, and the impacts of these actions on organizations and the public.

Detailed risk numbers may not adequately communicate risks to the public and non-technical audiences and the focus on risk numbers may shift the emphasis away from the source of the risks and the potential hazards. In (USBR 2011), it is recommended to explain these risks and hazards simply by stating the dam safety case is generally the goal of risk communication in non-technical settings.

Typically, communications actions for the public are group meetings, presentations and brochures. In these events, information should be presented in a manner that is easy to understand but not condescending to the audience. The following principles are recommended in these types of communication actions (FEMA 2015):

- Enhance communication with the public, internally within dam owners and regulating organizations, and Emergency Management Agencies.
- Emergency Action Plans and communication with the public are important and integral aspects of reducing risk to life.
- Communications should be open and transparent.
- Focus on the benefits and the risks posed by the infrastructure when presenting dam safety issues at a given dam.
- Early integration of risk communications in the process of responding to dam safety issues.
- Provide context for risk communications (compare with risks from other industries).
- Focus communication on actions that individuals/organizations need to take.
- Discuss uncertainty in risk estimates and the dam safety case:
  - What is certain
  - What is likely, but not certain
  - What is possible, but not likely

8.4 Overall Regulatory Framework

One of the keys aspects of Risk Governance is how dam safety is matched within the overall regulatory framework and the disaster management legislation. In this sense, it is important to develop Dam Safety Legislation that backs ups all Dam Safety activities and clarifies main roles, responsibilities and authorities.

Therefore, dam safety legislation is one of the fundamental elements for a dam safety program since it defines how the Dam Safety pillars are addressed and how the responsibilities are distributed between dam owners and regulatory bodies.

During development of these guidelines, the Indian Dam Safety Bill is being discussed to reinforce dam safety management in India. This bill defines dam owners' responsibilities to develop modern dam safety programs including inspections, monitoring, operation rules, Emergency Action Plans, dam safety evaluations and risk assessments. It also provides institutional mechanisms to ensure that these requirements are met.

8.5 Review and quality assurance

In the Portfolio Risk Management, review of Dam Safety Risk Assessment for each dam should be included within the management procedures before decision making.

In this sense, it is recommended to have within the organization an independent team (**primary reviewers**) who reviews every report, checks the consistency and homogeneity of approaches and the methods between them and ensures that quality is enough to inform decision making.

The reports prepared for Dam Safety Risk Assessment need to include sufficient detail so that the primary reviewers (as well as other risk analysts in future years) can understand the assumptions made, detailed results of studies, the analyses and risk analyses, and the technical basis for overall findings. Furthermore, these results may be called for at any future stage in the process (e.g., risk management, stakeholder review, etc.); thus, good documentation is essential.

In this sense, a key point to ensure quality assurance is capacity-building within the organization to have qualified personal for risk-informed decision making.

In addition, an appropriate technical review should be conducted for the inspection, evaluation, and design of every feature of risk reduction actions projects.

It is also advisable that a panel of **external international experts** review the whole Risk-Informed Dam Safety Program periodically, to provide suggestions and experiences from other countries for improving it. This review is recommended to be undertaken every 5 years.

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APPENDIX A – TEMPLATE FOR REPORT ON DAM SAFETY RISK ASSESSMENT

This template defines the recommended structure for a Report on Dam Safety Risk Assessment, following the procedures proposed in these guidelines. This template is a general guide, meaning that sections and details can be modified to be adapted to each dam. Texts to be replaced in this template are written in *grey and italic letters*. Examples on how this template should be completed can be found in practical cases of Appendix B and Appendix C.

Report on Dam Safety Risk Assessment

Name of Dam

Project Identification Code

Dam Picture

Prepared for ***Dam Owner Name***

Prepared by ***Name***

Date

Revision Number

Revisions of Risk Assessment Report

Report Date	Reason for Revision	Main changes made	Author
Revision date	*It can be: First Risk Assessment / Periodic Update / Update on new studies / Risk reduction measures implemented / New deficiency detected in inspection / Other (Specify) (see Section 7.3)*	*Brief description of updated parts within the report*	*Risk Assessment Author*

Data of next Risk Assessment periodic update:

Date of Last Complete Report Update + 4-10 years

(see Section 7.3)

Table of Contents

EXECUTIVE SUMMARY

Summary of main findings and recommendations from the risk assessment.

1. INTRODUCTION

1.1. Dam description

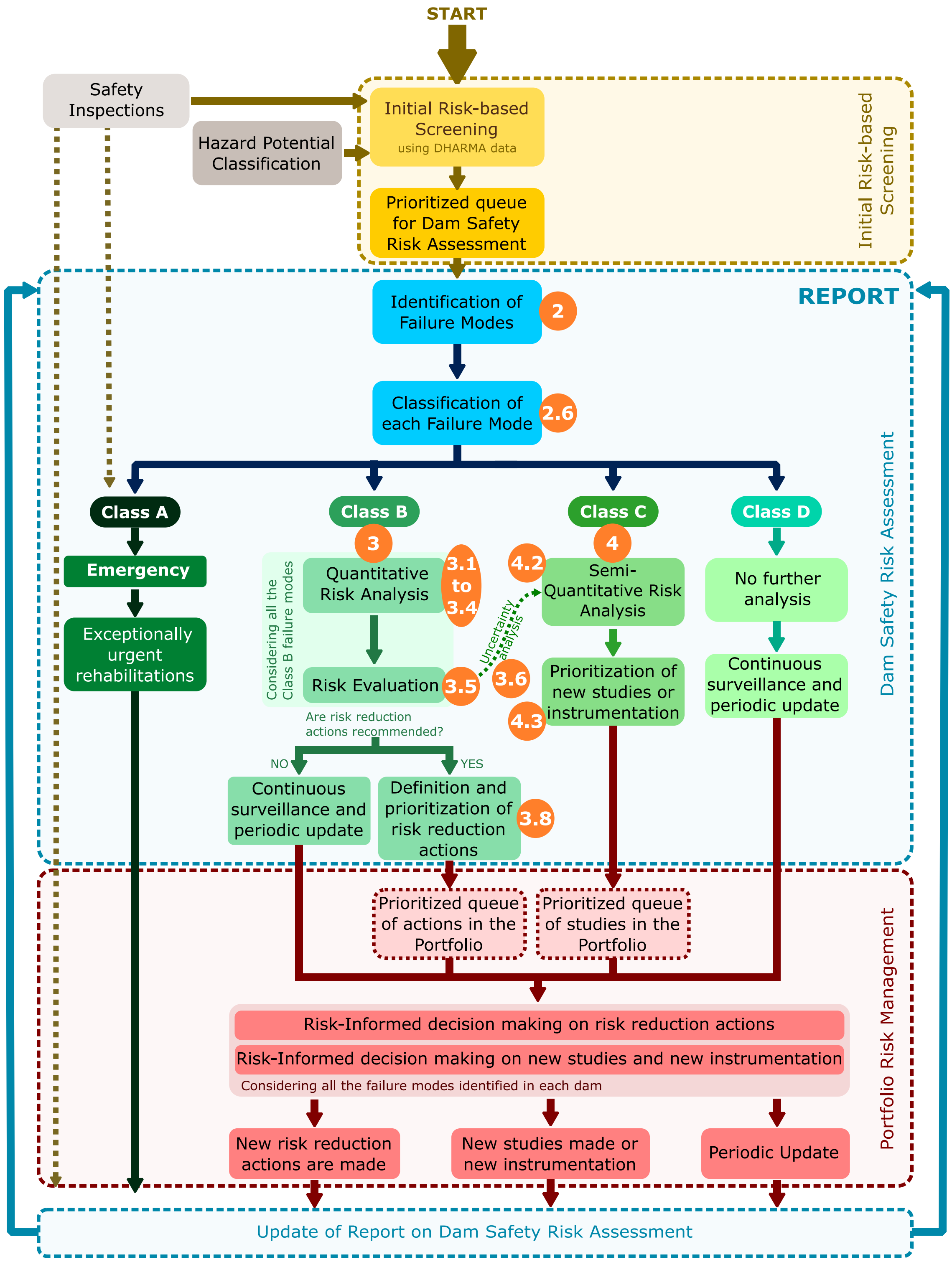
General description of the dam (typically 1-3 pages), including:

- *Main dam characteristics: dam owner, typology, height, crest length, crest level, Maximum Operation Level, reservoir volume, year of construction, purposes, river, etc.*
- *Location map.*
- *General layout plan.*
- *Cross section drawings.*
- *Description of outlet works and spillways.*
- *Brief description of major problems and rehabilitations in the past.*

Finally, according to the Hazard Potential Classification made in *[Report name and year]* made by *[Author]*, the *[Dam name]* Dam was classified as *[Hazard Class]*.

1.2. Risk Assessment and Management Framework

The current Risk Assessment Report is based on the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Within these guidelines, a Risk-Informed Dam Safety Management Program is given with the structure shown in the following figure:



Risk-Informed Dam Safety Management Program. Source: Guidelines for Assessing and Managing Risks Associated with Dams (CWC, 2018).

This Risk Assessment Report is focused on the central part of the management program, and the different steps of this central part are directly related with the different sections of the report (as shown by numbers in orange circles). Therefore, the main purpose of this report is to explain the identified failure modes, the results of the quantitative and semi-quantitative risk analysis, and the prioritization made for new studies and potential risk reduction actions for *[Name of the dam]* dam.

As shown in this figure, the **Dam Safety Risk Assessment** begins with a **Failure Mode Identification** process in each dam, which includes a review of the available information, a technical visit to the dam and multidisciplinary group working sessions, as explained in Chapter 2. Based on the information available and the credibility of each failure mode, they are classified in four categories:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and exceptionally urgent rehabilitation measures and/or emergency actions are needed.

- **Class B:** Failure mode is credible and available information is enough for a **Quantitative Risk Assessment**. Risk results are evaluated and if needed, potential risk reductions are proposed and prioritized. This assessment is explained in detail in Chapter 3.

- **Class C:** There is uncertainty about this failure mode, 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 (Chapter 4).

- **Class D:** Failure mode is not credible. This failure mode should be documented and reviewed in the following updates of the Risk Assessment process.

The results obtained from this report are intended to be used for Portfolio Risk Management, by combining the prioritized risk reduction actions on the dam to create a prioritized list of proposed actions in the whole Portfolio of dams. Similarly, the prioritized lists of new studies for each dam are combined to create a prioritized list of new studies and/or instrumentation in the Portfolio. Hence, new actions and studies are planned in the Portfolio taking into account administrative, legal or societal issues and analysing all the failure modes identified in each dam.

2. IDENTIFICATION OF FAILURE MODES

2.1. Introduction

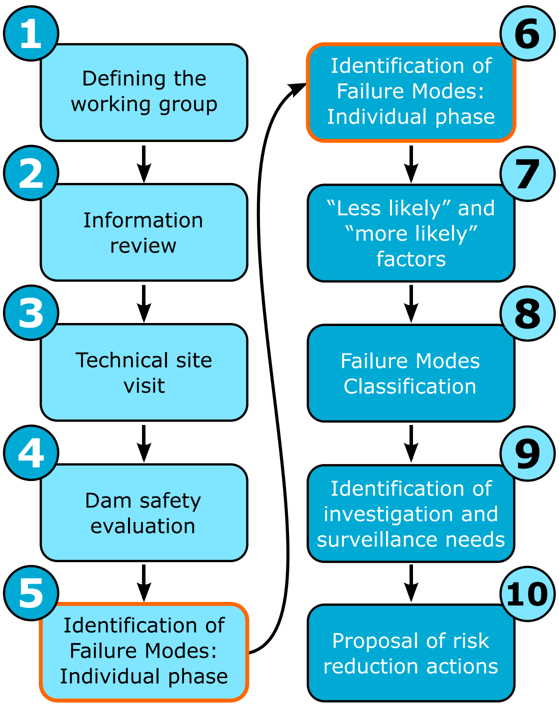
A **failure mode** is a specific sequence of events that can lead to a dam failure. This sequence of events must be linked to a loading scenario and will have a logic sequence: starting with an initiating event, one or more events of progressive failure and will end with dam failure or mission disruption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

In general, any failure mode with the potential to produce adverse social or economic consequences could be analysed. The identification is not limited to the dam structure and it may include any feature or component of the dam-reservoir system. *(This paragraph may be changed to define the scope of the analysis).*

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 *[Name of the dam]* Dam was made following the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* during different working sessions as shown in the following figure:



Step	Date
1	*First working session*
2	*Information review date*
3	*Site visit date*
4	*Step 4 date*
5	*Step 5 date*
6	*Step 6 date*
7	*Step 7 date*
8	*Step 8 date*
9	*Step 9 date*
10	*Step 10 date*

Identification of Failure Modes steps and dates.

Pictures of the team and sketches in the working sessions of Identification of Failure Modes

Working sessions of Identification of Failure Modes.

The process was made through a collaborative work of several engineers and technicians, including a comprehensive review of available information, a technical visit to the dam and 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.

The Identification of Failure Modes was made by a multidisciplinary group which includes engineers and technicians in charge of the dam's daily operation and regional/national experts in some of the topics addressed. Participants in these sessions are listed in the following table:

Name	Title (s)	Entity

Identification of Failure Modes sessions were facilitated by *[Name of the facilitator]*, who has proven experience in coordinating this type of sessions.

2.2. Information review

The information available about *[Name of the dam]* Dam was reviewed on *[Date of review]* to support the Risk Assessment process. The main documents reviewed during this working session were:

Document title	Author	Data

After this detailed reviewed, the main conclusions about the available information were:

- *What is the quality of the studies? Do they have enough level of detail?*
- *What studies or information is missed?*
- *What new studies would be recommended?*

2.3. Technical site visit

The technical visit to *[Name of the dam]* Dam was made on *[Date of review]*. This visit represented a very valuable source of information since it allowed for the verification of current conditions of the dam-reservoir system. This site visit was made with enough time to exhaustively inspect all the parts of the dam(s). Special attention was paid to main problems identified during the information review.

Picture/s of working group in the technical visit

Technical site visit in *[Name of the dam]* Dam.

The main conclusions about the technical site visit are:

- *Main deficiencies and problems observed in the site visit.*
- *Is the dam properly maintained and operated?*
- *These conclusions can be highlighted with pictures.*

2.4. Dam safety evaluation

After the field visit and the information review, a comprehensive evaluation of the dam safety is made as a basis for the identification of failure modes.

Main conclusions and available information about each aspect should be described in the following section after being discussed in the working sessions. They will be based on the information review and the technical visit. It is recommended to complete about ½-2 pages for each one. The following questions will help to understand which data should be explained in each part.

Flood hazard and hydrological adequacy

- *What is the available hydrological information? The age and method of computing hydrologic and hydraulic calculations should be examined in regards to current methods, particularly for extreme events.*
- *What is the design flood? How was it obtained?*
- *Has the hydrological adequacy of the dam been checked? When?*
- *What hypothesis has been followed for this check?*
- *What are the uncertainties sin this data?*
- *Are there seasonal freeboard requirements for flood routing?*

Gates operation and hydraulic behaviour

- *What are the gates operation rules?*
- *Where are they described?*
- *When were they updated?*
- *What is the real operation of gates? Does it differ from operation rules? Why?*
- *Were the operation rules followed in previous flood events?*
- *How is the hydraulic behaviour of the gates-spillway systems during previous floods?*
- *What is the elevation of gate controls in relation to the elevation of water pool levels in different loading conditions?*

Gates and electromechanical equipment condition

- *What is the current maintenance state of the gates? And other electromechanical equipment?*
- *Have they presented problems recently?*
- *How old are they?*
- *What are the power supply options?*
- *Do the gates have blockage problems due to debris, logs or ice?*

Current state of spillway and stilling basin

- *What is the current state of the spillway civil works?*
- *Can the stilling basin be observed? What is its current state?*
- *Are there any erosion signs in the downstream areas?*

Foundation and abutments

- *What are the main characteristics of the foundation and abutments?*
- *What is the available information about them?*
- *Were there any deficiencies detected during the construction or operation?*
- *Are there any signs about potential internal erosion problems?*
- *How was the foundation historical performance in past flood events?*

Monitoring data and state of monitoring system

- *What is the gathered instrumentation data?*
- *What is the current state of instrumentation?*
- *Is the gathered data being analysed?*
- *How often are the surveillance actions made?*
- *How are the technical inspections? Who makes them?*

Dam body condition

If there are different structures in the reservoir, a different section should be made for each one.

- *Are there any major alterations or dam changes since its construction?*
- *In concrete dams, what is the current concrete state?*
- *In embankments, is there solid material in water leakage? Are there any signs regarding potential internal erosion problems?*
- *Settlements, cracks and movements observed.*
- *What are the main conclusions about the dam body obtained from dam instrumentation?*
- *Review of dam body design and construction records and comparison with current standards for dam design and construction.*

Condition of the drainage system

- *In concrete dams, what is the state of dam foundation and body drainage systems?*
- *In embankments, what is the state of the dam body drains?*
- *What are the main conclusions about the drainage system obtained from dam instrumentation?*
- *Are there any boils observed in the vicinity of the downstream toe of the dam?*
- *Is the downstream area sufficiently clear and free draining?*

Dam stability in normal loading conditions

- *Has the dam stability been checked? When?*
- *What resistance parameters and hypothesis have been considered?*

Seismic hazard and dam stability during seismic events

- *How high is the seismic hazard in the dam area?*
- *Has the dam stability been checked for seismic events? When?*

- *What resistance parameter and hypothesis has been considered?*

Landslide in the reservoir

- *Does the reservoir have potential landslide areas?*
- *Have they been analysed?*
- *Are they dangerous for the dam safety?*

Emergency action planning and urban areas downstream

- *Has the Emergency Action Plan been developed? When?*
- *Is it implemented?*
- *Are the emergency agencies correctly coordinated?*
- *What are the main urban areas downstream?*
- *Have there been significant changes in downstream urban areas since dam's construction?*
- *Are dam accesses reachable in case of emergency?*

Engineering assessment

Engineering assessment consists of asking the participants to individually assess whether dams are meeting the established good international engineering practice. 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.

Results of this engineering assessment are shown in the following table:

Dam safety aspects	Participants initials												
Flood hazard and hydro-logical adequacy													
Gates operation and hy-draulic behaviour													
Gates and electromechani-cal equipment condition													
Current state of spillway and stilling basin													
Foundation and abutments													
Monitoring data and state of monitoring system													
Dam body state													
State of drainage system													
Dam stability in normal loading conditions													
Seismic hazard and dam stability in seismic events													
Landslide in the reservoir													
Emergency action planning													

In the working sessions, each participant should rate each aspect as pass/apparent pass/ apparent no pass/no pass /not applicable to complete this table with colours. One column for each participant.

Explanation of main conclusions derived from this table.

2.5. Failure Modes Identified

Failure modes for dam *[Name of the dam]* were identified on *[Date]* in an individual phase and in a group phase. In the first phase of the identification of failure modes, each participant in the session individually made a preliminary identification of failure modes in the dam, using the provided booklet. Once each participant had finished the individual identification of failure modes, all of them were put in common and combined into group sessions. In addition, for each failure mode, the factors that make them likely are 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 certain failure mode.

The results of this failure modes identification process are shown in the following tables:

One table for each failure mode.

Failure Mode 1	***Short description***
Description	
Detailed description of failure mode in text	
Graphical scheme	
More likely factors	**Less likely factors**
•	•

Failure Mode 2	***Short description***
Description	
Detailed description of failure mode in text	
Graphical scheme	

More likely factors	**Less likely factors**
• •	•

Failure Mode 3	***Short description***
Description	
Detailed description of failure mode in text	
Graphical scheme	
More likely factors	**Less likely factors**
•	•

2.6. 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:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and 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 B:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class B 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 C:** 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 D:** 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.

In the working sessions, Failure Modes were classified in the following classes after group discussion:

Number	Failure Mode short description	Class
1		
2		
3		
4		
5		
6		
7		
8		

One row for each failure mode.

Clarifications, explanations and comments about this classification.

2.7. 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 C, 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. Therefore, this first proposal of actions is lately developed in Section 4.3.

In addition, surveillance and monitoring needs can also be identified to support the detection of failure modes classified as B. 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 3.7.

New studies and/or new instrumentation should be recommended for all the failure modes ***classified as C****, since this classification means that more efforts can be made to gather more knowledge about them. The following questions should be answered during the working sessions to think about these measures:*

- *What additional variables could be measured in the dam to gather more knowledge about the occurrence of these failure modes?*
- *What additional studies/analysis/tests could be useful to know more about these failure modes?*

For each proposed investigation and surveillance action, the following table should be completed:

The following investigation and surveillance needs were identified in *[Name of the dam]* Dam:

Proposed studies	Related Failure Modes
Short description of each action (2-3 lines)	

Finally, during the working sessions the following analyses were recommended to be made with the quantitative risk model

- *What uncertainty analysis and tests can be made using the quantitative risk analysis? What analysis can be useful to know more about the dam using the risk model and its input data?*

Proposed analysis	Related Failure Modes
Short description of each action (2-3 lines)	

2.8. Proposal of risk reduction actions

This first part should be included ONLY if there are failure modes classified as A:

Since *[Number of failure mode]* was **classified as A**, risk reduction actions are recommended to be made as soon as possible. The following actions are proposed to solve this failure mode:

Name	*Name*
Description	
Detailed description of the proposed surveillance or investigation action	
Graphical scheme	

This second part should be completed in all the cases:

Actions proposed to reduce risk in failure modes **(especially in Class B failure Modes)**, are the basis for the prioritization of risk reduction actions using quantitative risk results and they are explained in detail in Section 3.7. The following actions were proposed in the working sessions:

In this stage, the following questions can be made to encourage the discussion:

- *What structural fixes could be made in the dam to avoid the occurrence of these failure modes?*
- *What non-structural measures (emergency action plans, coordination procedures…) could be implemented to reduce dam risk?*
- *What improvements could be made in dam operation?*
- *What additional variables could be measured in the dam to detect the occurrence of these failure modes?*
- *What improvements could be made in the surveillance and maintenance procedures?*

The following risk reduction actions were proposed in *[Name of the dam]* dam:

Proposed actions	Related Failure Modes
Short description of each action (2-3 lines)	

3. QUANTITATIVE RISK ASSESSMENT

3.1. Introduction

Fully quantitative risk assessment seeks to enumerate the risks in terms of probability and consequences in quantitative terms. This Quantitative Risk Assessment was a collaborative process, made during different working sessions. The participants of this working group are summarized in the following table:

Technicians that have been participating in the elaboration of the risk model data and expert judgment sessions.

Name	Title (s)	Entity

Quantitative Risk Assessment was coordinated and supervised by *[Name of the coordinator]*, who has proven experience in this type of analysis applied to dam safety.

3.2. Risk model architecture

In a first stage, model architecture was defined for *[Name of the Dam]* with all Class B failure modes. This model is based on outcomes from the failure mode identification session, aiming at analysing the risk of flooding in downstream areas. The failure modes included in the risk model are:

- *Class B Failure Modes*

The architecture of the quantitative risk model is shown in the following figure:

Risk model architecture (influence diagram or event tree architecture)

Risk model architecture of *[Name of the dam]* Dam.

General explanation of the risk model architecture.

General description of software and mathematical tools use to develop the risk model.

3.3. Risk model input data

Hydrological hazard

If a hydrologic scenario has been considered in one or several of the failure modes

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Seismic hazard

If a seismic scenario has been considered in one or several of the failure modes

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Pool levels probabilities

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Gates performance

If a hydrologic scenario has been considered in one or several of the failure modes and gates are used for flood routing

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Flood routing analysis

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Failure probabilities for Failure Mode *X*

One section for each failure mode

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Failure hydrographs

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Loss of life estimation

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Estimation of economic consequences

Data introduced in this part of the risk model

Source of this information

Methodologies followed to estimate this data

Description or other environmental/social consequences that could increase economic impact

3.4. Risk results in current situation

After completion of input data for risk calculation, and once incorporated in the risk model architecture, societal and economic risk were obtained. The following quantitative risk results were obtained:

Incremental risk
Fraction of risk that is exclusively due to dam failure. It is obtained by subtracting the consequences that would have happened even in case of non-failure from the consequences due to dam failure. In the following sections, this type of risk is compared with tolerability guidelines and is used to prioritize risk reduction actions. These results are shown in the following table:

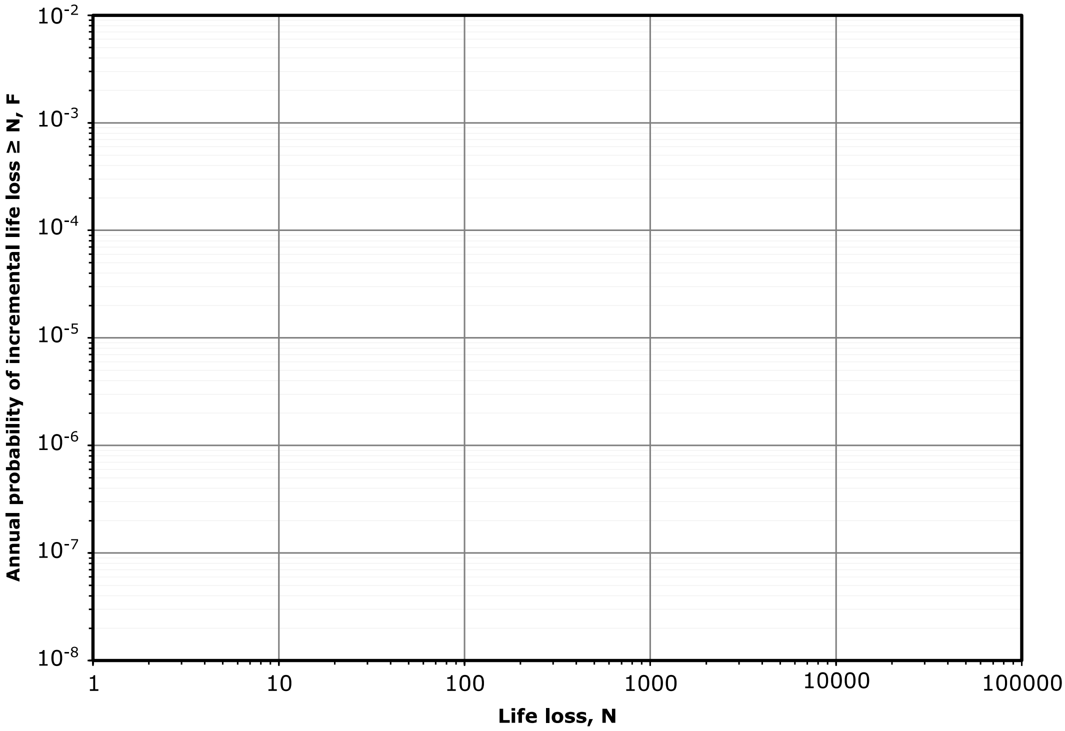
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
Failure Mode X			
Failure Mode XX			
.			
.			
.			
Total			

One row for each failure mode included in the risk model

General explanation of risk results

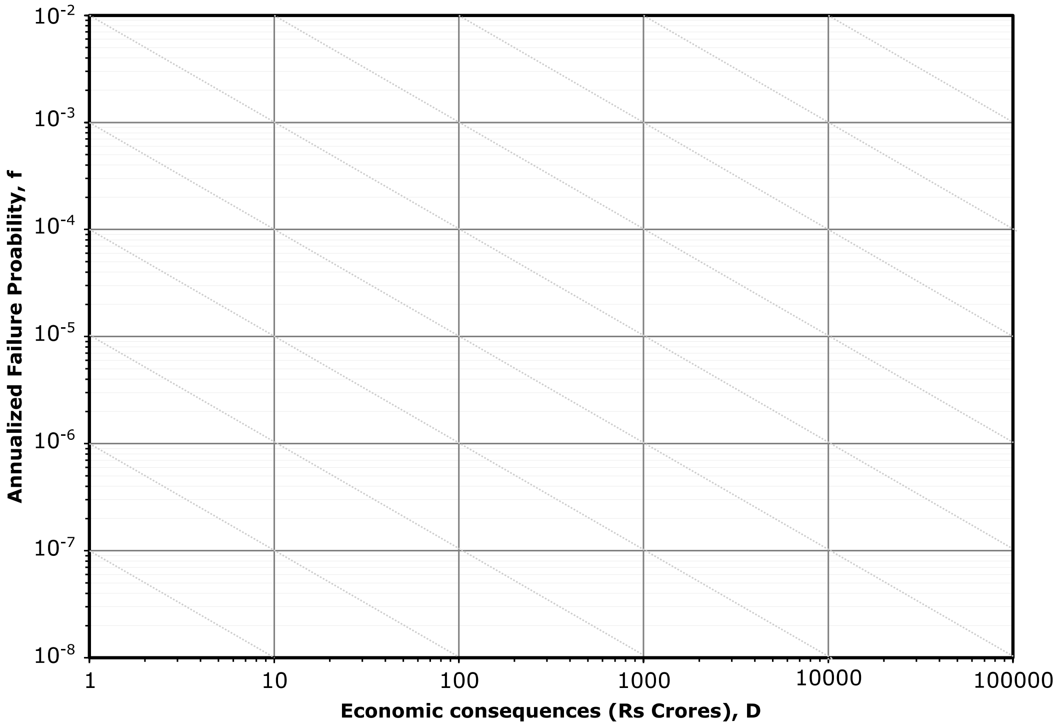
In the following figures, these incremental risk results are represented in fN, fD, FN and FD graphs:

Representation of risk results in an fN graph. One point for each failure mode and one for the total.



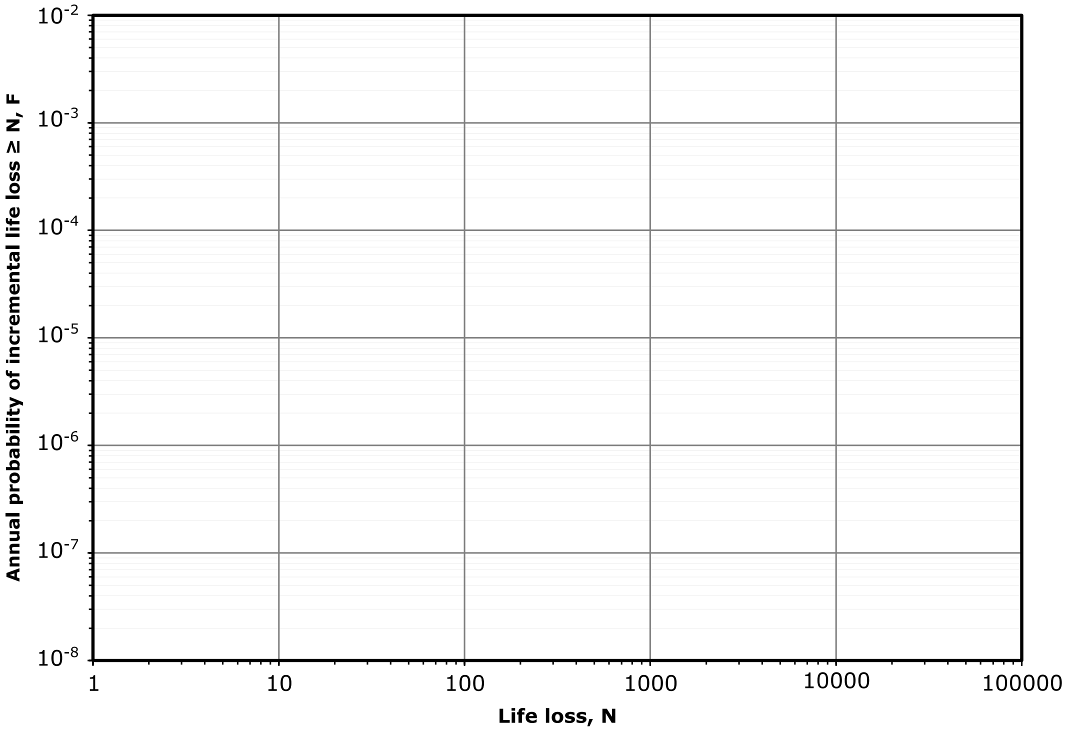
fN Graph with incremental risk results in current situation.

Representation of risk results in an fD graph. One point for each failure mode and one for the total.



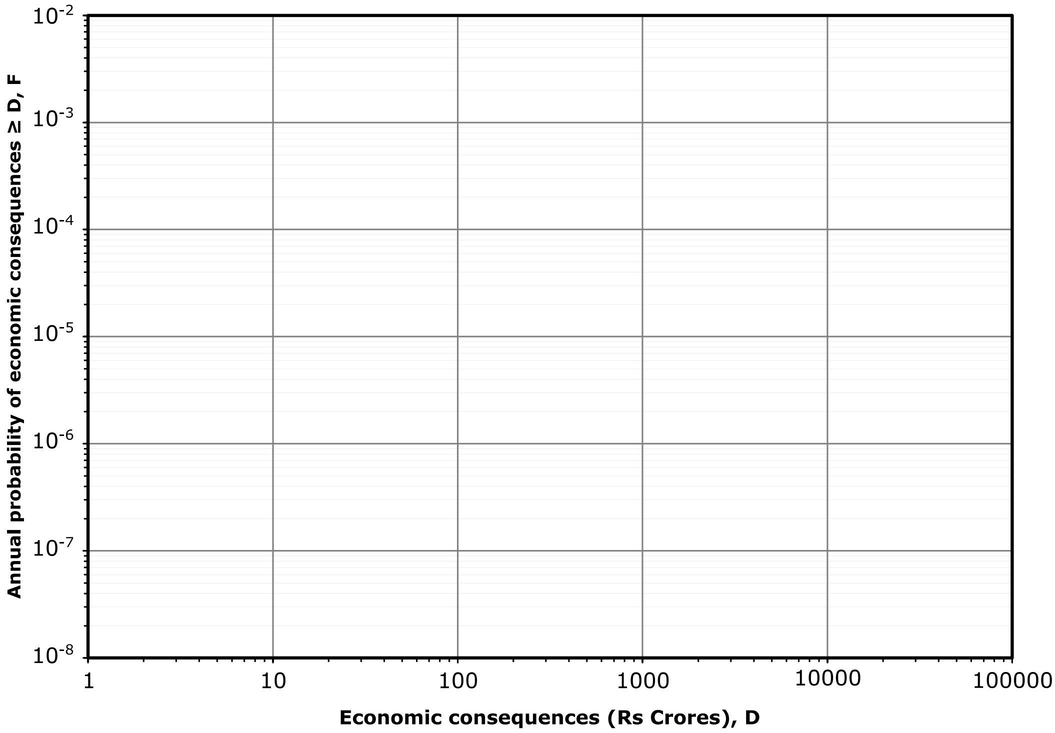
fD Graph with incremental risk results in current situation.

Representation of incremental risk results in an FN graph.



FN Graph with incremental risk results in current situation.

Representation of incremental risk results in an FD graph.



FD Graph with incremental risk results in current situation.

Comments on these graphs

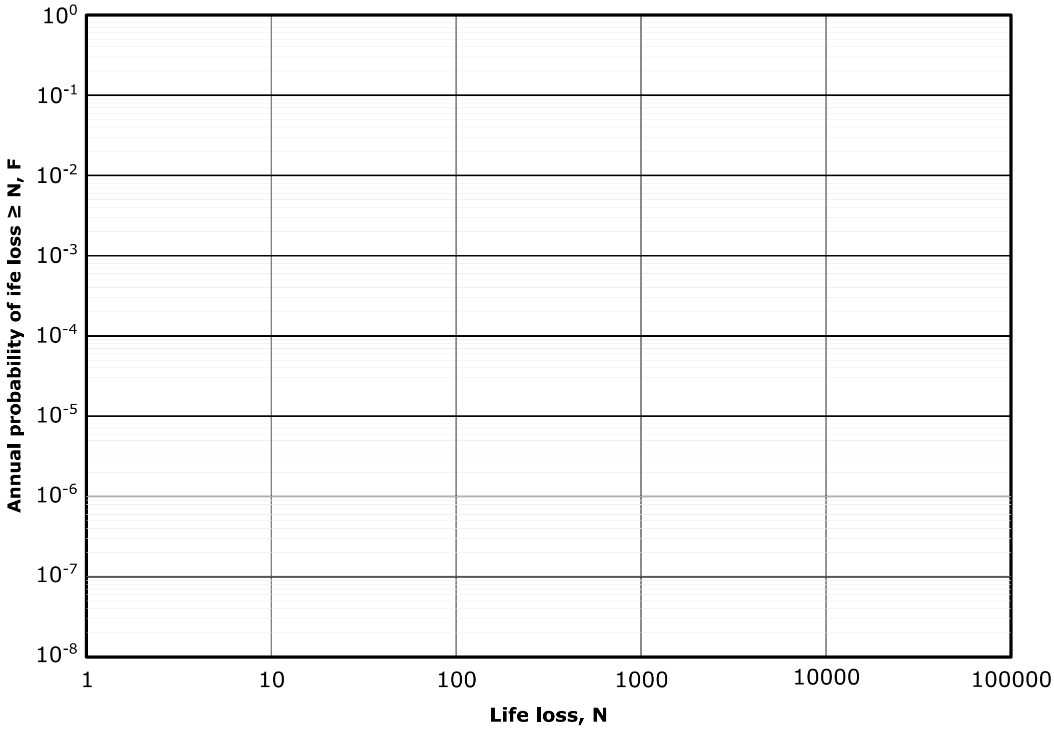
Total risk

Represents the total risk from flooding in downstream areas and includes both dam failure and non-failure cases. These results are shown in the following table:

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

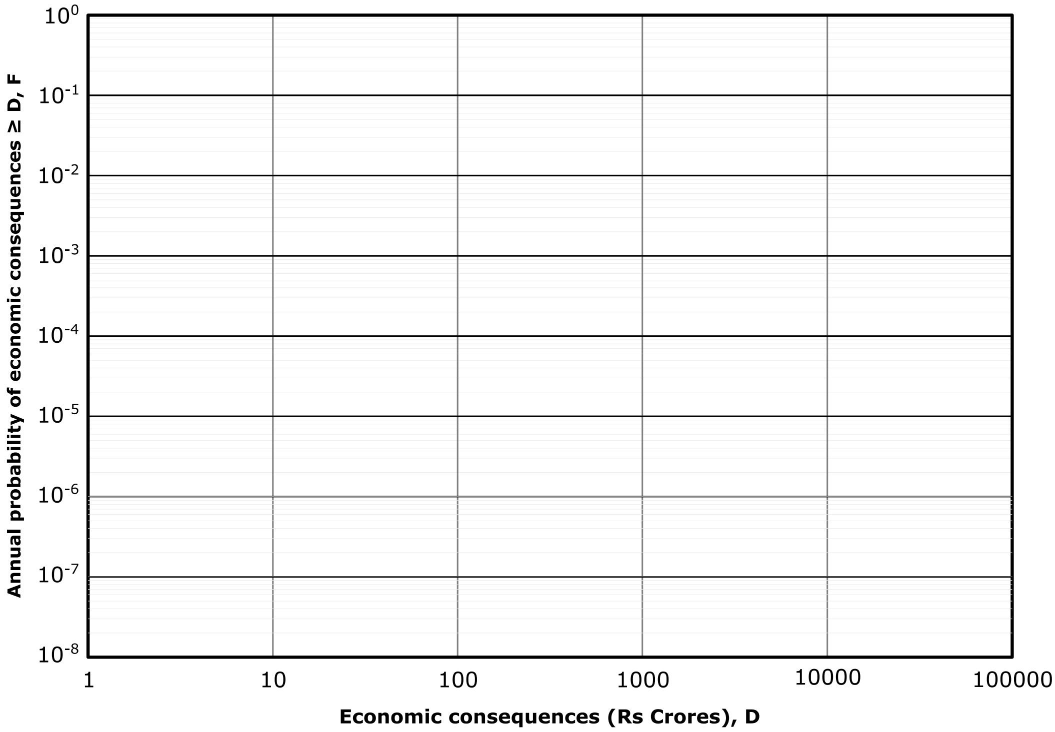
In the following figures, these total risk results are represented in FN and FD graphs:

Representation of total risk results in an FN graph.



FN Graph with total risk results in current situation.

Representation of total risk results in an FD graph.



FD Graph with total risk results in current situation.

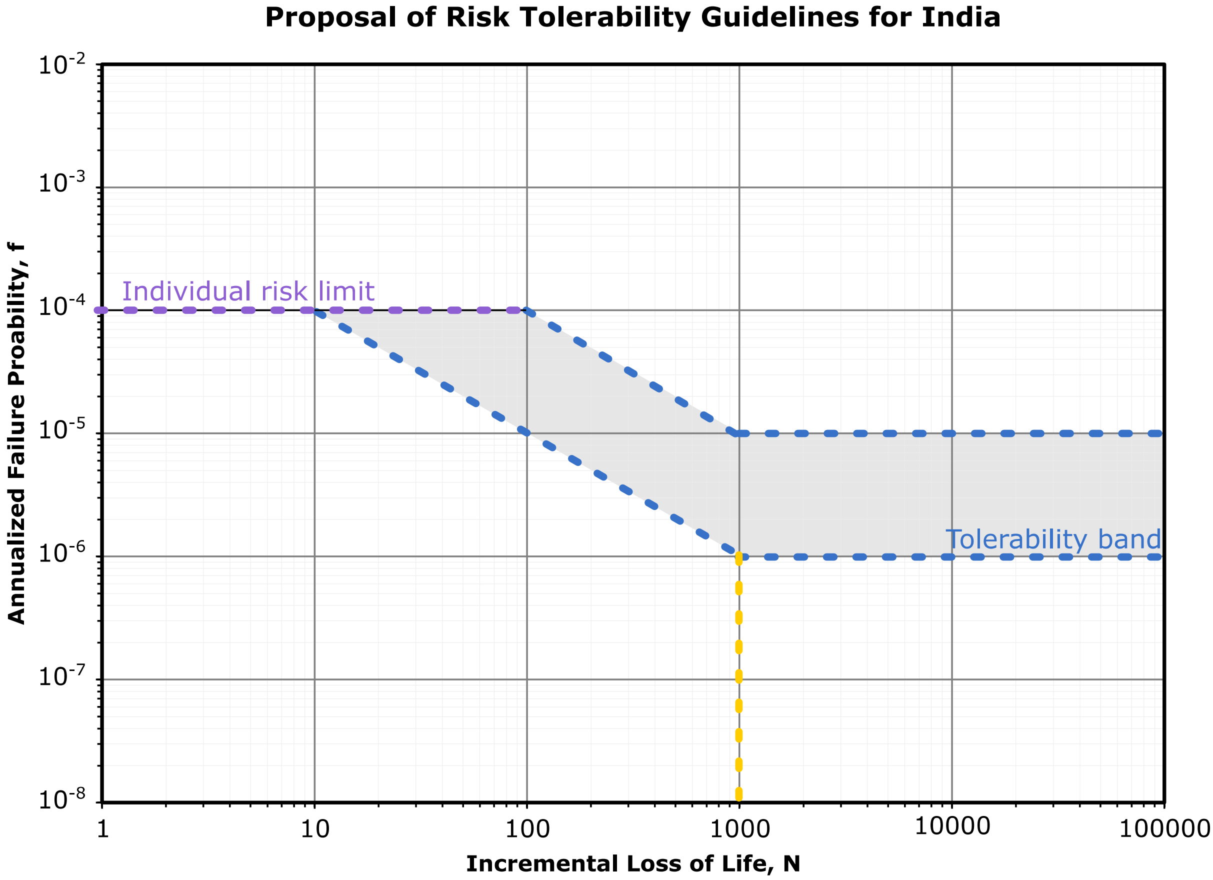
General explanation of total risk results and graphs

3.5. 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 the tolerability recommendations from the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Risk evaluation results are shown in the following graph:

Representation of risk results in the tolerability fN graph. One point for each failure mode and one for the total.



Individual and societal risk evaluation for current situation.

Risk tolerability conclusions. For each failure mode, is risk tolerable or not?

3.6. Uncertainty analysis

The objective of performing this uncertainty analysis is assessing if existing input data uncertainty could change the conclusions of risk evaluation. With the purpose, the following risk uncertainty analysis was made:

Risk model input data that can be analysed in an uncertainty analysis are:

Epistemic uncertainty analysis is typically focused in (some of) the following data:

- *Hydrologic hazards.*
- *Seismic hazards.*
- *Gates reliability.*
- *Probabilities estimated by expert judgment.*
- *Physical model parameters.*
- *Warning times and evacuation procedures to estimate loss of life.*

Due to uncertainty analysis results, Class B failure modes should also be included in the Semi-Quantitative analysis if the following conditions are met:

- *Epistemic uncertainty is considered too significant since uncertainty variation in a failure mode could make that risks move from tolerable regions to clearly not tolerable regions.*
- *More information can be reasonably gathered to reduce uncertainty, through new studies or new instrumentation.*

In these cases, these uncertainty reduction actions are prioritized based on a Semi-Quantitative Risk Analysis, and they should be implemented prior to new large rehabilitation actions.

3.7. Prioritization of risk reduction actions

Proposed risk reduction actions

The final stage in a Quantitative Risk Assessment is the study of potential risk reduction measures. *[Number of measures]* measures were selected from identification of failure modes recommendations, technical inspections and, in general, expected measures planned for each dam. Based on these inputs, the proposed measures were discussed by the team group, defining them with more detail. The proposed risk reduction actions are:

Before including them in the quantitative risk analysis, the feasibility of the proposed measures should be analysed.

Risk assessment results are essential to define these measures, and different trials can be made with the risk model to define the most efficient solution. For instance, risk model can be used to define the deep of a cut-off wall or the capacity of a new spillway. Therefore, a risk-informed approach is strongly recommended to design these measures in detail.

The measures explained in this section should include better monitoring actions that will help to detect Class B failure modes. When assessing the effectivity of these actions, possibilities of intervention once the failure mode is detected should also be considered.

For each measure, the following table should be completed:

<table>
<tr><th>Measure 1</th><th colspan="3">Short description</th></tr>
<tr><td>Introduction cost (Rs Crores)</td><td></td><td>Maintenance cost (Rs Crores/year)</td><td></td></tr>
<tr><td>Lifespan (years)</td><td></td><td>Failure Modes</td><td>Failure modes related with this action</td></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">Detailed description of the proposed surveillance or investigation action</td></tr>
<tr><td colspan="4">Graphical scheme</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Effect on risk model</td></tr>
<tr><td colspan="4">How do they modify risk model input data?</td></tr>
</table>

<table>
<tr><th>Measure 2</th><th colspan="3">Short description</th></tr>
<tr><td>Introduction cost (Rs Crores)</td><td></td><td>Maintenance cost (Rs Crores/year)</td><td></td></tr>
<tr><td>Lifespan (years)</td><td></td><td>Failure Modes</td><td>Failure modes related with this action</td></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">Detailed description of the proposed surveillance or investigation action</td></tr>
<tr><td colspan="4">Graphical scheme</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Effect on risk model</td></tr>
<tr><td colspan="4">How do they modify risk model input data?</td></tr>
</table>

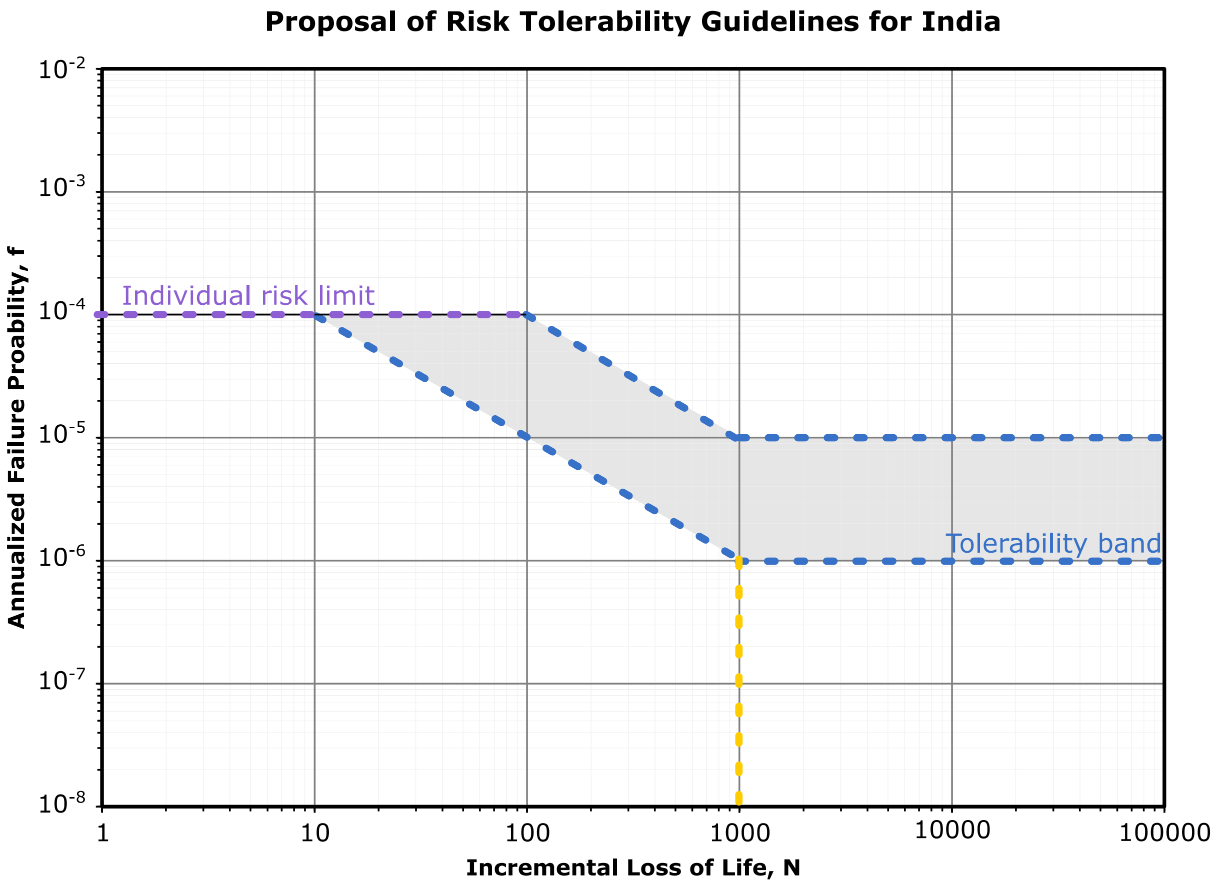
Effect on incremental risk results

After defining these measures, the next step was recalculating risk by incorporating the effect of each measure into the risk model with incremental risks. Results obtained for each measure are shown in the following table:

Current situation			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Failure Mode X			
Failure Mode XX			
.			
Total			
Measure 1: ***Name***			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Failure Mode X			
Failure Mode XX			
.			
Total			
Measure 2: ***Name***			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Failure Mode X			
Failure Mode XX			
.			
Total			
All measures			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Failure Mode X			
Failure Mode XX			
.			
Total			

One table for each measure analyzed. One final case with all the measures implemented.

These results can also be represented in the tolerability graph shown in the previous section:



Individual and societal risk evaluation for proposed risk reduction actions.

Representation of risk result for each measure.

Explanation of previous results and conclusions obtained.

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		
Measure 1: *Name*		
Measure 2: *Name*		
.		
.		
All measures		

*This table should be used to check that any measure produces an increment in total flood risk. If a measure produces an increment in this type of risk, it should be **modified and/or strongly justified.***

Effect of risks reduction measures was also represented in an FN graph for total risk:

Representation of total risk results in an FN graph. One line for each measure and all measures case:

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

Explanation of previous results and conclusions obtained.

Prioritization of risk reduction actions

Finally, proposed risk reduction actions were prioritized according to incremental risk and the EWACSLS indicator (with n = 1) to combine equity and efficiency criteria. The discount rate considered is *X%*. The results obtained for this indicator are summarized in the following table:

If other criterion is used to prioritize risk reduction actions, it should be justified.

ACSLS and EWACSLS are obtained comparing each measure with the current situation.

Measure	Annualized cost (Rs Crores/year)	ACSLS (Rs Crores/life)	EWACSLS (Rs Crores/life)
Measure 1: *Name*			
Measure 2: *Name*			
.			
.			

Explanation of previous results and conclusions obtained.

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

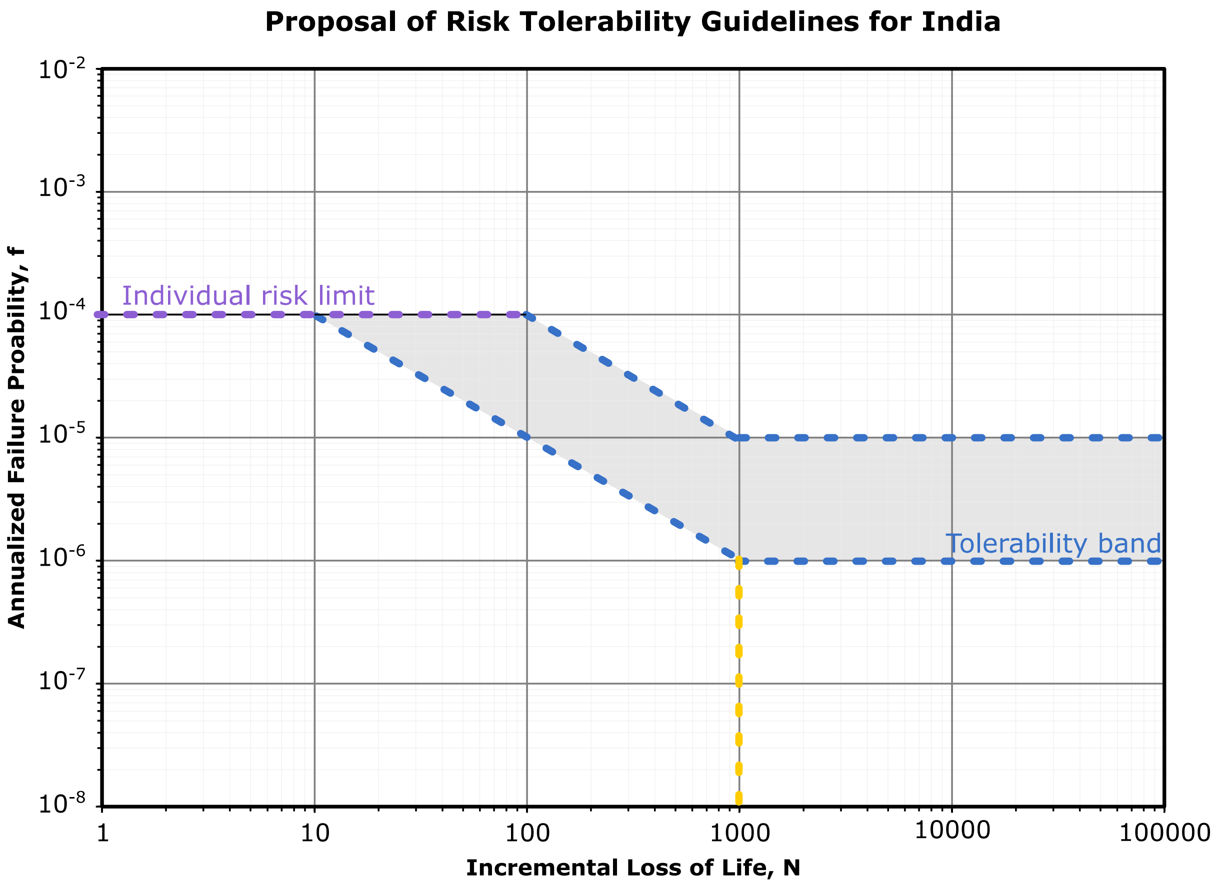
Societal risk and economic risk show how these risks are being reduced when these measures are implemented. In this case, ACSLS and EWACSLS should be obtained for each step of the sequence, comparing the situation in the step (i) with the previous step (i-1), as explained in these guidelines.

Step	Measure	Societal risk (ives/year)	Economic risk (Rs Crores /year)	ACSLS (Rs Crores/life)	EWACSLS (Rs Crores/life)
1	Measure X: *Name*				
2	Measure X: *Name*				

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

Explanation of previous results and conclusions obtained.

This itinerary can also be represented in the risk tolerability graph:



Itinerary followed by implementing the proposed sequence of actions in risk tolerability graph.

Representation of itinerary followed by the dam in reducing risk when the proposed sequence of measures is followed.

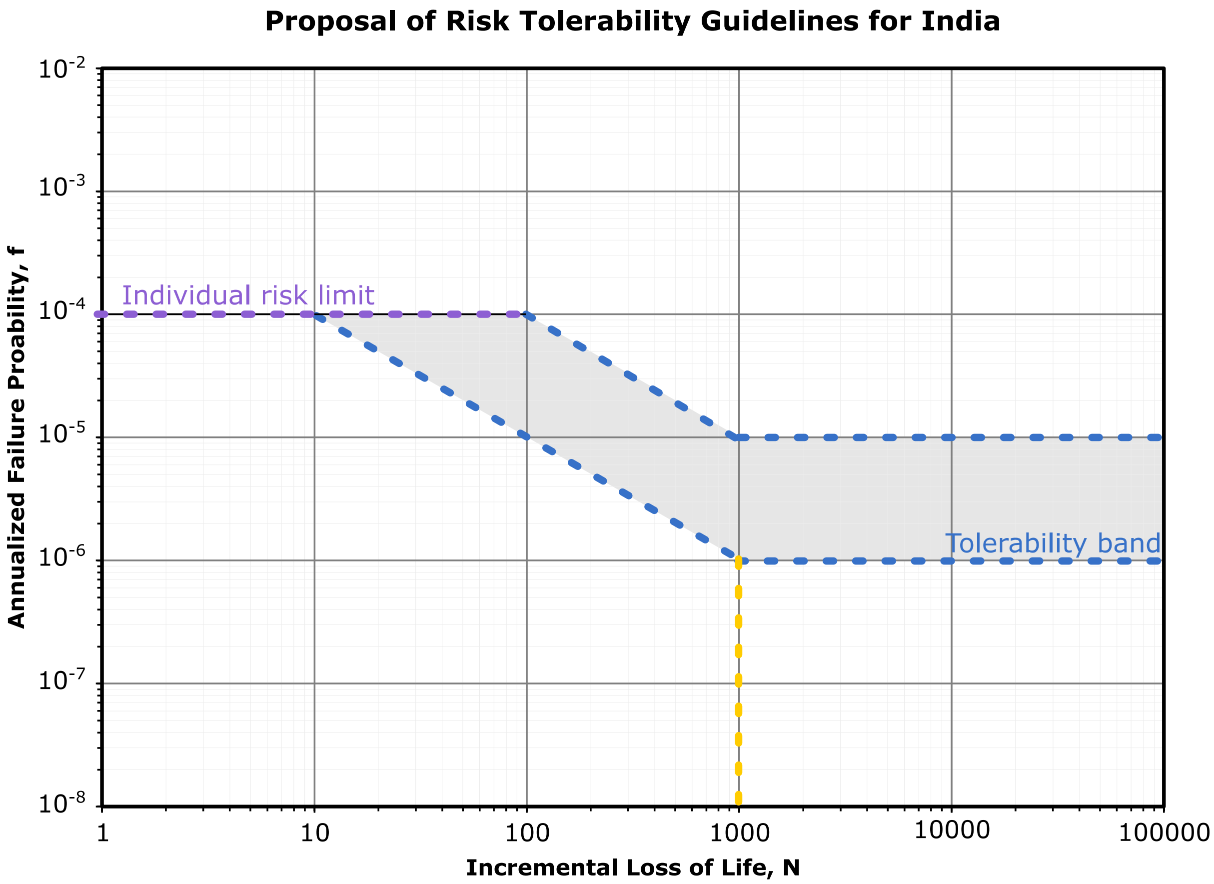
Explanation of previous results and conclusions obtained.

3.8. Portfolio Results

Optional

When risk has been estimated for several dams within the same portfolio, it is advisable to include an fN plot with the results of all these dams. These graphs are useful to compare the current state of the dam with the rest of the dams and to visually improve the understanding of risks in the Portfolio.

Short description of the Portfolio.



Risk results in the Portfolio of *Name of the Portfolio***.**

Comments on these results.

4. SEMI-QUANTITATIVE RISK ANALYSIS

4.1. Introduction

In a Semi-Quantitative Risk Analysis, a preliminary estimation of risk is made based on 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 C Failure Modes** to prioritize new studies and new instrumentation in the Portfolio of dams. In addition, **Class B 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 failure modes included in this analysis were:

- *Class C Failure Modes and Class B (only if uncertainty analysis recommends).*

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:

Technicians that have been participating in the elaboration of the risk model data and expert judgment sessions.

Name	Title (s)	Entity

Semi-Quantitative Risk Analysis was coordinated and supervised by *[Name of the coordinator]*, who has proven experience in this type of analysis applied to dam safety.

4.2. 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 component of risk is the magnitude of the **consequence** 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 popula-

tion 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 the economic consequences.

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

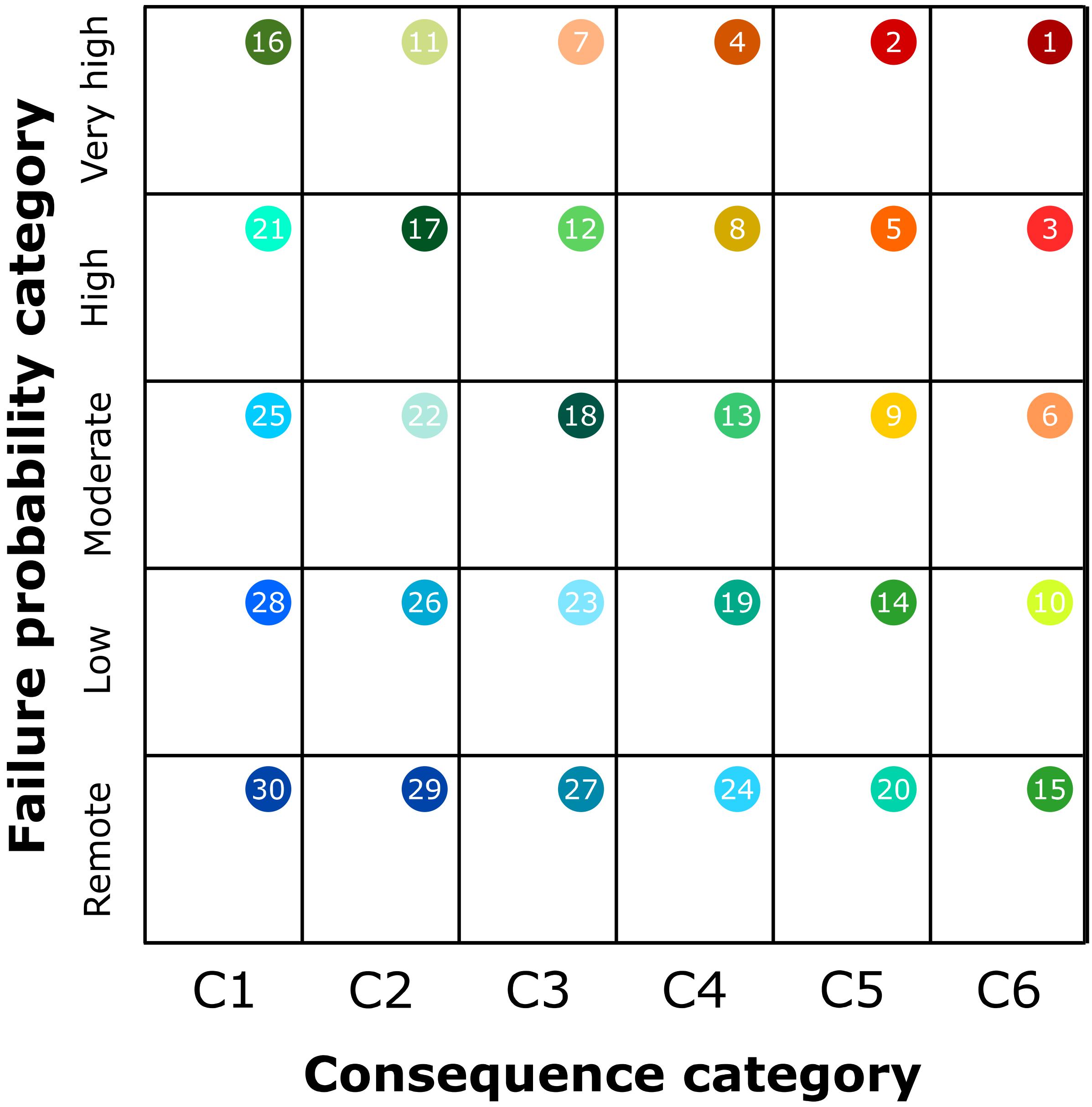
One table for each failure mode.

Failure Mode *Y: Short description*	
Failure probability category	*Remote/Low/Moderate/High/Very high*
Justification	
What data has been used to assign this category? *To assign the failure probability category of each failure mode, "less likely" and "more likely" factors detected during the IFM process are considered. Among these factors, the potential for detection and intervention to reduce the probability of failure must be considered when assigning the failure probability category.*	
Consequences category	*1/2/3/4/5/6*
Justification	
What data has been used to assign this category? *Consequences estimation made in quantitative risk analysis and existing flood risks maps provide useful information to assign this category.*	

Failure Mode *YY: Short description*	
Failure probability category	*Remote/Low/Moderate/High/Very high*
Justification	
What data has been used to assign this category? *To assign the failure probability category of each failure mode, "less likely" and "more likely" factors detected during the IFM process are considered. Among these factors, the potential for detection and intervention to reduce the probability of failure must be considered when assigning the failure probability category.*	
Consequences category	*1/2/3/4/5/6*
Justification	
What data has been used to assign this category? *Consequences estimation made in quantitative risk analysis and existing flood risks maps provide useful information to assign this category.*	

Failure Mode *YYY: Short description*	
Failure probability category	*Remote/Low/Moderate/High/Very high*
Justification	
What data has been used to assign this category? *To assign the failure probability category of each failure mode, "less likely" and "more likely" factors detected during the IFM process are considered. Among these factors, the potential for detection and intervention to reduce the probability of failure must be considered when assigning the failure probability category.*	
Consequences category	*1/2/3/4/5/6*
Justification	
What data has been used to assign this category? *Consequences estimation made in quantitative risk analysis and existing flood risks maps provide useful information to assign this category.*	

The results of this Semi-Quantitative Risk Analysis are represented for each failure mode in the following matrix:



Semi-Quantitative Risk Analysis results.

One circle should be drawn to represent each failure mode.

Explanation of previous results and conclusions obtained.

4.3. Prioritization of new studies or instrumentation

Once the risk of each Class C failure mode 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 C 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 B Failure Modes can also be introduced in this prioritization if they are recommended after quantitative risk evaluation and uncertainty analysis.

In this case, the following new studies and instrumentation are proposed:

One table for each proposed study.

Study 1	*Name*
Failure Modes	*Failure modes related with this proposed surveillance or investigation action*
Description	
Detailed description of the proposed surveillance or investigation action	

Study 2	*Name*
Failure Modes	*Failure modes related with this proposed surveillance or investigation action*
Description	
Detailed description of the proposed surveillance or investigation action	

Study 3	*Name*
Failure Modes	*Failure modes related with this proposed surveillance or investigation action*
Description	
Detailed description of the proposed surveillance or investigation action	

Second, based on the priority level of each failure mode, new studies and instrumentation are prioritized. The priority level of failure modes depends on their cell in the SQRA matrix, as shown in the previous matrix. As can be observed in this matrix, failure modes closer to the upper-right corner (higher failure probability and higher consequences) have a higher priority level. Following this procedure, the priority levels of the proposed studies are:

Studies	Priority level
Study 1: *Name*	
Study 2: *Name*	
Study 3: *Name*	
.	

This priority level is assigned with the number in the cell of the previous matrix corresponding to the related failure mode. If the proposed new studies or new instrumentation is directly related with several failure modes, the failure mode with the highest priority level should be considered for prioritization purposes.

Explanation of previous results and conclusions obtained.

5. CONCLUSIONS

Main conclusions obtained from the Risk Assessment process.

Summary of Risk Evaluation outcomes.

Summary of prioritization of risk reduction actions outcomes.

Summary of prioritization of new studies or instrumentation.

Other conclusions obtained from risk results.

Conclusions and recommendations for dam safety pillars: Emergency Action Planning, Operation rules, Maintenance, Surveillance….

If a failure mode has been classified as A, it should be clearly highlighted in the conclusions.

Other recommendations for decision making in the future.

The elaboration of this Risk Assessment Dam Safety Report was coordinated by:

(Signature)

Name and Title(s) of the coordinator of the report

Date

APPENDIX B – INDIAN CASE STUDY

The following Indian case study is based on a Risk Assessment performed in the Bhadra Dam (Karnataka). However, some data and results have been modified to fulfil the procedures proposed in these guidelines and to provide a more illustrative example of the whole Risk Assessment process. This Risk Assessment described in this Appendix was made within the DAMSAFE project (www.damsafe.eu).

In this sense, the presented Risk Assessment for the Bhadra Dam was made 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, in order to provide a more illustrative example, the following actions have been considered not to be implemented at this time 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.
- Repair actions to improve reliability of spillway gates in 2017.

It also allows quantifying the added value in terms of risk reduction of these corrective actions.

Report on Dam Safety Risk Assessment

Bhadra Dam

Prepared for KaWRD

Prepared by Consultancy Company

April 2018

Revisions of Risk Assessment Report

Report Date	Reason for Revision	Main changes made	Author
25/04/2018	First Risk Assessment	First Risk Assessment, including identification of failure modes and quantitative risk analysis	AAAA

Data of next Risk Assessment periodic update:

25/04/2022

Table of Contents

EXECUTIVE SUMMARY

This report summarizes the risk assessment process applied to the Bhadra Dam. 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.

In the risk analysis process, the 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 societal risk tolerability guidelines for overtopping and dam-foundation sliding failure modes.

Risk results show important uncertainties in hydrological data and dam structural behaviour and foundation characterization 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 to be above tolerability limits.

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.

1. INTRODUCTION

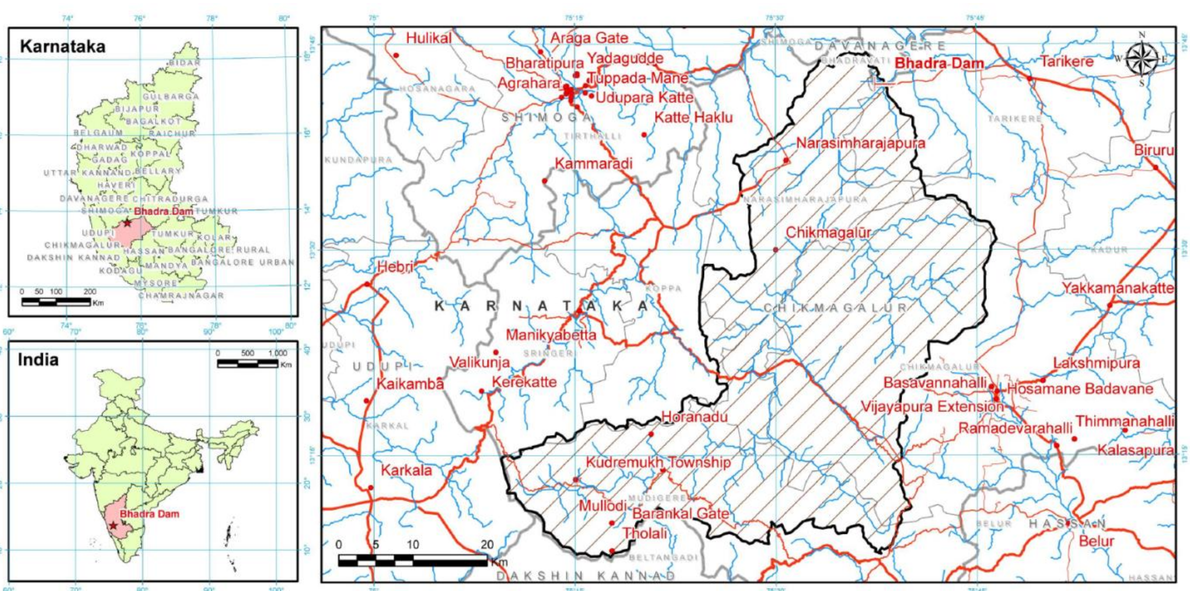
1.1. Dam description

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

Location map

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.

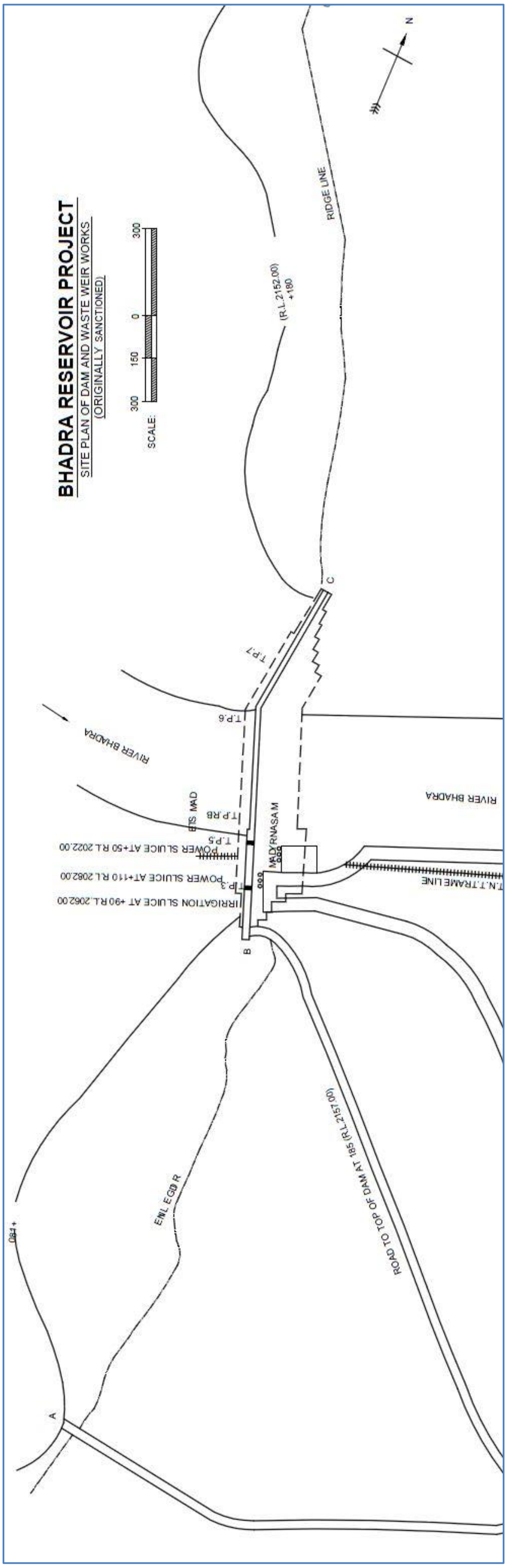
A sketch of the Bhadra Dam's location is presented below.



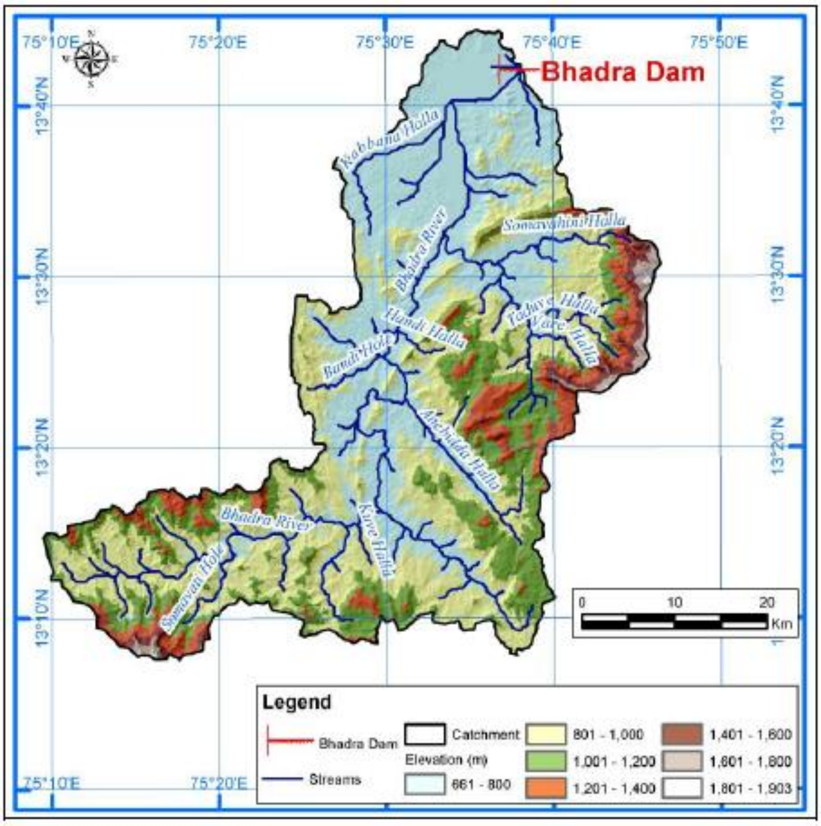
Bhadra Dam location. Source: Draft Design Flood Study of Bhadra Dam (2017).

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.



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



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

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 hm^3.

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 (main dam), and at 2011 ft (612.95 m) and 2067 ft (630.02 m) for saddle dams 1 and 2, respectively.

The following table 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

Bhadra Dam characteristics: crest levels.

Bhadra Dam is categorized as a large dam based on storage capacity (> 60 hm^3) 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 m^3/s. However, details of the estimation procedure are not available.

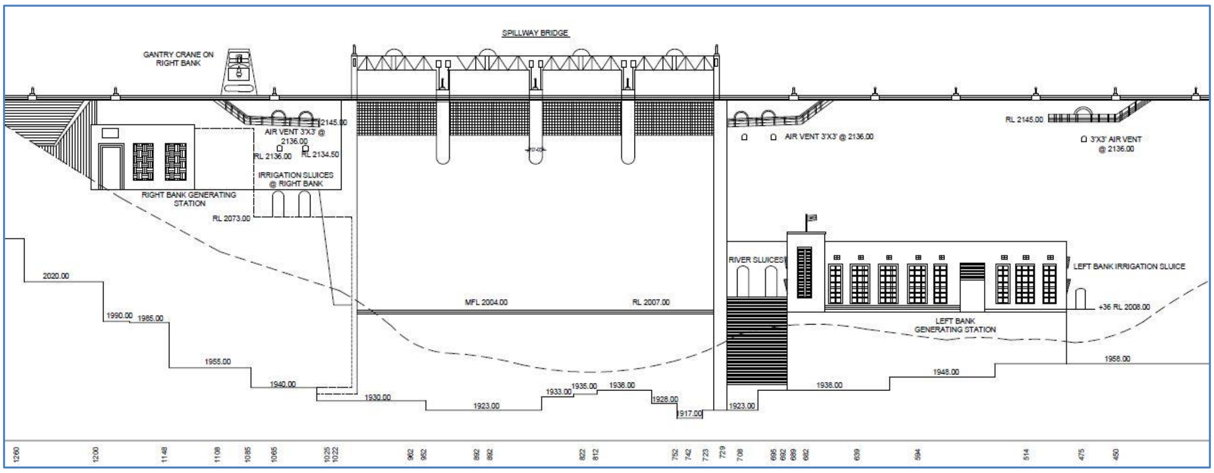
The following table summarizes reference characteristics of the Bhadra Dam-reservoir system.

Description	Value
Gross storage capacity	2025.87 hm^3
Live storage capacity	1785.15 hm^3
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 m^3/s

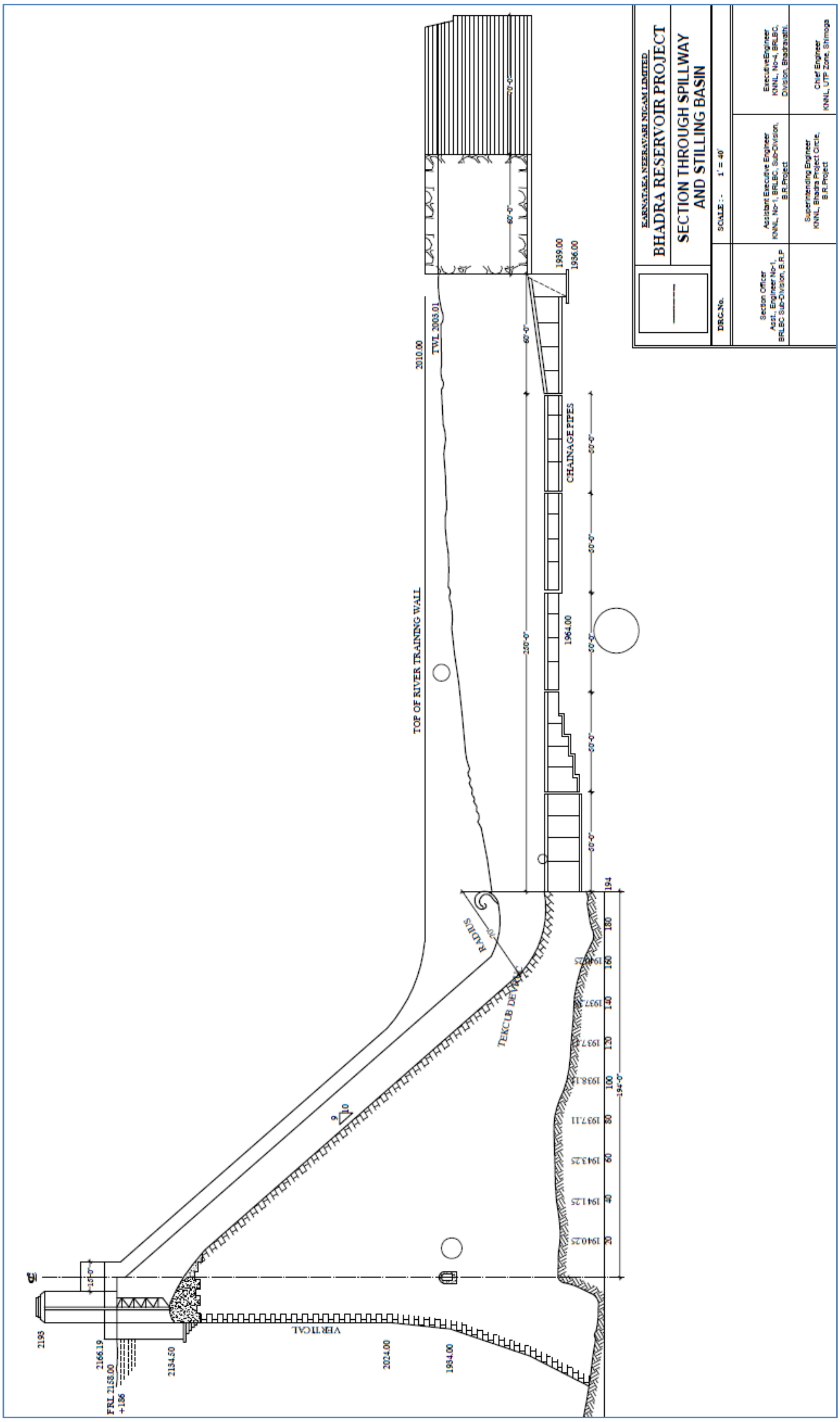
Bhadra Dam characteristics: key figures.

Cross section drawings

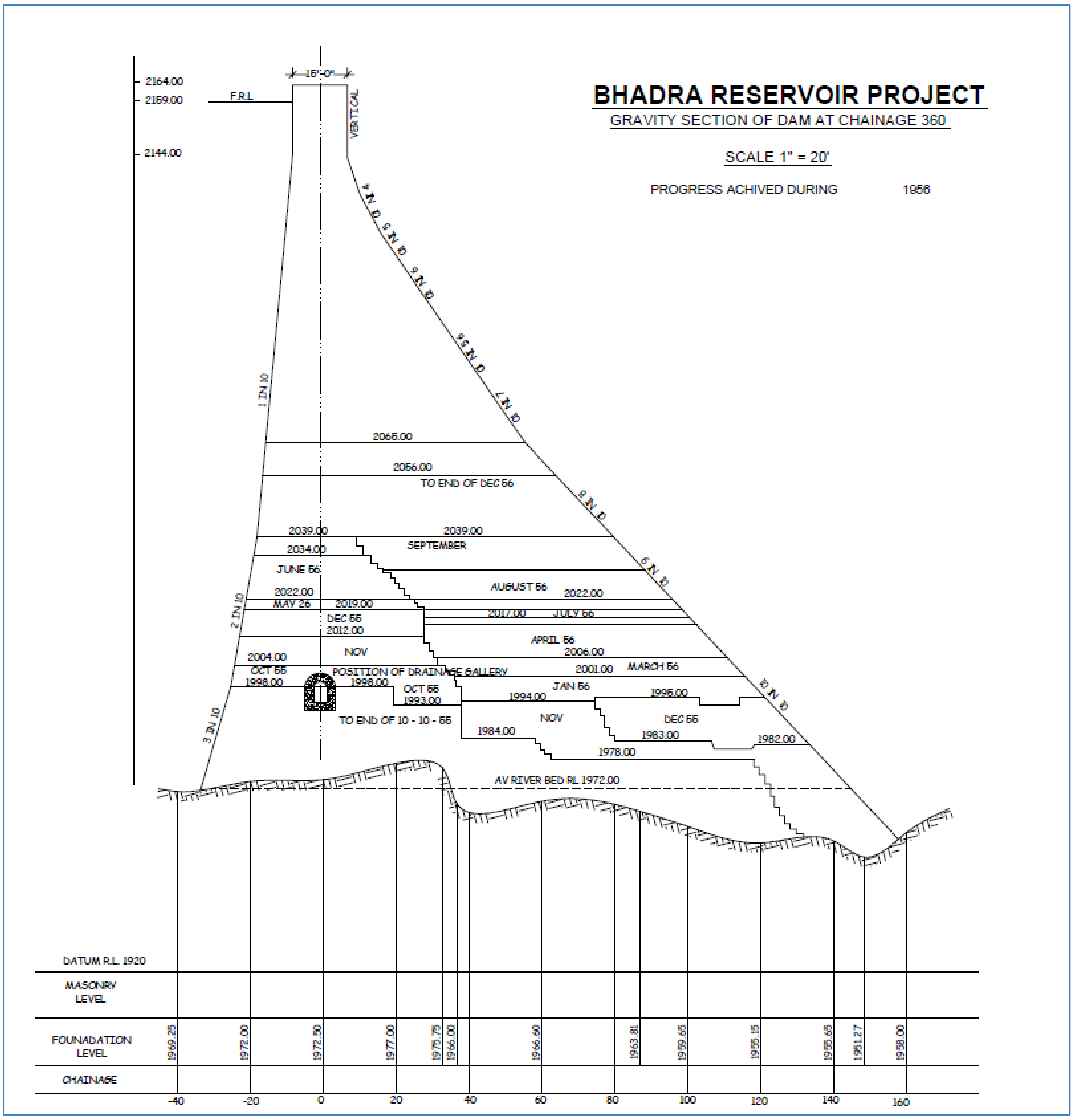
The following figures show cross sections of Bhadra Dam through the spillway and dam boy sections, respectively. These figures are obtained from drawings of the Bhadra Dam project.



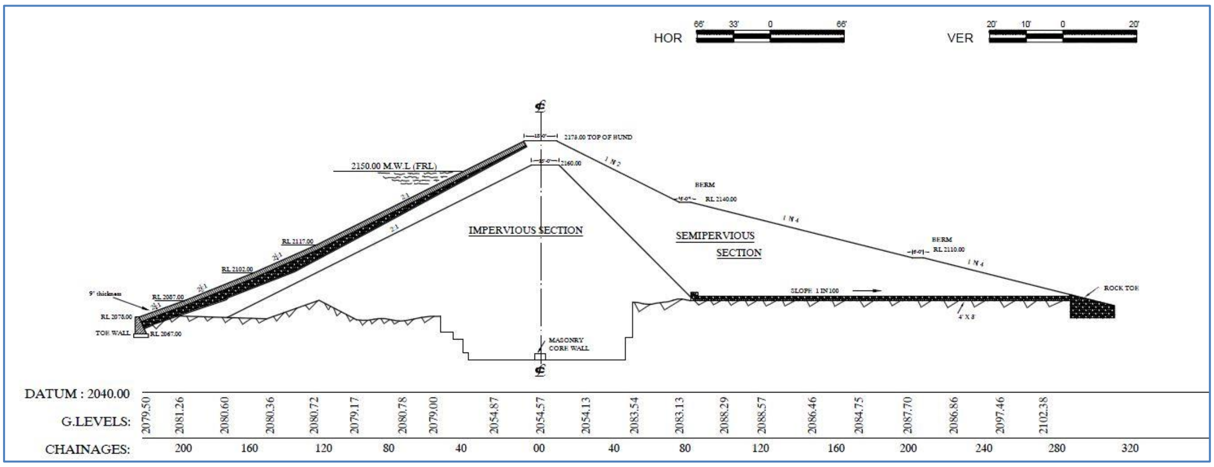
Main dam. Downstream view. Source: Bhadra reservoir project.



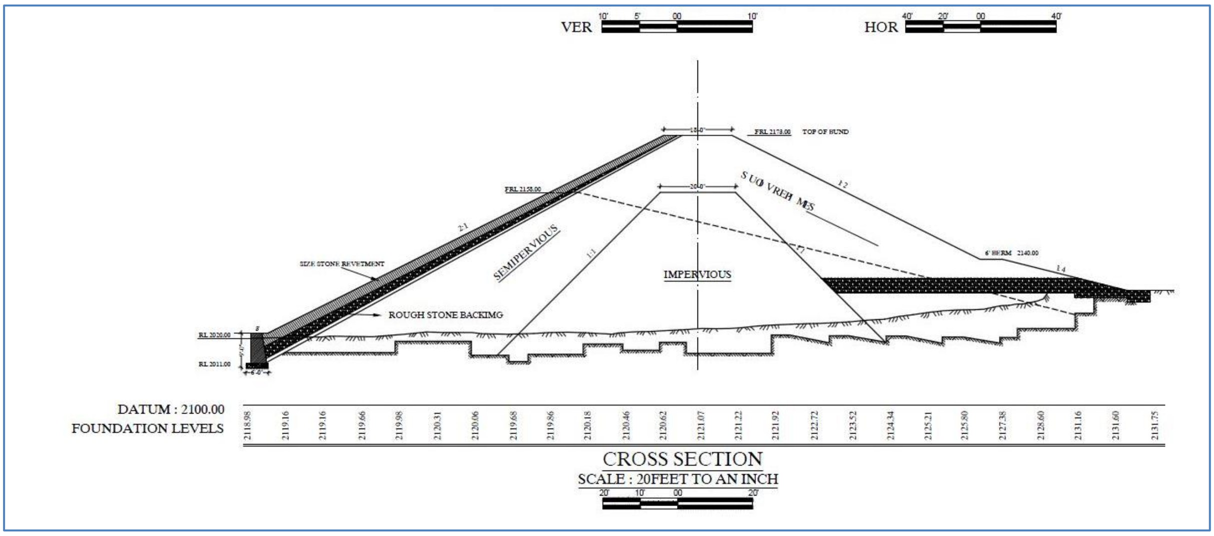
Spillway cross section of Bhadra Dam. Source: Bhadra reservoir project.



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



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



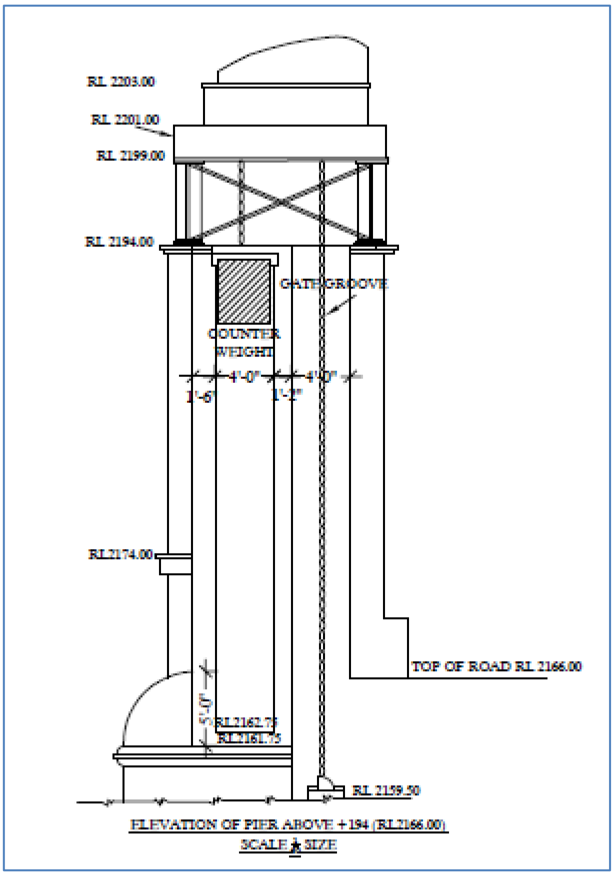
Saddle dam 2. Cross section. Source: Bhadra reservoir project.

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.

The next figures show a detail of spillway gates at Bhadra Dam.



Detail of spillway gates.

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 Bhadra's left side guide wall in the right bank 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.

Hazard Potential Classification

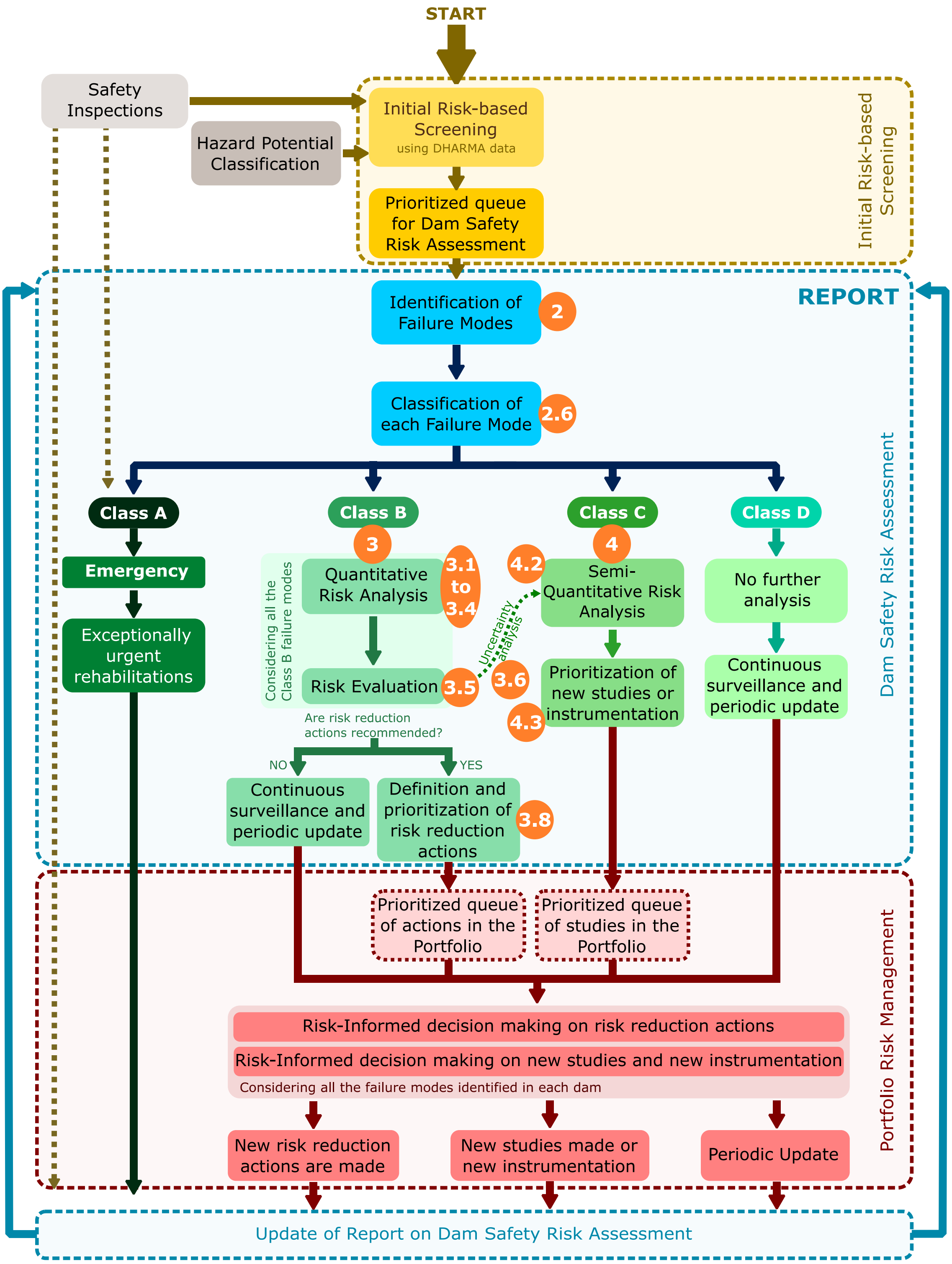
Hazard Potential Classification for Indian dams is described in the document *Guidelines for Classifying the Hazard Potential of Dams*. Hazard categorization is a commonly used method of classifying dams according to the degree of adverse incremental consequences of failure. However, hazard classification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

Based on the classification proposed within the document *Guidelines for Classifying the Hazard Potential of Dams*, Hazard Potential 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 denoted as 'Catastrophic'.

1.2. Risk Assessment and Management Framework

The current Risk Assessment Report is based on the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Within these guidelines, a Risk-Informed Dam Safety Management Program is given with the structure shown in the following figure:



Risk-Informed Dam Safety Management Program. Source: Guidelines for Assessing and Managing Risks Associated with Dams (CWC, 2018).

This Risk Assessment Report is focused on the central part of the management program, and the different steps of this central part are directly related with the different sections of the report (as shown by numbers in orange circles). Therefore, the main purpose of this report is explaining 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 for Green and Red Dams.

As shown in this figure, the **Dam Safety Risk Assessment** begins with a **Failure Mode Identification** process in each dam, which includes a review of the available information, a technical visit to the dam and multidisciplinary group working sessions, as explained in Chapter 2. Based on the information available and the credibility of each failure mode, they are classified in four categories:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and exceptionally urgent rehabilitation measures and/or emergency actions are needed.

- **Class B:** Failure mode is credible and available information is enough for a **Quantitative Risk Assessment**. Risk results are evaluated and if needed, potential risk reductions are proposed and prioritized. This assessment is explained in detail in Chapter 3.

- **Class C:** There is uncertainty about this failure mode, 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 (Chapter 4).

- **Class D:** Failure mode is not credible. This failure mode should be documented and reviewed in the following updates of the Risk Assessment process.

The results obtained from this report are intended to be used for Portfolio Risk Management, by combining the prioritized risk reduction actions of this dam to create a prioritized list of proposed actions in the whole Portfolio of dams. Similarly, the prioritized lists of new studies of each dam are combined to create a prioritized list of new studies and/or instrumentation in the Portfolio. Hence, new actions and studies are planned in the Portfolio taking into account administrative, legal or societal issues and analysing all the failure modes identified in each dam.

2. IDENTIFICATION OF FAILURE MODES

2.1. Introduction

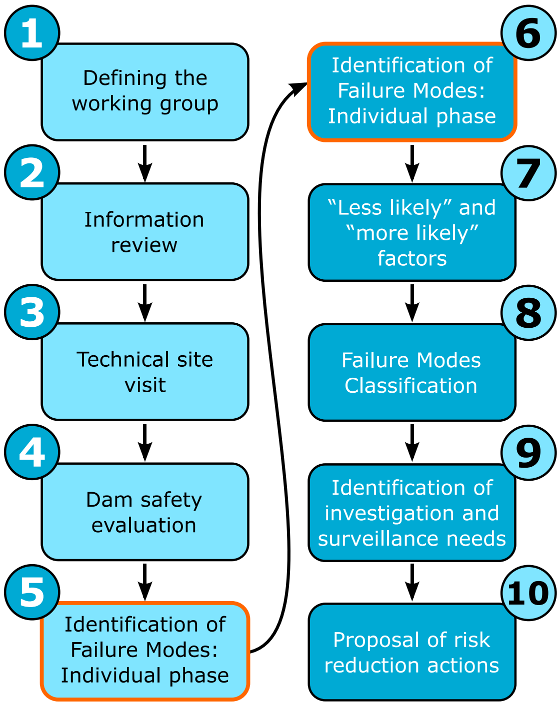
A **failure mode** is a specific sequence of events that can lead to a dam failure. This sequence of events must be linked to a loading scenario and will have a logic sequence: starting with an initiating event, one or more events of progressive failure and will end with dam failure or mission disruption 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 following the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* during a working session conducted in 2017 as shown in the following figure:



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

Identification of Failure Modes steps and dates.

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 (pilot project conducted in the period 2017-2018 for improving dam safety management in Bhadra Dam). Participants in these sessions are listed in the following table:

Name	Title (s)	Entity
Participant 1	Engineer in charge of Bhadra Dam	KaWRD
Participant 2	Dam Safety manager	KaWRD
Participant 3	Risk Analysis expert	YYYY
Participant 4	Risk Analysis expert	YYYY
Participant 5	Dam engineer	KaWRD
Participant 6	Dam engineer	KaWRD
Participant 7	Responsible of dam's maintenance	KaWRD

Participant 8	Responsible of dam gates	KaWRD
Participant 9	Hydrology expert	ZZZZ
Participant 10	Civil engineer	KaWRD
Participant 11	Civil engineer	KaWRD
Participant 12	Civil engineer	KaWRD
Participant 13	Civil engineer	KaWRD
Participant 14	Civil engineer	KaWRD
Participant 15	Civil engineer	KaWRD
Participant 16	Civil engineer	KaWRD
Participant 17	Civil engineer	KaWRD
Participant 18	Civil engineer	KaWRD
Participant 19	Civil engineer	KaWRD
Participant 20	Civil engineer	KaWRD
Participant 21	Civil engineer	KaWRD
Participant 22	Civil engineer	KaWRD
Participant 23	Civil engineer	KaWRD
Participant 24	Civil engineer	KaWRD
Participant 25	Civil engineer	KaWRD
Participant 26	Civil engineer	KaWRD
Participant 27	Civil engineer	KaWRD
Participant 28	Civil engineer	KaWRD
Participant 29	Civil engineer	KaWRD
Participant 30	Civil engineer	KaWRD
Participant 31	Civil engineer	KaWRD

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 AAAA BBBBB who has proved experience in coordinating these types of sessions.

2.2. 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 include:

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

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.

2.3. 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.

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.

Technical site visit of Bhadra Dam. 21 February 2017.

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.

2.4. 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.

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.

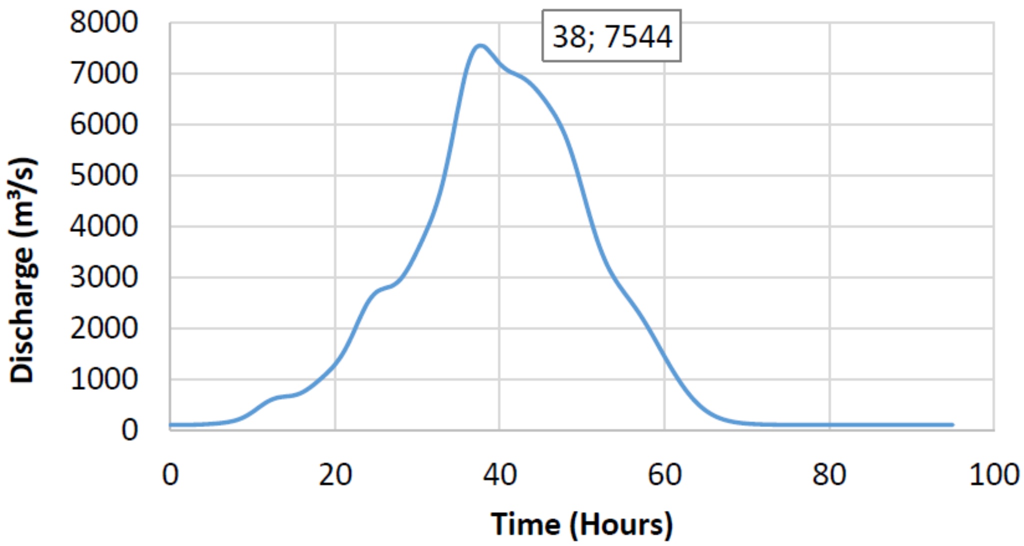
A substantial proportion of Indian dams are getting subjected to revisions in their design floods as part of the Dam Rehabilitation and Improvement Project (DRIP) project. A comparison of the revised design flood values of analysed dams with their respective original design flood values can be found 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 hydrometeorological approach (unit hydrograph method). The flood hydrographs for 4 subcatchments 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.



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 m^3/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.

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 m^3/s) and the spillway capacity is 1,06,700 cusecs (3021.41 m^3/s). The two scouring sluices provide an additional discharge of 13,300 cusecs (376.61 m^3/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 hm^3) 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".

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 m^3/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.

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.

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:

View of the stilling basin after dewatering and cleaning (21 Sept 2017). Source: CSV20170921.

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

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 centre 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."

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

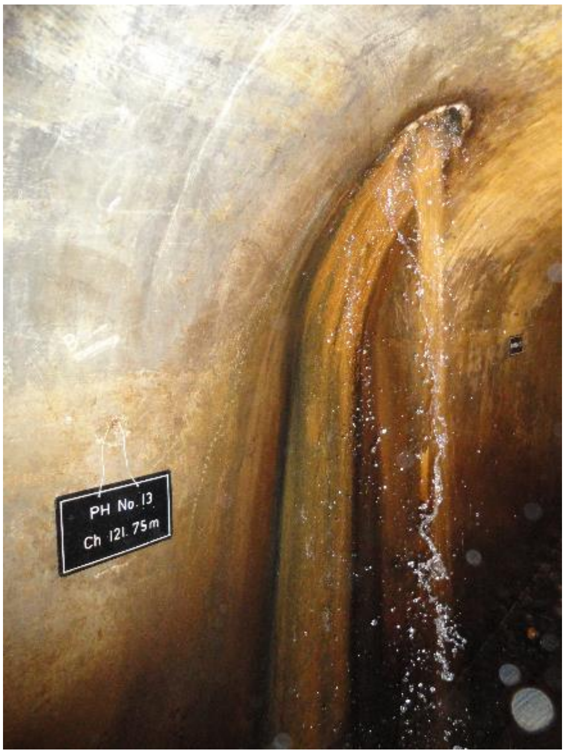
Monitoring data and state of monitoring system

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.

Dam body condition: 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.



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 in the pictures.

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.

Dam body condition: Saddle dams

In general, saddle dams 1 and 2 are in satisfactory condition with minor 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:

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.

Condition of the 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.

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.

Seismic hazard and dam stability during 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.

Landslide in the reservoir

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

Emergency action planning and urban areas downstream

Main urban areas located downstream Bhadra Dam with a population at risk of over 10,000 inhabitants are included in the table below:

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

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 considering 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	m³/s	121,847

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.

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.

Dam safety aspects	Participants									
	1	2	3	4	5	6	7	8	9	10
Flood hazard and hydrological adequacy										
Seismic hazard										
Gates operation and hydraulic behaviour										
Gates and electro-mechanical equipment condition										
Current state of spillway and stilling basin										
Foundation and abutments										
Monitoring data and state of monitoring system										
Main dam body state										

Saddle dams body state										
State of drainage system										
Dam stability in normal loading conditions										
Landslide in the reservoir										
Emergency action planning										

Results from dam safety evaluation assessment.

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 and it is explained in section 3.3.

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.

2.5. Failure Mode Identification

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

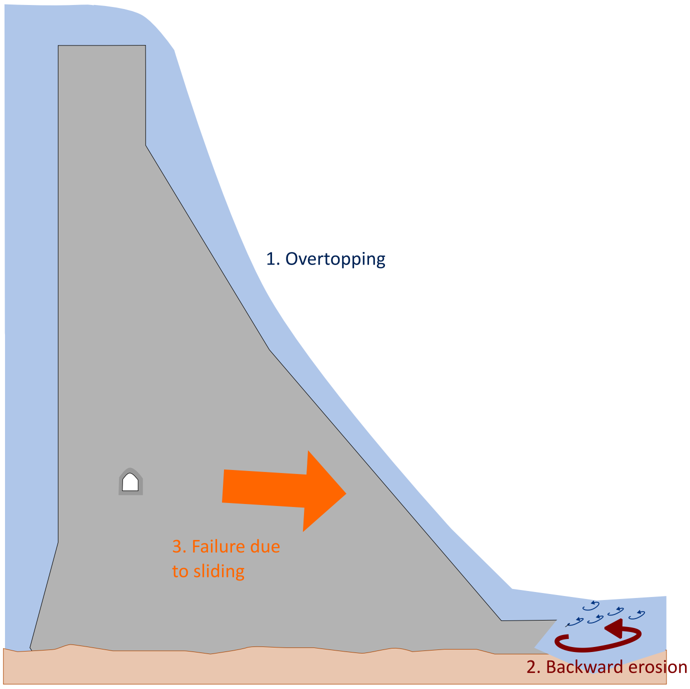
During the first phase of the identification of failure modes, each participant in the session individually made a preliminary identification of failure modes for Bhadra Dam, using the provided booklet. Once each participant finished the individual phase, all identified failure modes were put in common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

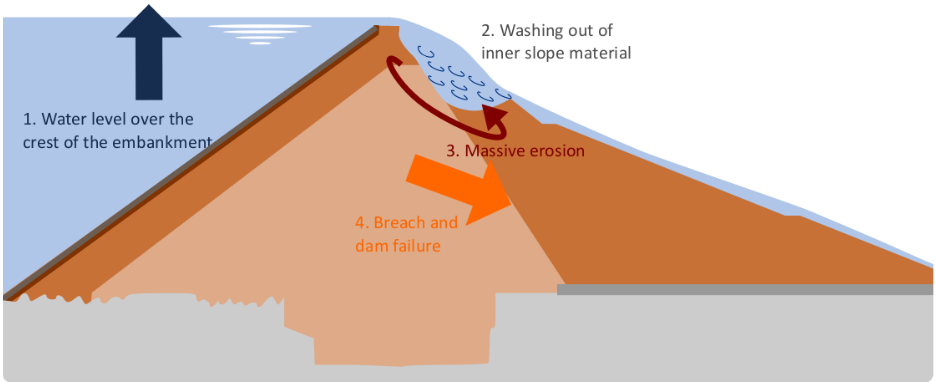
- FM1: Overtopping failure in the main dam.
- FM2: Overtopping failure in saddle dams.
- FM3: Sliding in the main dam along a failure surface at rock foundation.
- FM4: Sliding in the main dam along the dam-foundation surface.
- FM5: Sliding in the main dam due to degradation of masonry material.
- FM6: 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	

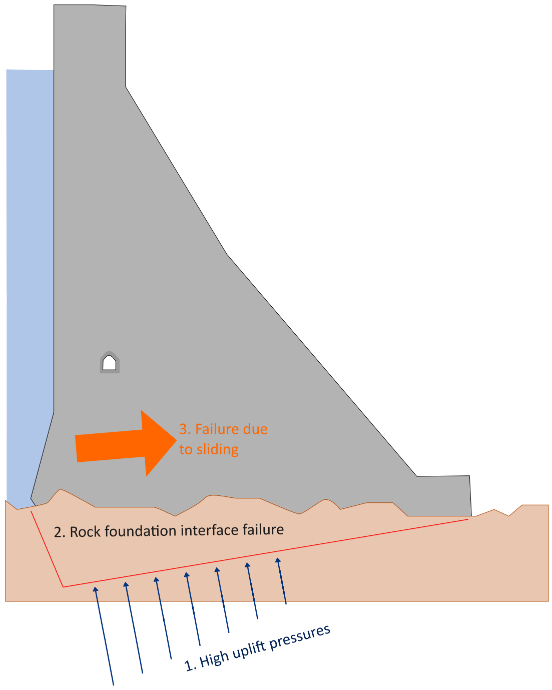


More likely factors	Less likely factors
Lack of detailed probabilistic hydrologic studies on Bhadra Dam-reservoir upstream river basin.	During the monsoon season, a different maximum reservoir level is fixed at RL 2156 ft, 2 ft below MOL.
Differences between original and reviewed design flood events (3,397.83 m^3/s vs. 7,544 m^3/s, respectively). The spillway capacity is 3,021.24 m^3/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 m^3/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, joint are in well state and the dam toe seems resistant to scouring.

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, therefore 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 m^3/s vs. 7,544 m^3/s, respectively). The spillway capacity is 3,021.24 m^3/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 m^3/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	
	

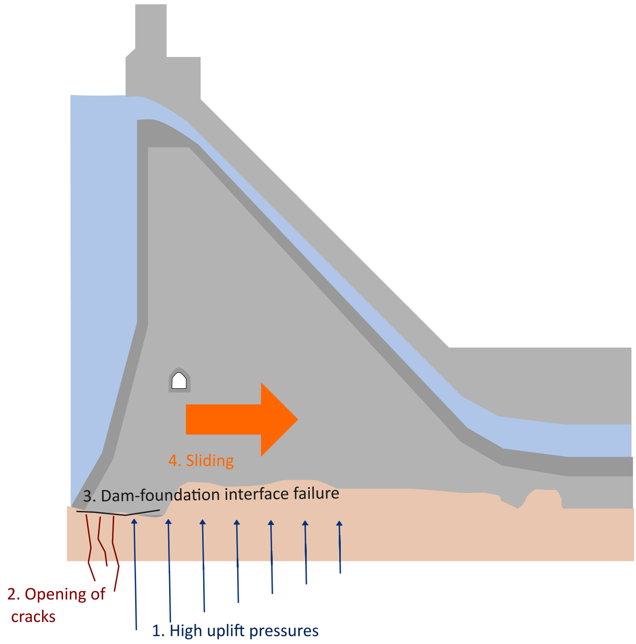
More likely factors	Less likely factors
Detection of high uplift pressures is not possible (there is no instrumentation in the main dam).	The maximum reservoir water level specified during the monsoon season is set 2 ft below MOL.
Detection of movements, as an indicator of an initiating failure mode, 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



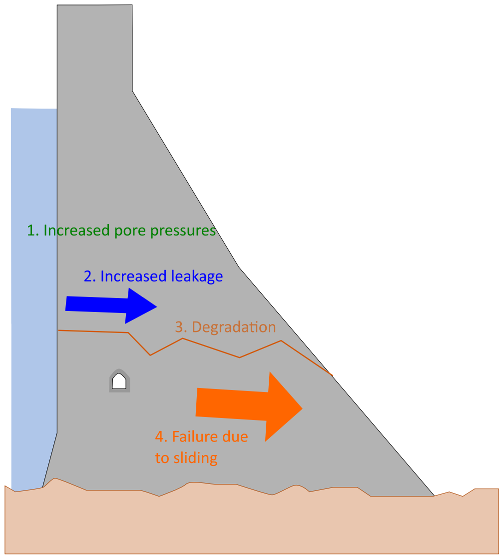
More likely factors	Less likely factors
Detection of high uplift pressures is not possible (there is no instrumentation in the main dam).	The maximum reservoir water level specified during the monsoon season is set 2 ft below MOL.
Detection of movements, as an indicator of an initiating failure mode, 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

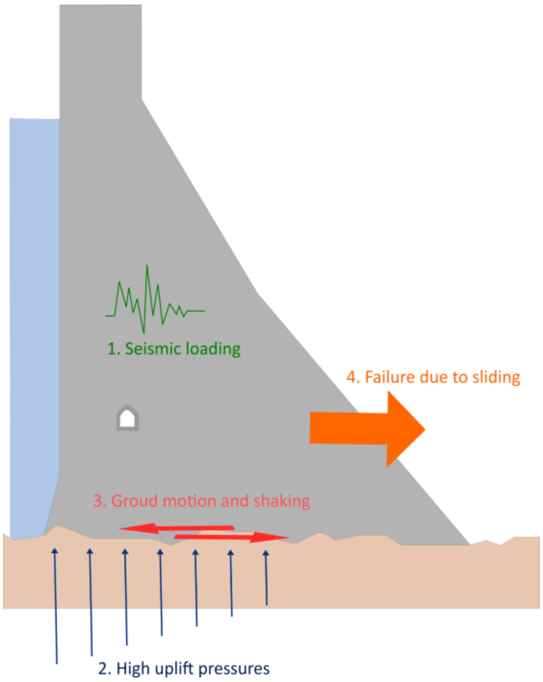
Description

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.	

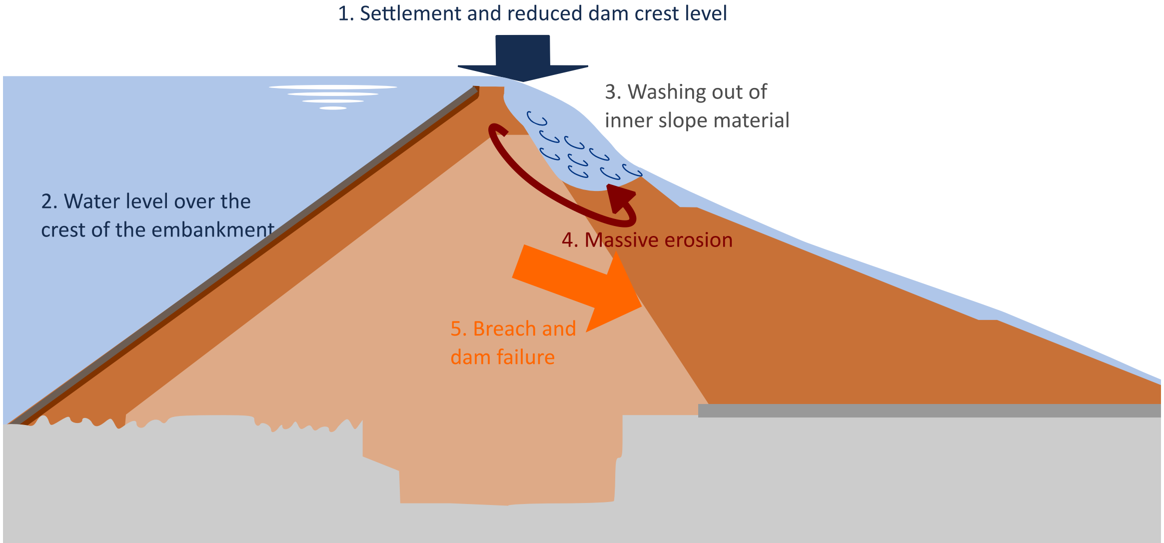
Failure Mode 6	Sliding in a seismic event in the main dam
Description	
In a seismic scenario, a combination of previous degradation of masonry material and dam foundation and a state of high uplift pressures with an earthquake that causes a ground motion with shaking, leads to a reduction of resistance 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

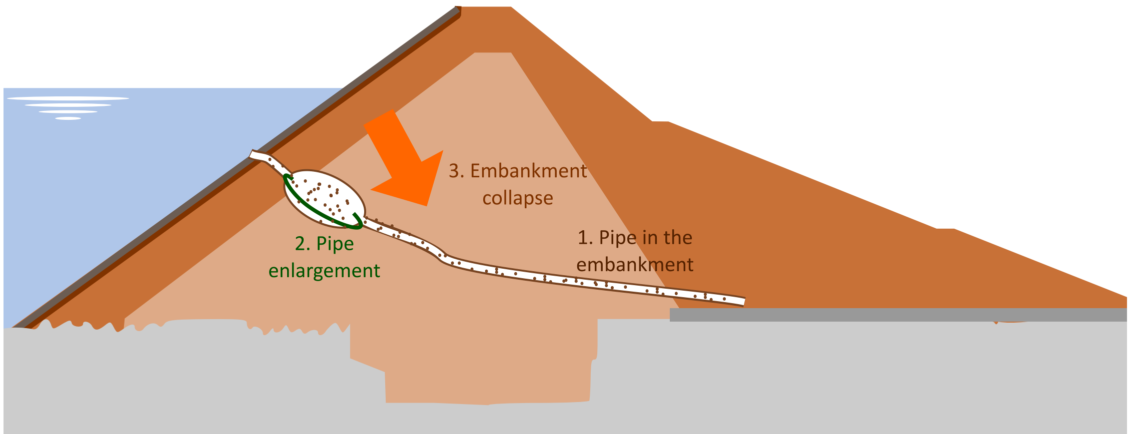
In a seismic scenario, an earthquake causes a ground motion with shaking and settlement of embankment dams with reduced dam crest level, then resulting in uncontrolled flow over the dam crest, degradation of inner slope material, massive erosion and dam collapse.

Graphical scheme



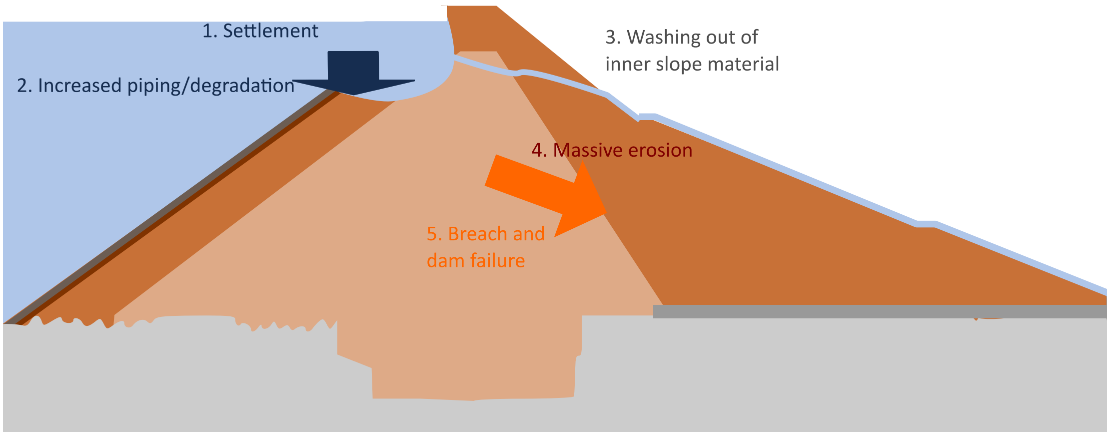
More likely factors	Less likely factors
Bhadra Dam is located in Zone 2 based on the Earthquake Zone Map for India. Seismic forces were not considered in the design.	Visual observations that provide the earliest indicators of a developing failure mode are conducted frequently.
There are no studies to 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).	

Failure Mode 8	Internal erosion in saddle dams
Description	
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.	
Graphical scheme	

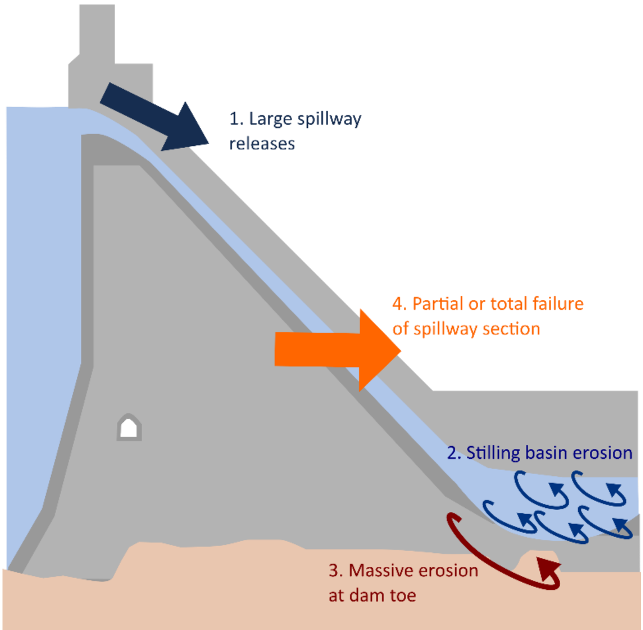


More likely factors	Less likely factors
No information is available on filtering materials (if any) neither properties of impervious layer.	Visual observations that provide the earliest indicators of a developing internal erosion failure mode are conducted frequently.
Detection through instrumentation 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).	Embankments height is relatively low and reservoir levels are 5 m below saddle dam crest level for MOL, so hydraulic gradients are not high.
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 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 due to the increment of pore pressures and deterioration of embankment-fill materials over time, resulting in settlement of the upstream slope and increased degradation of core materials. This deterioration initiates a piping process through the dam body, resulting in erosion of dam body material trough time and finally, the saddle 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.	

2.6. 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:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and 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 B:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class B 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 C:** 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 D:** 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	B
2	Overtopping failure in saddle dams	D
3	Sliding in the main dam along a failure surface at rock foundation	D
4	Sliding in the main dam along the dam-foundation surface	B
5	Sliding in the main dam due to degradation of masonry material	B
6	Sliding in a seismic event in the main dam	C

7	Overtopping in a seismic event in saddle dams	C
8	Internal erosion in saddle dams	C
9	Failure due to settlement at upstream face in saddle dams	C
10	Stilling basin failure in the main dam	D

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 B since flood probability can be analysed based on rainfall probability data in *PMP Atlas (CWC).*

Note: It should be remarked that existing information is not enough to make a Quantitative Risk Assessment for Failure Mode 4 (Sliding in the main dam along the dam-foundation surface), due to the absence of information on foundation characteristics.

Therefore, FM4 should be classified as C, but it has been classified as B to provide a more illustrative example in these guidelines. However, as can be observed in Section 3.6, this uncertainty is reflected in the high variation of risk results for this failure mode. Hence, the final recommendation on gathering more information about this foundation remains the same, independently on the failure mode classification.

2.7. 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 C, 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 B. 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 3.

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

2.8. Proposal of risk reduction actions

Actions proposed to reduce risk in failure modes **(especially in Class B failure Modes)**, are the basis for the prioritization of risk reduction actions using quantitative risk results and they are explained in detail in Section 3.7. 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 the dams 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

3. Quantitative Risk Assessment

3.1. Introduction

Fully quantitative risk assessment seeks to enumerate the risks in terms of probability and consequences in quantitative terms. This Quantitative Risk Assessment has been conducted as part of the DAMSAFE project (www.damsafe.eu), in the period 2017-2018, in a collaborative process with technicians of KaWRD and CWC. Participants on the Risk Assessment process for Bhadra Dam are summarized in the following table:

Name	Title (s)	Entity
AAAA BBBB	PhD. Civil Engineer	Consultancy company specialized in Dam Risk Analysis
CCCC DDDD	PhD. Civil Engineer	Consultancy company specialized in Dam Risk Analysis
EEEE FFFF	Civil Engineer	Consultancy company specialized in Dam Risk Analysis
GGGG HHHH	Civil Engineer	Consultancy company specialized in Dam Risk Analysis
IIII JJJJ	Assistant Engineer	Advanced Centre of Integrated Water Resources Management CWC
KKKK LLLL	Assistant Engineer	Advanced Centre of Integrated Water Resources Management CWC

Quantitative Risk Assessment was coordinated and supervised by AAAA BBBB who has proven experience in this type of analysis applied to dam safety.

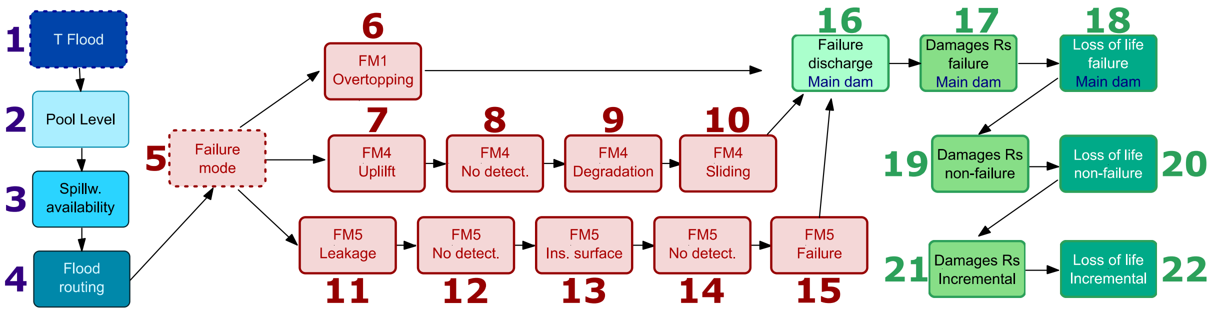
3.2. Risk model architecture

Based on outcomes from the failure mode identification session, five failure modes were considered to be included in the Quantitative Risk Analysis phase, classified as Class B. 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.

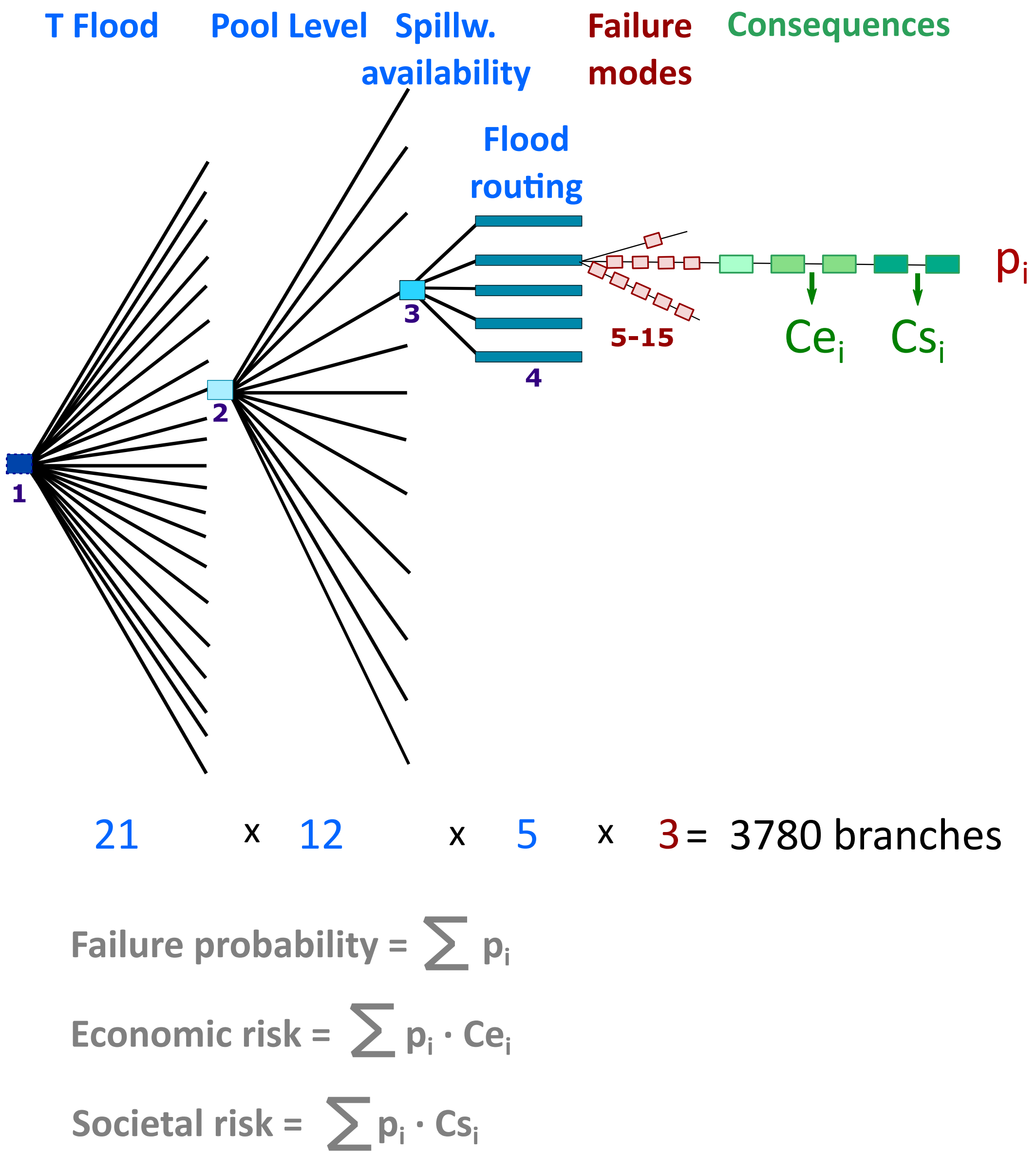
Influence diagrams are compact conceptual representations of the logic of a system. An influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and consequences. In this case, an influence diagram is defined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



Risk model architecture for Bhadra Dam.

The risk model architecture is used for computing incremental and total dam risk. Nodes include input data on loads, system response and consequences as described in section 3.3. In this architecture, the red nodes correspond to the failure modes probabilities (of both dams). To the left, the nodes that define loads (blue colour) are included, and, to the right, the nodes that define the consequences (green colour).

This influence diagram is converted by the iPresas software in an event tree with 3780 branches. In this event tree, probability and consequences of each branch are computed to estimate failure probability, economic consequences and societal risk in the dam, as shown in the following figure:



Event tree used to calculate risk in Bhadra Dam.

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

3.3. Risk model input data

Hydrological hazard: Node 1

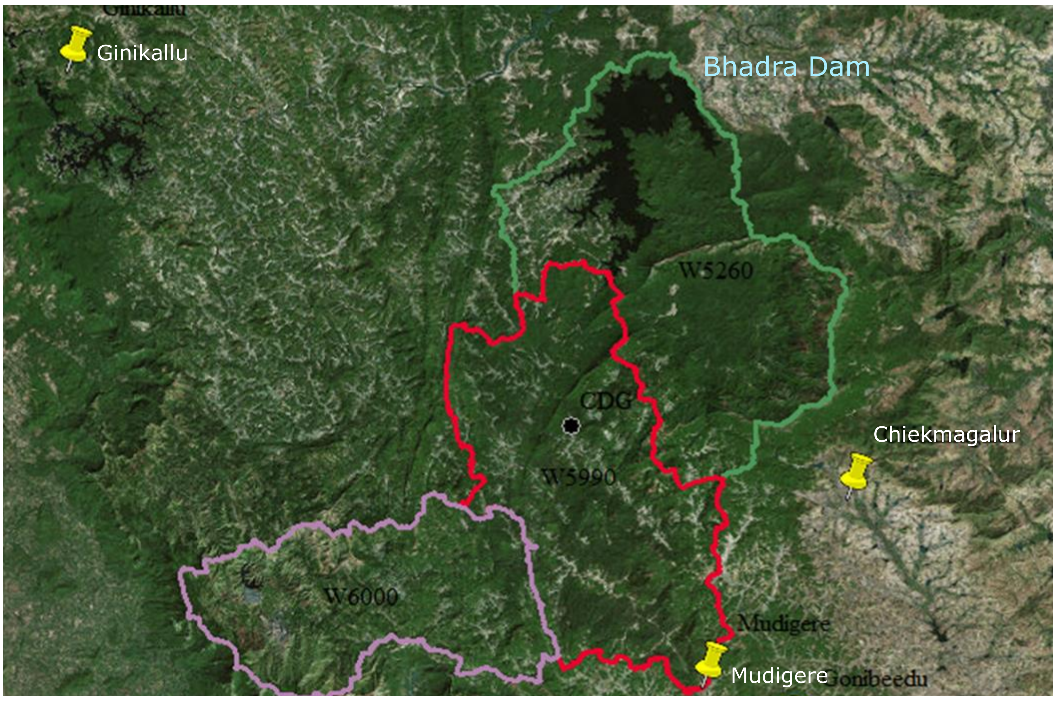
Currently, there is not a probabilistic hydrologic analysis available for the Bhadra Dam. In addition, hydrological studies show significant uncertainties due to the existing differences on original and reviewed design floods for Bhadra Dam.

In order to introduce different floods in the risk model with their 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. 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. The following table 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

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



Location of selected station from PMP Atlas related to Bhadra catchment.

For these stations, the *PMP Atlas* includes estimated precipitation values for different storm duration and return periods. The following table 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

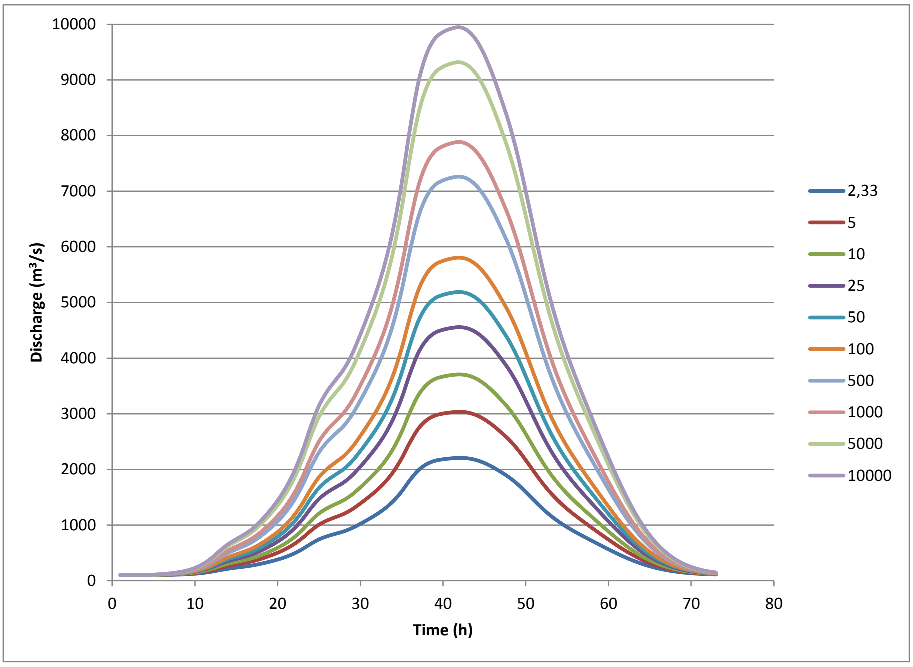
The hydrologic model developed in HEC-HMS by the CWC as part of the DRIP project was used to obtain flood events in the Bhadra reservoir system based on estimated rainfall distributions within the Bhadra river basin catchment. For each of the 3 sub catchments defined within the model (depicted in the 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**
Sub catchment SC1	112.2	153.8	187.0	229.6	261.0	291.9	364.1	395.4	467.1	498.3
Sub catchment SC2	93.6	131.3	161.5	200.2	228.6	256.6	322.3	350.7	415.7	444.1
Sub catchment SC3	75.2	105.9	130.3	161.6	184.6	207.4	260.7	283.6	336.3	359.3

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. The following results were obtained:

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

The following figure shows obtained flood hydrographs for a range of return periods from 2.33 to 10,000 years.



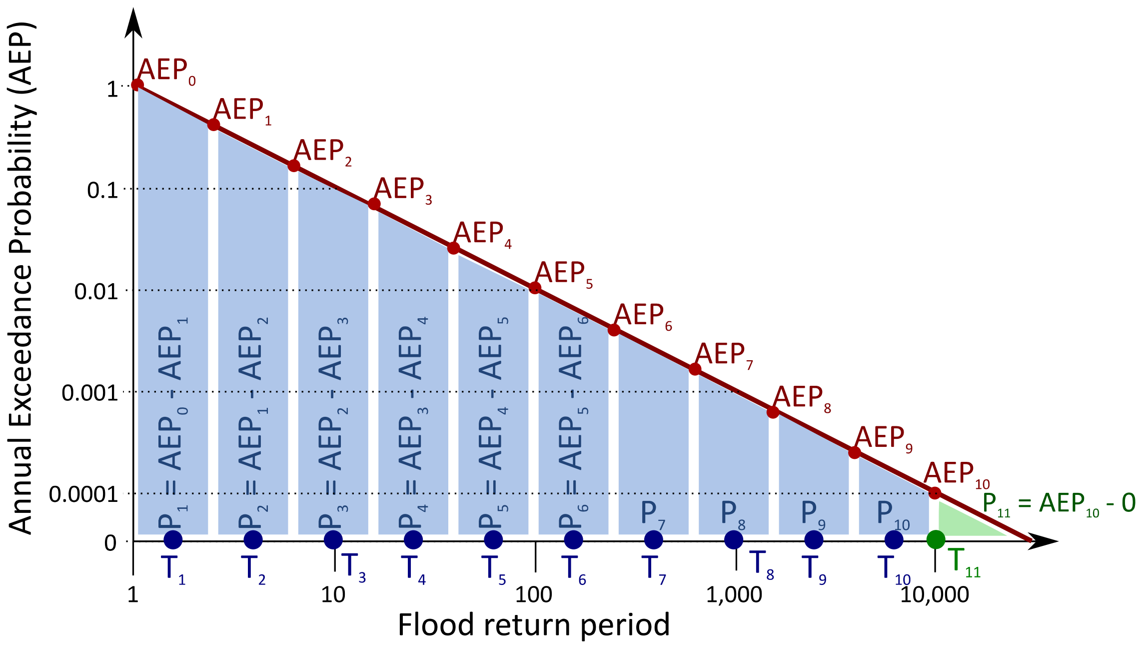
Estimated flood hydrographs for Bhadra Dam: Base Case.

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 of the hydrological study of this system of dams, the range of return periods ranges 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.

The scheme for calculating flood probabilities is shown in the following figure. 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.



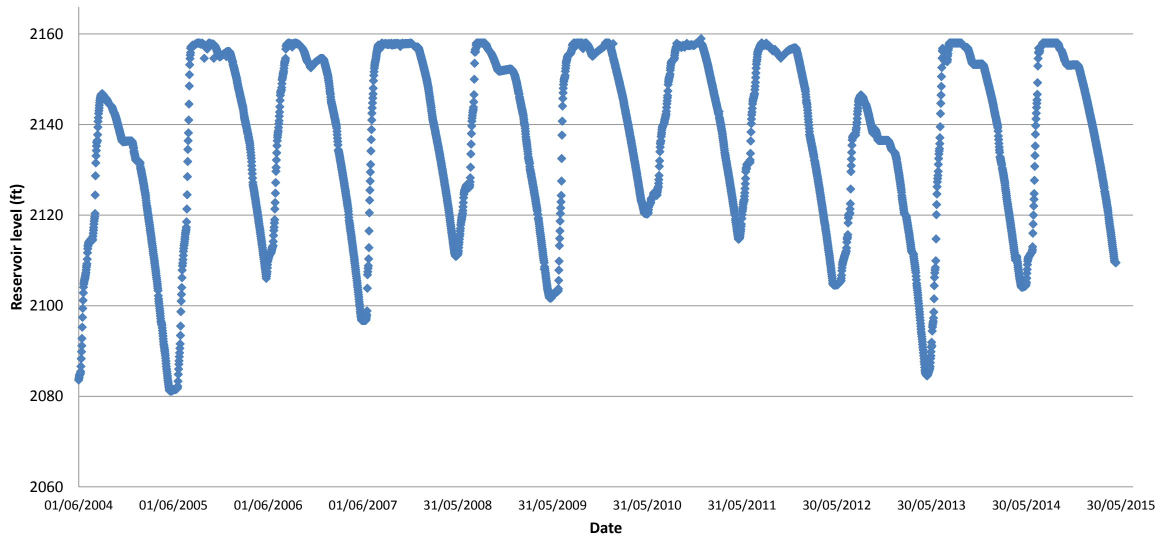
Division of Intervals for the Range of Flood Events.

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. The following figure shows the historical record of water reservoir levels:

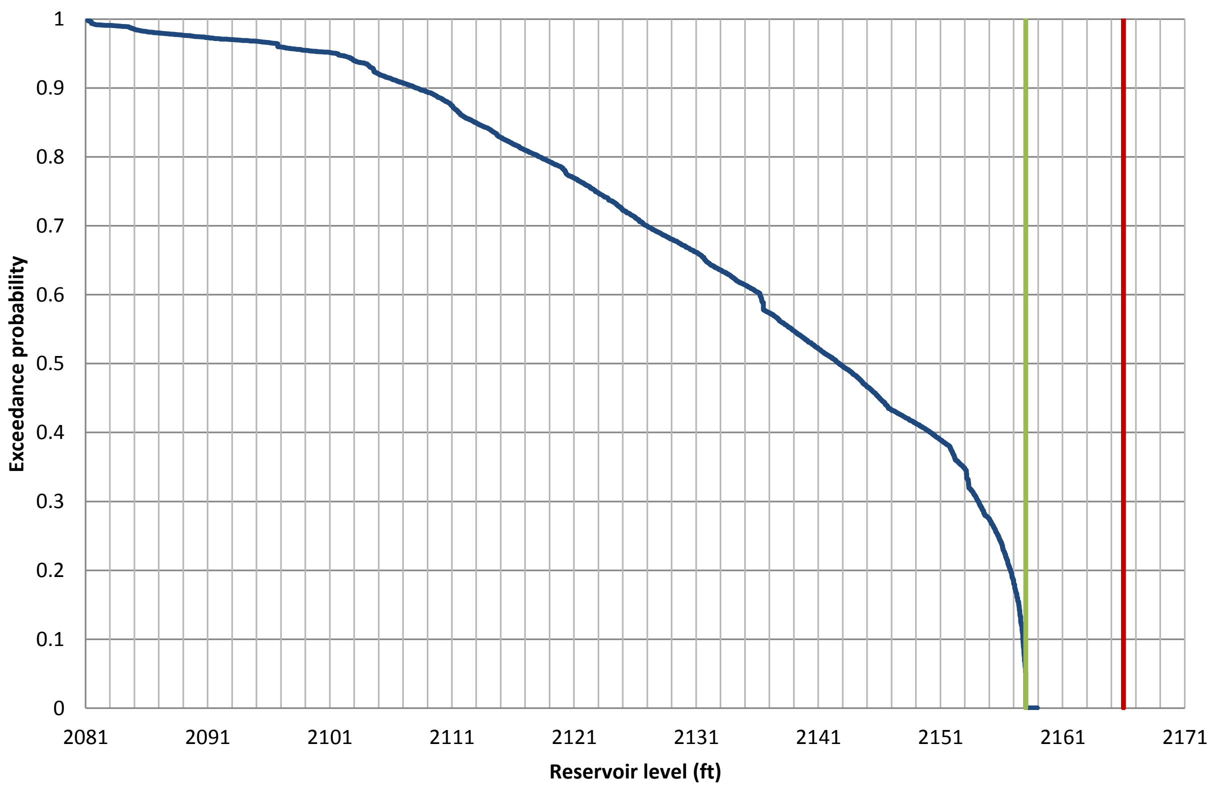


Register of reservoir level in Bhadra Dam.

The exceedance probability curve has been obtained and discretized in order to analyse 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 the table below.
- 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.

The following figure 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).



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 the following table:

Water level (ft)	Water level (ft)	Water level (ft)	Water level (m)	Probability
Interval Min	Interval Max	Interval Average	Interval Average	
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%

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 2.4.

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:

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

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.

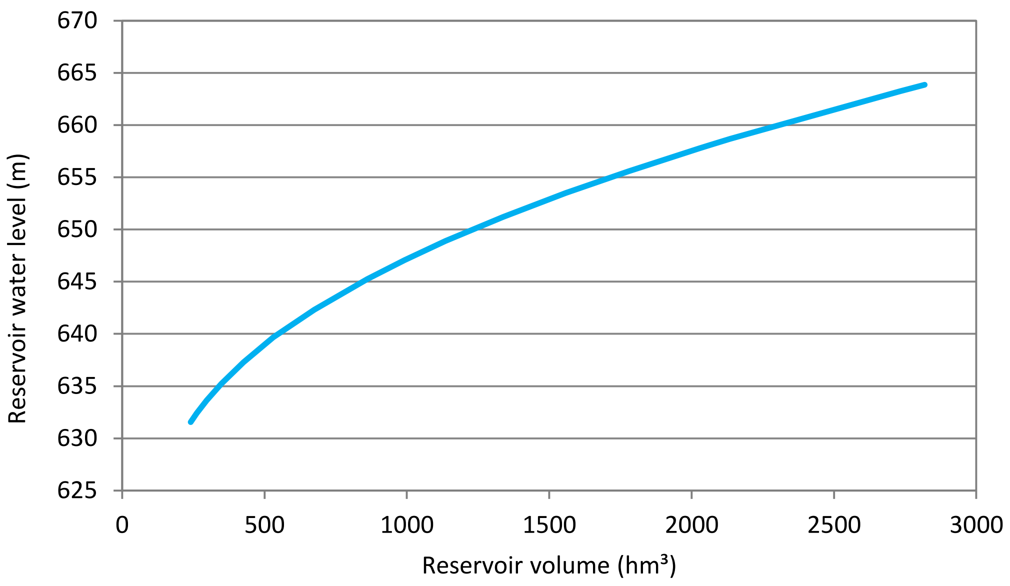
Therefore, the following data for gates performance probability is introduced in the risk model:

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

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.

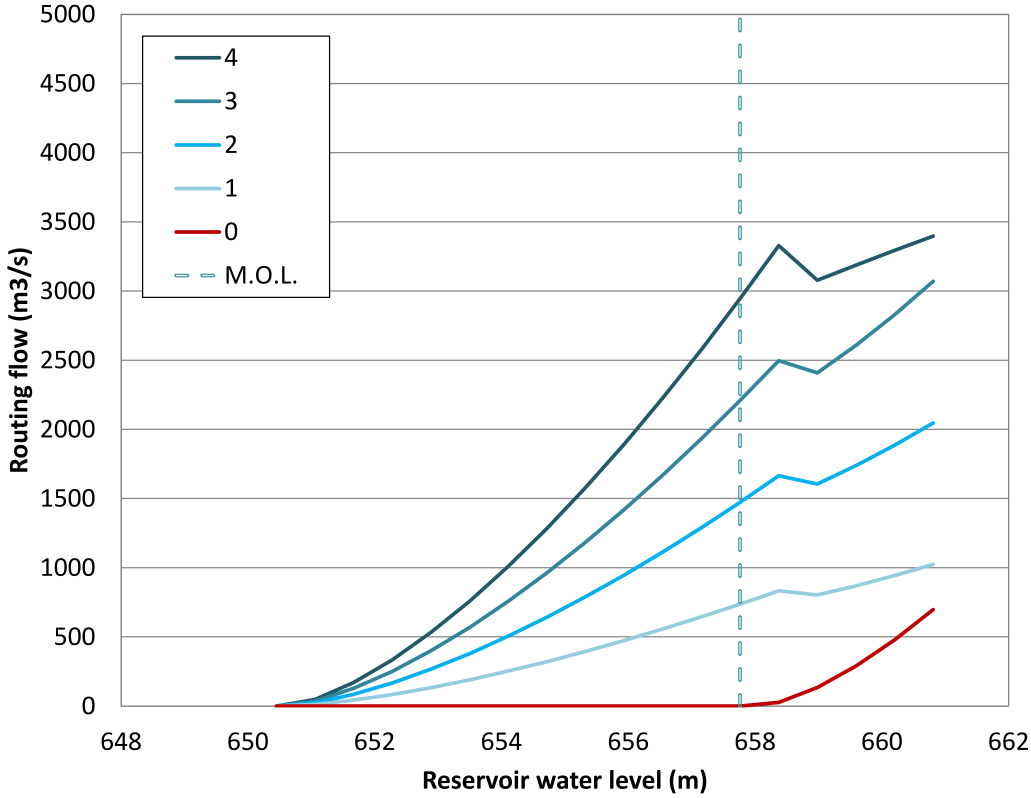
The flood routing computation was made using a spreadsheet that represents the behaviour of the dam-reservoir system, analysing inflow and outflow in the reservoir with a time interval of 1 hour. In the computation, the following stage-volume curve in the reservoir was used:



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's performance are shown in the following figure:



Rating curve for different cases of gates availability.

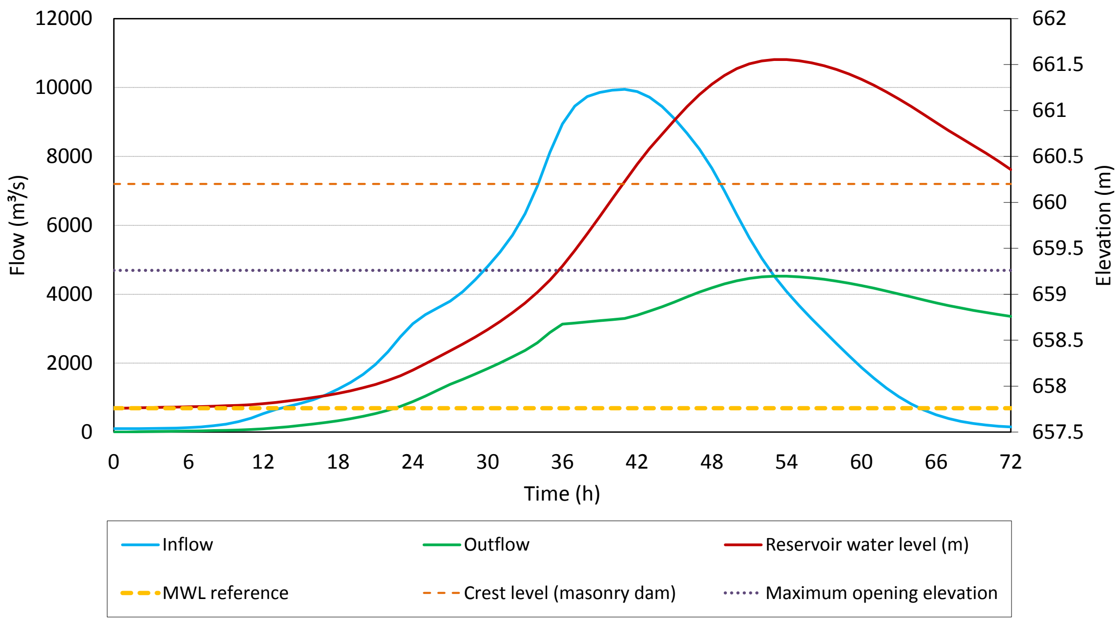
The following gates' operation rules have been considered to analyse flood appurtenance:

- 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 the 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. These events are detailed in the first part of this section.
- 12 cases of previous pool levels in Bhadra Reservoir.
- 5 cases of gates availability: 0, 1, 2, 3 or 4 gates work properly when the flood arrives.

In total, 600 combinations for flood routing analysis were made (11·12·5), 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 the following figure:



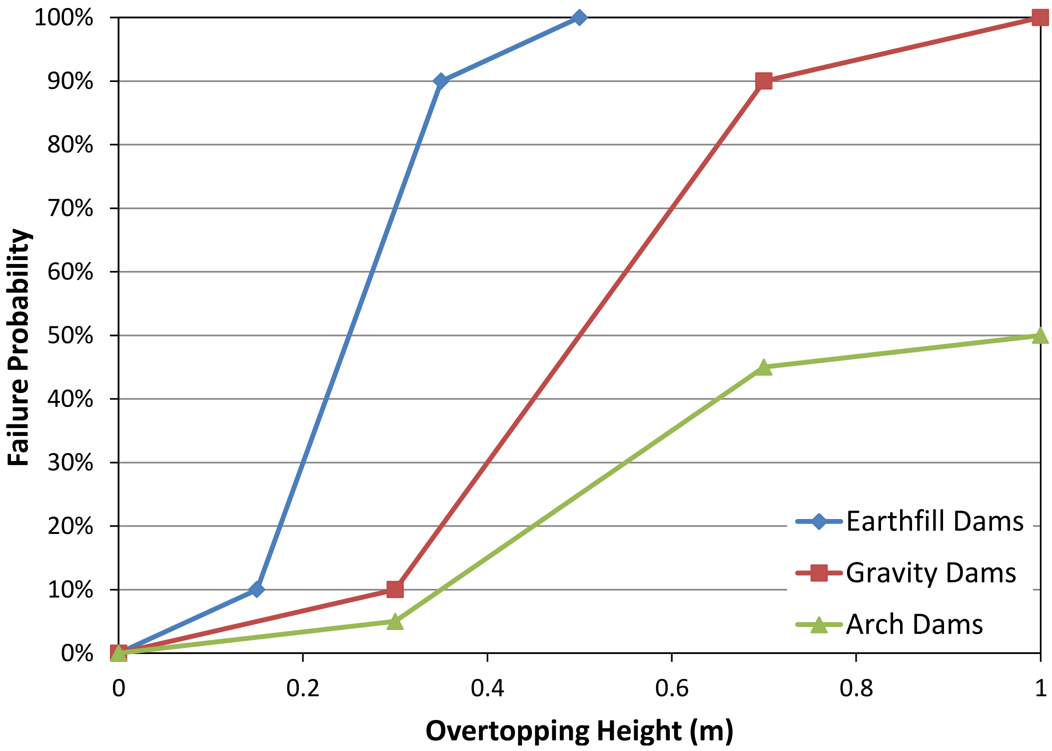
Example of flood routing calculation case for 10,000-years return period flood with 4 gates available and previous level of 65.76 m.

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 the following figure:

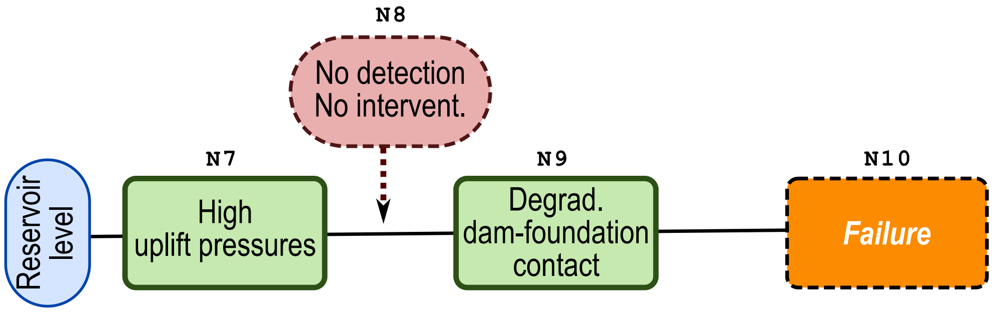


Fragility curves recommended for the overtopping failure mode. Source: (Altarejos García et al. 2014)**.**

As can be observed from this graph, resistance to overtopping is greater in arch gravity dams, because of 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: Node 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 this figure:



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.

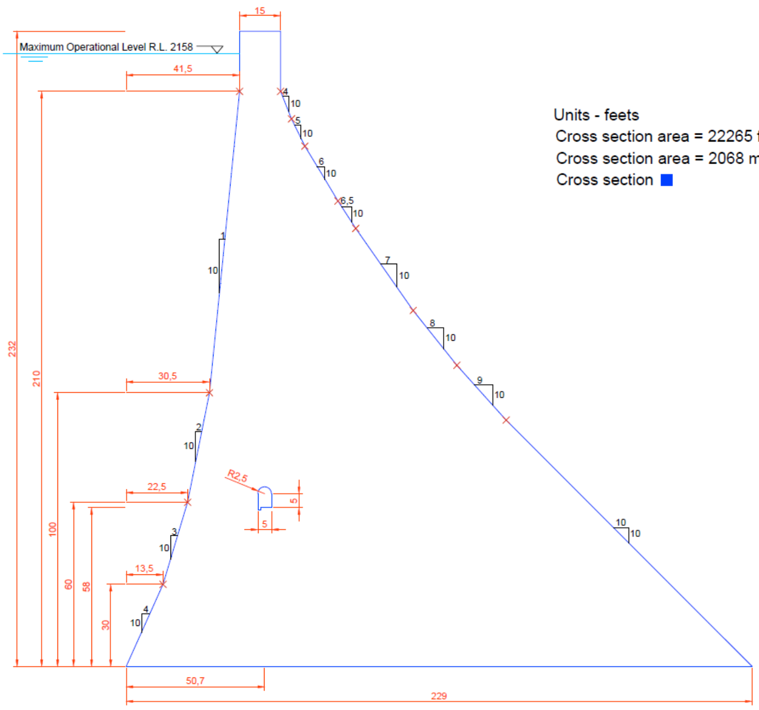
In **Node 7**, probability of high uplift pressures in the foundation was estimated by expert judgment in 70%), between 50% and 90%. This probability was estimated after reviewing exiting monitoring information and dam documentation. This probability was estimated based on the lack of data about uplift 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 monitoring information and dam documentation. This probability was estimated high because currently there are no measurements about uplift pressures in the foundations; hence, probability of detecting high uplift values in the foundation without them 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 the **Node 10** (node Failure) with the aim of obtaining the fragility curve for the main Bhadra 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 the following figure:



Cross section for sliding computation.

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-Coulomb 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 the following tables:

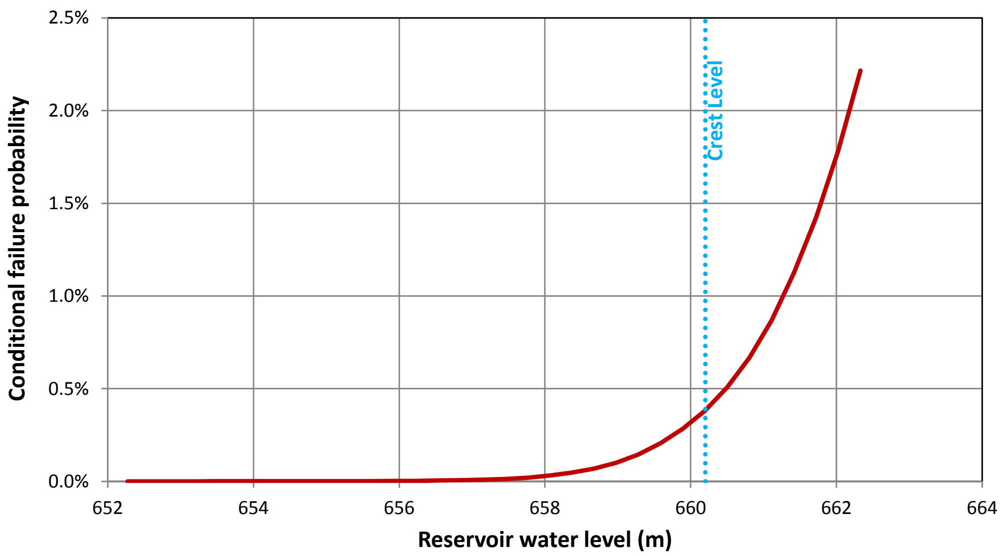
Variable	Mean	St. deviation	Max	Min	Type of distribution
Friction angle (°)	36	3.6	28	44	Truncated Normal
Cohesion (MPa)	0.35	0.1225	0	0.8	Truncated Lognormal

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

$$P_f = \frac{N_f}{N}$$

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.

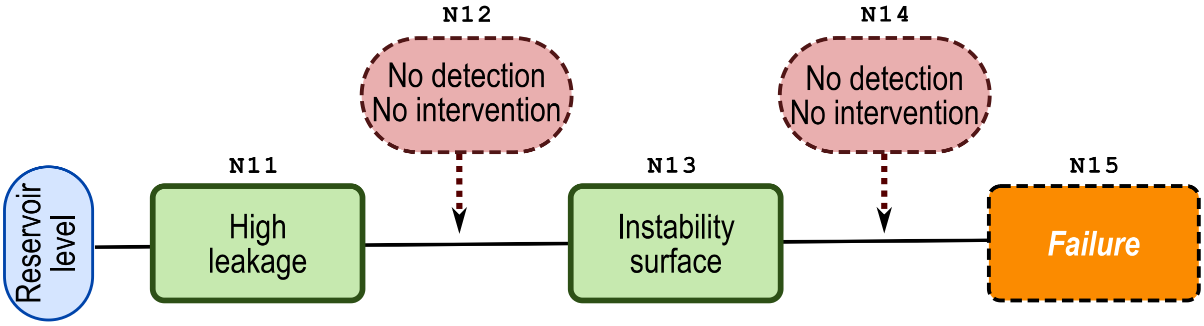
Therefore, the following fragility curves were obtained to be introduced in Node 10:



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 this figure:



Failure Mode 4 scheme (five events).

Five events are considered for this failure:

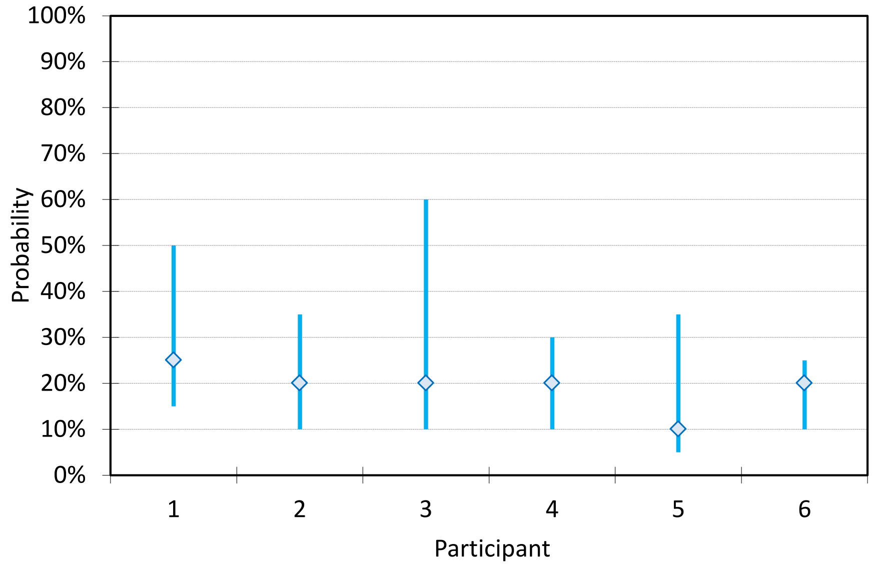
- Event 1 (Node 11): Higher leakage in dam body and this leakage is enough to degrade and to augment the dam body cracks.
- Event 2 (Node 12): Neither detection nor intervention to stop the progression of this failure mode.
- Event 3 (Node 13): Higher degradation and creation of an instability surface 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:



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%

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 program (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.

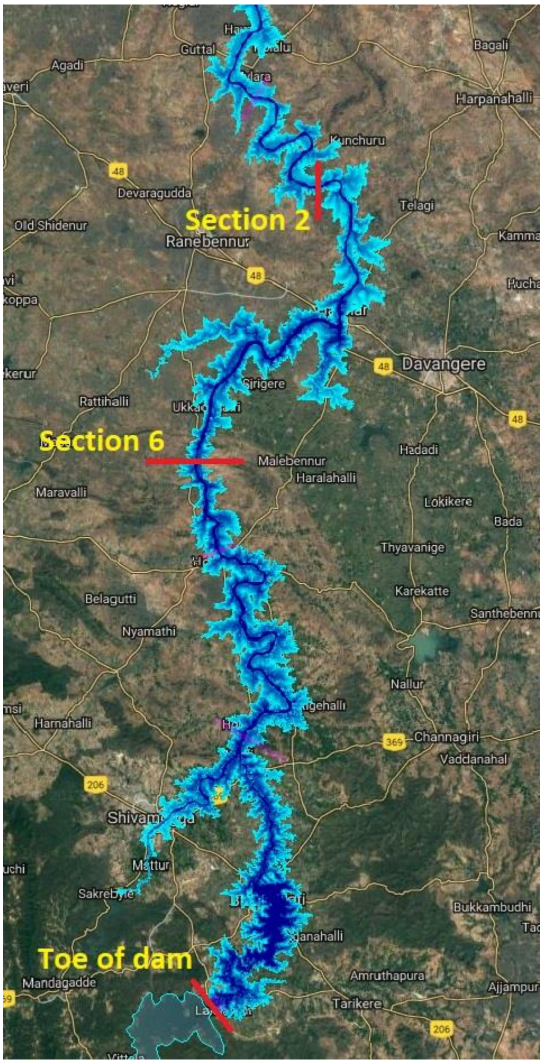
Dam breach characteristics leading to failure are the same for each scenario and shown in the following table:

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

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). The following represents the location of considered sections:

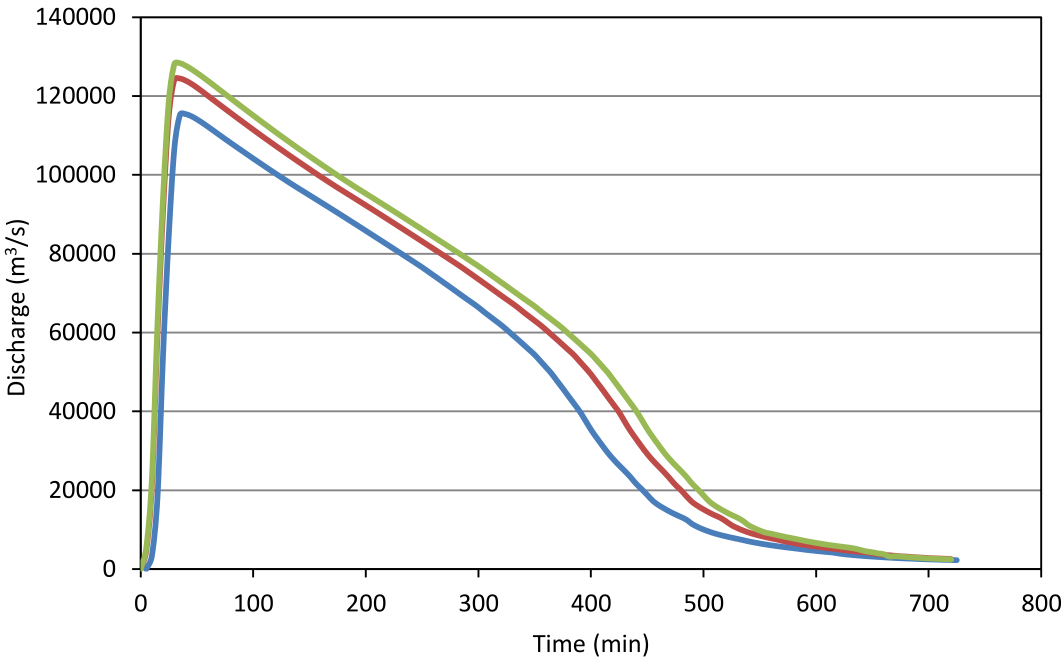


Location for the sections considered to show hydraulic model results.

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

Max Water Depth (m)			
Section	**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
Peak discharge (m^3/s)			
Section	**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

In addition, failure hydrographs at dam location for the three cases analysed are shown in the following figure:



Failure hydrograph in the three hydraulic computations made.

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 analysed 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 boundary are located inside the Shimoga district in Karnataka region (India). The following table 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%

For the economic consequence estimation it is also necessary to establish a depth-damage curve for each land-use. 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 was 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

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. The following results were obtained for each scenario:

Case	Flooded area (km^2)	Agricultural Land (km^2)	%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

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. Next table presents the relative average damage-depth function used from this source:

Water depth (m)	Damage factor	Damage (Rs/m^2)
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

For economic consequence estimation of potential damages in downstream settlements, the 26 main populations 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 computation are shown in the following table:

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**

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:

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

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, the following table shows 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.

	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

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.

Finally, in Node 21 incremental economic consequences were computed for each branch of the event tree by subtracting consequences in 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 (I. 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

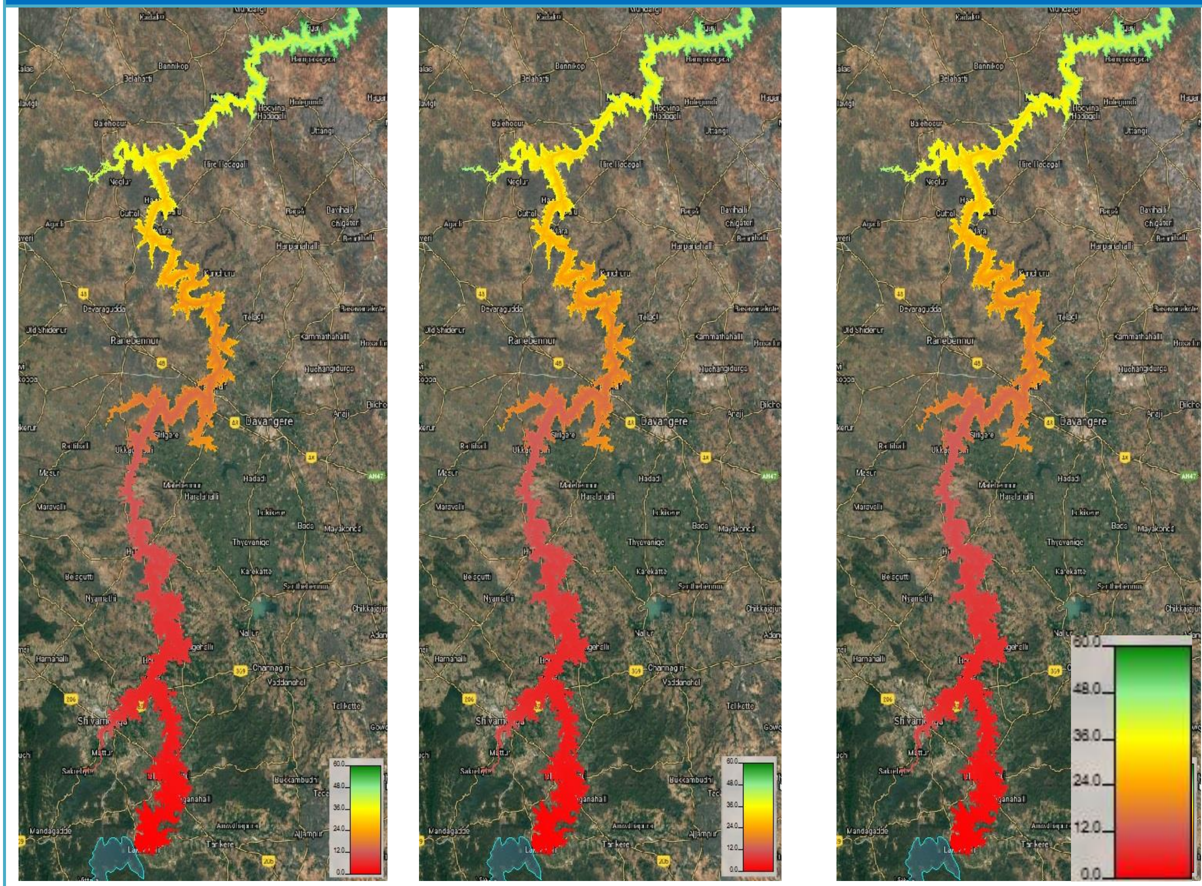
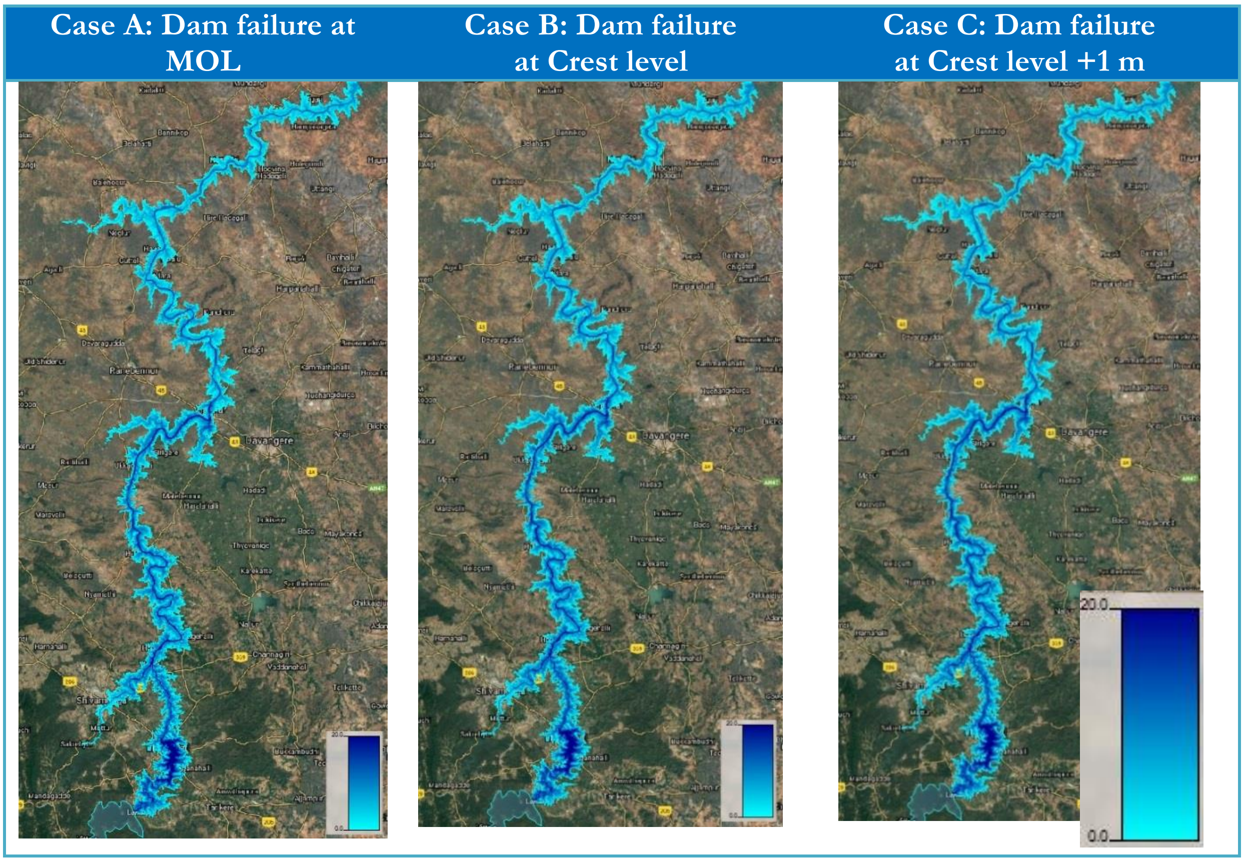
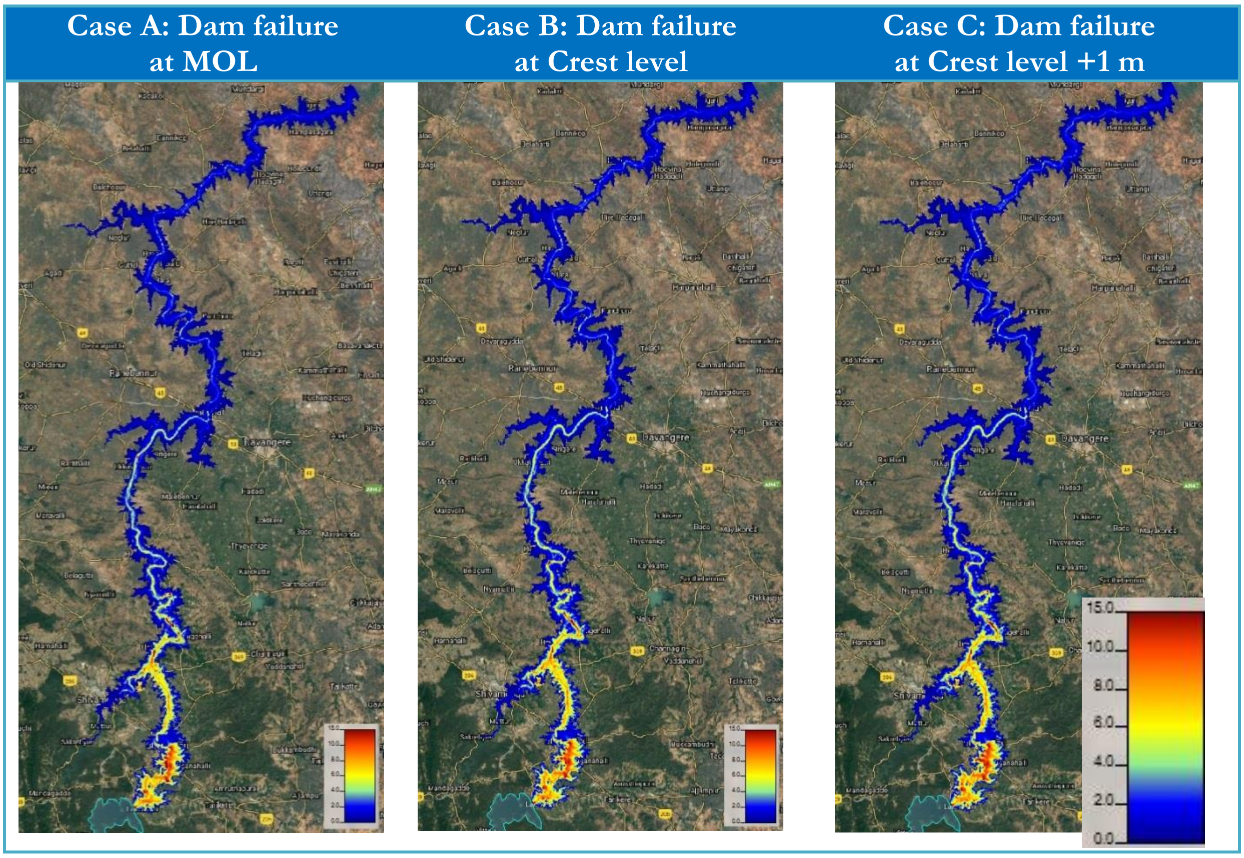


Figure 2.1. Flood inundation Map. Arrival time in min. (Three scenarios)



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

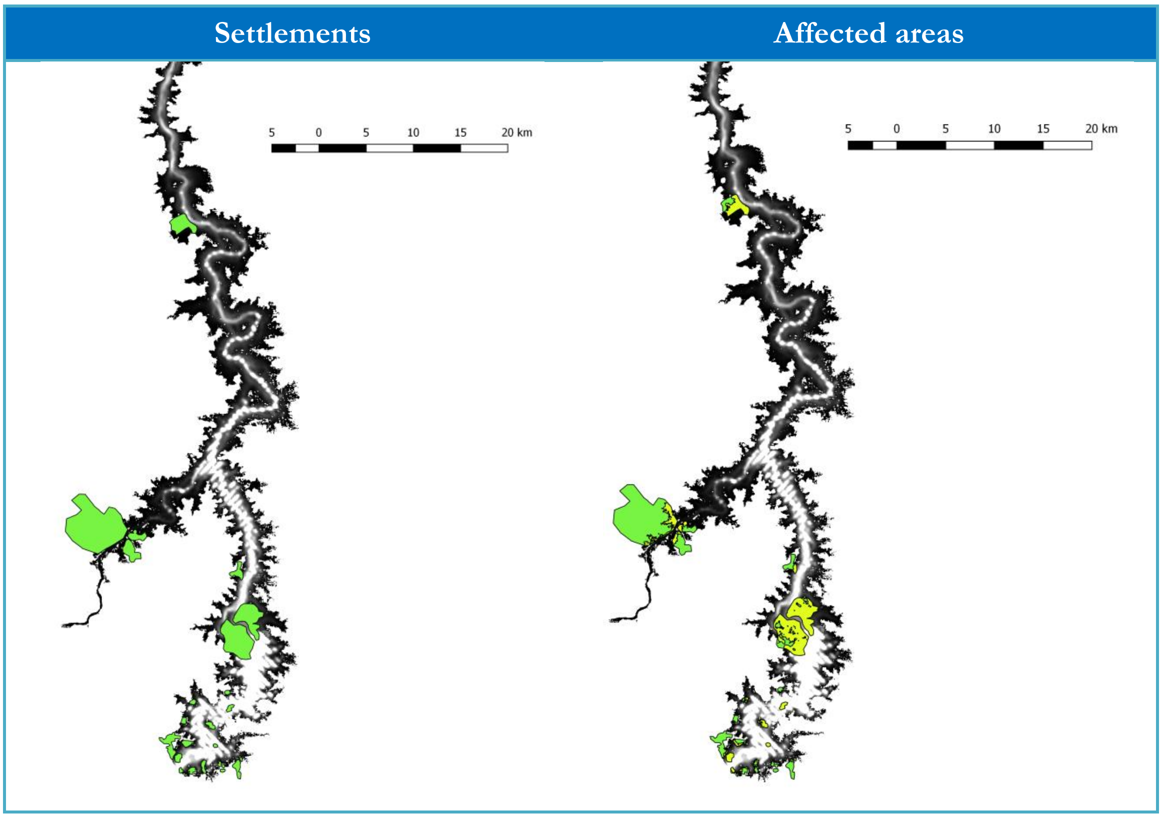


Flood Inundation Map. Maximum Water Velocity in m/s (Three Scenarios).

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 the following figure:



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 (I. Escuder-Bueno et al. 2012) for Category 3:

		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

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. The following table show potential loss of life estimations for each computed dam failure scenario:

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

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.

3.4. 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.

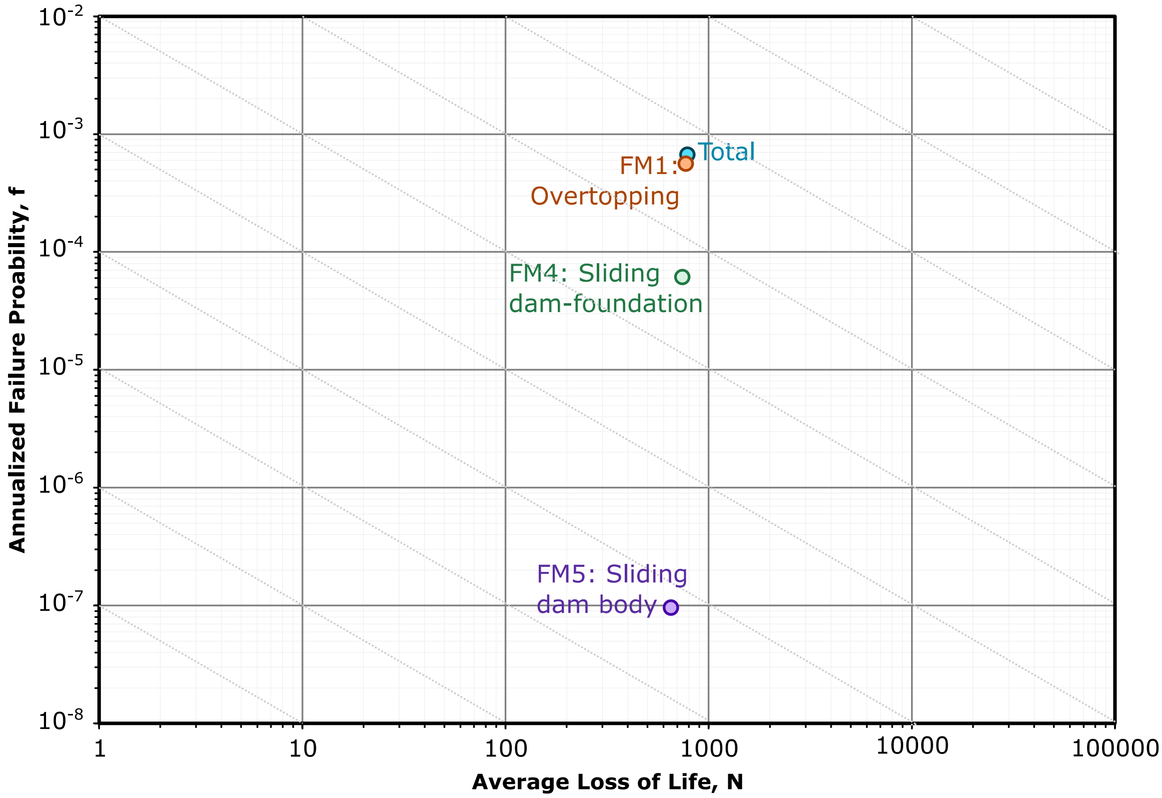
Incremental risk

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.

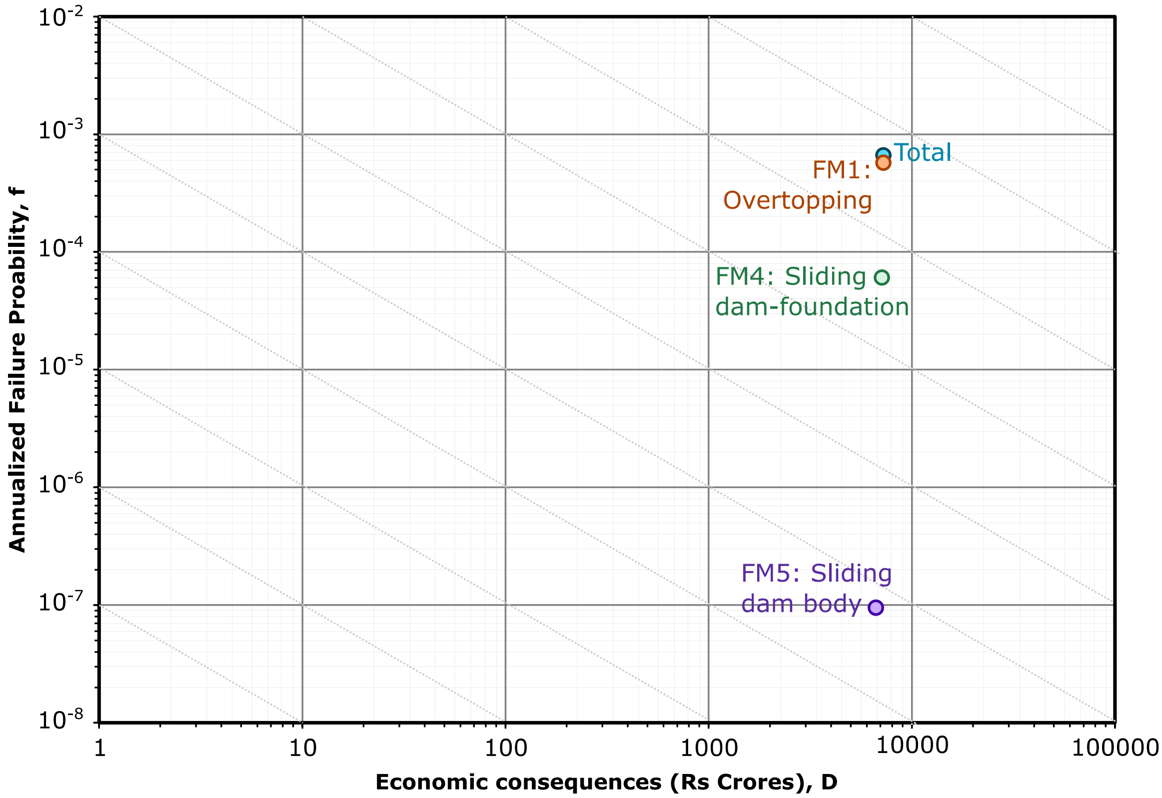
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
Failure mode 1: Overtopping	5.700E-04	4.470E-01	4.217E+00
Failure mode 4: Sliding dam-foundation	6.031E-05	4.457E-02	4.321E-01
Failure mode 5: Sliding dam body	9.519E-08	6.325E-05	6.338E-04
Total	**6.304E-04**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

Results show that the predominant failure mode is overtopping, clearly 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.

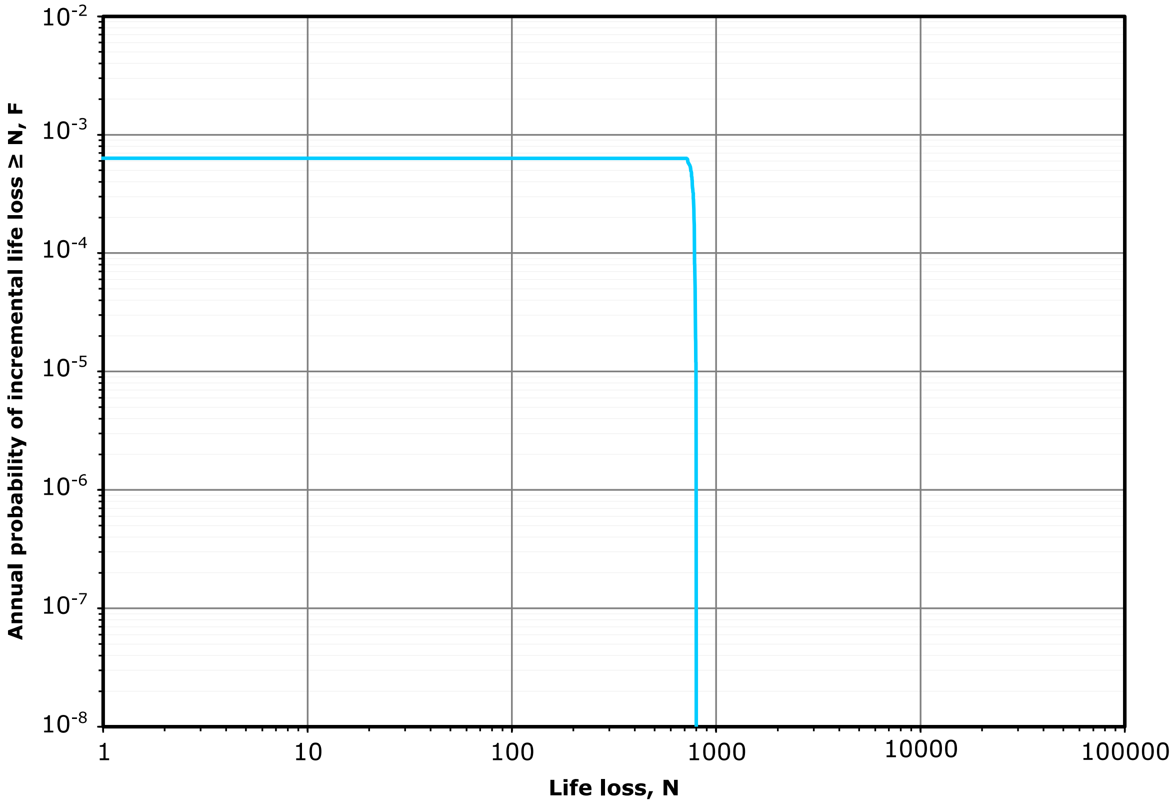
In the following figures, these incremental risk results are represented in fN, fD, FN and FD graphs:



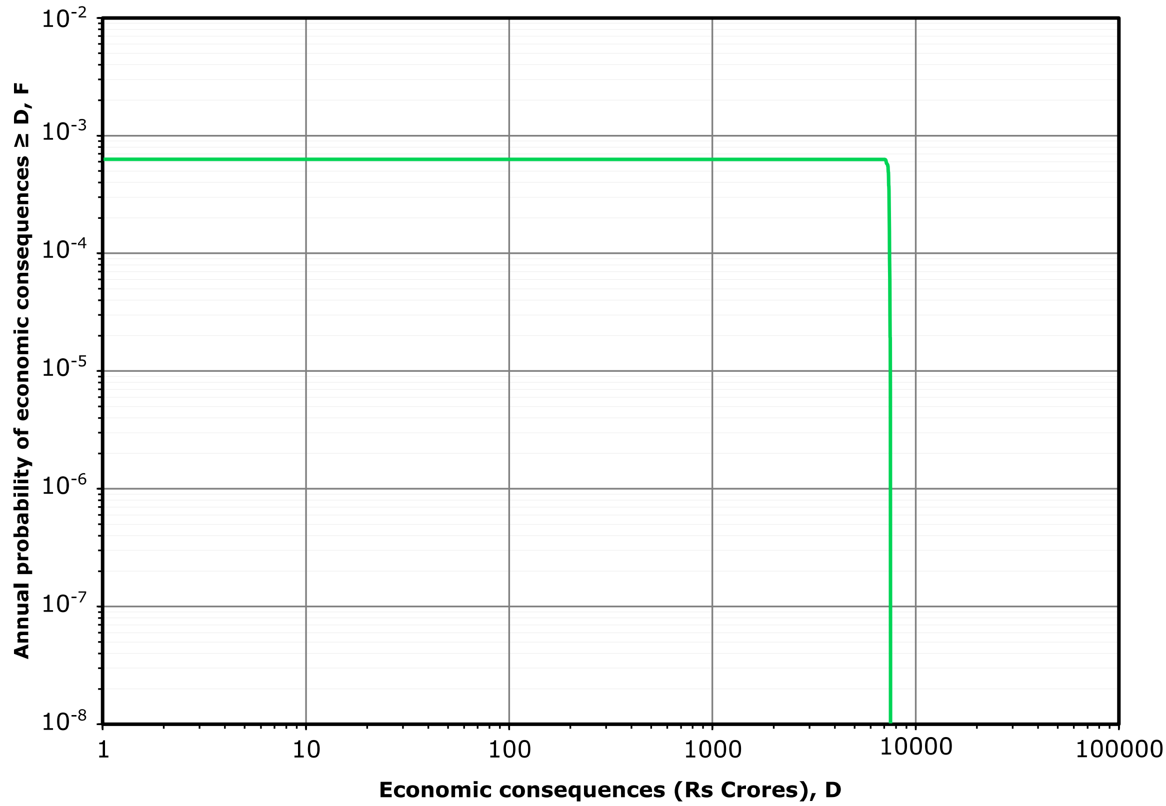
fN Graph with incremental risk results in current situation.



fD Graph with incremental risk results in current situation.



FN Graph with incremental risk results in current situation.



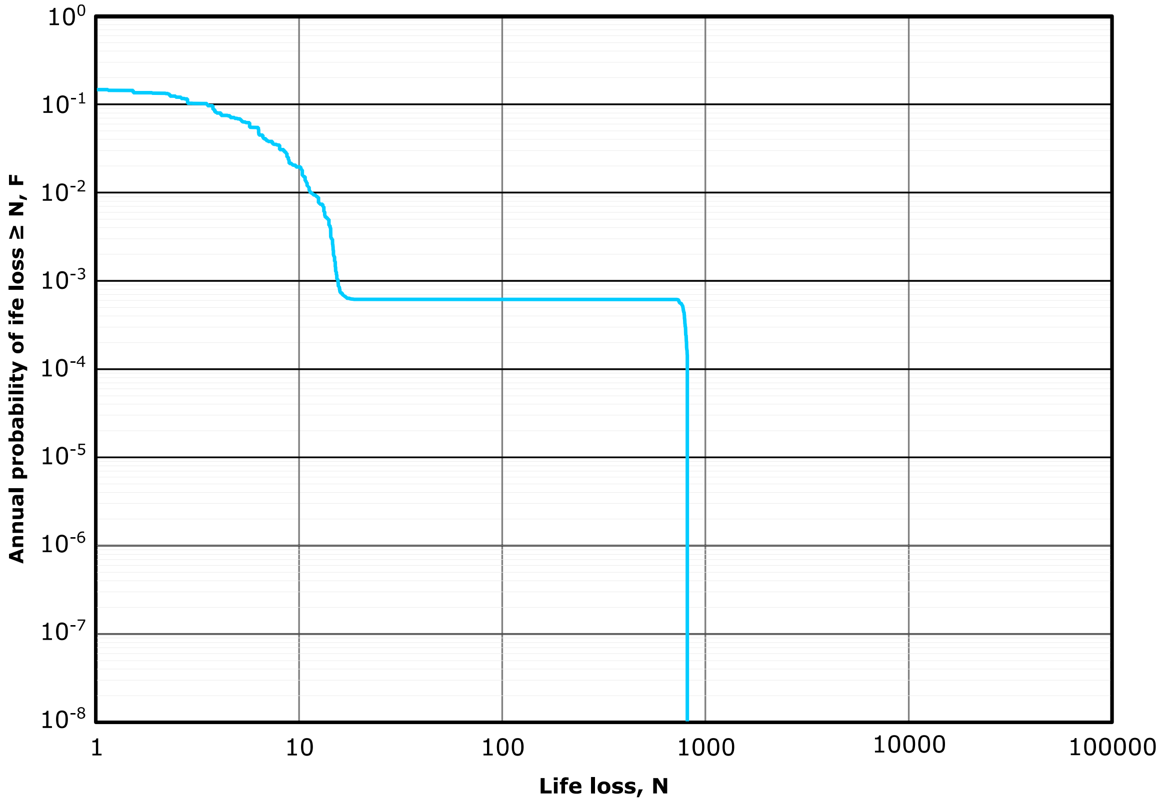
FD Graph with incremental risk results in current situation.

Total risk

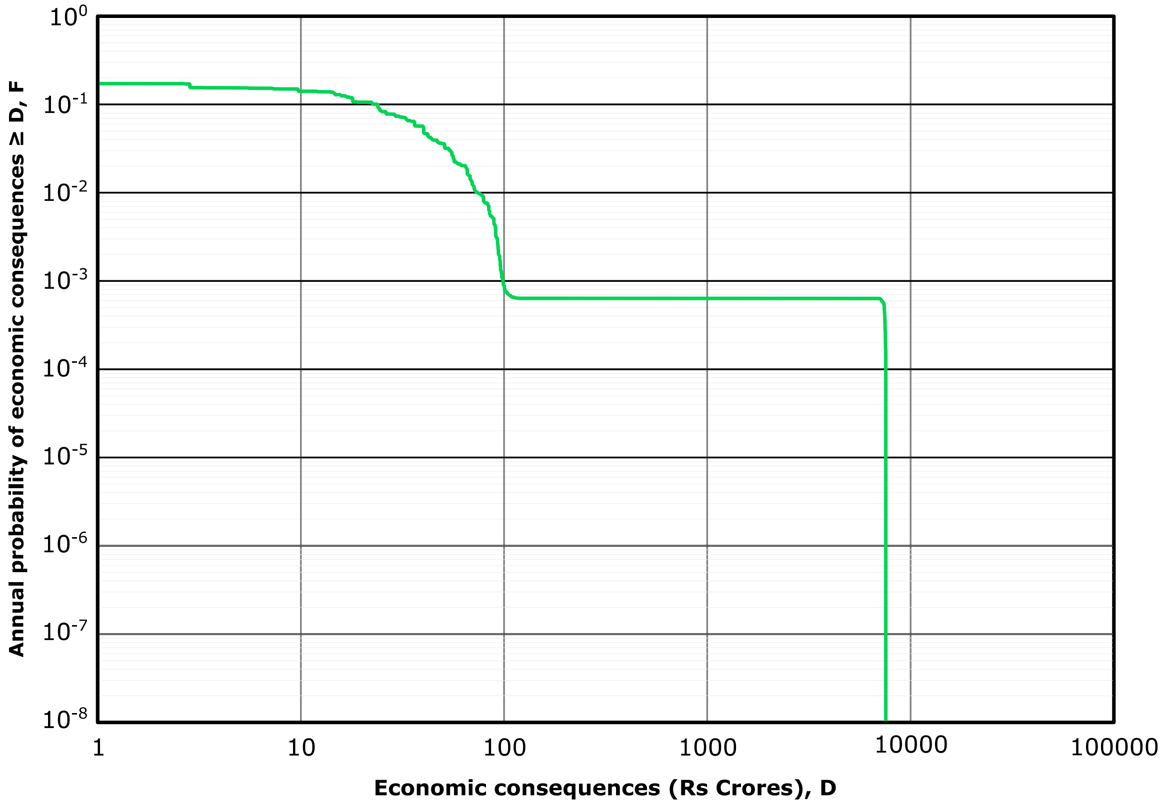
It represents total risk from flooding in downstream areas and includes both dam failure and non-failure cases. These results are shown in the following table:

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

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



FN Graph with total risk results in current situation.



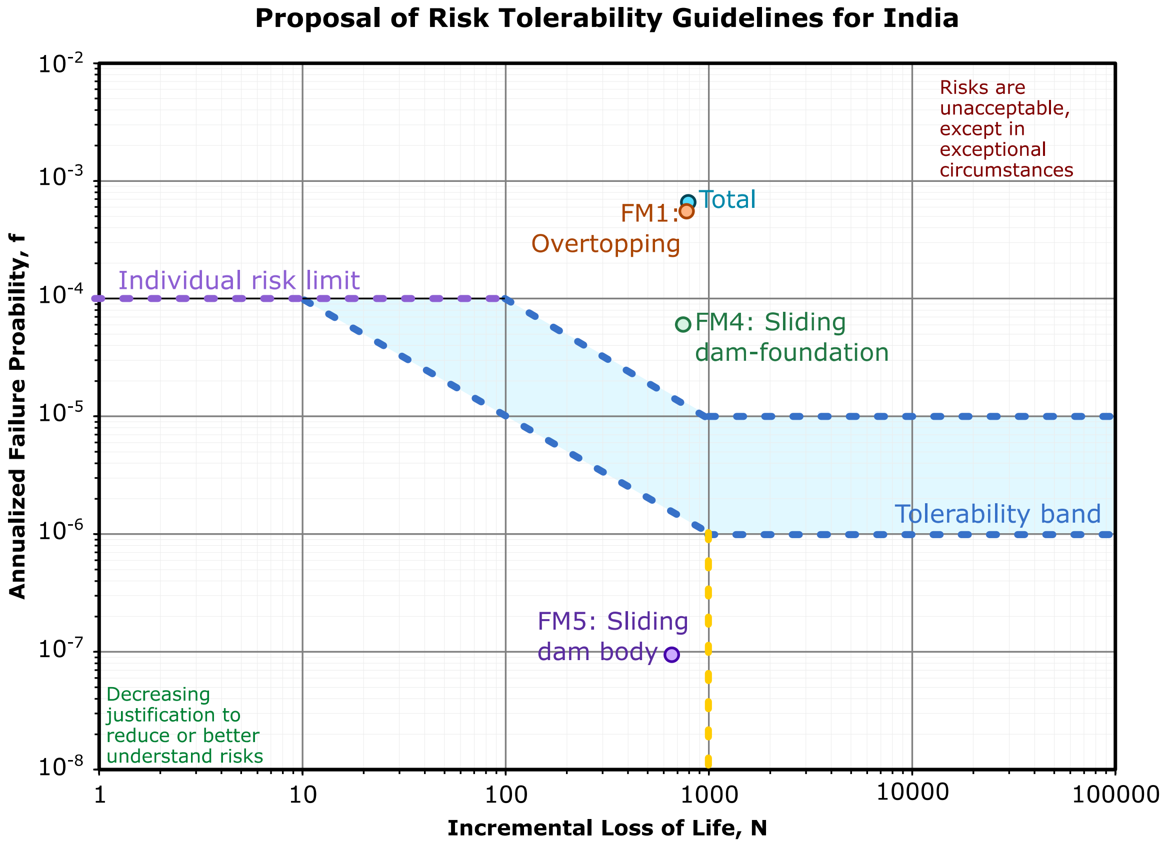
FD Graph with total risk results in current situation.

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).

3.5. 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 the tolerability recommendations from the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Risk evaluation results are shown in the following graph:



Individual and societal risk evaluation for current situation.

These results show that risks of overtopping and sliding are not aligned with tolerability recommendations. In overtopping failure mode, these results are directly influence by existing uncertainty on need to rainfall 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.

3.6. 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.

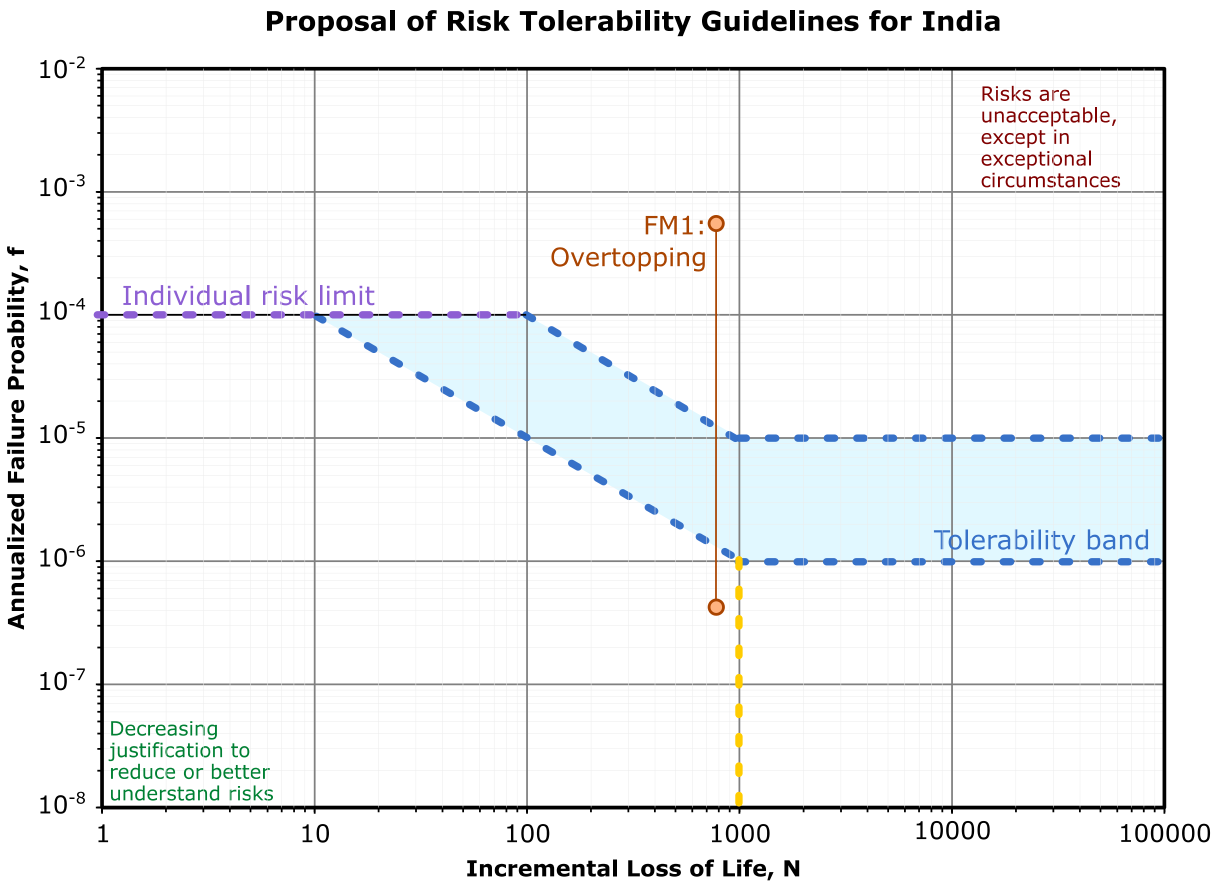
Hydrologic hazards

As explained above, overtopping risk results are above tolerability limits 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

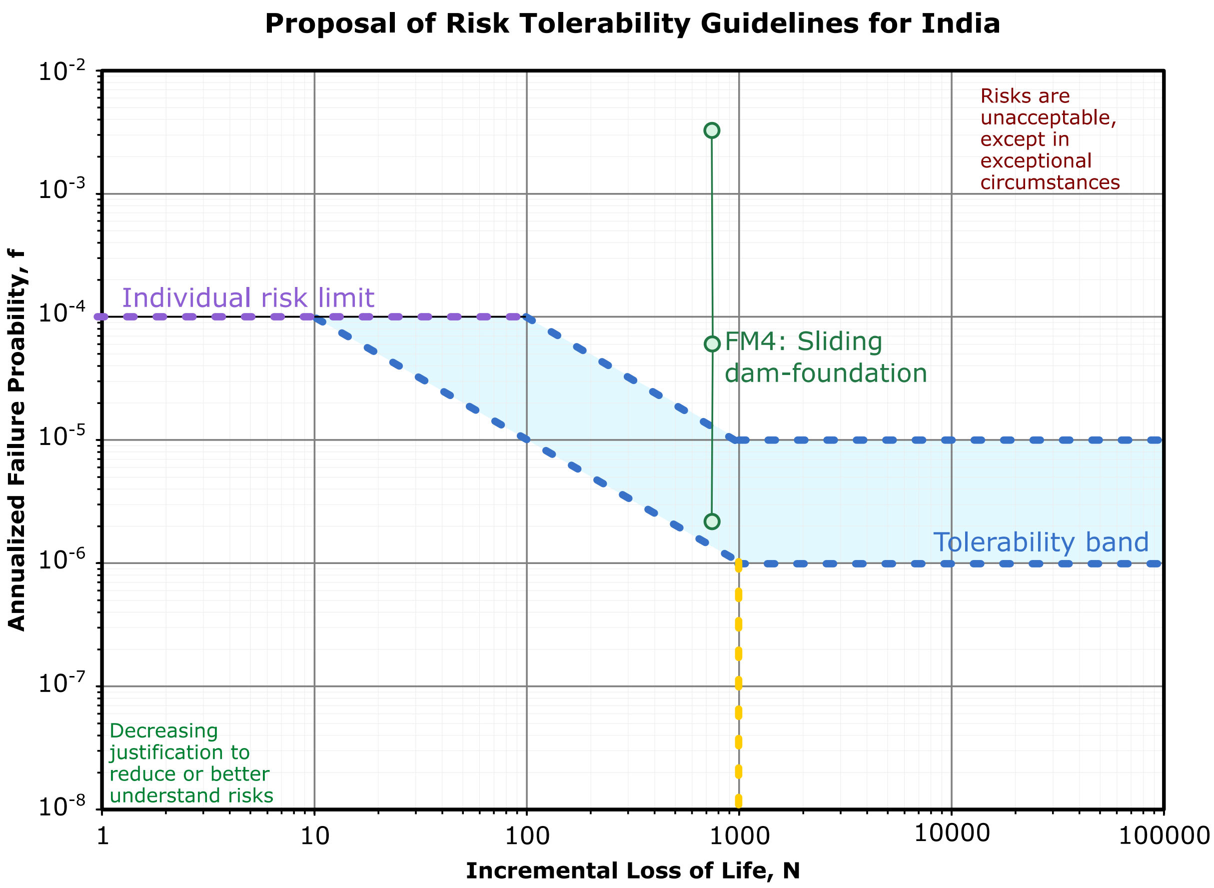
As can be observed in the following figure, the overtopping failure probability for the Bhadra Dam moves from clearly non-tolerable area to tolerable are when rainfall data from Chickmagalur station is used, decreasing about three orders of magnitude. These results highlight the high uncertainty on rainfall 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.



fN graph for uncertainty analysis on hydrologic hazards.

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 the fN graph below. 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).



fN graph for uncertainty analysis on sliding physical model parameters.

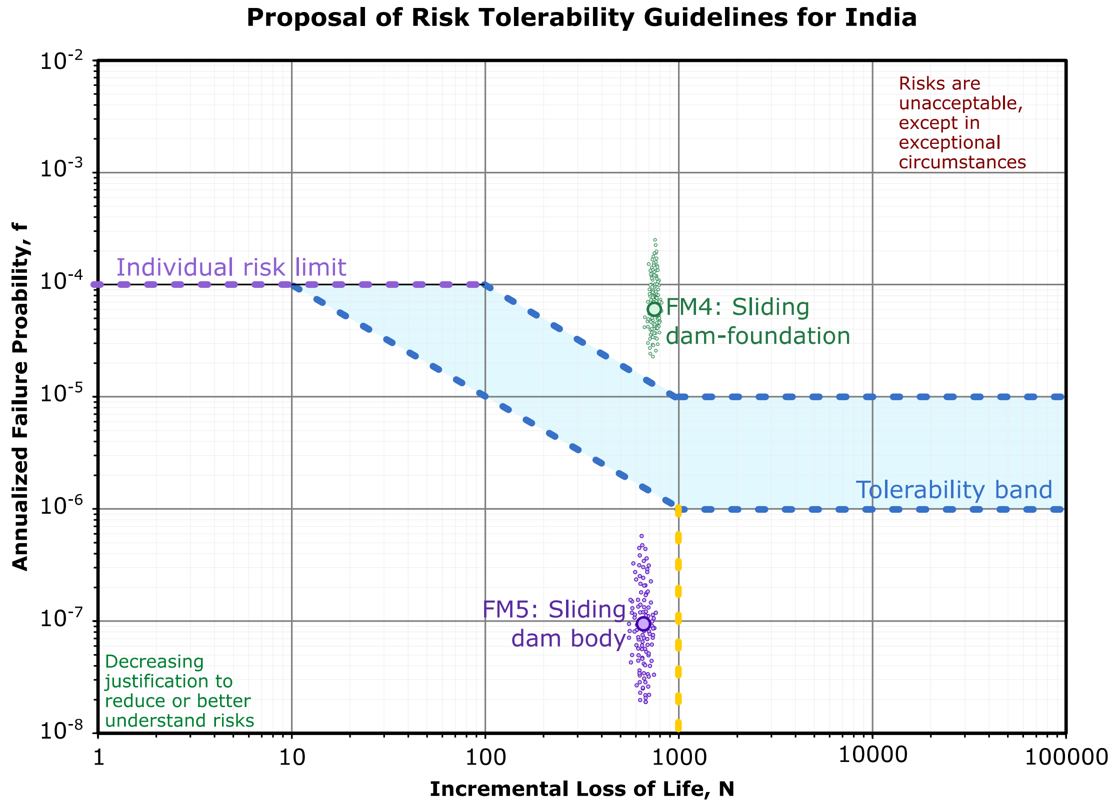
This result indicates the need for geotechnical tests to reduce existing uncertainty on foundation conditions and further studies on this failure mode with more complex numerical models. However, all the sensitivity results are above tolerability risk limits, so simple risk reduction actions could also 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.

Probabilities estimated by expert judgment

As explained in Section 3.3, most of the probabilities in failure modes 4 and 5 were estimated by expert judgment. For each node, a better estimate of the probability was obtained and also a lower limit and an upper limit for these estimates. The best estimate was the value used to obtain the risk results shown in the previous graphs.

In order to analyse the uncertainty of these estimates, a triangular probability distribution was defined in each node. The extremes of this distribution were defined by the lower limit and the upper limit of the probability estimated in each node, while the midpoint was defined by its best estimate.

From these distributions, a Monte Carlo analysis was carried out by sampling independently 100 times each of the nodes and thus obtaining 100 different groups of probabilities. With these groups of probabilities, 100 different risk results were obtained that characterize the uncertainty in the estimates. In this way, the variation in the risk results can be analysed according to the uncertainty expressed by the participants in the failure probabilities estimation session. The 100 risk results form a point cloud that is shown in the following figures, classified by failure modes.



fN graph for uncertainty analysis on probabilities estimated by expert judgement.

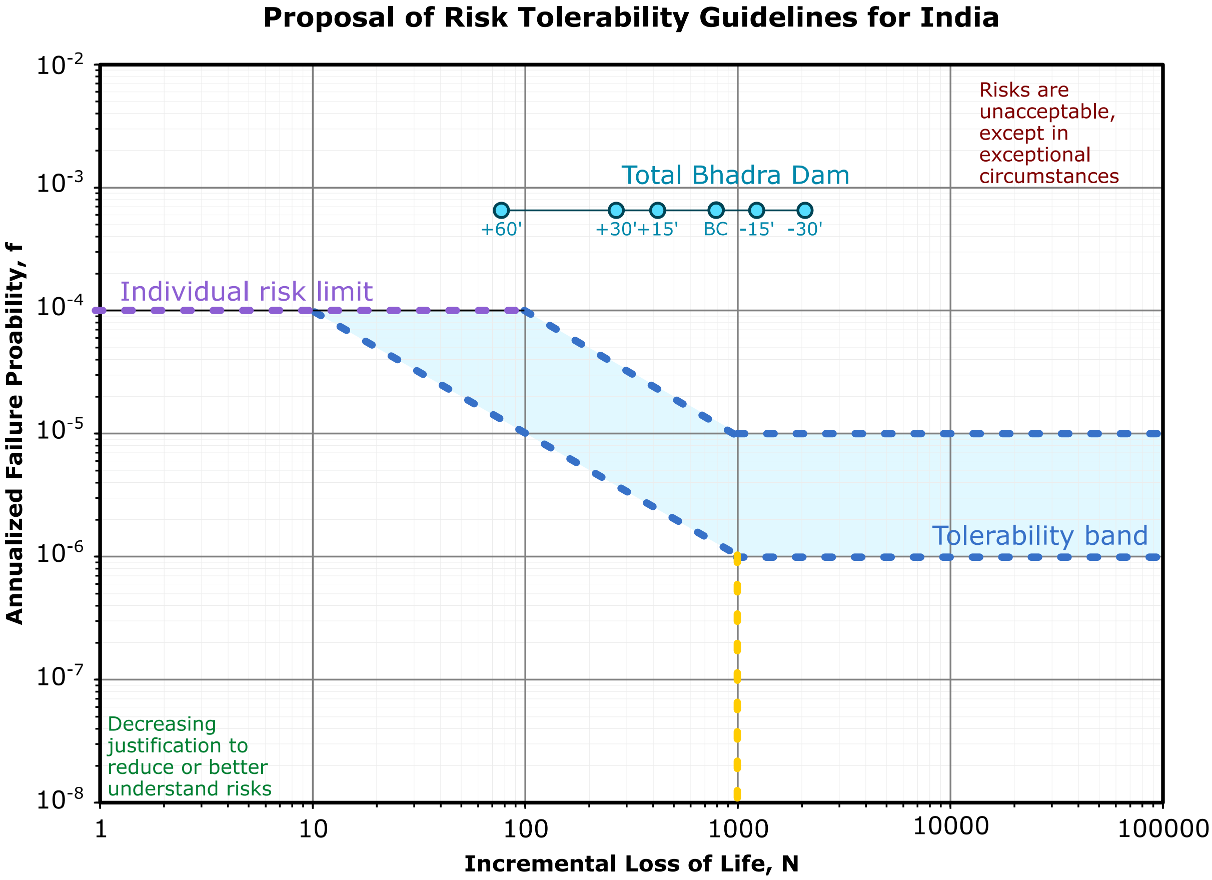
These results show that expert judgement uncertainty does not have a high influence on the conclusions reached based on risk results. FM5 risk is still below the tolerability limits and FM4 risk is still above tolerability limits in all the cases.

Warning times and evacuation procedures to estimate loss of life

Since there are very important populations living downstream of theBhadra 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

The results obtained are shown in the following figure. 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.



fN graph for uncertainty analysis of different warning times.

3.7. Prioritization of risk reduction actions

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:

<table>
<tr><th>Measure 1</th><th colspan="3">Emergency Action Plan</th></tr>
<tr><td>Introduction cost (Rs Crores)</td><td>0.8</td><td>Maintenance cost (Rs Crores/year)</td><td>0.04</td></tr>
<tr><td>Lifespan (years)</td><td>20</td><td>Failure Modes</td><td>All Failure Modes</td></tr>
<tr><th colspan="4">Description</th></tr>
<tr><td colspan="4">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.</td></tr>
<tr><th colspan="4">Effect on risk model</th></tr>
<tr><td colspan="4">These types of measures do 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.</td></tr>
</table>

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.

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.

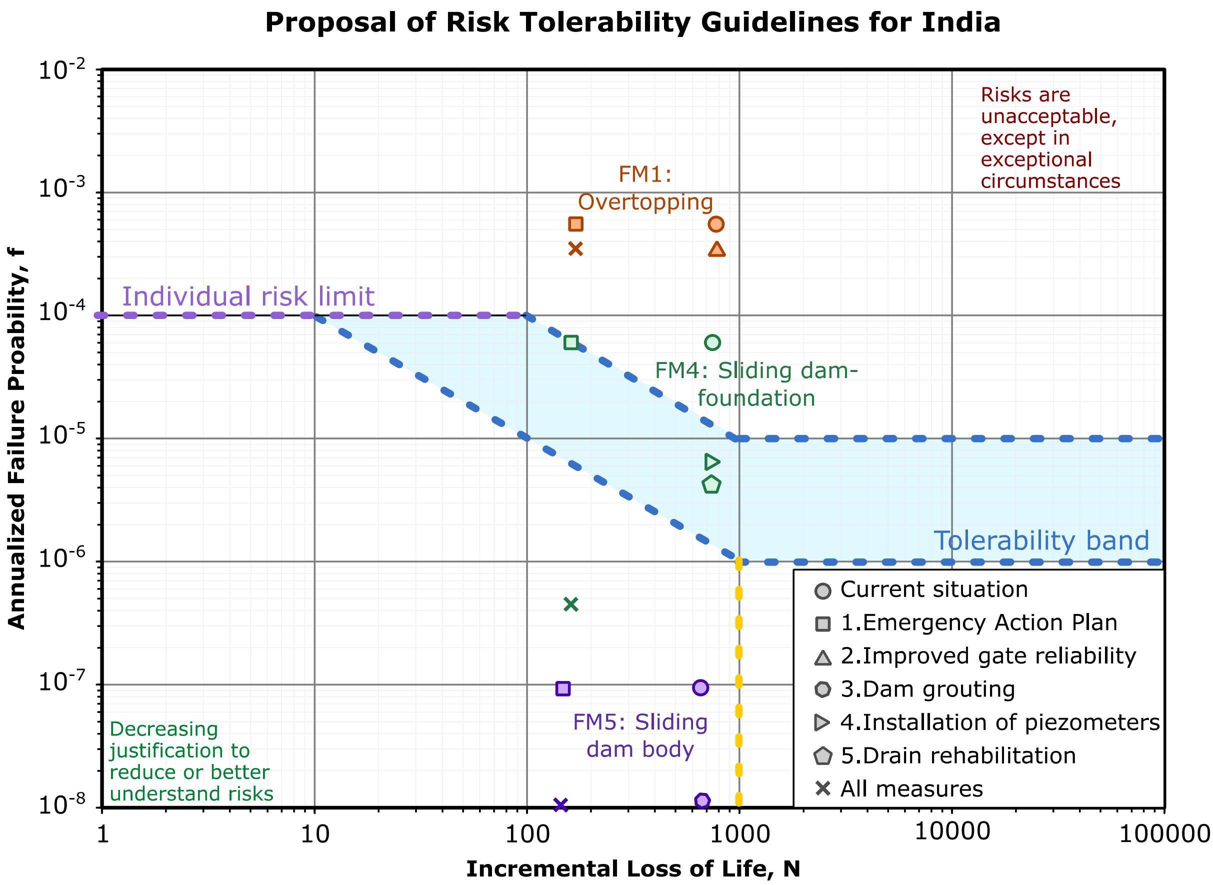
The results obtained for each measure are shown below. In this table, the results in green show the measures that produce a decrease with respect to the Base Case, while the results in red show an increase. The results include the effect of jointly implementing all risk measures.

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
Measure 4: Installation of piezometers			
Failure mode	**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
Measure 5: Drain rehabilitation			
Failure mode	**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
All measures			
Failure mode	**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 the tolerability graph shown in the previous section:



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 3.6. 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.

Effect on total risk results

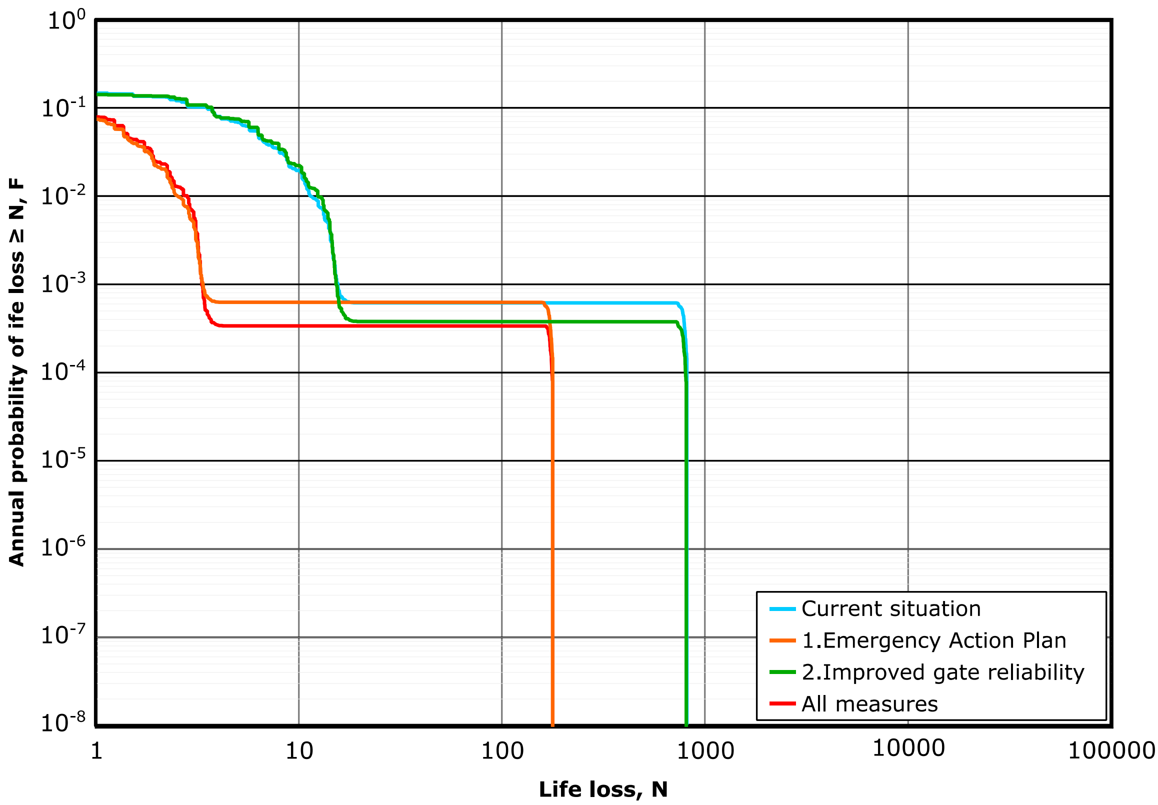
Total risks were also recalculated including the effect of each risk reduction action. Results obtained for each measure are shown in the following table:

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

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.



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.

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

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).

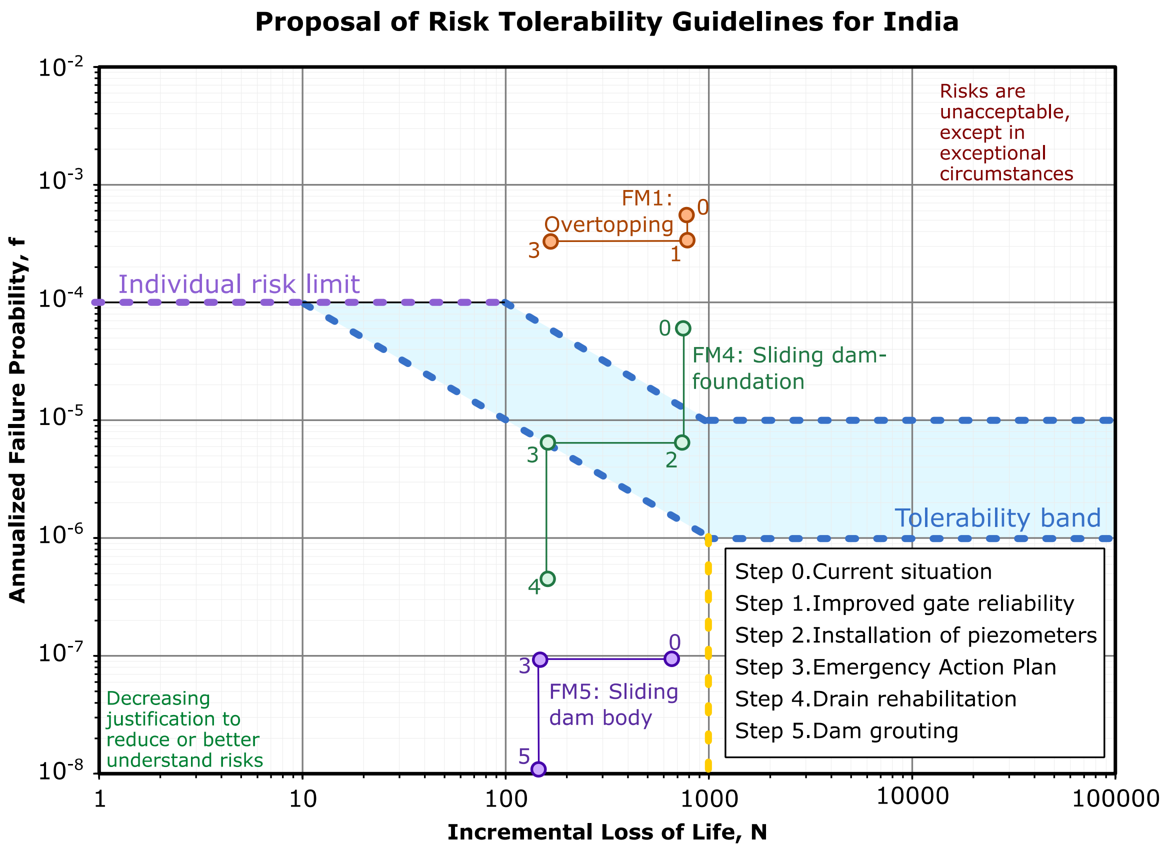
These results are used in an iterative process to obtain a sequence of risk reduction actions. The steps of the obtained sequence are:

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

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 ACLSS 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.

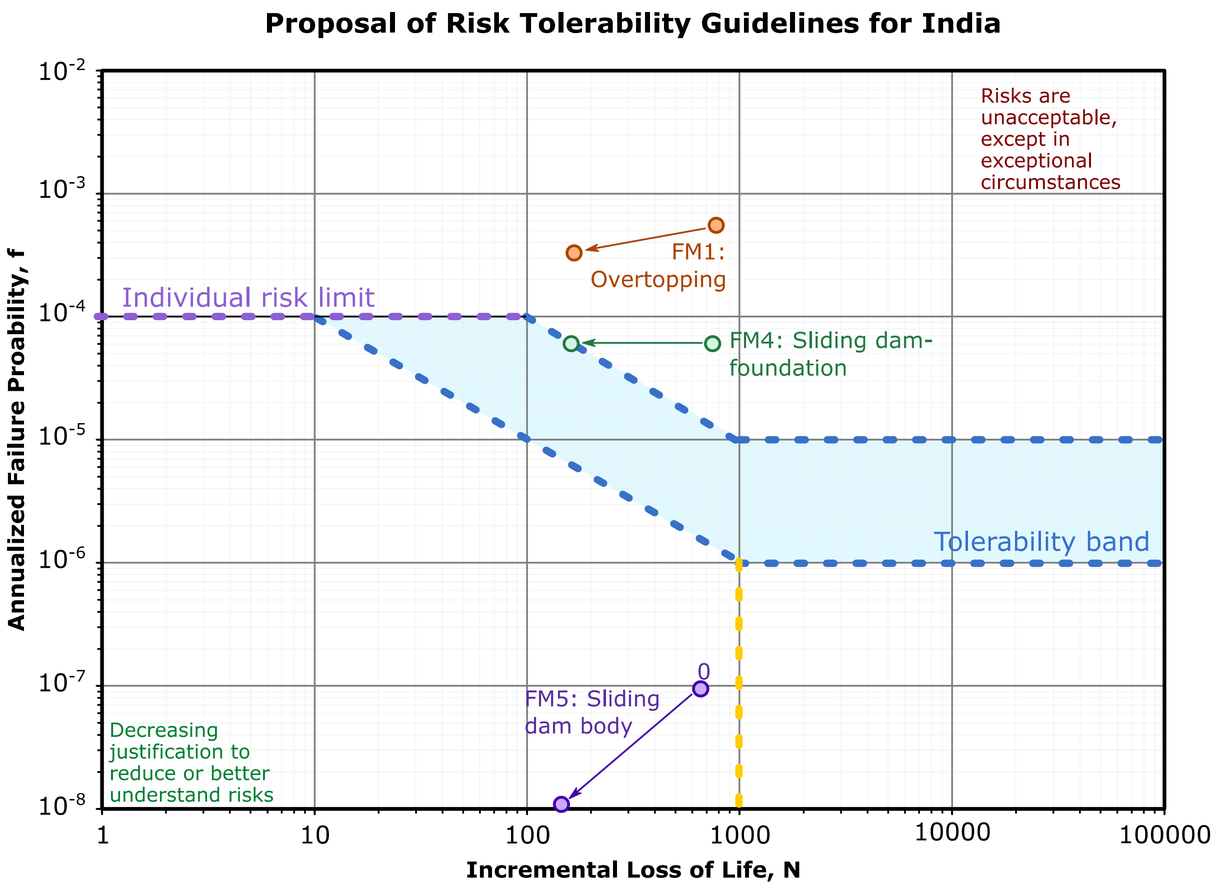
This itinerary can also be represented in the risk tolerability graph for the three failure modes:



Itinerary followed by implementing the proposed sequence of actions in risk tolerability 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 the following figure:



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

4. Semi-Quantitative Risk Analysis

4.1. 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 C Failure Modes** to prioritize new studies and new instrumentation in the Portfolio of dams. In addition, **Class B 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 C 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 B Failure Modes to be included in this analysis following uncertainty analysis recommendations are:

- 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
AAAA BBBB	Phd. Civil Engineer	Consultancy company specialized in Dam Risk Analysis
CCCC DDDD	Phd. Civil Engineer	Consultancy company specialized in Dam Risk Analysis
EEEE FFFF	Civil Engineer	Consultancy company specialized in Dam Risk Analysis
IIII JJJJ	Assistant Engineer	Advanced Centre of Integrated Water Resources Management CWC
KKKK LLLL	Assistant Engineer	Advanced Centre of Integrated Water Resources Management CWC

Semi-Quantitative Risk Analysis was coordinated and supervised by AAAA BBBB who has proven experience in this type of analysis applied to dam safety.

4.2. 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 popula-

tion 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:

Failure Mode 6: Sliding in a seismic event in the main dam	
Failure probability category	Low
Justification	
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.	
Consequences category	4
Justification	
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.	

Failure Mode 7 : Overtopping in a seismic event in saddle dams	
Failure probability category	Remote
Justification	
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.	
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 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.	

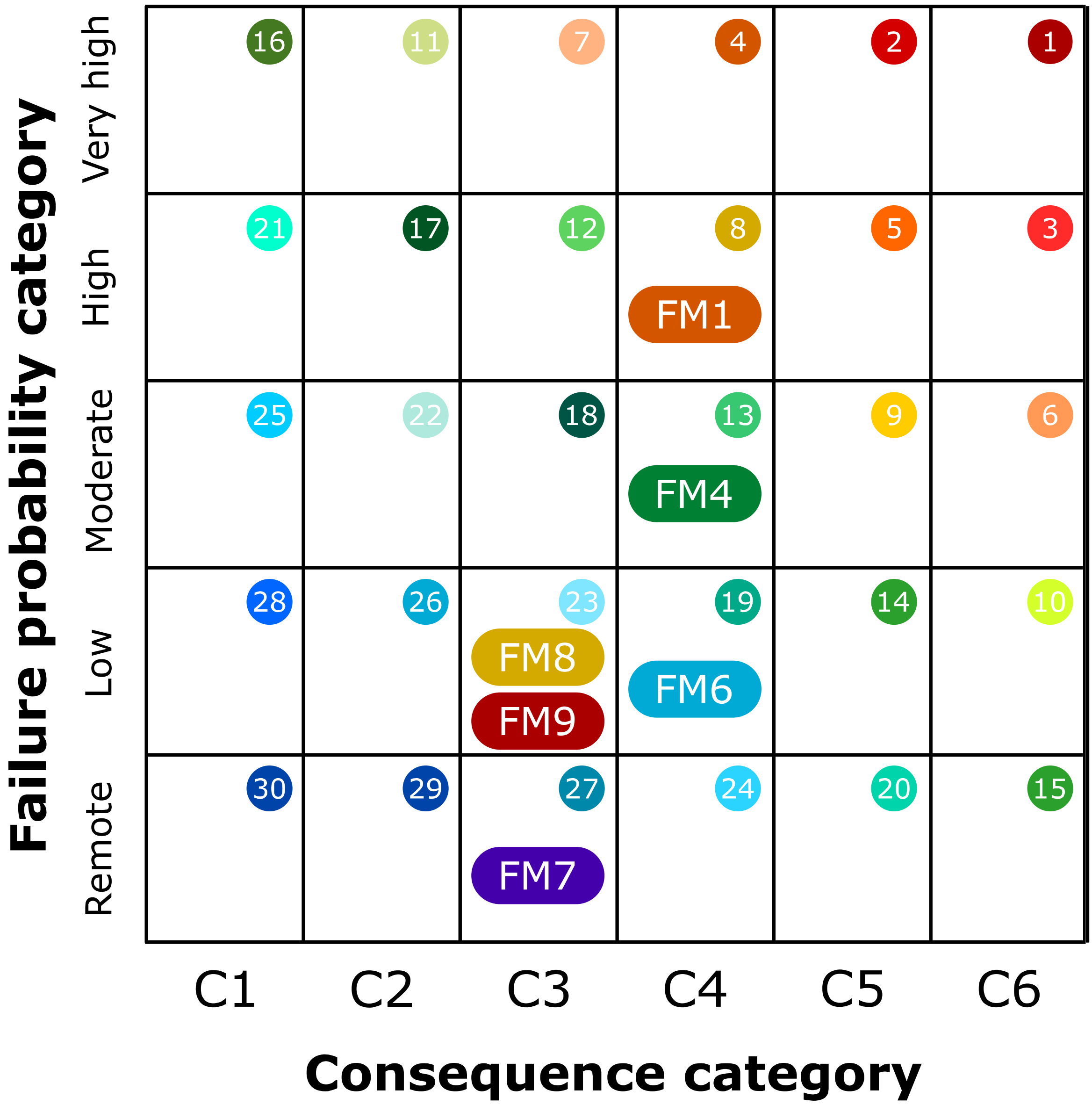
Failure Mode 9: Failure due to settlement at upstream face in saddle dams	
Failure probability category	Low
Justification	
This probability category was estimated according to the following factors: • Embankments height is relatively low and reservoir levels are 5 m below saddle dam crest level for MOL. • 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 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.	

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 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.	

The results of this Semi-Quantitative Risk Analysis are represented for each failure mode in the following matrix:



Semi-Quantitative Risk Analysis results.

4.3. Prioritization of new studies or instrumentation

Once the risk of each Class C failure mode 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 C 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 B Failure Modes can also be introduced in this prioritization if they are recommended after quantitative risk evaluation and uncertainty analysis.

In this case, the following new studies and instrumentation are proposed:

Study 1	Probabilistic Hydrologic Analysis
Failure Modes	FM1
Description	
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.	

Study 2	Sliding analysis and geotechnical tests
Failure Modes	FM4
Description	
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.	

Study 3	Analysis of settlements in saddle dams
Failure Modes	FM8 and FM9
Description	
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.	

Study 4	Seismic stability analysis
Failure Modes	FM6 and FM7

Description
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.

Second, based on the priority level of each failure mode, new studies and instrumentation are prioritized. The priority level of failure modes depend on their cell in the SQRA matrix, as shown in the previous matrix. As can be observed in this matrix, failure modes closer to the upper-right corner (higher failure probability and higher consequences) have a higher priority level. Following this procedure, the priority levels of the proposed studies are:

Studies	Priority level
Study 1: Probabilistic Hydrologic Analysis	8
Study 2: Sliding analysis and geotechnical tests	13
Study 3: Analysis of settlements in saddle dams	23
Study 4: Seismic stability analysis	19

As expected, higher priority levels are obtained for the two studies focused to reduce 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 priority since this data is conditioning risk results and decision making in this dam.

5. 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 societal risk tolerability guidelines for overtopping and dam-foundation sliding failure modes.
- 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.
- 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 above tolerability limits, 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.
- 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 to be above tolerability limits. 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 legislation and safety standards and/or best practices at national and/or international levels.

The elaboration of this Risk Assessment Dam Safety Report was coordinated by:

AAAA BBBBB, Technical Director of YYYY Company

25/04/2018

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APPENDIX C – INTERNATIONAL CASE STUDY

The following international case study is based on a Risk Assessment performed in a real system of two dams. However, some data and results have been modified to fulfil the procedures proposed in these guidelines and to provide a more illustrative example of the whole Risk Assessment process.

Report on Dam Safety Risk Assessment

Blue River System: Green Dam and Red Dam

150001

Prepared for Blue River Authority

Prepared by YYYY

May 2015

Revision Number 1

Revisions of Risk Assessment Report

Report Date	Reason for Revision	Main changes made	Author
15/05/2015	First Risk Assess-ment	First Risk Assessment, including identification of failure modes and quantitative risk analysis	YYYY

Data of next Risk Assessment periodic update:

15/05/2019

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EXECUTIVE SUMMARY

The risk assessment process applied to the Green and Red Dams involved a number of positive effects derived from its own nature and structure, due to the participation of technical personnel from the dam management and regulation entities and risk analysis experts. Results obtained can be used to guide and define future activities of dam response reporting and actions to improve dam safety and reduce uncertainty.

The process for identification of failure modes allowed a comprehensive safety review of both 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.

Existing risk in this system of dams was reasonably characterized by a quantitative risk model with 5 failure modes (2 for the Green Dam and 3 for the Red Dam) and a semi-quantitative risk analysis for 2 failure modes.

Quantitative risk results show that failure probability is clearly higher for the Green Dam than for the Red Dam, mainly due to overtopping failure mode. However, societal risk is higher for the Red Dam, since loss of life is much higher when this dam fails, due to the importance of the populations located downstream.

Risk evaluation shows that the Green Dam risks are above individual risk limit for both failure modes, especially overtopping. Instead, all the failure modes in the Red Dam are aligned with the tolerability guidelines, since failure probability is much lower.

Based on results of the risk model, six risk reduction measures were analysed for both dams. A prioritization sequence was obtained for these measures, combining efficiency and equity principles. The first measure of this sequence is reinforcing the Green Dam parapet wall to avoid overtopping. This measure is not very expensive and it is the measure that has the highest influence on reducing failure probability in the Green Dam. Next, drainage rehabilitation reduces the Green Dam's risk results to be aligned with tolerability guidelines. The following measures will help to reduce failure probability and risks in the tolerable area in both dams. These prioritization results are useful to prioritize the proposed risk reduction actions within the Dams Portfolio management.

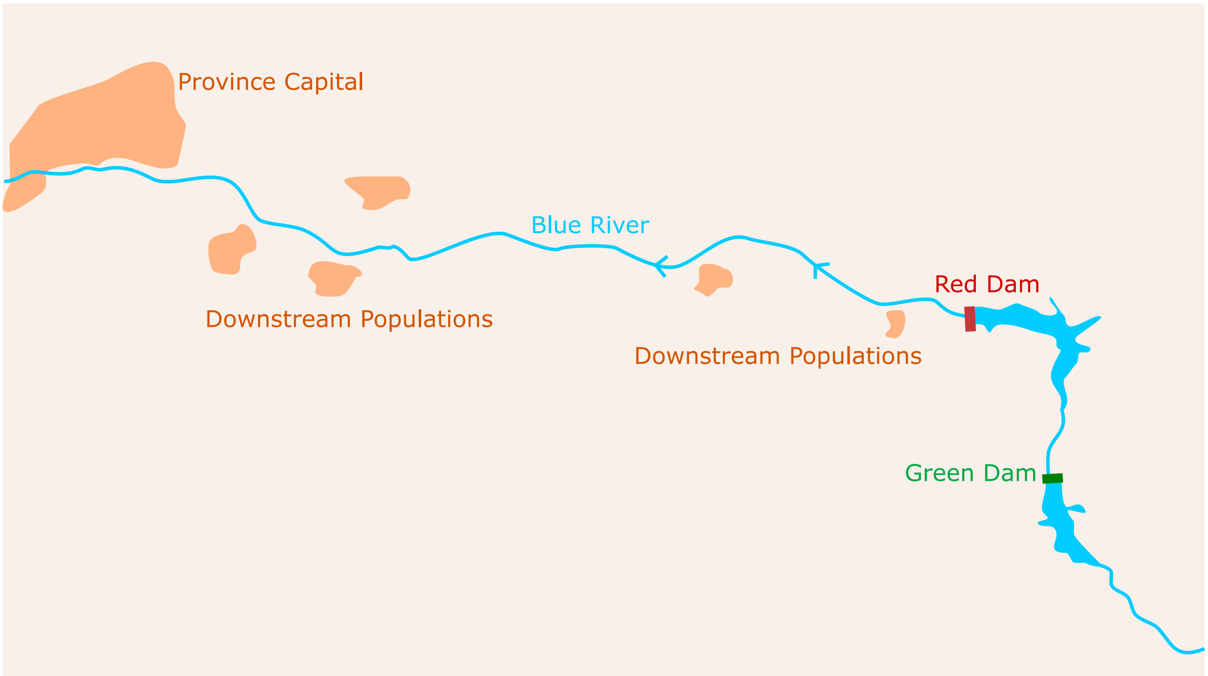
Sensitivity analysis shows a very high dependence on the loss of life with respect to the warning time to the population. The result highlights the importance of a proper Emergency Action Plan, even though it is not in the first steps of the prioritization sequence.

Semi-Quantitative Risk Assessment was used to prioritize new studies and instrumentation in both dams. After this analysis, it is recommended to make a first stability analysis of Red Dam with available data and to check this study with the results of pore pressures after some years of measurements. Priority levels obtained for these studies are useful to prioritize new studies within the Dams Portfolio management.

1. INTRODUCTION

1.1. Dam system description

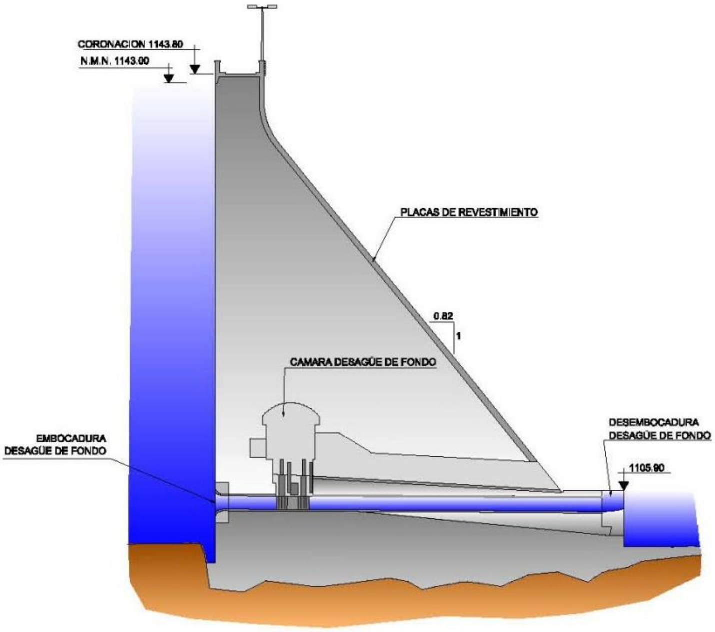
In this Risk Assessment, the Blue River System of dams is analyzed. In this case, it has been decided to analyze both dams in the system (Green Dam and Red Dam) within the same risk model, since they are operated together and both reservoirs have similar magnitude, so the failure of the upstream dam (Green Dam) could produce (or not) the failure of the downstream dam (Red Dam). These dams are managed by the Blue River Authority. Location of both dams in the Blue River system of dams is shown in the following figure:



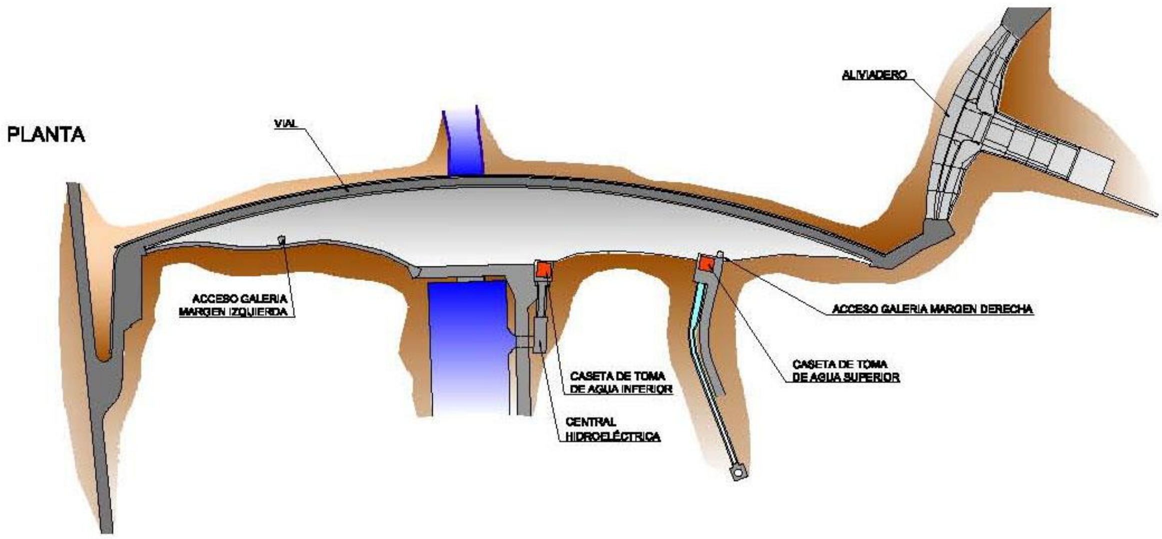
Location of Green Dam and Red Dam.

The distance between both dams is 5 kilometers. The basin area upstream the Green Reservoir is 104.9 km^2 and its average annual contribution is 76 hm^3, so the average inflow of the Blue River at this point is 2.41 m^3/s. The volume of the Green Reservoir for the Maximum Operation Level is 22.4 hm^3. The main water uses of this reservoir are urban water supply, irrigation and hydroelectric production. In the Red Reservoir, the average annual contribution is 89 hm^3, so the average inflow at this point is 2.82 m^3/s. The volume of this reservoir for the Maximum Operation Level is 75 hm^3. The main water uses of this reservoir are urban water supply and irrigation. The construction of Green Dam finished in 1933 and the construction of Red Dam finished in 1989.

The Green Dam is a curved plant gravity dam without transverse joints. Its height on foundations is 47.2 m, with the crest level at 1143.8 m.a.s.l. The coronation length is 267 m. The upstream slope is vertical, and the downstream slope is 0.82. The Green dam has an ungated spillway located on the left margin of the dam, following the abutment and separated from it. In addition, it also has a bottom outlet and two water intakes. The general layout and the highest cross section of this dam are shown in the following figures:



Cross section of Green Dam.

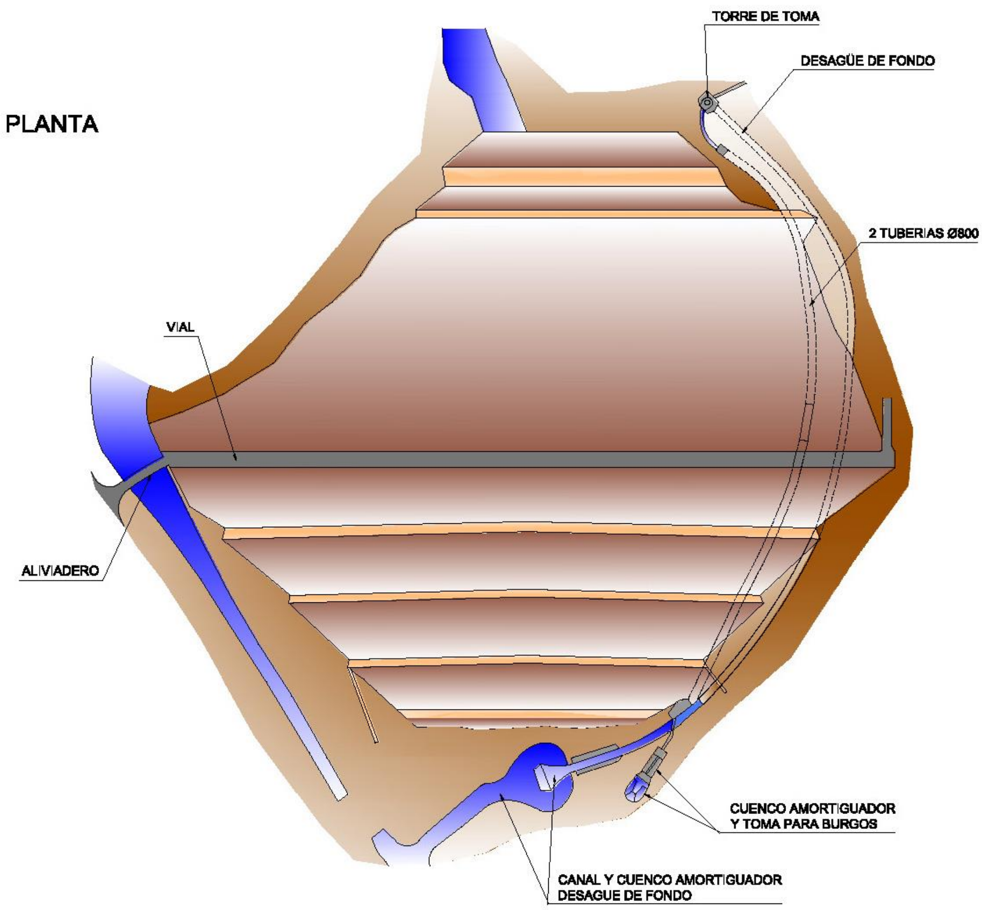


General layout of Green Dam.

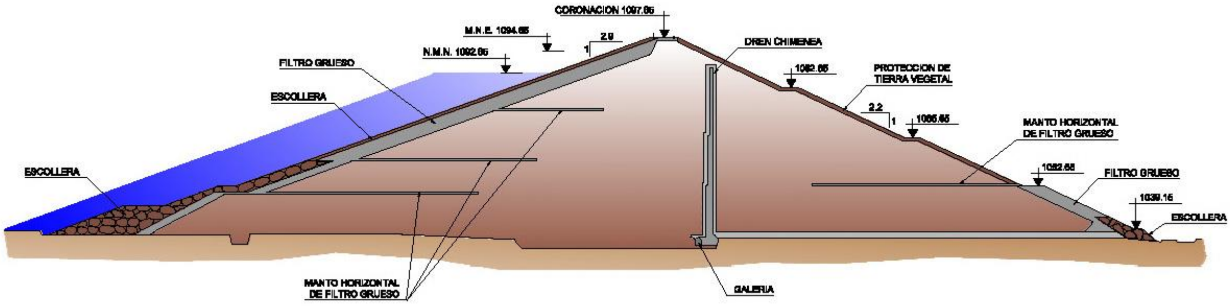
In 1992, this dam was rehabilitated due to the significant leakage through the dam's body due to the poor quality of its concrete. The main works made were: injecting the dam body to reduce leakage, excavating a drainage gallery in the dam body, rehabilitating the drainage system, installing an impervious screen in the upstream face and anchoring concrete plates to the downstream face of the dam to improve its conditions. In the following picture, a general view of this dam is shown previous to this rehabilitation:

General view of Green Dam previous to rehabilitation.

The Red Dam is a homogenous embankment with straight plant. Its height on foundations is 65 m, with the crest level at 1097.85 m.a.s.l. The coronation length is 460 m. The Red Dam has an ungated spillway that is attached to the body of the dam, on its right abutment. In addition, it also has a bottom drain and a water intake. The general layout and the highest cross section of this dam are shown in the following figures:



Cross section of Red Dam.



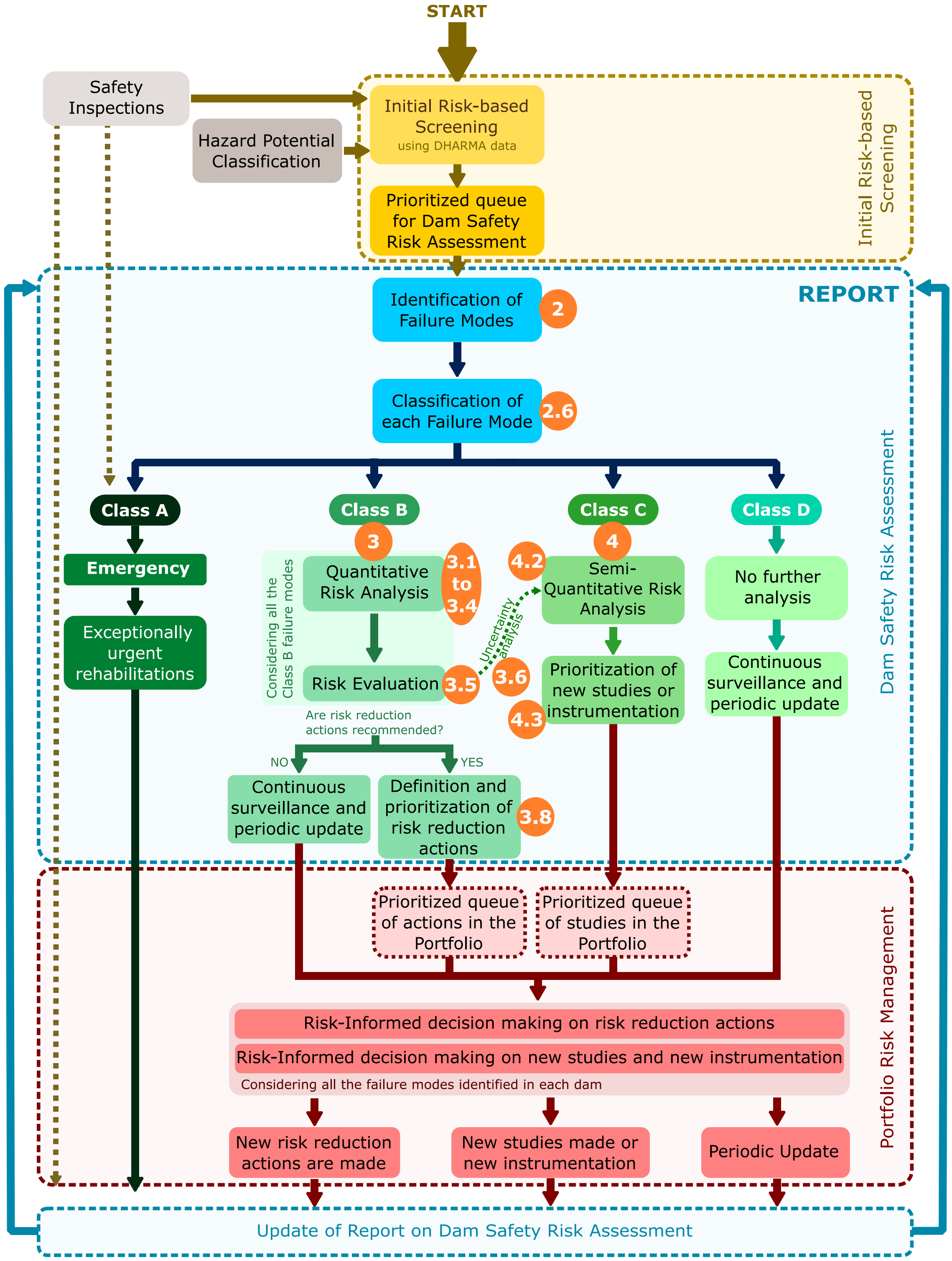
General layout of Red Dam.

There have not been major rehabilitations in the Red Dam since it was constructed in 1989.

Finally, according to the Hazard Potential Classification made in January 2014 made by CCCC the Green Dam and the Red Dam were classified as Catastrophic, due to the high population located downstream in the floodplain area. This population is higher than 1,50,000 people.

1.2. Risk Assessment and Management Framework

The current Risk Assessment Report is based on the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Within these guidelines, a Risk-Informed Dam Safety Management Program is given with the structure shown in the following figure:



Risk-Informed Dam Safety Management Program. Source: Guidelines for Assessing and Managing Risks Associated with Dams (CWC, 2018).

This Risk Assessment Report is focused on the central part of the management program, which different steps are directly related with the different sections of the report (as shown by numbers in orange circles). Therefore, the main purpose of this report is explaining 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 for Green and Red Dams.

As shown in this figure, the **Dam Safety Risk Assessment** begins with a **Failure Mode Identification** process in each dam, which includes a review of the available information, a technical visit to the dam and multidisciplinary group working sessions, as explained in Chapter 2. Based on the information available and the credibility of each failure mode, they are classified in four categories:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and exceptionally urgent rehabilitation measures and/or emergency actions are needed.

- **Class B:** Failure mode is credible and available information is enough for a **Quantitative Risk Assessment**. Risk results are evaluated and if needed, potential risk reductions are proposed and prioritized. This assessment is explained in detail in Chapter 3.

- **Class C:** There is uncertainty about this failure mode, 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 (Chapter 4).

- **Class D:** Failure mode is not credible. This failure mode should be documented and reviewed in the following updates of the Risk Assessment process.

The results obtained from this report are intended to be used for Portfolio Risk Management, by combining the prioritized risk reduction actions of this dam to create a prioritized list of proposed actions in the whole Portfolio of dams. Similarly, the prioritized lists of new studies of each dam are combined to create a prioritized list of new studies and/or instrumentation in the Portfolio. Hence, new actions and studies are planned in the Portfolio taking into account administrative, legal or societal issues and analysing all the failure modes identified in each dam.

2. Identification of Failure Modes

2.1. Introduction

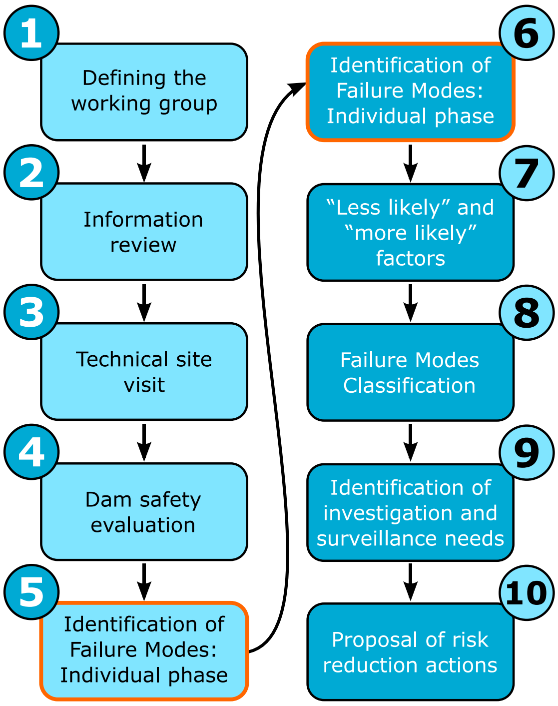
A **failure mode** is a specific sequence of events that can lead to a dam failure. This sequence of events must be linked to a loading scenario and will have a logic sequence: starting with an initiating event, one or more events of progressive failure and will end with dam failure or mission disruption 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 Green and Red Dams were made following the recommendations provided by the *Guidelines for Assessing and Managing Risks Associated with Dams* during different working sessions as shown in the following figure:



Step	Date Green Dam - Red Dam
1	15/12/2014 - 17/12/2014
2	15/12/2014 - 17/12/2014
3	15/12/2014 - 17/12/2014
4	16/12/2014 - 18/12/2014
5	16/12/2014 - 18/12/2014
6	16/12/2014 - 18/12/2014
7	16/12/2014 - 18/12/2014
8	19/12/2014 - 19/12/2014
9	19/12/2014 - 19/12/2014
10	19/12/2014 - 19/12/2014

Identification of Failure Modes steps and dates.

Working sessions of Identification of Failure Modes.

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

The Identification of Failure Modes was made by a multidisciplinary group that includes the engineers and technicians in charge of the daily operation of the dam and regional/national experts in some of the topics addressed. Participants in these sessions are listed in the following table:

Name	Title (s)	Entity
AAAA BBBB	Engineer in charge of Red Dam	ZZZZ
CCCC DDDD	Engineer in charge of Green Dam	ZZZZ
EEEE FFFF	Risk Analysis expert	YYYY
GGGG HHHH	Risk Analysis expert	YYYY
IIII JJJJ	Dam engineer	ZZZZ
KKKK LLLL	Dam engineer	ZZZZ
MMMM NNNN	Responsible of dams' maintenance	ZZZZ
OOOO PPPP	Responsible of dam gates	ZZZZ
QQQQ RRRR	Hydrology expert	University of WWW
SSSS TTTT	Geotechnical expert	University of WWW
UUUU VVVV	Emergency procedures expert	ZZZZ

Identification of Failure Modes sessions were facilitated by EEEE FFFF, who has proved experience in coordinating these types of sessions.

2.2. Information review

The information available was reviewed on 15/12/2014 for the Green Dam and on 17/12/2014 for the Red Dam to support the Risk Assessment process. The main documents reviewed during this working session were:

Document title	Author	Data
Maintenance Manual of Green Dam	ZZZZ	1997
Maintenance Manual of Red Dam	ZZZZ	1997
Flood Operation Rules in the Blue River system	ZZZZ	1999
Report on history and current state of Green Dam	ZZZZ	1999
Report on history and current state of Red Dam	ZZZZ	1999
Emergency Action Plan of Green Dam	ZZZZ	2008
Emergency Action Plan of Red Dam	ZZZZ	2008
Project to implement Emergency Action Plan in Green Dam	ZZZZ	2008
Project to implement Emergency Action Plan in Red Dam	ZZZZ	2008
Report on General Safety Review of Green Dam	ZZZZ	2008
Report on General Safety Review of Red Dam	ZZZZ	2008
Hydrological analysis of Blue River system	ZZZZ	2012
Numerical model on Red Dam spillway behaviour	ZZZZ	2012
Annual Reports of both dams with monitoring data	ZZZZ	2007-2013

After this detailed reviewed, the main conclusions about available information were:

- Good information is available about the dams. The General Safety Reviews include a complete hydrological and structural analysis of both dams.
- It is recommended to update these reviews with the new data gathered in recent years.
- Recent hydrological study with a high level of detail.

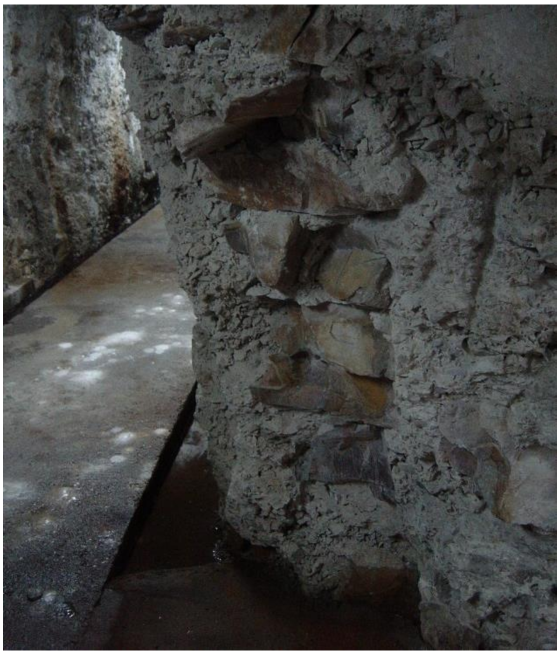
2.3. Technical site visit

The technical visit to Green Dam was made on 15/12/14. The technical visit to Red Dam was made on 17/12/14. These visits represented a very valuable source of information since it allowed verifying current conditions of the dam-reservoir systems. This site visit was made with enough time to exhaustively inspect all the part of the dams. Special attention was paid to main problems identified during the information review.

Technical site visit in Green Dam.

The main conclusions about the technical site visit to these dams are:

- In the Green Dam, the poor quality of the concrete could be observed, being very heterogeneous and made without a proper quality control. Injections can be observed in the different parts of the dam (crest, galleries…). The poor quality of this concrete can be observed in the following figure:



Detail view of heterogeneous concrete in Green Dam.

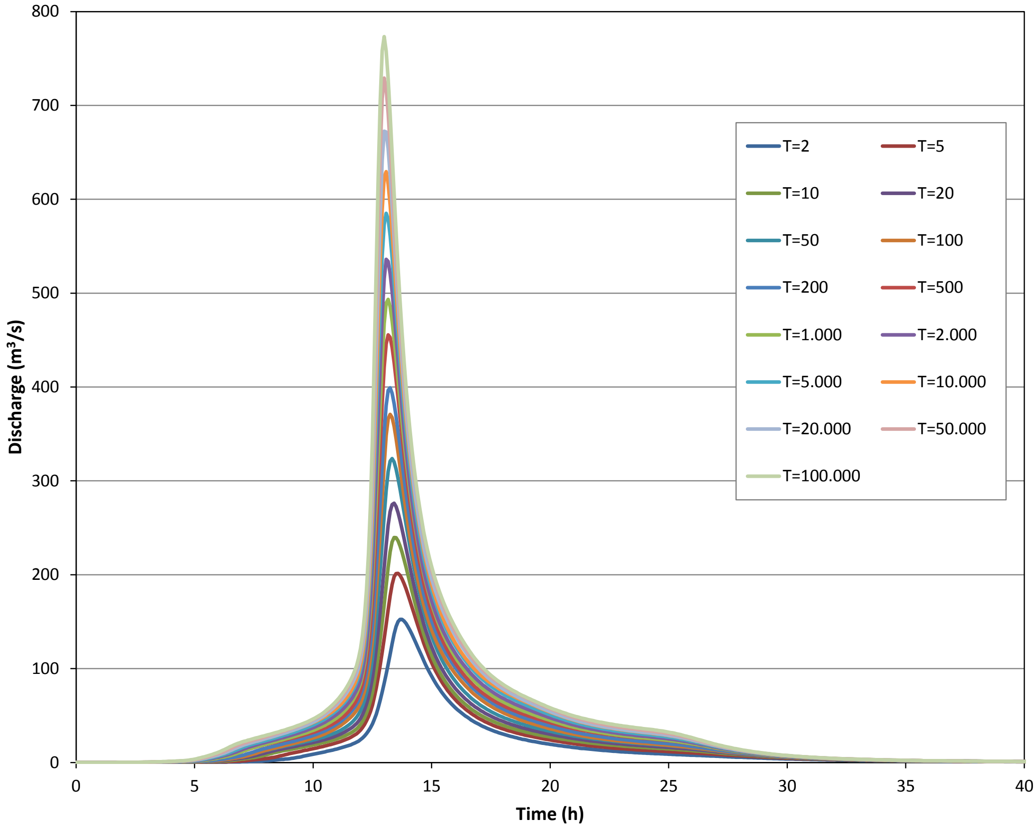
- Some foundation drains are not working properly due to its age. Also, obstructions can be observed.
- In the Red Dam, the monitoring data and the direct observation shows good geotechnical behaviour of the embankment, without abnormal settlements or movements.
- In this dam, piezometers embed in the embankment have never worked properly, so they are not currently measured.
- The spillway has never been used for flood routing (only in two tests) and there are some doubts about its hydraulic behaviour.
- Both dams are properly maintained and operated.

2.4. Dam safety evaluation

After the field visit and the information review, a comprehensive evaluation of the dam safety is made as a basis for the identification of failure modes.

Flood hazard and hydrological adequacy in the Blue River system

The most updated hydrological analysis was made in 2012, based on probabilistic rainfall data and a hydrologic model made with HEC-HMS. The main results of inflow floods in the Green Reservoir for different return periods are shown in the following figure:



Results of hydrological analysis in Green Dam.

Results from comparing these discharges with the capacity of the Green Dam spillway show that the dam hydrological adequacy is not enough. The spillway capacity for dam crest level is lower than peak inflow for return periods higher than 50 years. In addition, the spillway crest (1143 m.a.s.l.) is very close to crest level (1143.8 m.a.s.l.).

In the Red Dam, spillway capacity is similar to the Green Dam spillway, so there should not be hydrological capacity problems if there is not overtopping in the Green dam. In addition, in the Red Dam there are 5 meters between the spillway crest level and embankment crest level, which provides additional volume for flood routing.

In rainy seasons, freeboard requirements are implemented in Red Dam to avoid downstream flooding. In these months, water level in the reservoir is maintained 7 meter below the spillway crest level, which means a freeboard volume for flood routing of 20 hm^3. These freeboards are maintained releasing water through the bottom outlet.

Gates operation and hydraulic behaviour

In this case, both the Red and Green spillways are ungated, so there are not specific gates operation rules for flood routing.

Gates and electromechanical equipment condition

In this case, both the Red and Green spillways are ungated, so there are not gates in the spillways to be maintained.

In the Green Dam, gates and equipment of bottom outlet and water intakes are correctly maintained. Electric equipment is also in a good state. There is a generator to supply electricity as an alternative source.

In the Red Dam, gates and equipment of bottom outlet and water intakes are also correctly maintained. Electric equipment is also in a good state. There is also a generator to supply electricity as an alternative source.

Current state of spillway and stilling basin in Green Dam

Spillway concrete and the stilling basin are in a good state, despite of its age. The experiences in previous floods have shown a good behaviour of the spillway and the stilling basin.

The spillway discharge point is located far from the dam toe, so there is no danger regarding dam toe erosion.

Foundation and abutments in the Green Dam

The dam is founded and supported on compact and impermeable quartzite that dive into the reservoir, whose favourable characteristics of resistance and imperviousness were confirmed by the drilling carried out for the project, by the excavation of the work and by the drilling conducted in the injections and drainage rehabilitation works done during the operation. Technical inspections and monitoring data have not shown any signs that put these good properties of the foundation in question.

No direct information on the geotechnical parameters of the foundation has been found.

Monitoring data and state of monitoring system in Green Dam

Monitoring data is correctly gathered and analysed. Available monitoring data is summarized in the following table:

Parameter	Period	Periodicity
Water pool level	1971/2014	Daily
Rainfall and temperature	1997/2014	Daily
Dam movements with plumb lines	1995/2014	Weekly
Dam body temperature	1997/2014	Weekly
Uplift pressures with piezometers	1996/2014	Weekly

Water leakage in drainage gallery	1996/2014	Weekly

As can be observed, the two basic exogenous parameters (the water level in the reservoir and the temperature) explain the variations of the endogenous auscultation parameters - movements of the pendulum, uplift pressures in piezometers and filtrations. The radial movements of the plumb line are explained by the temperature and the level of the reservoir and the variation in uplift pressures, are basically related with the pool level in the reservoir. In the case of water leakage, it is difficult to fit a behavioural model because of the relatively random character of the cracks that are formed naturally in the dam. However, the leaks occurrence is related to the evolution of temperature.

The oscillation of the radial movement of the pendulum varies between ± 5 mm in recent years, which is a normal variation for this type of dam.

The uplift pressures present reasonable and stable values in relation to the evolution of the reservoir level and in general, they show the effectiveness of the drainage system.

Water leakage present reasonable average values and likewise stable with maximums in winter/ spring and minimums in summer/autumn, although a detailed follow-up must be carried out to confirm that this stability is maintained in the future, since after the change of the reading system carried out in November 2002, there was an increase in maximum and average leakage values.

According to this, all the parameters present moderate, reversible variations with a tendency to stability. Therefore, these results do not reflect any symptom of abnormality in the behaviour of the dam and its foundation that could put its structural safety at risk.

Dam body condition in the Green Dam

Green Dam was built in 1933, using a poor and very homogenous concrete and without transverse joints. For these reasons, this dam has always presented significant leakage and cracks in the dam body.

Because of this, it was completely rehabilitated in 1992. The main jobs done were injecting the dam body to reduce leakage, excavating a drainage gallery in the dam body, rehabilitating the drainage system, installing an impervious screen in the upstream face and anchoring concrete plates to the down-stream face of the dam to improve its conditions.

The excavation of the gallery reveals the homogenous concrete with which the dam body is built, with cavities and cement injections applied in different times. This poor quality of the dam concrete is shown in the figure included in Section 2.3.

However, water leakage has been controlled after the rehabilitations and injections made, presenting normal values for a dam of these characteristics.

Condition of the drainage system in the Green Dam

Currently, the foundation drainage system seems to work properly since high values of uplift pressures are not detected in the piezometers.

However, obstruction symptoms were observed during the technical visit in some of the drain pipes of the gallery, which are part of the foundation and dam body drainage systems. Water leakage does not concentrate in the drains, but it seems to soak the whole lower part of the dam body, producing water leakage and uplift pressures dissipation in the drainage gallery.

These drains have not been rehabilitated recently, so a complete rehabilitation was recommended to ensure a good state of the drainage system.

Dam stability in normal loading conditions in the Green Dam

Dam stability in the dam has not been checked numerically in recent years. The only available computations are the one made for the original project (1930) with simplified methods.

Monitoring results do not reflect any symptom of abnormality in the behaviour of the dam or its foundation that could endanger its structural safety.

Likewise, in the inspections carried out, neither the dam body nor the foundations have detected symptoms that pose a risk to structural safety.

In any case, this uncertainty about sliding safety was highlighted during the working sessions and a numerical analysis of this failure mode was recommended.

Seismic hazard and dam stability during seismic events in Green Dam

Green Dam is located in low-hazard seismic area. For this reason, dam stability during seismic events has not been checked.

Landslide in the reservoirs in Green Dam

Potential landslide movements have not been detected in the Green Reservoir. The reservoir is located on Silurian land with powerful Quartzose sandstone banks with some slate shales and quartzite banks and without faults that could put their imperviousness at risk.

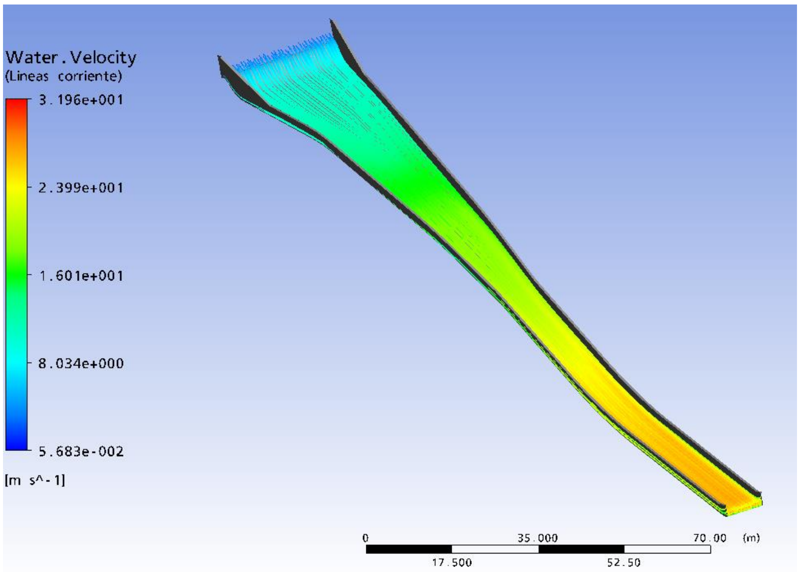
The reservoir's slopes are low and they are not prone to this type of sudden landslides that could put the dam in danger.

Current state of spillway and stilling basin in Red Dam

The Red Dam spillway has only been used twice, to check its operation, by forced discharges from the Green Dam, in 1996 and 1997. During these experiences, it was observed how the land located at the toe of the spillway trampoline could be eroded by the operation of the spillway. The tests were made with discharge flows around 12 m^3/s. Two pictures of these tests can be observed:


Spillway tests of Red Dam made in 1996.

The results of these tests (with relatively low discharges) and the narrow geometry of this spillway have produced doubts about its behaviour during significant flood events. For this reason, a numerical model was made in 2012 to check this behaviour:



Numerical model made to analyse the Red Dam spillway behaviour.

The results of this model showed that significant overflow could be produced over the lateral walls when spillway discharges are higher than 100 m^3/s. Therefore, higher walls would be needed to solve this hydraulic behaviour problem.

Foundation and abutments in Red Dam

Dam foundation is constituted by a substrate of Paleozoic quartzites with slate alternations that ensure its imperviousness and resistance, as confirmed by the drillings conducted and the excavation during the construction of the dam.

Monitoring data and state of monitoring system in Red Dam

Available monitoring data is summarized in the following table:

Parameter	Period	Periodicity
Water pool level	1993/2014	Daily
Rainfall and temperature	1993/2014	Daily
Pore pressures in embankment with piezometers	1993/2014	Weekly
Water leakage in gallery	1993/2014	Daily
Water leakage in drains	1993/2014	Daily
Water level in chimney drain	1993/2014	Daily
Settlements in dam crest	1993/2014	Variable

Monitoring data is correctly gathered and analysed for all these instruments. The main problems have been found in the dam body piezometers since they have never worked properly since they were installed during the construction.

According to this, all the parameters present moderate, reversible variations with a tendency to stability. Therefore, these results do not reflect any symptom of abnormality in the behaviour of the dam and its foundation of such magnitude that it could put its structural safety at risk.

Dam body condition in Red Dam

Reviewed documentation shows that the construction of the dam was carried out with high quality standards, in the first filling process the dam showed a good general behaviour and during the exploitation, the foundation and the dam achieved an excellent behaviour. As explained before, the only doubts are related to the reliability of the installed piezometers in the dam body.

In this sense, no significant leakage or symptoms of settlements or landslides have been detected in the dam body or in foundations and abutments.

Condition of the drainage system in Red Dam

The embankment has the following filter and drainage elements:

- A chimney drain, consisting of two layers of filter material and an intermediate layer of drain, with a total width between 3 and 5 meters.
- Three horizontal filter layers in the upstream slope, 50 cm of thickness, constituted by filter material, at different heights.
- Another similar horizontal filter layer in the downstream slope, at the level of the lower berm.
- A layer of filtering material between the upstream slope and the riprap mantle between 2 and 4 m. of thickness.
- A lower filter layer, located on the contact surface between the downstream slope and the foundation, transversely communicating the chimney drain with the downstream face. It has a thickness of 2.10 m. (0.60 m of filter material and the rest of drain).

According to the measured leakage, the drainage and filtering systems seems to work properly, without significant changes in the leakages measured and without detecting any particles in the drains.

Dam stability in normal loading conditions in the Red Dam

Dam stability in the dam has not been checked numerically since the dam design (last 80s). For the calculation of stability of the project, certain geotechnical parameters of the dam and foundation body materials were used, but no precise information is available on the geotechnical parameters of the materials actually used in each area.

During the working sessions, it was recommended to check the hypothesis followed and the computations made in this project with a new stability analysis.

Monitoring results do not reflect any symptom of abnormality in the behaviour of the dam and its foundation of a magnitude that could endanger its structural safety.

Seismic hazard and dam stability during seismic events in Red Dam

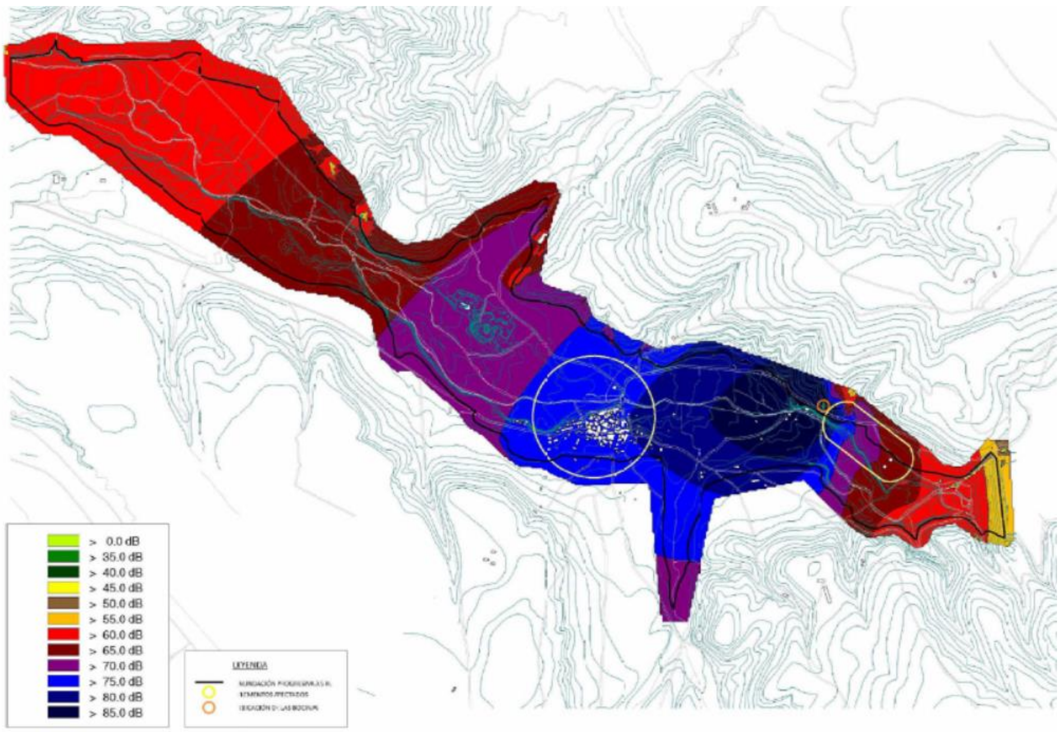
Red Dam is located in a low-hazard seismic area. For this reason, dam stability during seismic events has not been checked.

Landslide in the reservoirs in the Red Dam

Potential landslide movements have not been detected in Red Reservoir. The reservoir is located on slates and quartzites that ensure its imperviousness. Landslide movements have never been detected in the reservoir.

Emergency action planning and urban areas downstream

An Emergency Action Plan was written for both dams in 2008. Since then, this plan has not been implemented. The implementation of this plan includes awareness campaigns with downstream population, building and emergency house in the dam and installation of sirens in the closest populations, as shown in the following figure:



Sirens to be installed downstream Red Dam according to its Emergency Action Plan.

It is foreseen that these plans will be implemented in the upcoming years. They are currently being discussed and coordinated with emergency agencies and municipalities.

Main urban areas are located downstream Red Dam, including the capital of the province with a population of more than 1,50,000 people. No significant populations can be found between Green and Red Dams.

Accesses are correct for both dams, so they can be accessed without problems in case of emergency.

Engineering assessment

Engineering assessment consists in asking the participants to individually assess whether dams are 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 dams, 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.

Results of this engineering assessment are shown in the following table (where the colour indicates the assessment of each participant **pass**/**apparent pass**/ **apparent no pass**/**no pass** /**not applicable**):

Dam safety aspects	Participants initials										
	AB	CD	EF	GH	IJ	KL	MN	OP	QR	ST	UV
Green dam											
Flood hazard and hydrological adequacy											
Gates operation rules											
Gates and electromechanical equipment condition											
Current state of spillway and stilling basin											
Foundation and abutments											
Monitoring data and state of monitoring system											
Dam body state											
State of drainage system											
Dam stability in normal loading conditions											
Seismic hazard and dam stability in seismic events											
Landslide in the reservoir											
Emergency action planning											
Red dam											
Flood hazard and hydrological adequacy											
Gates operation rules											
Gates and electromechani-											

cal equipment condition											
Current state of spillway and stilling basin											
Foundation and abutments											
Monitoring data and state of monitoring system											
Dam body state											
State of drainage system											
Dam stability in normal loading conditions											
Seismic hazard and dam stability in seismic events											
Landslide in the reservoir											
Emergency action planning											

As can be observed in the previous table, the main aspects related with dam safety where the working group had the main doubts about its compliance with international dam safety standards were:

- Hydrological adequacy of the system, especially in Green Dam.
- Concrete state of the Green Dam body.
- State of drainage system in the Green Dam, due to the clogging of some of the drains.
- Uncertainties in the Green Dam stability, since no recent checks have been made.
- Behaviour of the Red Dam spillway.
- Monitoring data in the Red Dam, since piezometers should be replaced to gather proper results.
- Uncertainties in the Red Dam's stability, since no recent checks have been made.
- Emergency Action Plans, these plans have been elaborated for both dams but not implemented.

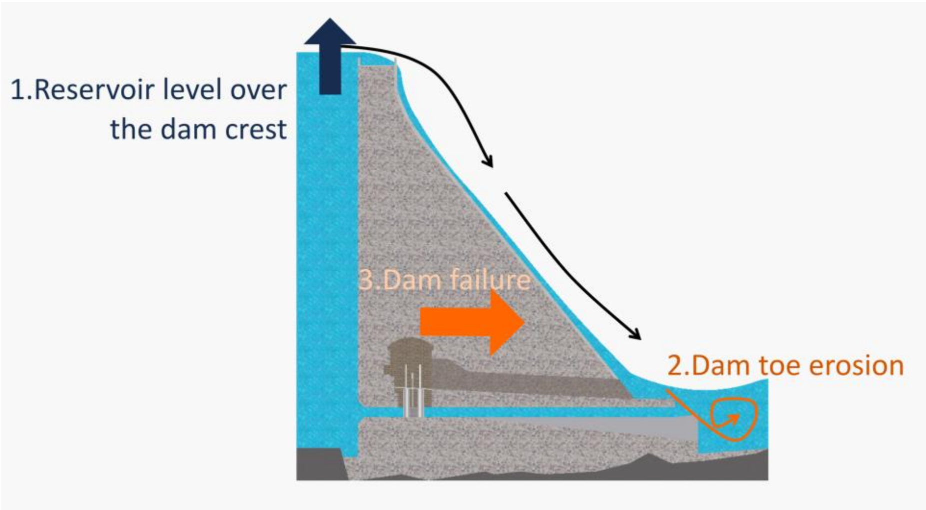
2.5. Failure Modes Identified

Failure modes for the Green Dam were identified on 16 December 2014 in an individual phase and in a group phase. In the Red Dam, failure modes were identified on 18th December 2014. In the first phase of the identification of failure modes, each participant in the session individually made a preliminary identification of failure modes in each dam, using the provided booklet. Once each participant finished the individual identification of failure modes, all of them were put in common and combined into groups sessions. In addition, for each failure mode, the factors that make them likely are 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 certain failure mode.

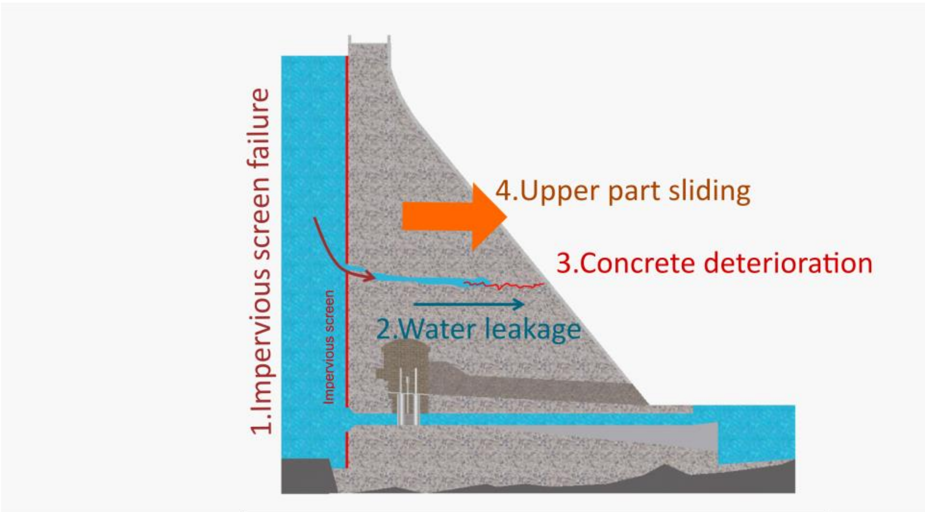
The results of the failure modes identification process are shown in the following tables:

Green Dam

Failure Mode 1G	Overtopping
Description	
In a hydrologic scenario, due to a severe flood and/or inadequate spillway capacity, adequate water pool levels are not maintained and this results in overtopping over the dam crest level. Flow over the crest washes out material into the dam toe and causes massive erosion that progresses leading to dam failure.	
Graphical scheme	

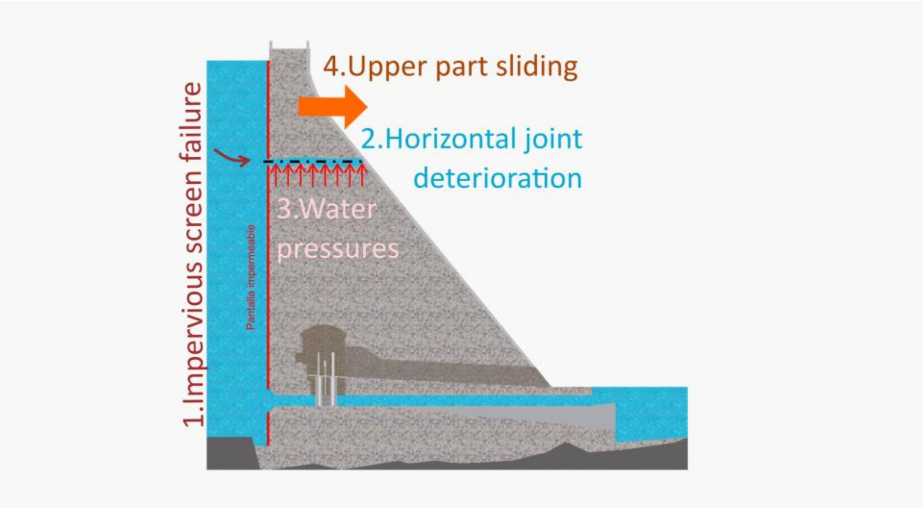


More likely factors	Less likely factors
• Existing hydrological data shows inadequate capacity of spillways to deal with extreme floods.	• The foundation at the dam toe does not present any sign of alteration that indicates the possibility of erosion. • All the contact of the dam with the foundation at the downstream toe is lined by stairs or very healthy rock. • The parapet wall in the dam crest was deliberately extended on the right abutment until the rock's contact. In addition, there is a structural connection between the parapet wall and the dam body. • The concrete plates anchored to the downstream face of the dam favorably increase the weight of the structure. • In general, the duration of the floods is not very high, so, time for complete erosion of the dam toe would not be enough. • Ungated spillway.

Failure Mode 2G	Deterioration of dam body
Description	
In a normal or hydrologic scenario, a failure occurs in the upstream impervious screen, and in addition the dam body concrete has suffered significant deterioration due to the leakage, the washing of the material and the formation of voids. This deterioration continues and combined with high levels in the reservoir, leads to a breakage due to instability in the dam body.	
Graphical scheme	
	

More likely factors	Less likely factors
• There has been an increase in leakage during the last few years. • The impervious screen in the upstream face shows some specific damages. • In the dam rehabilitation, the cross section of the dam body was not completely injected.	• The dam has shown significant leakage through the dam body for many years, without any instability. • Even if there are large cavities or leakage through the dam body, the coefficient of friction in the concrete-concrete contact is not negligible. • A major failure in the impervious screen could be easily detected and repaired.

Failure Mode 3G	Deterioration of horizontal joint
Description	
In a normal or hydrologic scenario, a failure occurs in the upstream impervious screen, and in addition there is deterioration in one of the horizontal joints of the concrete due to the leakage. This deterioration continues and when combined with high levels in the reservoir and uplift water pressures in the joint, leads to a breakage due to instability in the upper part of the dam body.	
Graphical scheme	



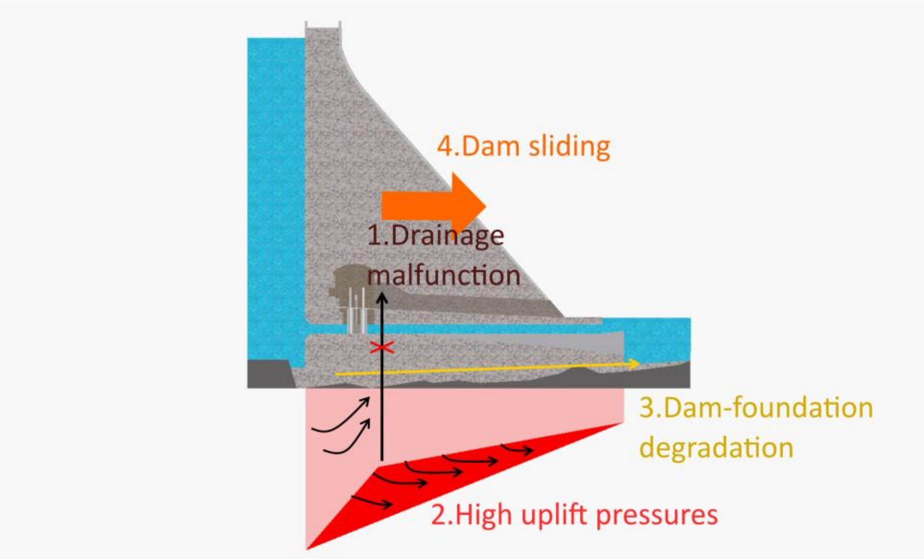
More likely factors	Less likely factors
• There has been a leakage increase during the last few years. • The impervious screen in the upstream face shows some specific damages. • In the dam rehabilitation, the cross section of the dam body was not completely injected.	• The dam has shown significant leakage through the dam body for many years, without any instability. • Even if there are large cavities or leakages through the dam body, the coefficient of friction in the concrete - concrete contact is not negligible. • A major failure in the impervious screen could be easily detected and repaired.

Failure Mode 4G	Sliding

Description

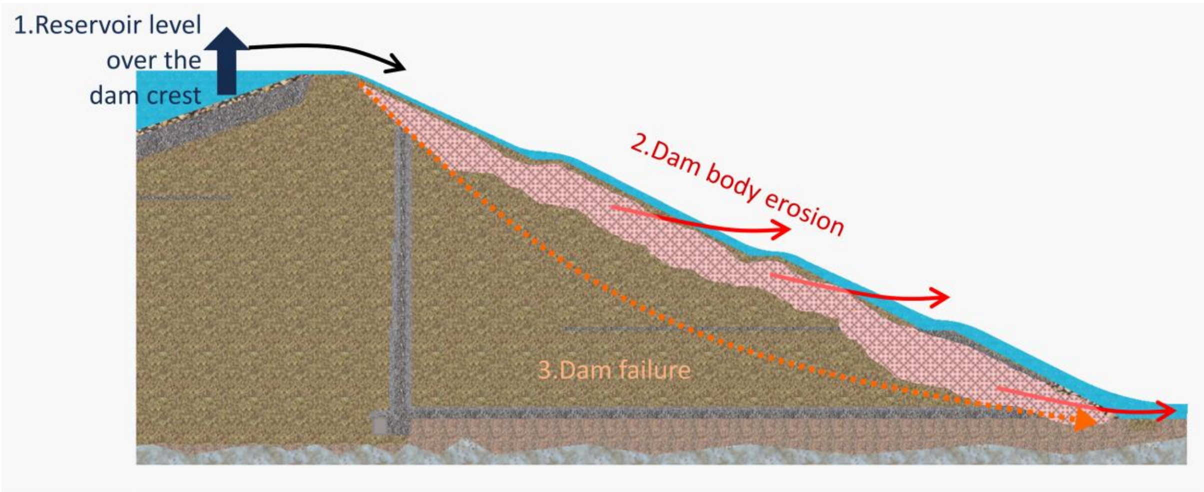
In a normal or hydrologic scenario, there could be high uplift pressures in the foundation produced by a malfunction in the drainage system. The combination of hydrostatic loads and uplift pressures produces a degradation in the dam-foundation interface and, finally, sliding of some blocks of the concrete dam along this surface.

Graphical scheme



More likely factors	Less likely factors
• Some foundation drains are not working properly.	• Currently, existing piezometers do not show high levels of uplift pressures. • The dam has a curvature that gives it more margin of structural safety due to the arch effect. • The apparent inclination of the foundation strata is very favorable to avoid sliding. • The concrete plates that are anchored to the downstream face of the dam favorably increase the weight of the structure.

Red Dam

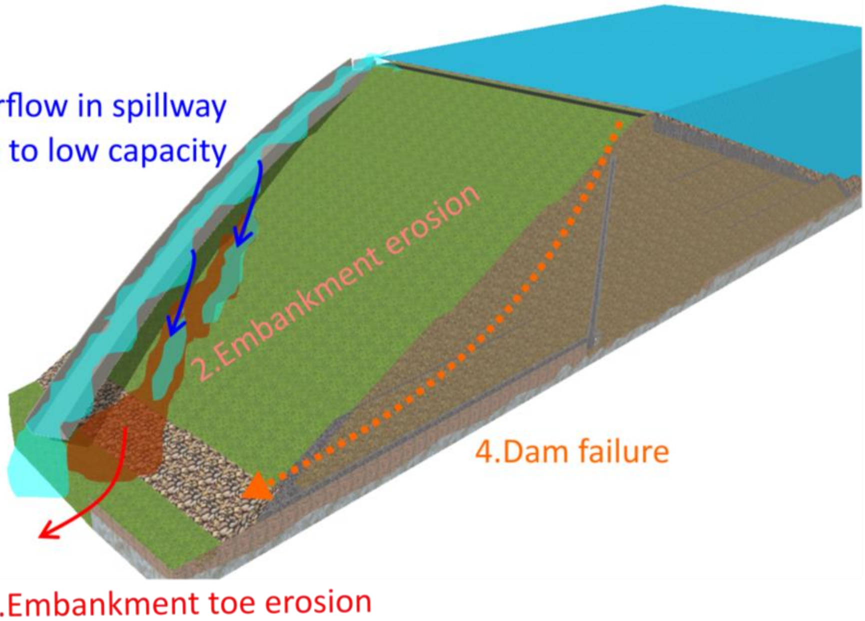
Failure Mode 1R	Overtopping
Description	
In a hydrologic scenario, due to a severe flood and/or inadequate spillway capacity and/or a failure of the Green Dam, water level raises over the crest of the dam. Flow over the dam crest causes massive erosion in the downstream slope of the embankment that progresses leading to slope instability, breach and dam failure.	
Graphical scheme	
	
More likely factors	**Less likely factors**
• The spillway design capacity is 150 m³/s. However, the peak flow associated with the 10000 years return period flood is approximately 600 m³/s. • The spillway has only worked during forced fillings of the reservoir, so there is uncertainty about the real evacuation capacity of the spillway. • Existing hydrological data shows inadequate capacity of spillways to deal with extreme floods upstream of the Green dam.	• Upstream Green reservoir helps to flood routing. • There is a high freeboard of several meters between the Maximum Operating Level and the crest level. • In general, the duration of floods is not very high, so time for complete erosion on the embankment would not be enough. • Vegetation on the downstream slope would reduce erosion. • Ungated spillway.

Failure Mode 2R	Insufficient spillway capacity

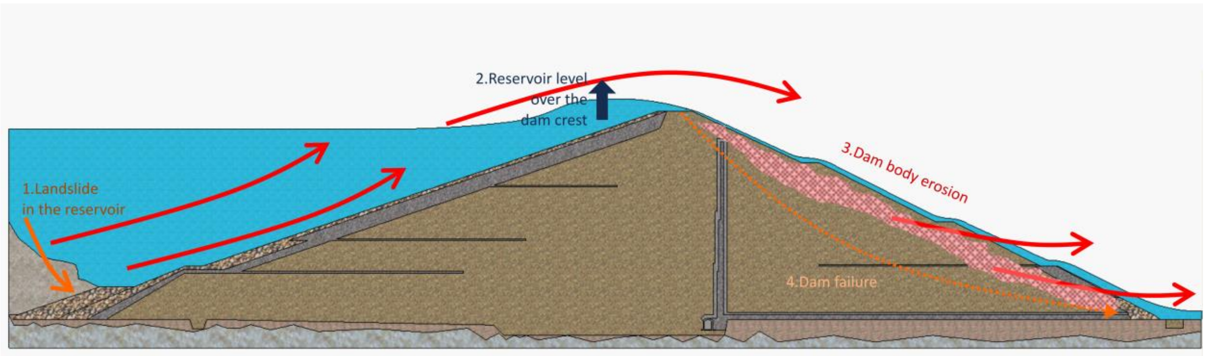
Description

In a hydrologic scenario, a flood produces high discharges though the ungated spillway and the emulsified water level exceeds the crest of the spillway left wall in the lower part. This overflow produces an erosion of the embankment toe and body and, finally, the dam fails due to toe erosion and collapse.

Graphical scheme



More likely factors	Less likely factors
• There is not instrumentation in the reservoir slopes, only visual inspection. • The spillway design capacity is 150 m^3/s. However, the peak flow associated with the 10000 years return period flood is approximately 1000 m^3/s. • The spillway has only worked during forced fillings of the reservoir, so there is uncertainty about the real evacuation capacity of the spillway. • There is uncertainty about hydrological data and methods used. • It is an ungated spillway, so outflow cannot be stopped if there is a problem in the spillway capacity.	• In general, the duration of floods is not very high, so time for complete erosion on the embankment would not be enough. • The spillway rests on natural rocky terrain, separated from the body of the dam by a wooded area. • Vegetation on the downstream slope and natural terrain would reduce erosion. • This dam is relatively new and built under good quality standards.

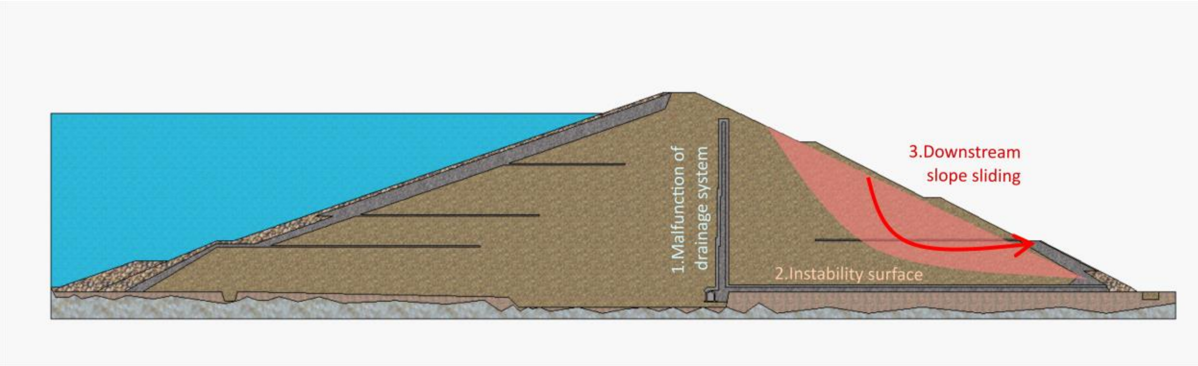
<table>
<tr><th>Failure Mode 3R</th><th>Landslide and overtopping</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">In a normal scenario, there is a massive landslide in the slopes around the reservoir that produces a high wave that then produces a flow over the crest of the dam. This flow over the dam crest causes massive erosion in the downstream slope of the embankment that progresses leading to slope instability, breach and dam failure.</td></tr>
<tr><th colspan="2">Graphical scheme</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><th>More likely factors</th><th>Less likely factors</th></tr>
<tr><td>• There is not monitoring in the reservoir slopes, only visual inspection.</td><td>• The shape and surface of the reservoir would favor a hypothetical wave to attenuate.
• There has not been any movement detected, sliding or creep in the reservoir slopes previously.
• Potential landslides volume seems to be insufficient to cause such a high increase in the level of the reservoir.
• There is a high freeboard of several meters between the Maximum Operating Level and the crest level.
• Vegetation on the downstream slope would reduce erosion.</td></tr>
</table>

Failure Mode 4R	Downstream sliding

Description

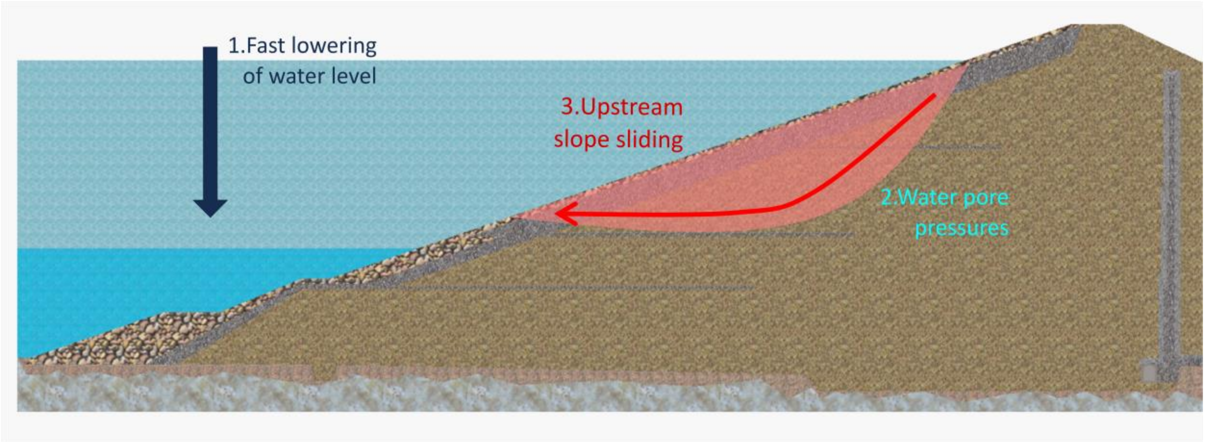
In a normal scenario, a malfunction of the dam body drains produces high hydraulic heads in the downstream part of the embankment slope. These high hydraulic heads lead to a failure in the shear capacity through an instability surface and a sliding of the downstream slope of the embankment.

Graphical scheme



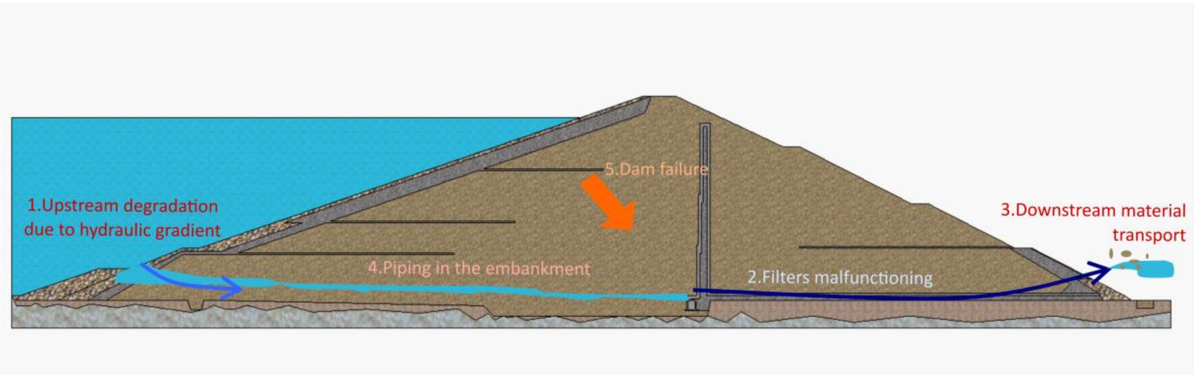
More likely factors	Less likely factors
• Some parts of the ditches in the embankment toe have deteriorated punctually. • The vertical poles that were setup for wild birds have been inclined over the years, although it could not be due to movements in the downstream slope. • One drain shows that the downstream part of the gallery is saturated. • No topographic campaigns have been done either at the dam crest or on the berms of the downstream upstream. • There are not recent studies on embankment stability.	• Measures in the drains that discharge in the gallery do not show any pressure. • No clear or important instability signs have been observed in the embankment. • During the construction of the dam, special care was taken in the quality control and placement of the materials. • This dam is relatively new and built under good quality standards.

Failure Mode 5R	Upstream sliding
Description	
In a normal scenario, a rapid water drawdown occurs in the reservoir that results in a bad dissipation of water pore pressures in the upstream slope of the embankment. These water pressures lead to a failure in the shear capacity and a sliding of the embankment through an instability surface.	
Graphical scheme	



More likely factors	Less likely factors
• When the reservoir is emptied during the dry season, it implies an average decrease of more than 1.50 meters per day. • There are not recent studies on embankment stability.	• In the upstream slope, there are horizontal draining layers at different levels, which would avoid the permanence of pore pressures in the embankment material. • During the construction of the dam, special care was taken in the quality control and placement of the materials. • This dam is relatively new and built under good quality standards.

Failure Mode 6R	Internal erosion
Description	
In a normal scenario, a crack is produced in the upstream impervious cover of the embankment due to the high hydraulic gradient. Filters and gradation of downstream material does not work properly and water filtrations through this cover produce downstream material transport and erode the embankment body, which produces a pipe that is not detected or can be avoided. This pipe enlarges backwards and finally causes the collapse of the embankment.	
Graphical scheme	



More likely factors	Less likely factors
• The discontinuity between the embankment material and the conduits of the monitoring equipment is a potential point of weakness in terms of leakage.	• Good compaction of the embankment impervious materials during construction. • Visual inspection of galleries does not reveal the presence of any type of material in the drainage system. • The existence of filters in the embankment, both upstream and downstream, hinders the evolution of internal erosion phenomena. • This dam is relatively new and built under good quality standards.

2.6. 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:

- **Class A:** Failure is in progress or imminent, so there is an emergency situation and 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 B:** Failure mode is credible and available information is enough for a Quantitative Risk Assessment. All the Class B 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 C:** 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 D:** 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.

In the working sessions, Failure Modes were classified in the following classes after group discussion:

Number	Failure Mode short description	Class
Green Dam		
1G	Overtopping	**B**
2G	Deterioration of dam body	**D**
3G	Deterioration of horizontal joint	**D**
4G	Sliding	**B**
Red Dam		
1R	Overtopping	**B**
2R	Insufficient spillway capacity	**B**
3R	Landslide and overtopping	**D**
4R	Downstream sliding	**C**
5R	Upstream sliding	**C**

6R	Internal erosion	**B**

2.7. 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 C, 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. Therefore, this first proposal of actions is lately developed in Section 4.3.

In addition, surveillance and monitoring needs can also be identified to support the detection of failure modes classified as B. 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 3.7.

The following investigation and surveillance needs were identified in Green and Red Dams:

Proposed studies	Related Failure Modes
Replacement and improvement of piezometers located within the embankment to measure pore pressures. Automatization of measure system for these devices to improve its reliability.	FM4R, FM5R and FM6R
Detailed study on the Red Dam's stability with numerical models to analyse instability in upstream and downstream slopes.	FM4R and FM5R

Finally, during the working sessions the following analyses were recommended to be made with the quantitative risk model:

Proposed analysis	Related Failure Modes

Currently, seasonal freeboards are only introduced in the Red Dam. Since hydrological adequacy seems to be lower in the Green Dam, a redistribution of freeboards could be tried in order to reduce overtopping probability in the Green Dam.	FM1G and FM1R
Use of a numerical model and geotechnical tests to estimate sliding probability in the Green Dam.	FM4G

2.8. Proposal of risk reduction actions

Actions proposed to reduce risk in failure modes **(especially in Class B failure Modes)**, are the basis for the prioritization of risk reduction actions using quantitative risk results and they are explained in detail in Section 3.7. The following actions were proposed in the working sessions:

The following risk reduction actions were proposed in Green and Red Dams:

Proposed actions	Related Failure Modes
Implementation of the Emergency Action Plan to reduce loss of life in case of failure.	All Failure Modes
Reinforcement of the parapet wall in the Green Dam to avoid overtopping until 1145 m.a.s.l.	FM1G
Rehabilitation of the Green Dam's drainage system to ensure a proper dissipation of uplift pressures in the foundation.	FM4G
Higher walls in the Red Dam spillway and improvement of discharge channel to ensure a good behaviour and avoid damaging the embankment toe.	FM2R

3. Quantitative Risk Assessment

3.1. Introduction

Fully quantitative risk assessment seeks to enumerate the risks in terms of probability and consequences in quantitative terms. This Quantitative Risk Assessment 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
AAAA BBBB	Engineer in charge of the Red Dam	ZZZZ
CCCC DDDD	Engineer in charge of the Green Dam	ZZZZ
EEEE FFFF	Risk Analysis expert	YYYY
GGGG HHHH	Risk Analysis expert	YYYY
IIII JJJJ	Dam engineer	ZZZZ

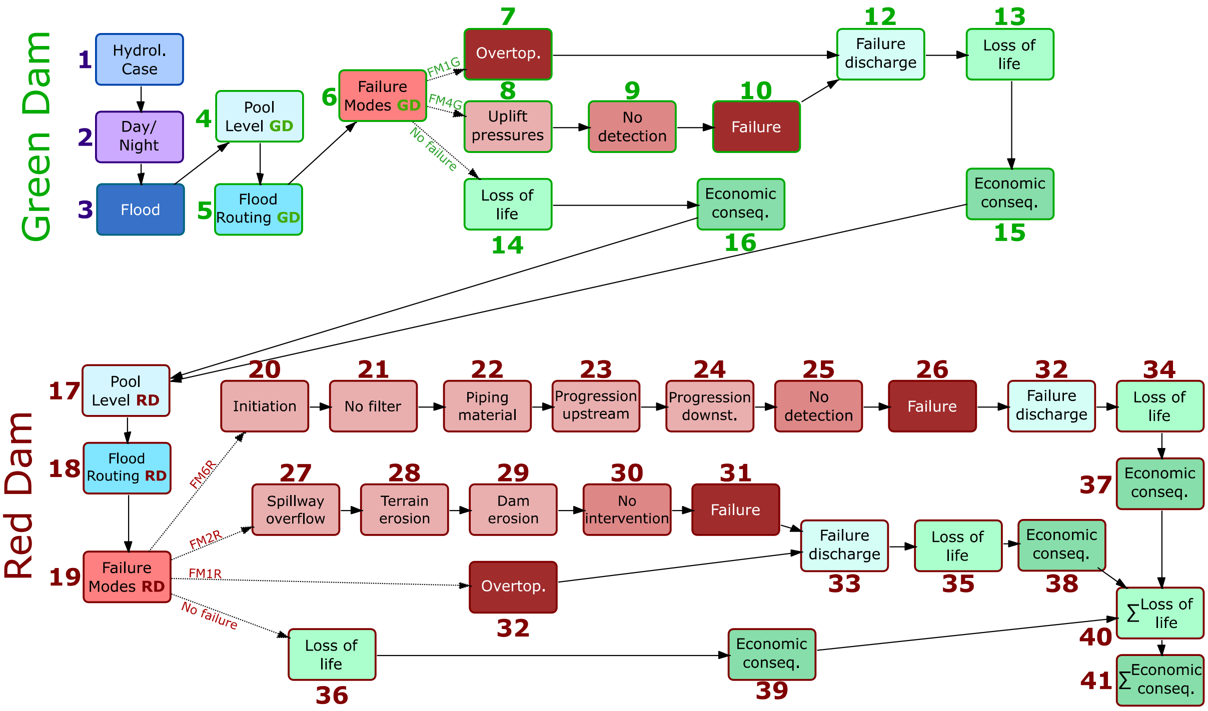
Quantitative Risk Assessment was coordinated and supervised by AAAA BBBB who has proven experience in this type of analysis applied to dam safety.

3.2. Risk model architecture

In the first stage, model architecture was defined for the Green and Red Dams, with all Class B failure modes. This model is based on outcomes from the failure mode identification session, aiming at analysing risk of flooding in downstream areas. The failure modes included in the risk model are:

- FM1G: Overtopping in the Green Dam.
- FM4G: Sliding of the Green Dam.
- FM1R: Overtopping in the Red Dam.
- FM2R: Insufficient spillway capacity in the Red Dam.
- FM6R: Internal erosion in the Red Dam.

The architecture of the quantitative risk model is shown in the following figure:



Risk model architecture for Green and Red Dams.

As can be observed in this influence diagram, both dams have been integrated in the same quantitative risk models, in order to consider how failure and outflows from the Green Dam (GD) could produce the failure (or not) of the Red Dam (RD). These two parts of the model can be clearly differentiated in the model architecture. In this architecture, the red nodes correspond to the failure modes probabilities (of both dams). To the left, the nodes that define loads (blue colour) are included, and, to the right, the nodes that define the consequences (green colour).

This risk model has been developed with iPresas software for risk calculation (iPresas 2016), which uses event trees to compute dam risk. This event tree is a logical mathematical structure that includes all possible event chains that can lead to Green and/or Red Dams failure and calculates the probability of each of these branches. The probability of total failure is obtained by adding the probability of all combinations that may lead to failure for each dam. These branches are created in the following nodes as explained in the following pages:

- Node 1. Hydrological case: 2 branches: snowed and non-snowed catchment.

- Node 2. Day/night: 2 branches.
- Node 3. Flood: The flood range is divided in 21 intervals.
- Node 4. Pool level GD: 6 branches for 6 pool level cases in the Green Reservoir.
- Node 6. Failure Modes GD: 3 branches for 2 failure modes in the Green Dam and non-failure case.
- Node 17. Pool level RD: 14 branches for 14 pool level cases in the Red Reservoir.
- Node 19. Failure Modes RD: 4 branches for 3 failure modes in the Red Dam and non-failure case.

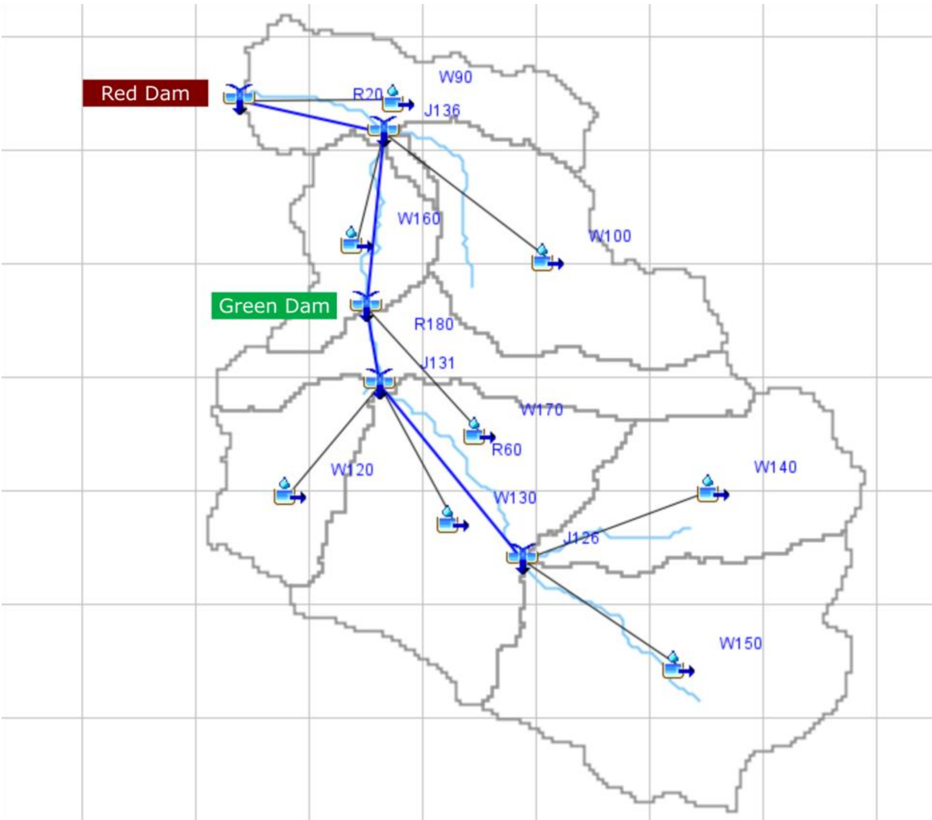
Therefore, this event tree has $2 \cdot 2 \cdot 21 \cdot 6 \cdot 3 \cdot 14 \cdot 4 = 84{,}672$ branches, considering failures and variables combinations for both dams.

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

3.3. Risk model input data

Hydrological hazard: Nodes 1 and 3

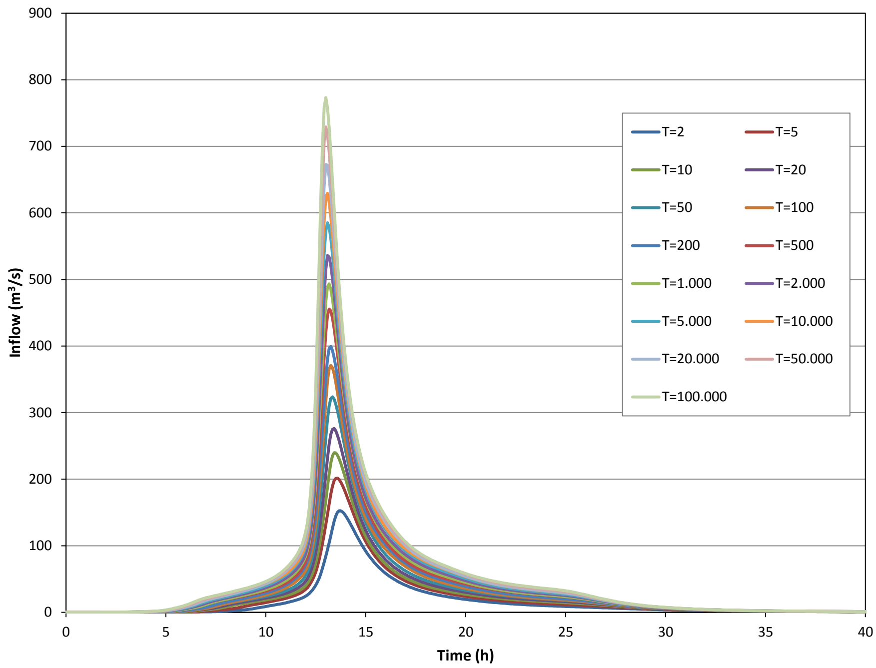
Numerical data of complete hydrographs (inflows to the reservoir as a function of time, and for different return periods) are used to define flood routing at the dam-reservoir system. They are used to perform flood routing calculations as explained in the following nodes. In this case, hydrological data was obtained from Hydrological analysis of the Blue River system (2012). In this analysis, inflow hydrographs in the Green Dam and Red Dam were estimated from 2 to 100,000 years return period based on probabilistic analysis of rainfall data and a HEC-HMS model of the upstream catchment. This model can be observed in the following figure:



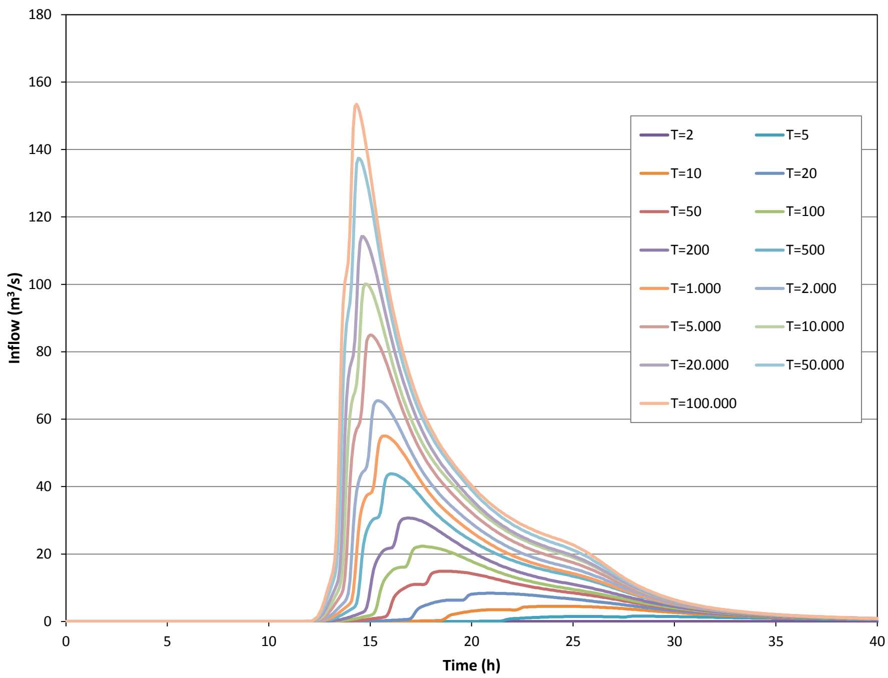
HEC-HMS model used to estimate inflow hydrographs in the Green and Red Dams.

Flow hydrographs were estimated for two cases: with and without snow in the upstream catchment. When there is snow, peak inflows are higher due to the higher imperviousness of the terrain. After analysing past rainfall events, the probability of snowed catchment when rainfall happens is 35%. The probability of these two cases, 35% (snowed catchment) and 65% (not snowed catchment), are introduced in **Node 1**.

According to this hydrological analysis, the Green Reservoir inflow hydrographs in the snowed and non-snowed catchment cases are shown in the following figures:

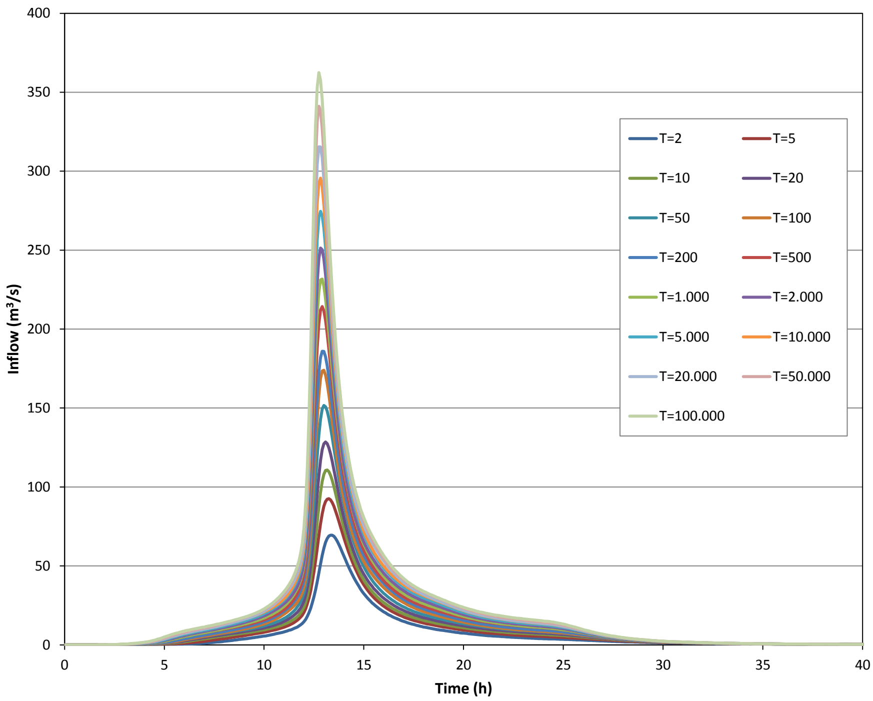


Results of hydrological analysis for snowed catchment in the Green Reservoir.

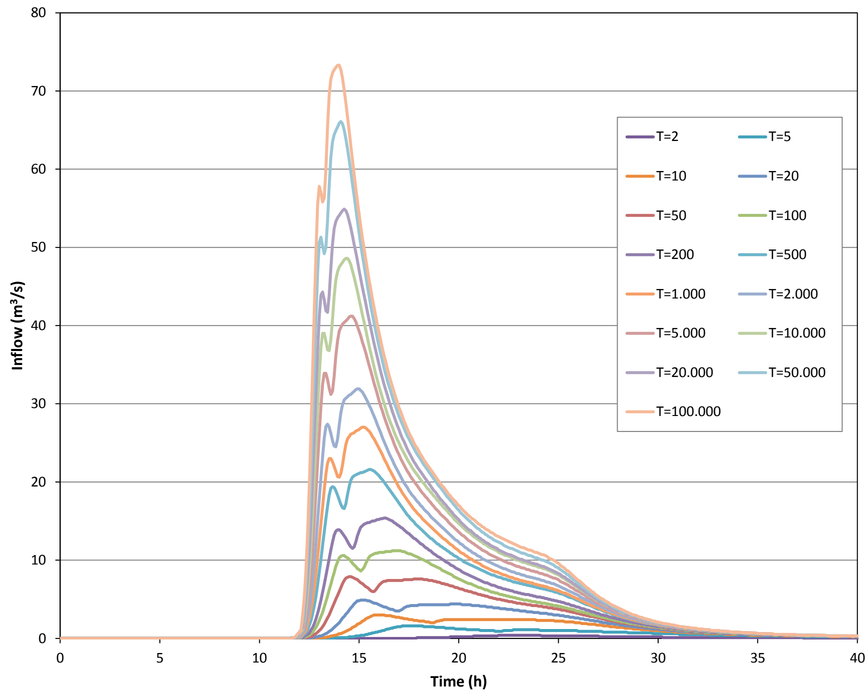


Results of hydrological analysis for non-snowed catchment in the Green Reservoir.

The Red Reservoir inflow hydrographs in the snowed and non-snowed catchment cases are shown in the following figures. These hydrographs represent the catchment located between both reservoirs. Therefore, total inflow in the Red Reservoir is the sum of these hydrographs and the outflows from the Green Dam.



Results of hydrological analysis for snowed catchment in the Red Reservoir.



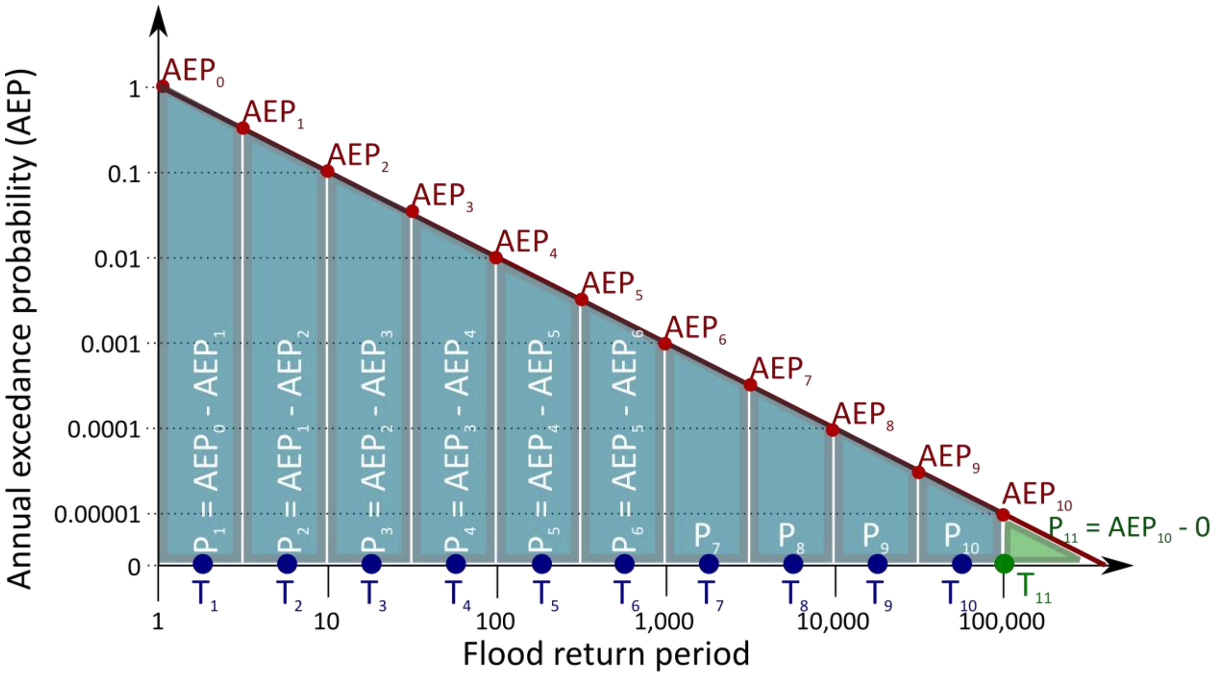
Results of hydrological analysis for non-snowed catchment in the Red Reservoir.

In addition, the objective of **Node 3** 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, data to be incorporated in this node correspond to the range of return periods considered in the flood routing analysis. In the case of the hydrological study of this system of dams, the range of return periods ranges from T = 1 year to T = 100,000 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.

The scheme for calculating flood probabilities is shown in the following figure. 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 100,000 years.



Division of Intervals for the Range of Flood Events.

Pool levels' probabilities: Nodes 4 and 17

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.

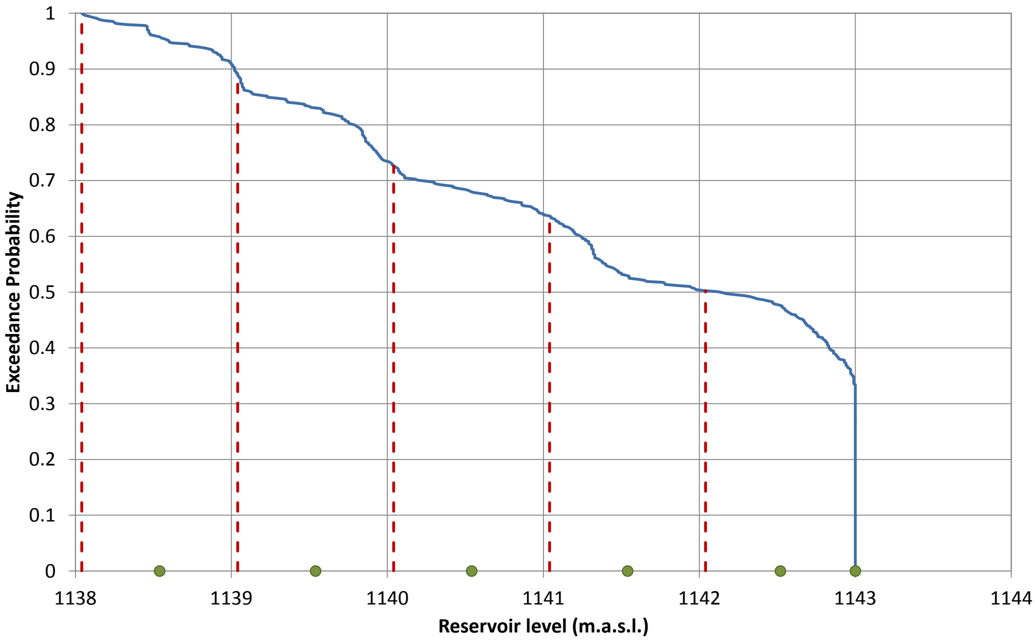
The probabilities of being at a certain previous water level when the flood arrives are included in **Node 4** for the Green Dam and **Node 17** for the Red Dam.

Therefore, the objective is to establish the relationship between probability and reservoir levels. The exceedance probability curve of water pool levels was obtained by adjusting an empirical curve to historical records for each reservoir. For the study of reservoir levels of the reservoirs, registered data provided by the dam's operator from the period of 1992 to 2014 have been used.

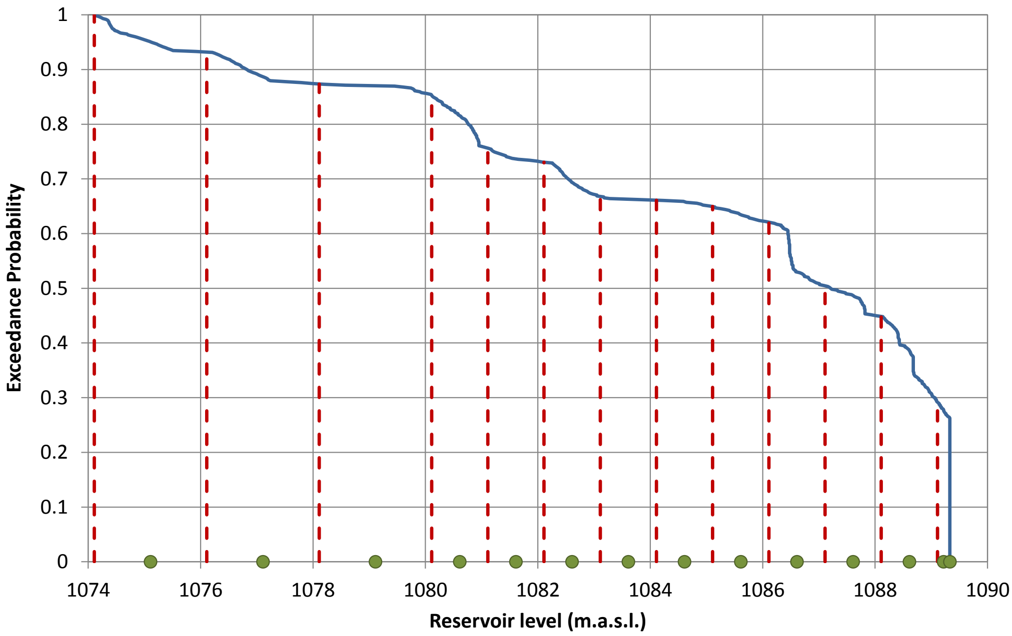
The exceedance probability curve was obtained and discretized in order to analyse the probabilities of the different previous levels and to select characteristic values. The following process was followed:

- The historical series of levels was sorted by increasing order.
- For each level, the probability of exceedance was calculated obtaining the curve represented in blue colour in the following figures.
- The range of possible levels was divided into 6 intervals for the Green Reservoir and 14 intervals for the Red Reservoir, since there are higher variations in water pool levels. In the Red Reservoir, more intervals were defined for the steeper part of the curve.

- Average levels of each interval were calculated.
- Each average level is associated with probability obtained as the difference between the exceedance probabilities of starting and end points of its interval.



Annual Exceedance Probability Curve for Water Pool Levels of the Green Reservoir.



Annual Exceedance Probability Curve for Water Pool Levels of the Red Reservoir.

The previous figures show exceedance probabilities of water reservoir levels for both reservoirs (blue line), intervals used to divide the range of water pool levels (red dotted line) and average levels for each interval that are used as input data in node Flood routing (green points). Therefore, there are 6 previous water pool levels for the Green Reservoir and 14 levels for the Red Reservoir that represent each interval, with an associated probability used by the risk model. Values introduced in the risk model are shown in the following table:

Green Reservoir			Red Reservoir		
Interval	Average value	Probability	Interval	Average value	Probability
1138.04 - 1139.04	1138.54	11.01%	1074.11 - 1076.11	1075.11	6.80%
1139.04 - 1140.04	1139.54	16.33%	1076.11 - 1078.11	1077.11	5.85%
1140.04 - 1141.04	1140.54	8.99%	1078.11 - 1080.11	1079.11	2.07%
1141.04 - 1142.04	1141.54	13.41%	1080.11 - 1081.11	1080.61	9.67%
1142.04 - 1143	1142.52	18.33%	1081.11 - 1082.11	1081.61	2.56%
1143	1143.00	31.93%	1082.11 - 1083.11	1082.61	6.24%
	TOTAL	**100.00%**	1083.11 - 1084.11	1083.61	0.71%
			1084.11 - 1085.11	1084.61	1.14%
			1085.11 - 1086.11	1085.61	2.88%
			1086.11 - 1087.11	1086.61	11.63%
			1087.11 - 1088.11	1087.61	5.60%
			1088.11 - 1089.11	1088.61	15.68%
			1089.11 - 1089.33	1089.22	3.09%
			1089.33	1089.33	26.09%
				TOTAL	**100.00%**

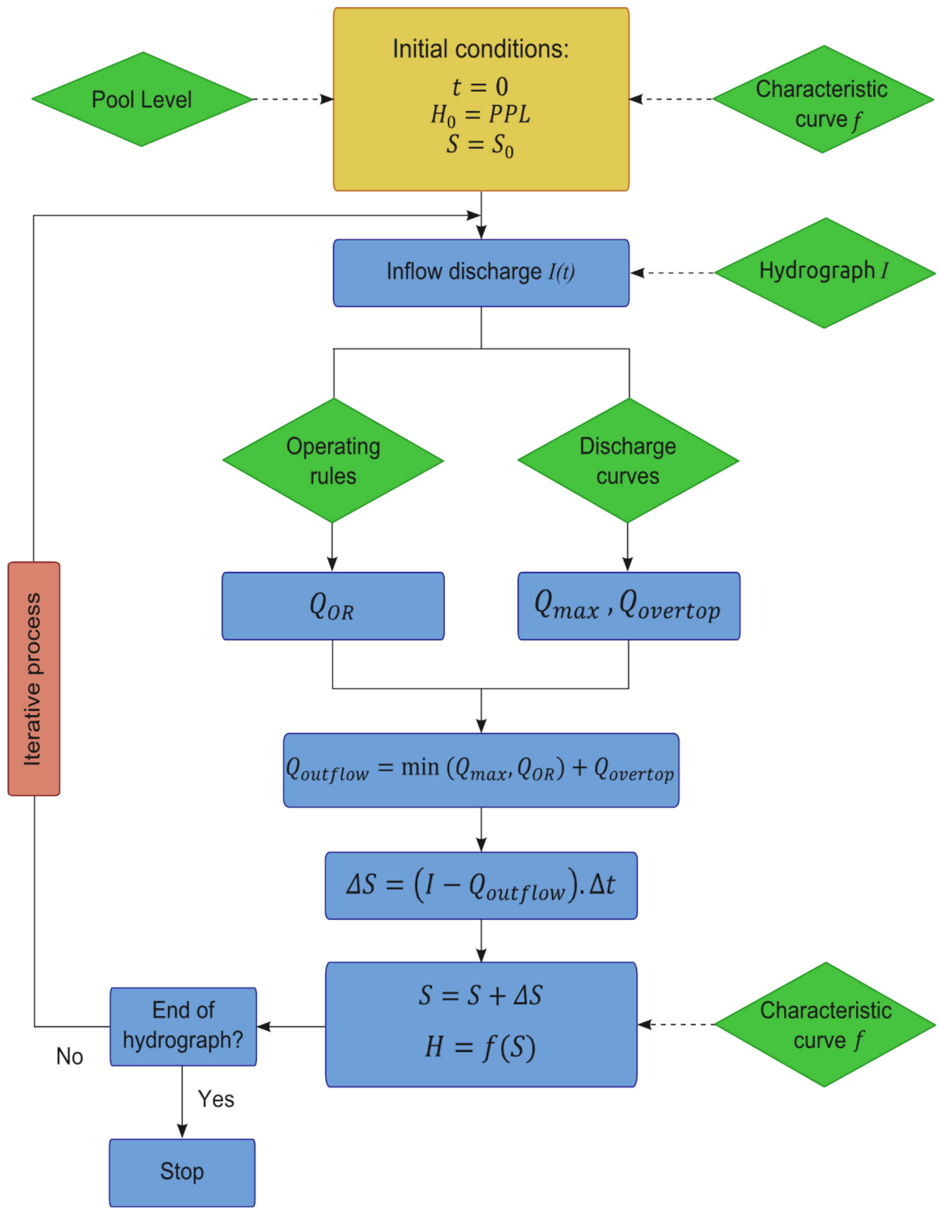
Flood routing analysis: Nodes 5 and 18

The main scope of the flood routing analysis is to obtain maximum levels reached at the reservoir for analysed loads, but the results can also be used to define consequences downstream of the reservoir due to dam releases. Both results are obtained directly from the flood routing study. For each possible combination of previous level, flood event and outlet availability, these variables are obtained.

Input data are based on results from the flood routing analysis in these two dams. This flood routing analysis was made using a spreadsheet, representing the system of dam's behaviour considering the input hydrographs, reservoir-elevation curve for each reservoir and discharge curve for each spillway. The time interval used for flood routing computations was 6 minutes. This flood routing analysis was made for all the combinations of the following cases:

- 2 hydrological cases: snowed and non-snowed catchment.
- 16 flood events: 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, and 100000 years. These events are detailed in the first part of this section.
- 6 pool level cases in the Green Reservoir.
- 14 pool level cases in the Red Reservoir.
- Failure and non-failure cases for the Green Dam, analysing what pool levels would be reached in the Red Reservoir for each case.

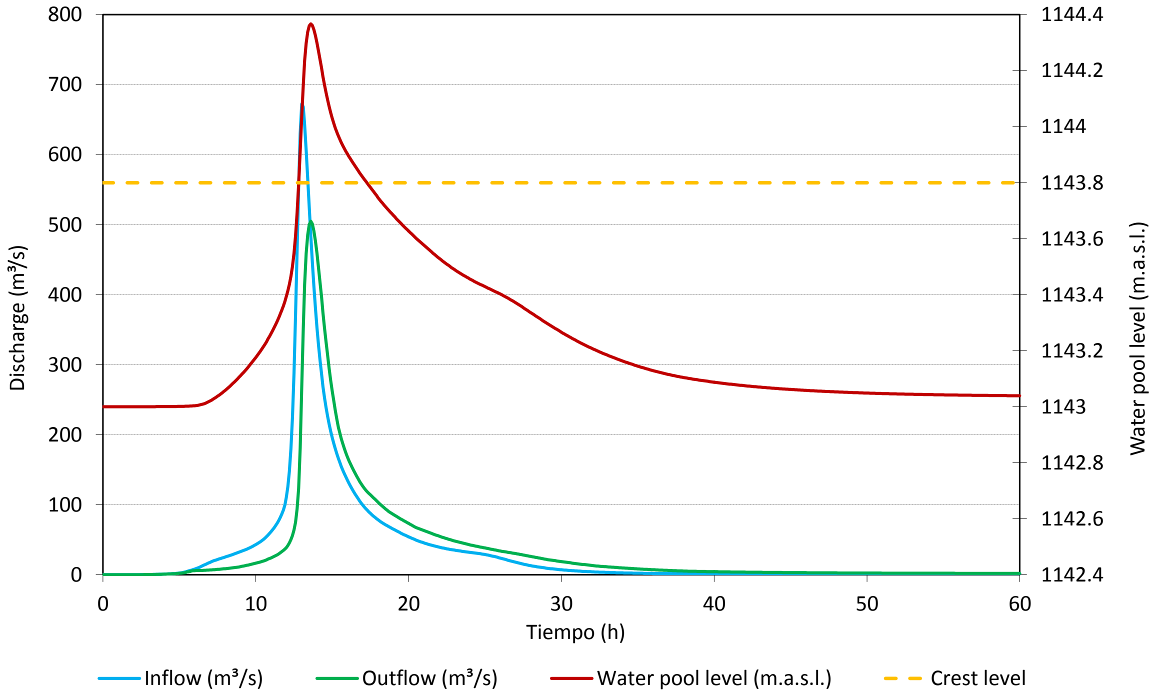
In total, 5736 combinations for flood routing analysis were made (2·16·6·14·2), obtaining results of maximum water level in the Green and Red Reservoirs and peak outflow discharge (dam release) for each one. The process followed for this computation is showed in the following figure:



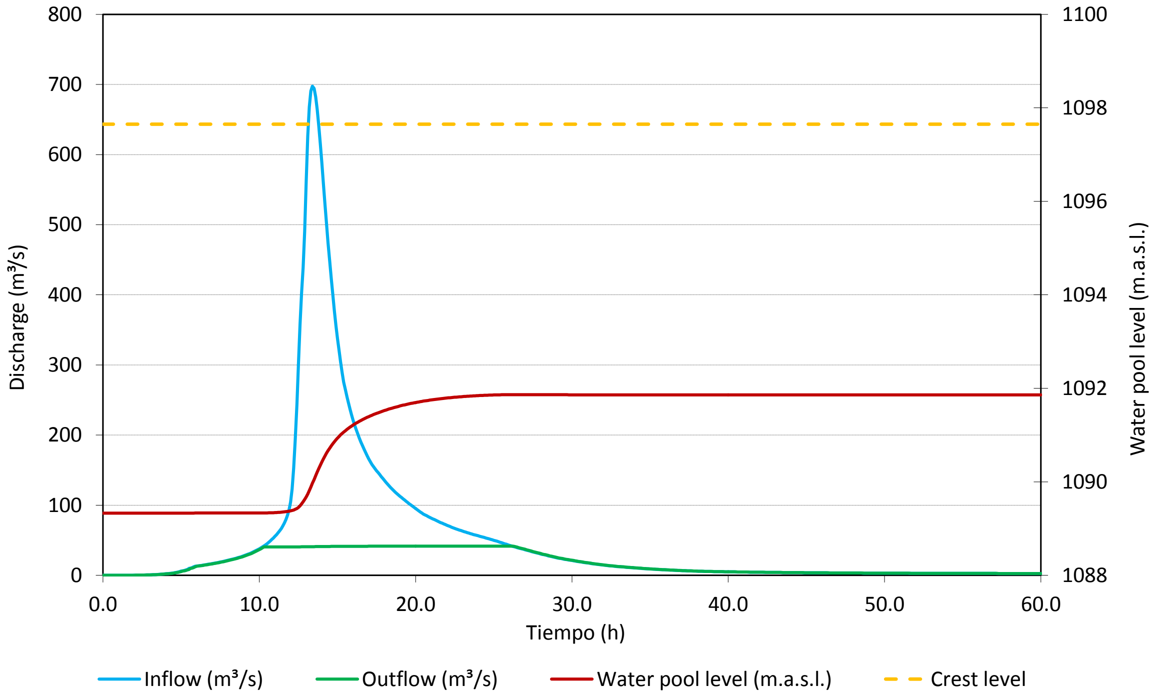
Scheme of flood routing process in both reservoirs using a spreadsheet.

With such approach it was possible to characterize the hydraulic behaviour of each dam-reservoir system based on the above variables and, thus, to 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 unique previous water level in the reservoir.

As an example of flood routing calculations performed for each combination, the following shows the results obtained for the 10,000-year return period flood with snowed catchment, a previous level of 1143 m.a.s.l. in the Green reservoir and 1089.33 m.a.s.l. in the Red reservoir.



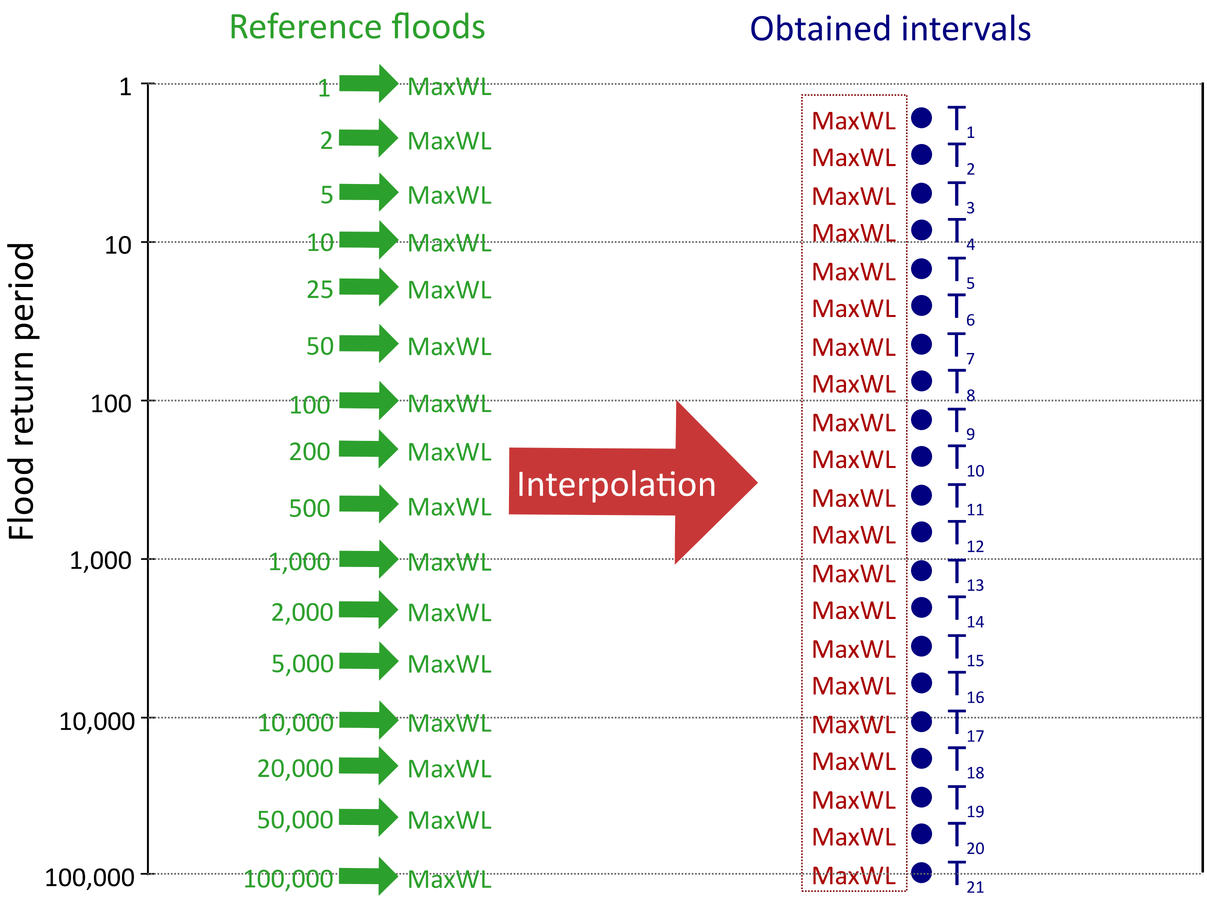
Flood Routing Results in the Green Reservoir for Flood Event of 10,000 Years of Return Period with snowed catchment, a previous level of 1143 m.a.s.l. in the Green reservoir and 1089.33 m.a.s.l. in the Red reservoir.



Flood Routing Results in the Red Reservoir for Flood Event of 10,000 Years of Return Period with snowed catchment, a previous level of 1143 m.a.s.l. in the Green reservoir and 1089.33 m.a.s.l. in the Red reservoir.

This flood routing study has been carried out from the stage-volume curve of the reservoir (relating water height and volume) and rating curves of outlet works. Thus, in this node, results of the maximum water level reached in the two reservoirs and peak flow discharges for each calculated flood routing case are incorporated into the risk model using a spreadsheet. Therefore, these results are introduced onto a spreadsheet within the risk model to quantify risk.

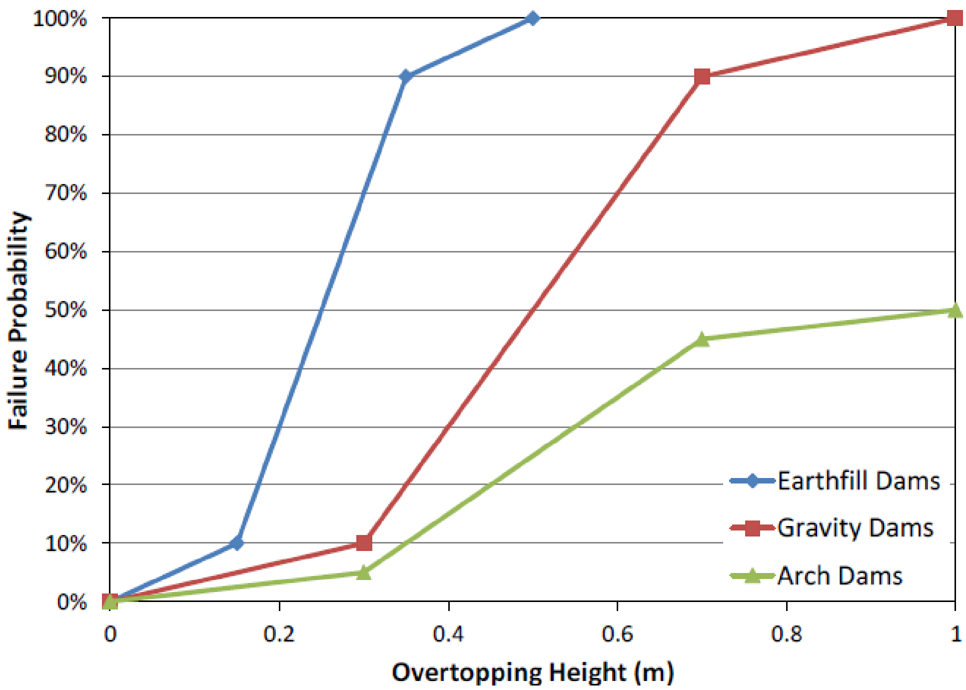
From these results, the software tool performs an interpolation to obtain in each branch of the event tree the maximum level reached in the reservoir and the corresponding flow discharge. Results of reference flood events are used to obtain flood routing outcomes for the 21 cases of flood events analysed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



Interpolation Process for Flood Routing Results and Flood Intervals Used in the Risk Model.

Failure probabilities for Failure Modes 1G and 1R: Nodes 7 and 32

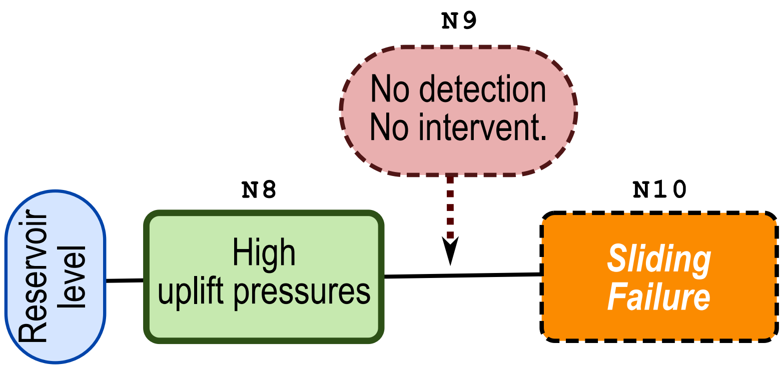
This node includes the probability of dam failure due to overtopping as a function of the water reached in the reservoir. For this purpose, published reference curves (Altarejos García et al. 2014) have been used for this failure mode according to the dam typology. These reference curves are shown in the following figure. 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, embankments are more vulnerable to overtopping. For the Green Dam node, the curve for earth fill dams is used with a dam crest level of 1143.8 meters and for the Red Dam node, the curve for earth fill dams is used, with a dam crest level of 1032.65 meters.



Reference Fragility Curves for Overtopping Failure Mode.

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

The failure mode FM4G (sliding of the Green Dam) has been included into the risk model based on the structure presented in this figure:



Failure Mode 4G scheme (three events).

Three events are considered for this failure:

- Event 1 (Node 8): 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 9): No detection and/or no intervention of these high uplift pressures with the current monitoring system.
- Event 3 (Node 10): Failure due to dam instability. Failure probability for this node was estimated with a reliability analysis and a Limit Equilibrium Model, as recommended in the IFM sessions.

In **Node 8**, probability of high uplift pressures in the foundation was estimated by expert judgment as 5% (best estimate), between 2% and 15%. This probability was estimated after reviewing exiting monitoring information and dam documentation. This probability was estimated based on the following factors:

- Maximum uplift pressures values are measured in the highest sections of the dam with maximum values around 7/10 m of water (upstream piezometers) which is equivalent to percentages of around 20% of the load maximum water in those sections, reflecting the effectiveness of the drainage system.
- Monitoring system does not manifest any symptom of abnormality in the behaviour of the foundation that puts the stability of the structure at risk.
- All measures indicate that uplift pressures are, currently, correctly dissipated.
- However, obstruction symptoms were observed during the technical visit in some of the drains pipes of the gallery, which are part of the foundation and dam body drainage systems. Water leakage does not concentrate in the drains, but it seems to soak the whole lower part of the dam body, producing water leakage and uplift pressures dissipation in the perimeter gallery.
- Sub-vertical strata that give a lot of imperviousness.

In **Node 9**, probability of not detecting (or intervening to avoid) high uplift pressures in the dam-foundation interface was estimated by expert judgment as 20% (best estimate), between 10% and 35%. This probability was estimated after reviewing exiting monitoring information and dam documentation. This probability was estimated based on the following factors:

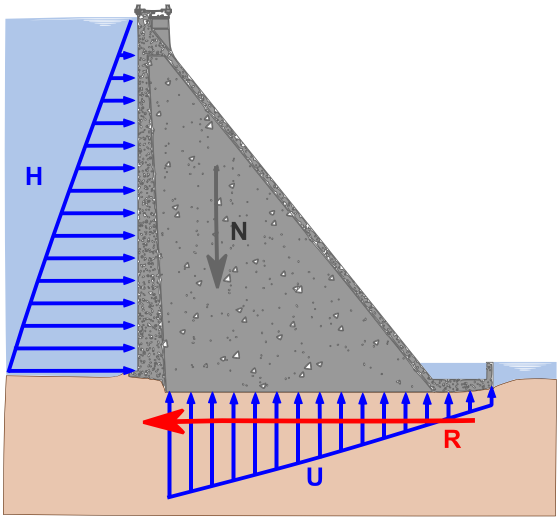
- There is control of uplift pressures in foundations using 14 piezometers.
- There is control of total leakage.
- There is control of dam movements through direct plumb lines.
- Concrete bases have been built for topographic control of movements.

A Monte Carlo analysis is carried out for providing input data for the **Node 10** (node Failure) with the aim of obtaining the fragility curve for the Green 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 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 that 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-Coulomb equation.

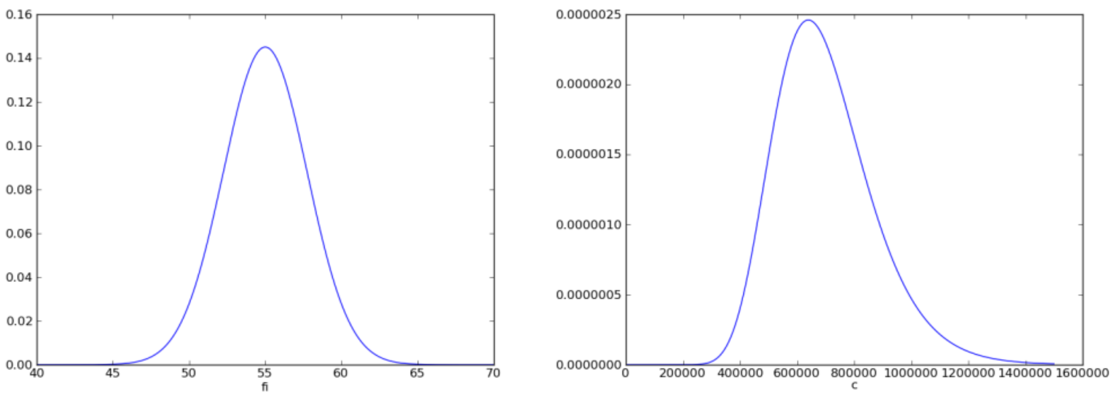
The driving forces are the reservoir water pressure and the uplift pressure. Water and uplift pressures directly depend on the water level in the reservoir. Main forces considered in this model are summarized in this figure:



Forces considered in the Limit Equilibrium Model.

Selected random variables in this Limit Equilibrium Model are the friction angle and cohesion, which defines the resistance for sliding in the dam-foundation contact. Probability distributions were selected for these two variables based on exiting geotechnical data and existing references. These distributions are summarized in the following tables and figures:

Variable	Mean	St. deviation	Max	Min	Type of distribution
Friction angle (°)	55	2.75	70	40	Truncated Normal
Cohesion (MPa)	0.7	0.175	-	-	Lognormal



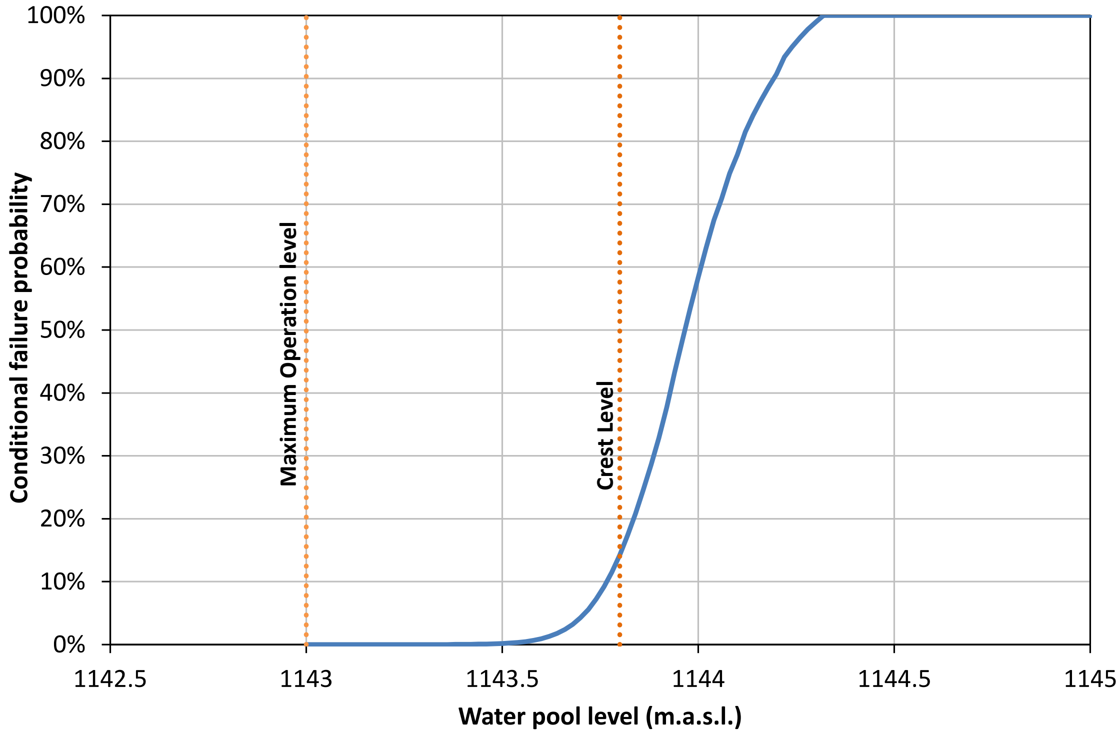
Probability distributions defined for friction angle (left) and cohesion (right).

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

$$P_f = \frac{N_f}{N}$$

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 Monte Carlo simulations performed should be large enough to capture the searched probability. Finally, results from 1,000,000 simulations are used.

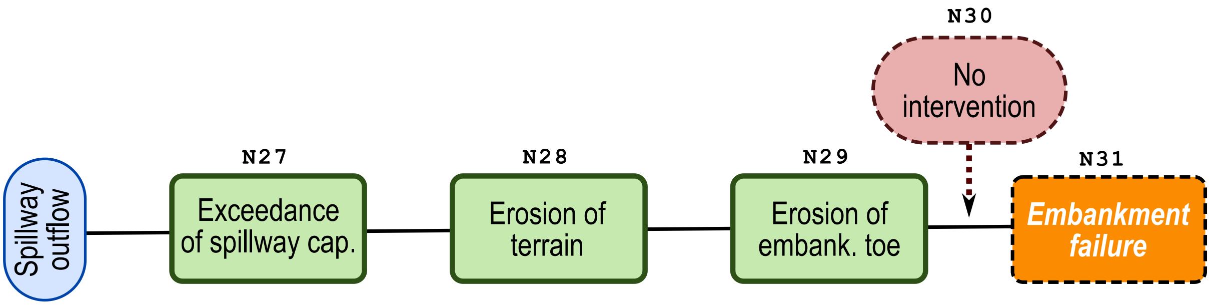
Therefore, the following fragility curves were obtained to be introduced in Node 10:



Fragility curve introduced in Node 10.

Failure probabilities for Failure Mode 2R: Nodes 27, 28, 29, 30 and 31

The failure mode FM2R (insufficient spillway capacity) has been included into the risk model based on the structure presented in this figure:



Failure Mode 2R scheme (five events).

Five events are considered for this failure:

- Event 1 (Node 27): Emulsified water level exceeds the crest of the spillway left wall in the lower part.
- Event 2 (Node 28): Overflow produces an erosion of the terrain between the embankment and the spillway.
- Event 3 (Node 29): Overflow continues and it produces an erosion of the embankment toe.
- Event 4 (Node 30): The continuity of this failure mode cannot be stopped.

- Event 5 (Node 31): Erosion continues and produces the embankment failure due to toe erosion and collapse.

Probability of each event was estimated through expert judgment sessions based on the results of the numerical analysis made regarding the spillway behaviour. Different discharge values were tried with this model and these results were used to estimate spillway capacity. The general layout of this model is shown in Section 2.4.

This expert judgement session took place on 16th February,2015, with the participation of 5 experts. 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:

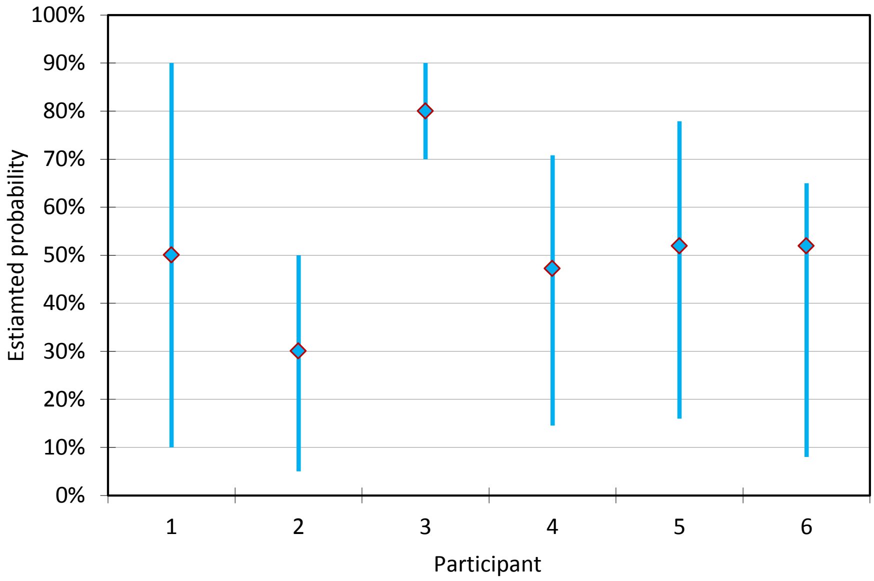
"More likely" factors:

- The spillway capacity is relatively small compared to the peaks of high return period floods.
- The spillway has only worked twice as a result of an artificial test with low discharge, so the proper working of the spillways has not been checked. In this test, it was observed that the rock at the trampoline's toe could be affected.
- The spillway does not have flow aeration elements.
- The state of deterioration of the spillway surface is a very important factor when considering potential turbulences.
- The numerical model shows that there could be overflow when spillway discharge is higher than 80 m^3/s.

"Less likely" factors:

- If the seasonal freeboards are respected, the flood routing capacity of the reservoir would absorb most of the flood volume, so that the spillage's time through the spillway would be short.
- Upstream the Green reservoir contributes to the routing of the peak inflow.

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 with a spillway discharge of 160 m^3/s by the session participants:



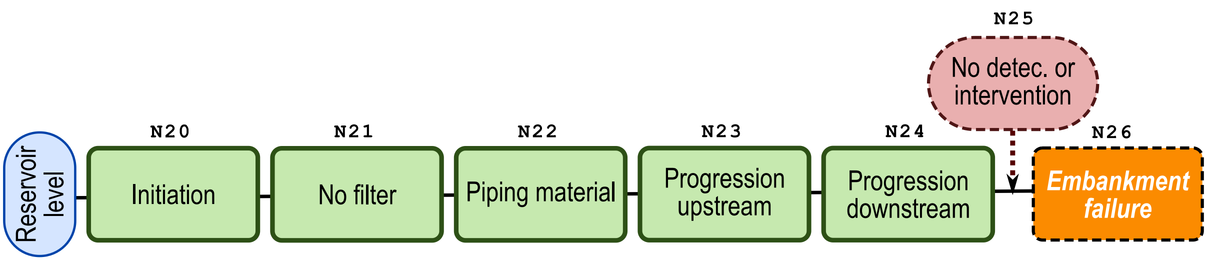
Probability estimations for Node 27 (discharge 160 m³/s).

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

Discharge (m³/s)	Node 27	Node 28	Node 29	Node 30	Node 31
133.33	0.00%	0.00%	0.00%	78.30%	0.00%
160	49.32%	7.94%	0.79%	78.30%	0.91%
444	81.51%	59.67%	3.68%	78.30%	2.71%

Failure probabilities for Failure Mode 6R: Nodes 20, 21, 22, 23, 24, 25 and 26

The failure mode FM6R (internal erosion) has been included into the risk model based on the structure presented in this figure:



Failure Mode 6R scheme (seven events).

Seven events are considered for this failure:

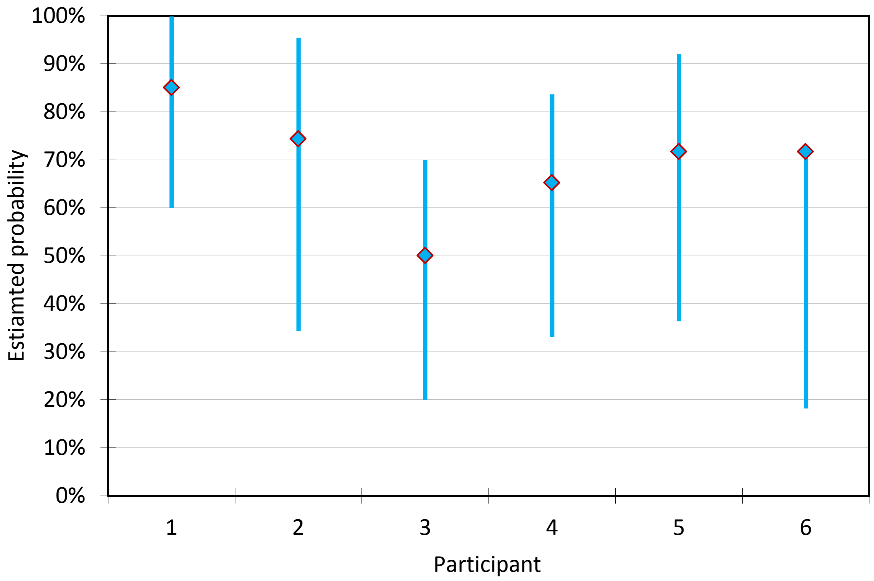
- Event 1 (Node 20): Initiation of an internal erosion process in the Red embankment.
- Event 2 (Node 21): Filters in the embankment do not work properly to avoid material transport towards downstream.

- Event 3 (Node 22): Embankment material is able to create pipes.
- Event 4 (Node 23): There are no barriers for progression of internal erosion towards upstream.
- Event 5 (Node 24): There are no barriers for progression of internal erosion towards downstream.
- Event 6 (Node 25): No detection or no intervention of this internal erosion problem.
- Event 7 (Node 26): Internal erosion progression and embankment failure due to internal erosion.

Probability of each event was estimated through expert judgment sessions based on the international recommendations for internal erosion failure modes, monitoring data, available information and properties of embankment material. In these sessions, the internal erosion process was reviewed in detail, analysing dam body materials (coefficient of uniformity, size distribution, erodibility), potential filtered exists of material and existing hydraulic gradients in different loading conditions.

This expert judgement session also took place on 16th February 2015, with the participation of 5 experts. For each node, "less likely" and "more likely" factors were discussed in detail, and probabilities were estimated for each event.

For instance, the probability results for the last node (embankment failure) and elevation reservoir of 1094.65 m.a.s.l. can be observed in the following figure:



Probability estimations for Node 26 (reservoir level 1094.65 m.a.s.l.).

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

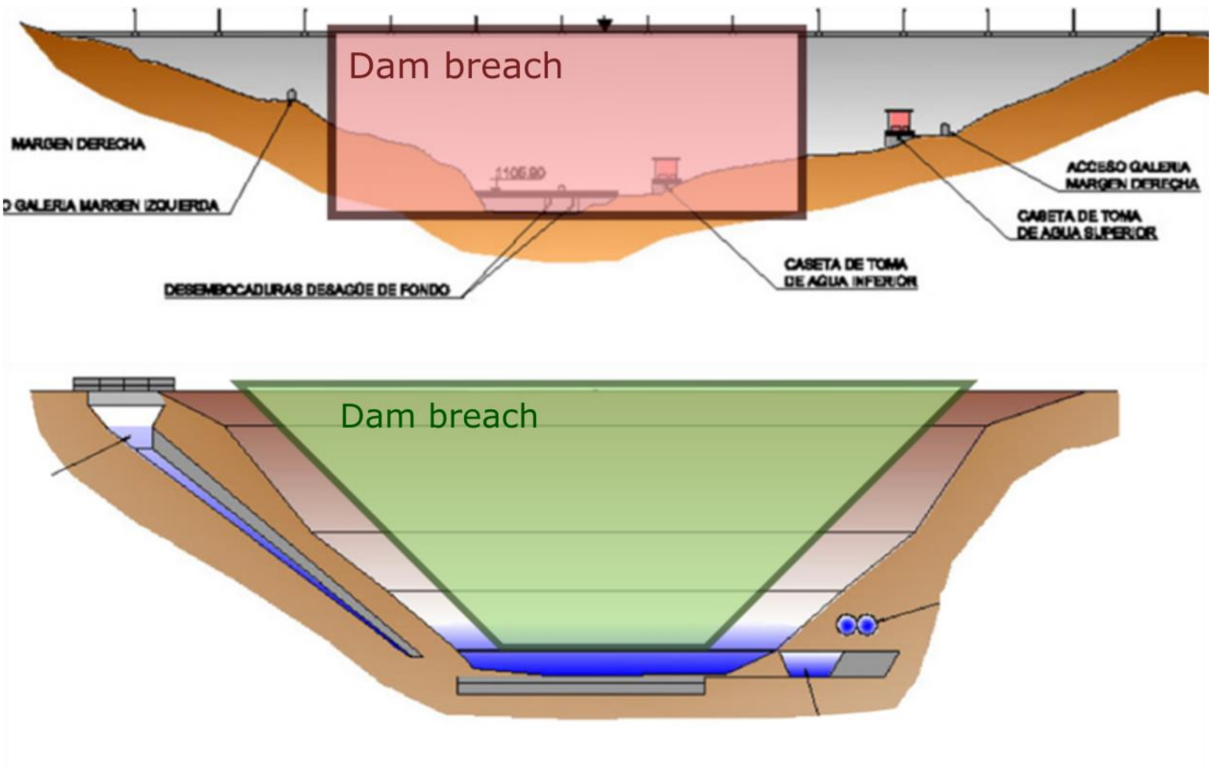
Reservoir Level	Node 20	Node 21	Node 22	Node 23	Node 24	Node 25	Node 26
1058.95	0.06%	2.24%	85.65%	60.48%	87.49%	16.98%	0.00%
1090	0.06%	2.24%	85.65%	60.48%	87.49%	16.98%	57.93%
1094.65	0.06%	2.24%	85.65%	60.48%	87.49%	16.98%	72.76%
1097.65	0.06%	2.24%	85.65%	60.48%	87.49%	16.98%	86.17%

Failure hydrographs: Nodes 12, 32 and 33

Dam failure hydrographs were obtained as a first step to do a consequence analysis and to relate maximum water levels in both reservoirs when the failure occurs and peak failure discharges to downstream areas (which represent dam failure hydrographs downstream). Therefore, in Nodes 12, 32 and 33 this relation between reservoir levels and peak failure discharge is introduced for each dam.

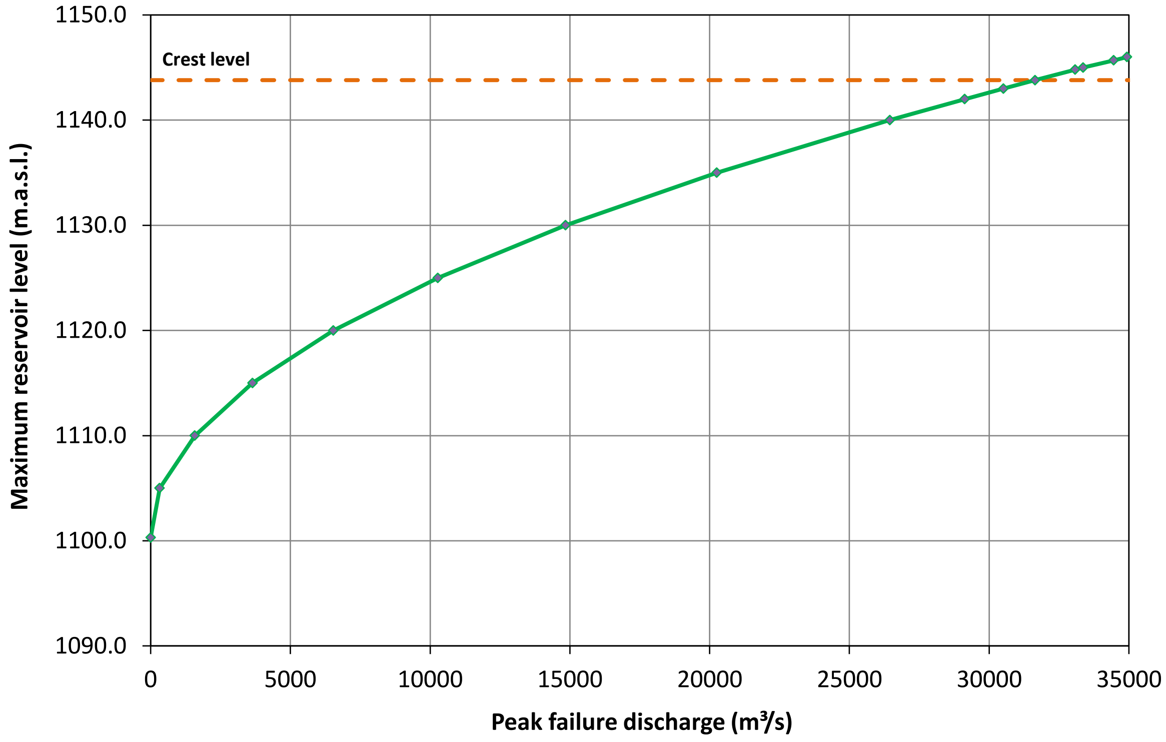
In this case, these relations have been obtained using the dam failure model that was developed for the Emergency Action Plan. Within this model, different reservoir elevations were introduced for each reservoir and these curves were obtained for the Green and Red dams.

Dam breach parameters were based on assumptions made to develop the Emergency Action Plans. These breaches can be observed in the following figure:

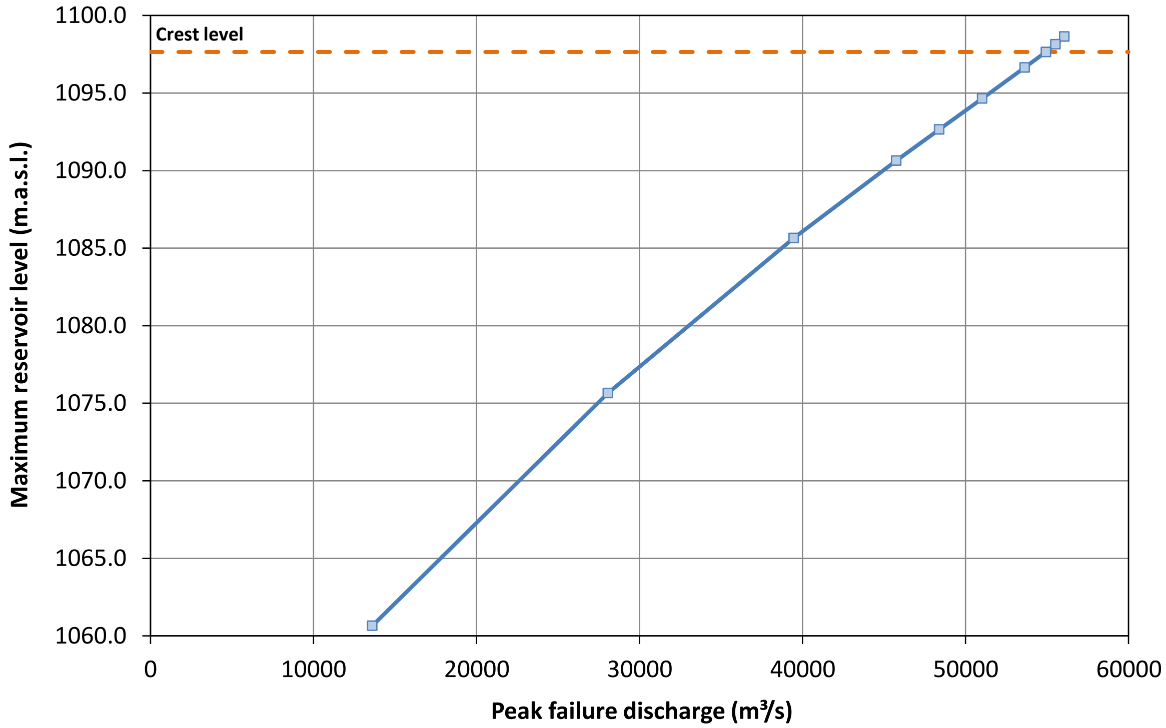


Dam breach parameters considered in the Green Dam (above) and Red Dam (bellow).

The curves obtained with the hydraulic model that relate the maximum level in the reservoir with the peak flow discharge for both dams can be observed in the following figures:



Reservoir level – Peak failure discharge curve for the Green Dam.



Reservoir level – Peak failure discharge curve for the Red Dam.

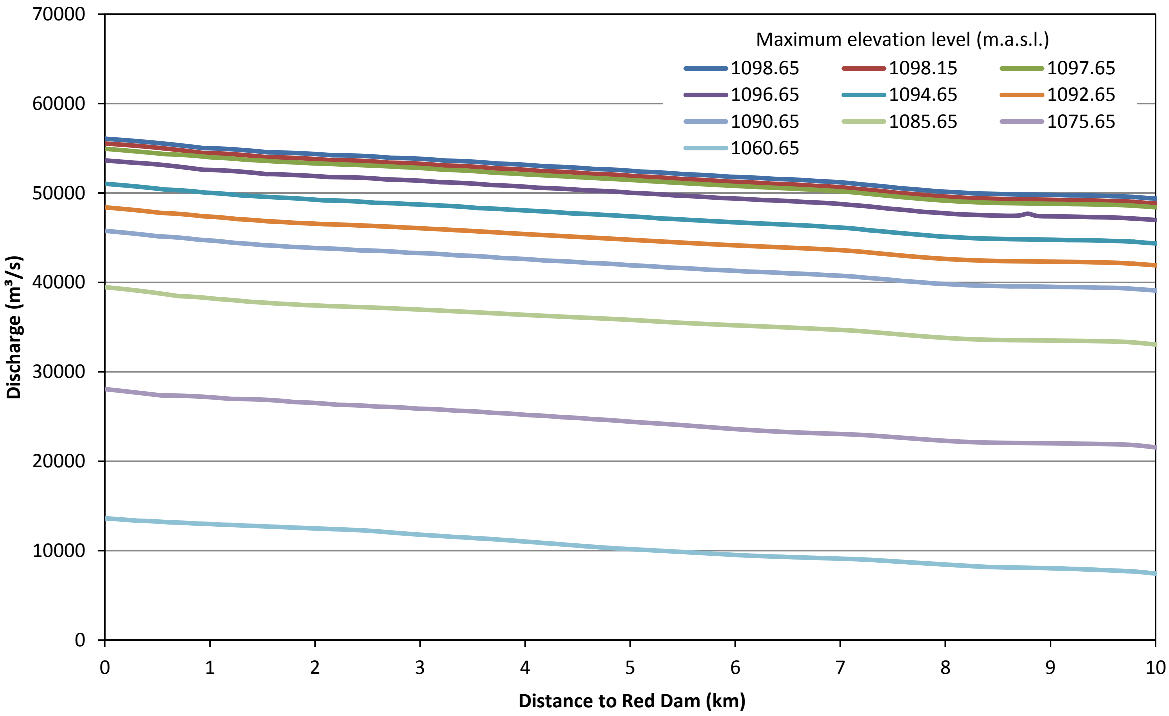
These curves were introduced in the quantitative risk model (Node 12 for Green Dam and Nodes 32 and 33 for the Red Dam) to estimate dam failure consequences in each case.

Loss of life estimation: Nodes 2, 13, 14, 34, 35, 36 and 40

First, **Node 2** was introduced in the risk model to create two potential scenarios for loss of life: Nigh failure or Day Failure. Loss of life can be different in these two cases since in some areas (industrial, services…) there are people only during the day. In addition, people response to floods is usually slower at night, so more warning time is needed.

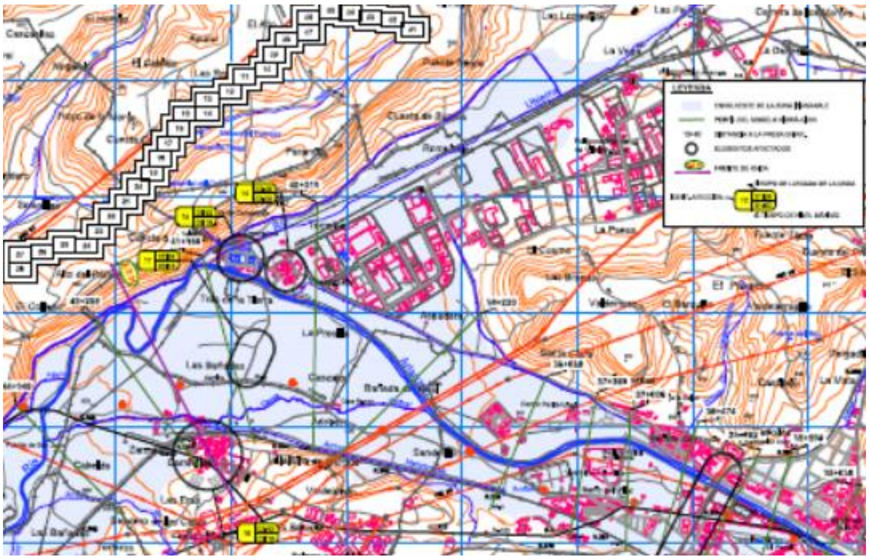
Node 13 and 14 introduce loss of life between the Green and Red Dams in failure and non-failure cases respectively. In this case, there are not significant urban areas between both reservoirs, so loss of life introduced in these nodes is 0.

Loss of life downstream the Red Dam is included in **Nodes 34, 35 and 36** based on results of estimation of potential loss of life due to flooding for ten failure cases for the Red Dam. Each case was computed with the existing hydraulic model and different initial levels in the Red reservoir. For each hydraulic model computation, main flood characteristics (water depth, discharge, velocity, time of arrival…) were obtained in the main populations downstream. These hydraulic results were the basis to estimate loss of life and economic consequences, and they are summarized in the following figure:



Hydraulic model results for different initial levels in the reservoir.

An example of the inundation maps obtained for these computations is shown in the following figure:



Example of the inundation maps obtained.

The method proposed by Wayne Graham (1999) was used to estimate loss of life. This method estimates population at risk multiplied by a fatality rate that 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 warning notice is issued to the population and the moment when the flood wave arrives, therefore, it is the time available for evacuation and protection. Based on international recommendations, in this case it has been considered that warnings are initiated when dam failure begins during the day and 15 minutes later during the night. Thus, in case of failure, warning time in each population is obtained as the arrival wave time minus the starting time of warning issues.

In the Red Dam, a different warning time was considered for hydrologic scenarios (FM1R and FM2R) and for a normal scenario, as the hydrologic scenario usually has more warning since a high flood is usually predicted in advance and emergency agencies are more prepared. In addition, when the Red Dam fails it is due to the previous failure of the Green Dam, warning time will be also higher. For these reasons, eight different loss-of-life curves were obtained combining all the cases of day/night, overtopping/other failure modes and only Red Dam/cascade failure.

In addition, a sensitivity analysis of results with respect to warning times has been conducted for the most critical case, as shown in Section 3.6.

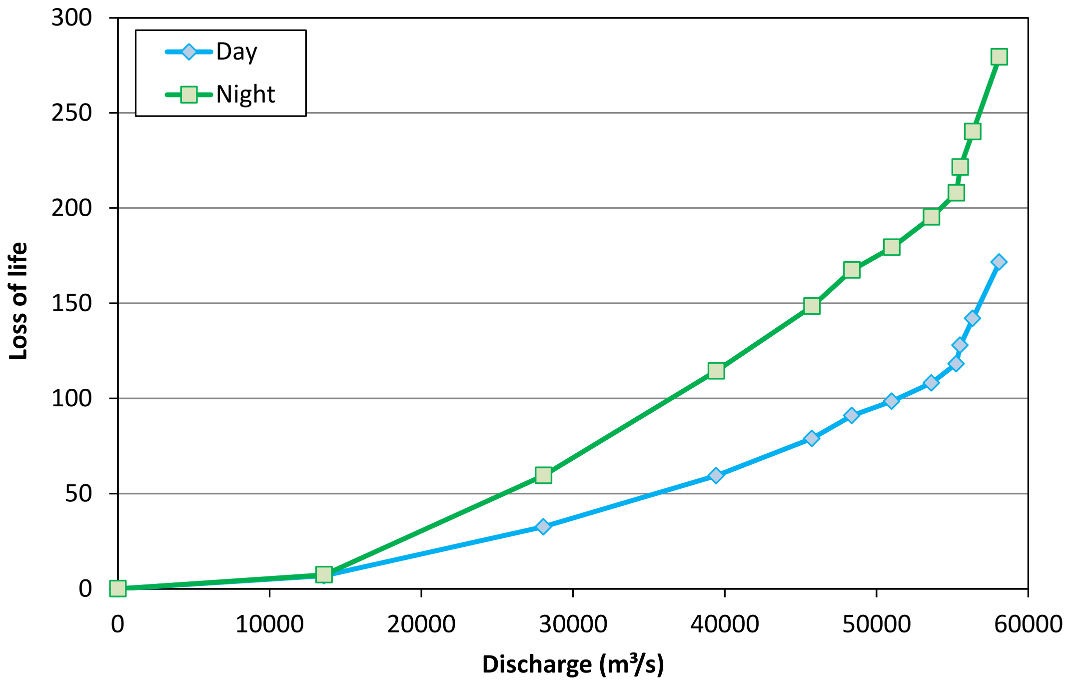
Flood severity has been estimated from flood characteristics—that is, flow, water depth, and velocity. To distinguish between different cases of flood severity, the Graham method recommends the use of the DV parameter, which is obtained by dividing the maximum flow rate by the maximum width of the flood. DV values lower than 4.6 m^2/s indicate cases of low flood severity, in which no structural damage is foreseen in buildings or foundations. In contrast, values above this threshold indicate cases of medium severity, where significant structural damage can occur, but a total destruction of the area is not expected. High flood severity cases are considered in areas devastated by flooding due to the proximity to the flood defense infrastructure, or areas that are totally destroyed by flooding (for example, camping sites).

Fatality rates are obtained based on available warning times and flood severity levels at each location. These rates should be applied to the population at risk within the flooded area. For the estimation of this population, the density of each urban area is considered and has been estimated from the most recent census data. On the other hand, flooded areas in each location have been estimated from flood maps obtained from the hydraulic models. Multiplying the flooded area by population density, population at risk is estimated for each urban area.

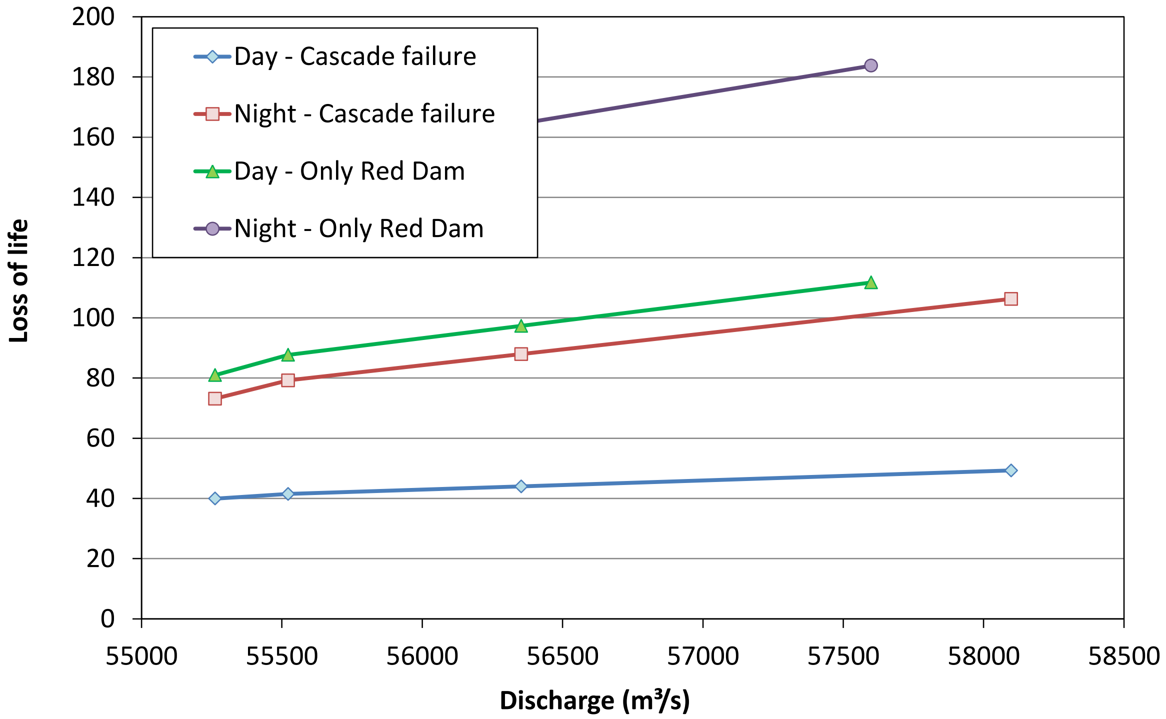
Within the European project SUFRI (SUstainable strategies for Flood RIsk reduction to cope with the residual risk), in the period of 2009–2011, fatality rates of the Graham method were adapted to incorporate different degrees of flood severity understanding depending on available warning systems, the existence of the Emergency Action Plan and the coordination between emergency services and authorities and education and training for the affected population. Fatality rates were divided into ten categories (table 10).

For the analysis of the Red Dam, category 3 was selected, since the Emergency Action Plan of the dam is already developed but not yet implemented.

Life loss calculations were performed for each of the identified potentially affected urban areas and facilities, and for each of the ten cases of the hydraulic model. The obtained curves of loss of life for downstream the Red Dam are shown in the following figures:



Loss of life results for FM6R and non-failure cases downstream Red Dam (Nodes 34 and 36).



Loss of life results for FM1R and FM2R downstream the Red Dam (Node 35).

Finally, **Node 40** is a node used by the risk model to sum all the loss of life data introduced in the different parts of the model.

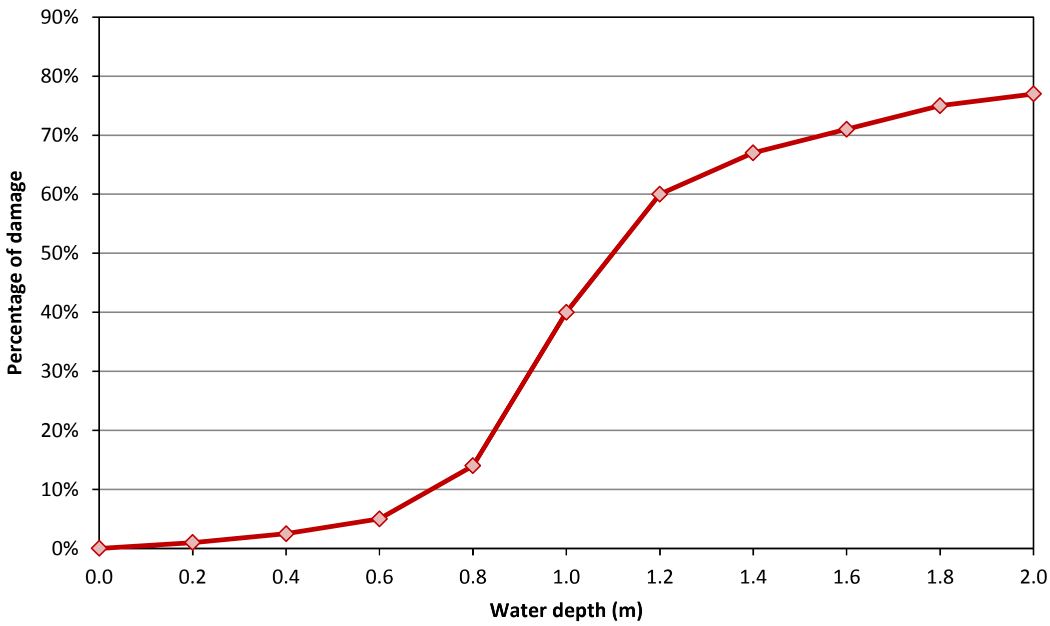
Estimation of economic consequences: Nodes 15, 16, 37, 38, 39 and 41

After analysing life-loss consequences, economic consequences have been estimated for failure and non-failure cases. All economic consequence calculations in this report are shown in Rs Crores.

These economic consequences were estimated based on the same hydraulic computations used to estimate loss of life. Two different curves were obtained: one for the economic consequences between the Green Dam (due to the agricultural crops between both reservoirs) and the other for the consequences downstream Red Dam.

The followed procedure for estimating consequences from flooding was to obtain a total destruction value for each flooded area, according to land uses, which is then multiplied by a coefficient of damage depending on flood depth. This relationship is usually represented by depth-damage curves or damage functions.

In this case, the depth-damage curve used is the one proposed by the PATRICOVA, Flood Risk Management Plan of the Valencian Region in Spain (Generalitat Valenciana 2015), for developing flood risk analyses and maps, and it is shown in the following figure:



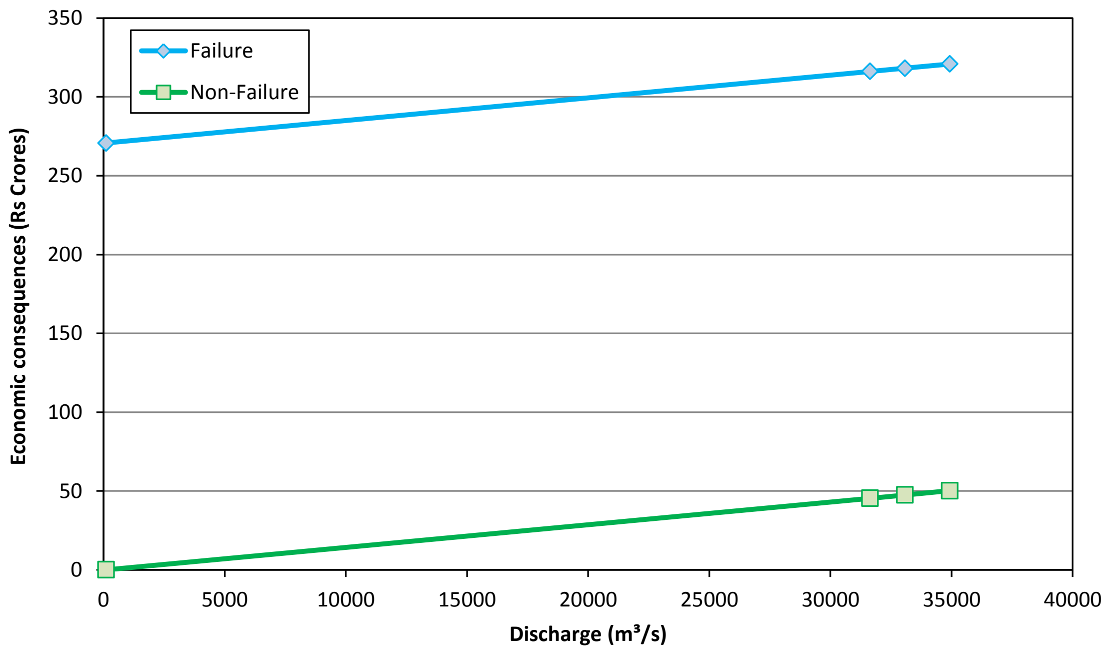
Depth-Damage Curve used to estimate direct economic consequences (Generalitat Valenciana 2015).

Reference land use values in urban areas have been estimated based on the recommendations from this Plan as well. Economic consequences are then obtained by combining the proposed depth-damage curve, land use values and maximum flood depths for each analysed case.

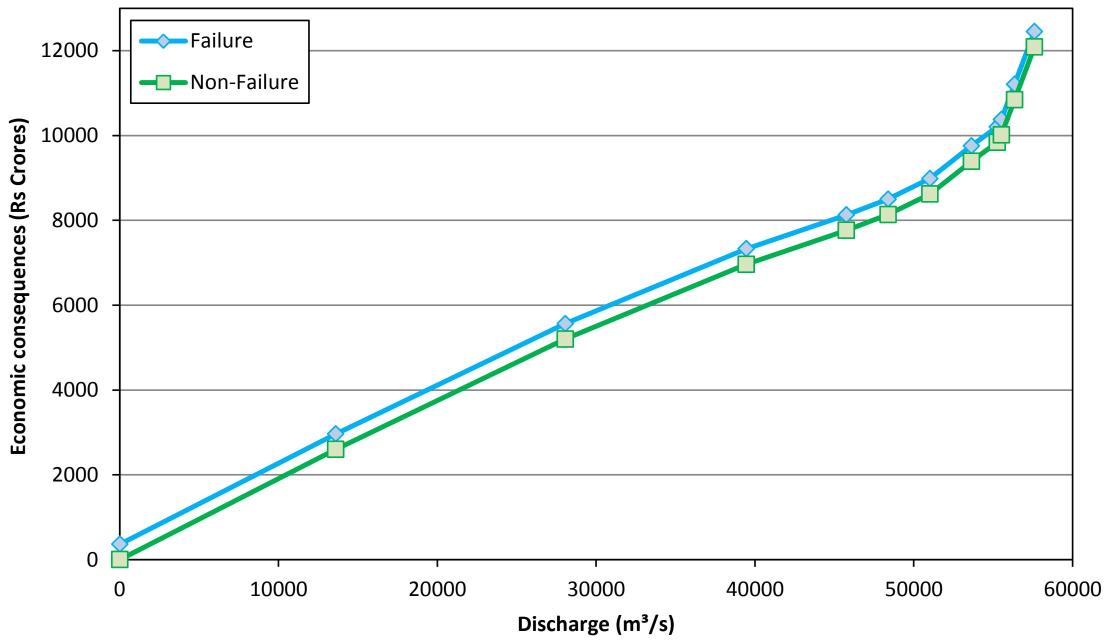
In addition, indirect costs of flooding have also been added, based on a rate of 27.5% of total direct costs of flooding, following recommendations from PATRICOVA (Generalitat Valenciana 2015) and including economic consequences from regional flooding. This plan includes a method for consequence estimation that has been a reference procedure for other analyses in Spain.

First economic consequences are produced when outflow is higher than 15 m^3/s.

Finally, the dam's reconstruction cost was also estimated from data on the construction cost of similar dams in Spain. In addition, the cost of loss of hydroelectric production in Green Dam based on the average annual flow and the height of the dam, using electricity production data from similar dams, has also been estimated. The result of this cost is 270.72 Rs Crores for Green Dam and 363.3 Rs Crores for the Red Dam. This reconstruction cost is the difference between failure and non-failure cases.



Economic consequences between Green and Red Dam (Nodes 15 and 16).



Economic consequences downstream Red Dam (Nodes 37, 38 and 39).

In order to compute economic consequences with these curves, the risk model uses failure peak discharges for failure cases and flood routing outflow discharges for non-failure cases.

Finally, **Node 41** is a node used by the risk model to sum all the economic consequences introduced in the different parts of the model.

3.4. Risk results in current situation

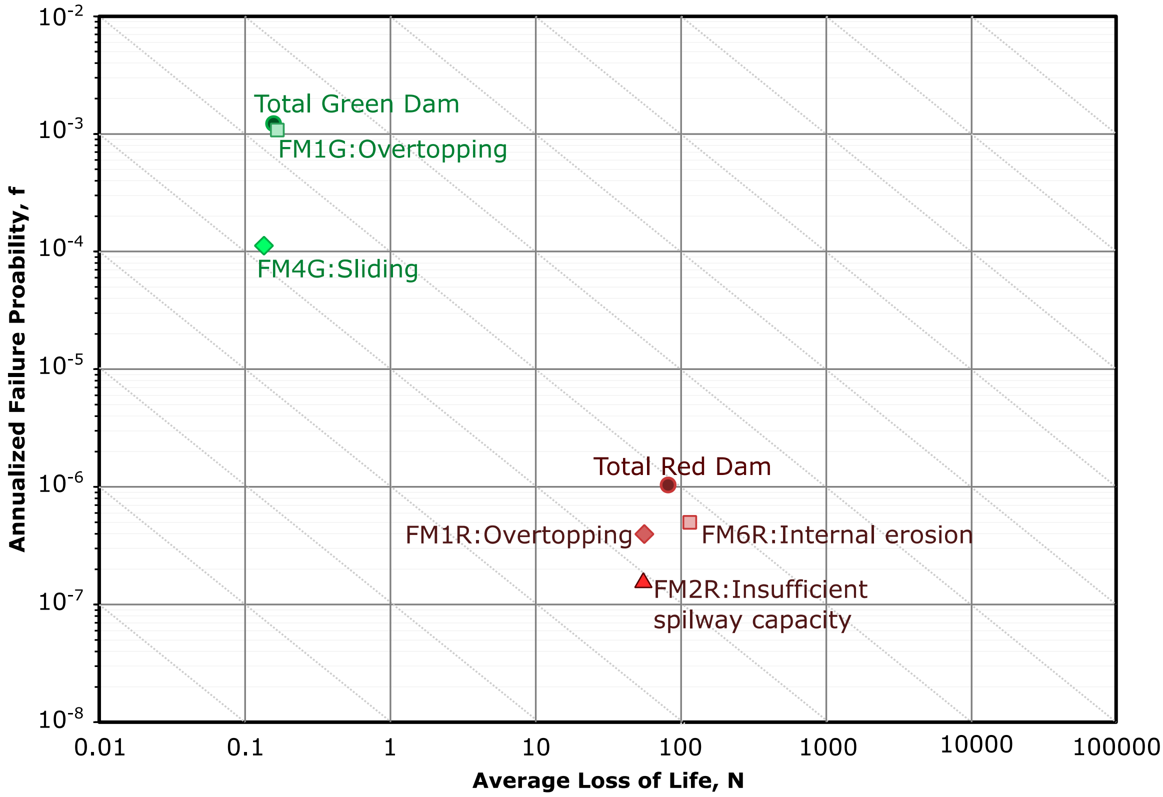
After completion of input data for risk calculation, and once incorporated in the risk model architecture, societal and economic risk was obtained. The following quantitative risk results were obtained:

Incremental risk
Fraction of risk that is exclusively due to dam failure. It is obtained by subtracting the consequences that would have happened even in case of non-failure from the consequences due to dam failure. In the following sections, this type of risk is compared with tolerability guidelines and is used to prioritize risk reduction actions. These results for both dams are shown in the following table:

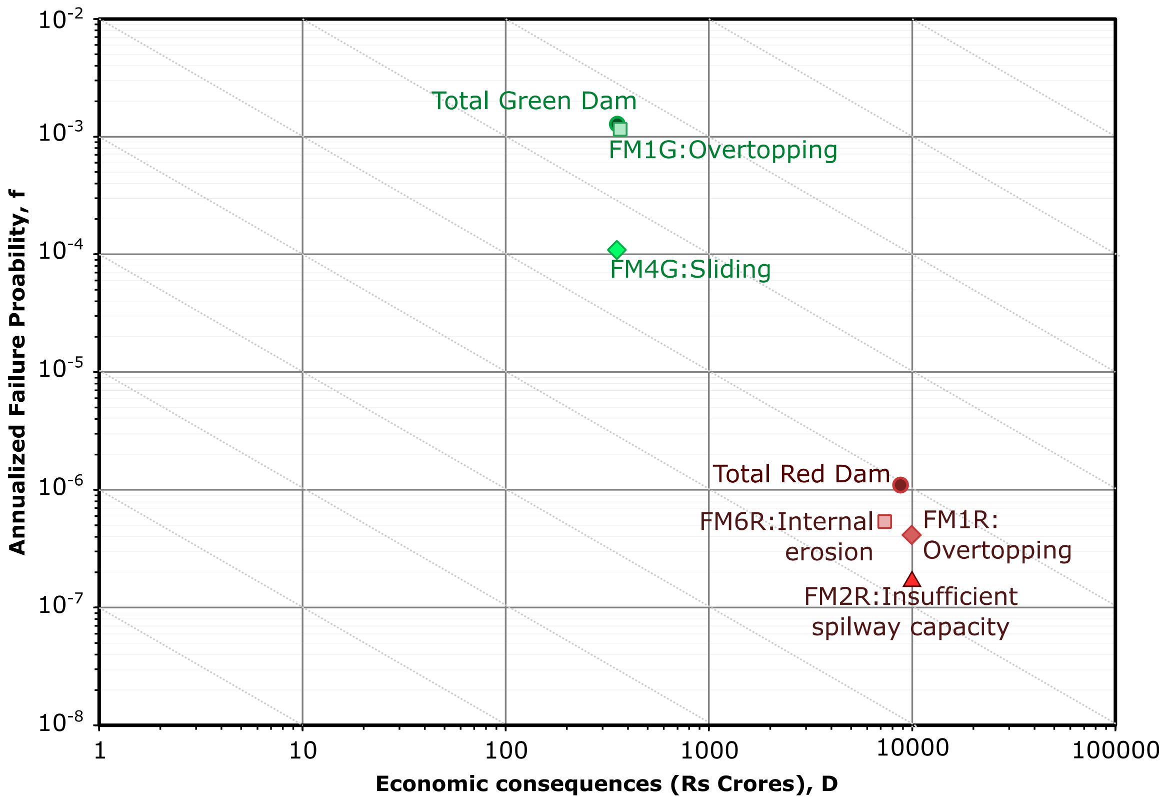
Failure mode	Failure probability (1/year)	Societal risk (lives/year)	Economic risk (Rs Crores/year)
Green Dam			
FM1G: Overtopping	1.108E-03	1.810E-04	4.003E-01
FM4G: Sliding	1.106E-04	1.498E-05	3.926E-02
Total	1.219E-03	1.960E-04	4.396E-01
Red Dam			
FM1R: Overtopping	3.960E-07	2.199E-05	4.003E-03
FM2R: Insufficient spillway capacity	1.598E-07	8.889E-06	1.620E-03
FM6R: Internal erosion	5.026E-07	5.816E-05	3.738E-03
Total	1.058E-06	8.904E-05	9.360E-03

Failure probability is clearly higher for the Green Dam than for the Red Dam, mainly due to overtopping failure mode. These results indicate that the Red Dam does not fail in most of the cases that the Green Dam fails, since this reservoir is able to manage the failure flood wave. However, societal risk is higher for the Red Dam, since loss of life is much higher if this dam fails, due to the importance of the populations located downstream. The three failure modes in the Red Dam have low probability with similar values.

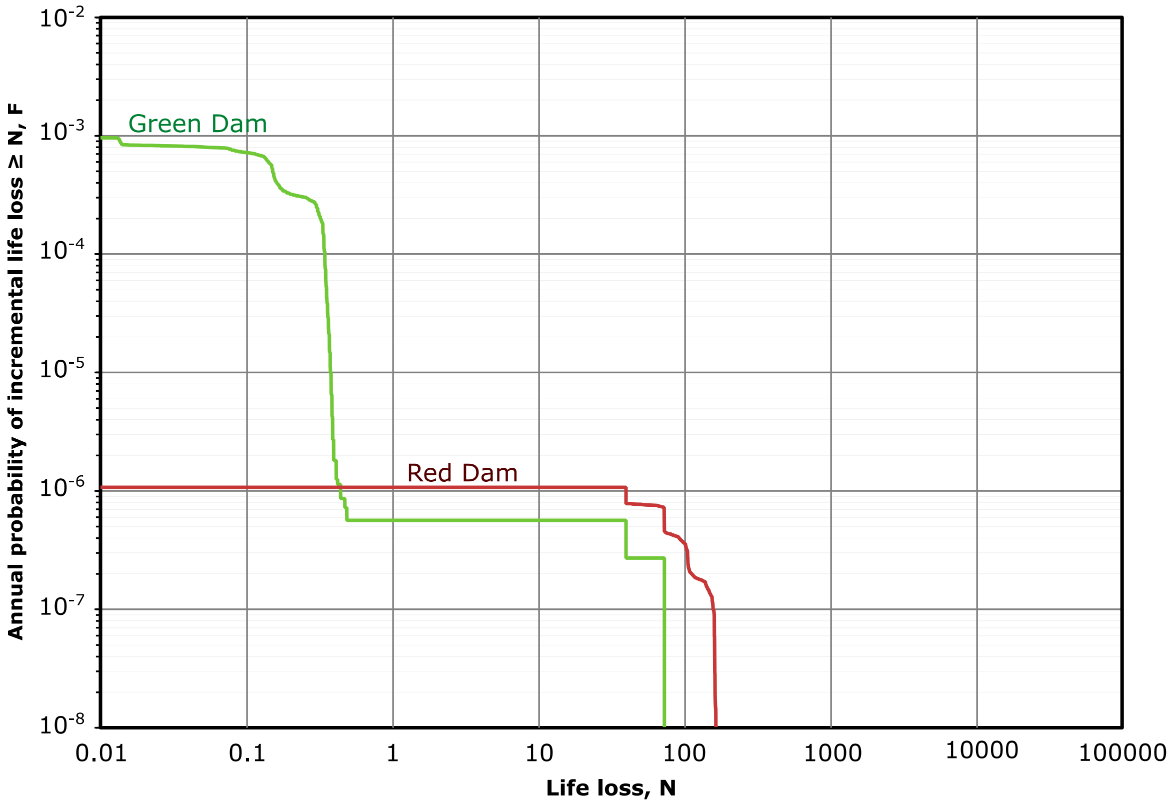
In the following figures, these incremental risk results are represented in fN, fD, FN and FD graphs:



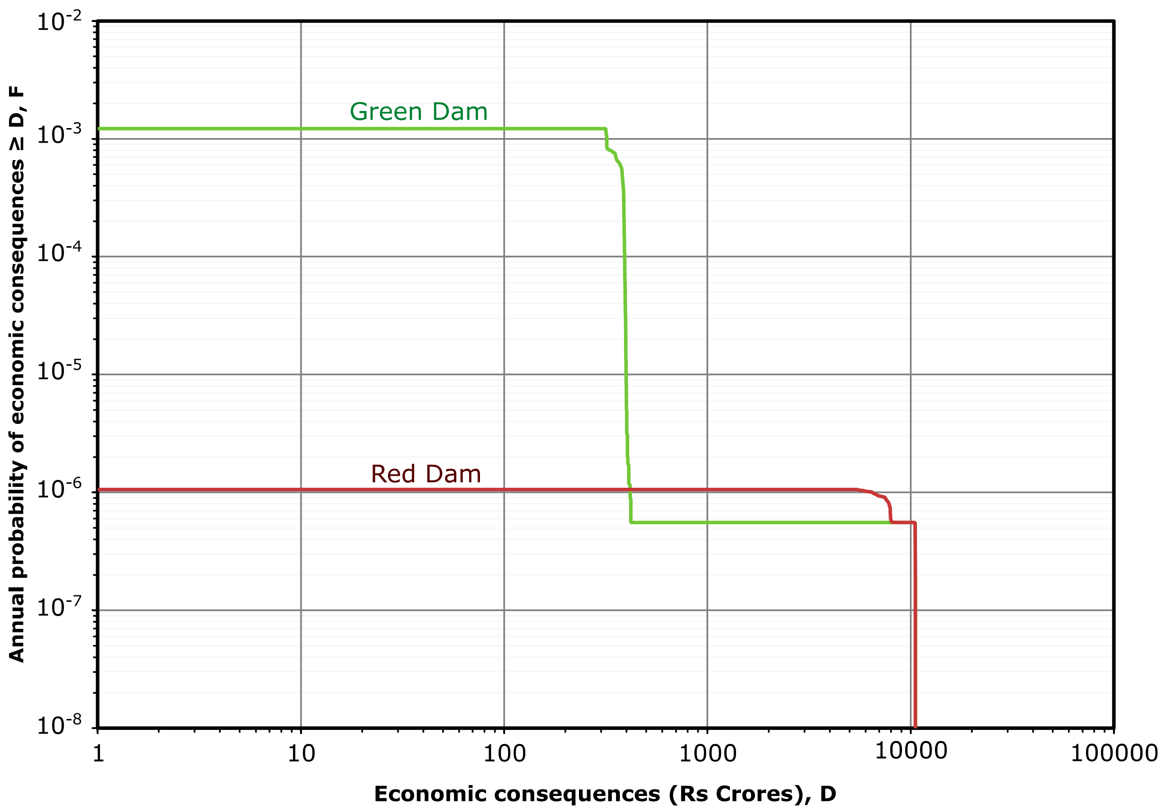
fN Graph with incremental risk results in current situation.



fD Graph with incremental risk results in current situation.



FN Graph with incremental risk results in current situation.



FD Graph with incremental risk results in current situation.

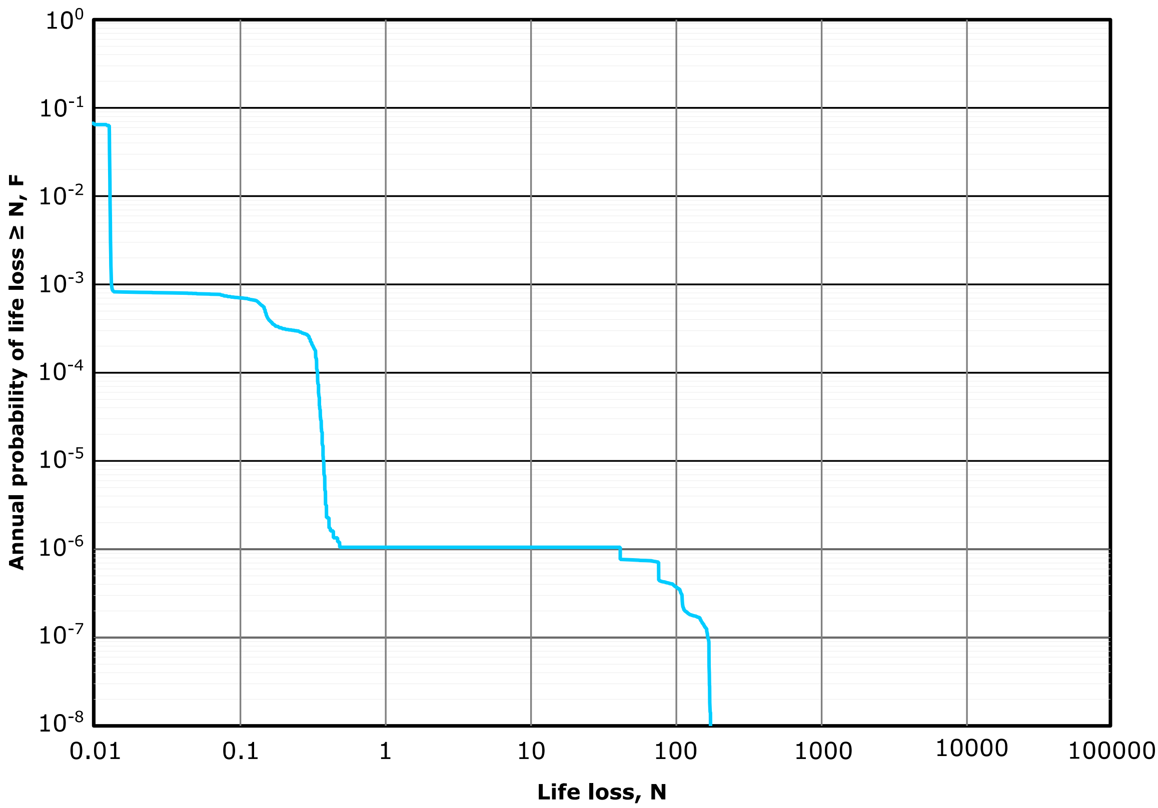
Hydrological failure modes of the Red Dam produce lower loss of life (due to higher warning times) and higher economic consequences (since inundation areas are larger). In addition, it can clearly be observed the difference between risks results in both dams. The Red Dam has lower failure probability with higher consequences while the Green Dam has higher failure probability with lower consequences, especially loss of life. In this sense, FN and FD graphs of the Green Dam show two clear parts, once when only the Green Dam fails (with lower consequences) and when there is a cascade failure (with lower probability and higher consequences). This cascade failure is the main cause of overtopping failure of the Red Dam.

Total risk

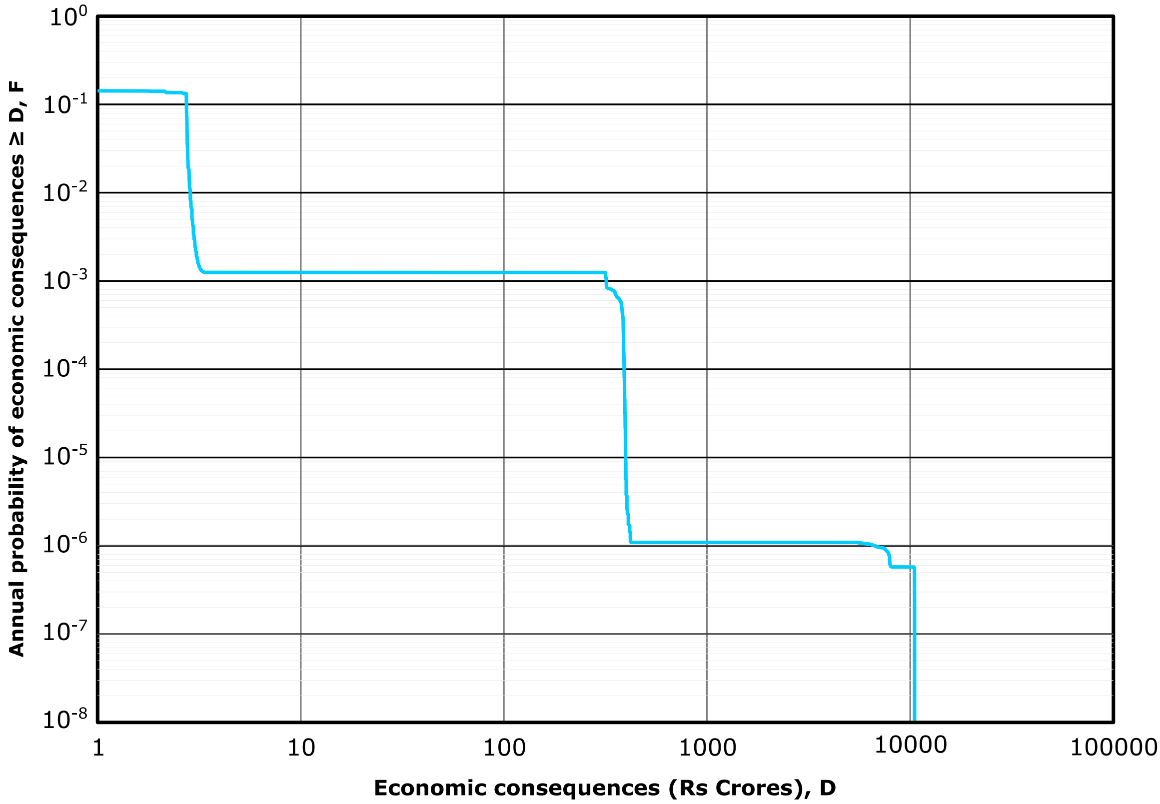
It represents total risk from flooding in downstream areas and includes both dam failure and non-failure cases. These results are shown in the following table:

Economic risk (Rs Crores/year)	Societal risk (lives/year)
8.296E-01	1.554E-03

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



FN Graph with total risk results in current situation.



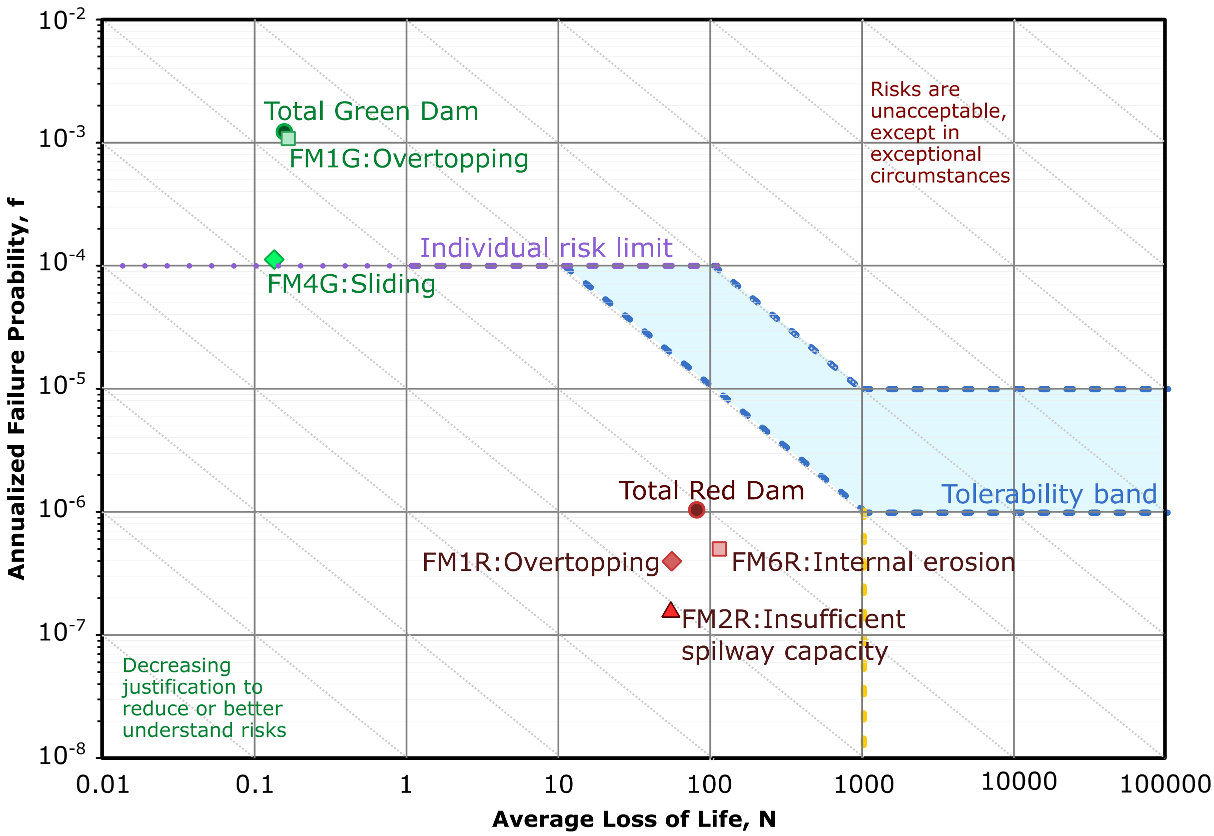
FD Graph with total risk results in current situation.

In these graphs, it can be observed the three main sources of flood risk downstream: due to normal floods (higher part with more probability and less consequences), due to the Green Dam Failure (middle part) and due to the Red Dam failure (lower part with lower probability and higher consequences).

3.5. 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 into decision-making by including the notion of risk importance.

In this case, individual and societal risks are evaluated following the tolerability recommendations from the *Guidelines for Assessing and Managing Risks Associated with Dams* elaborated by CWC in 2018. Risk evaluation results are shown in the following graph:



Individual and societal risk evaluation for current situation.

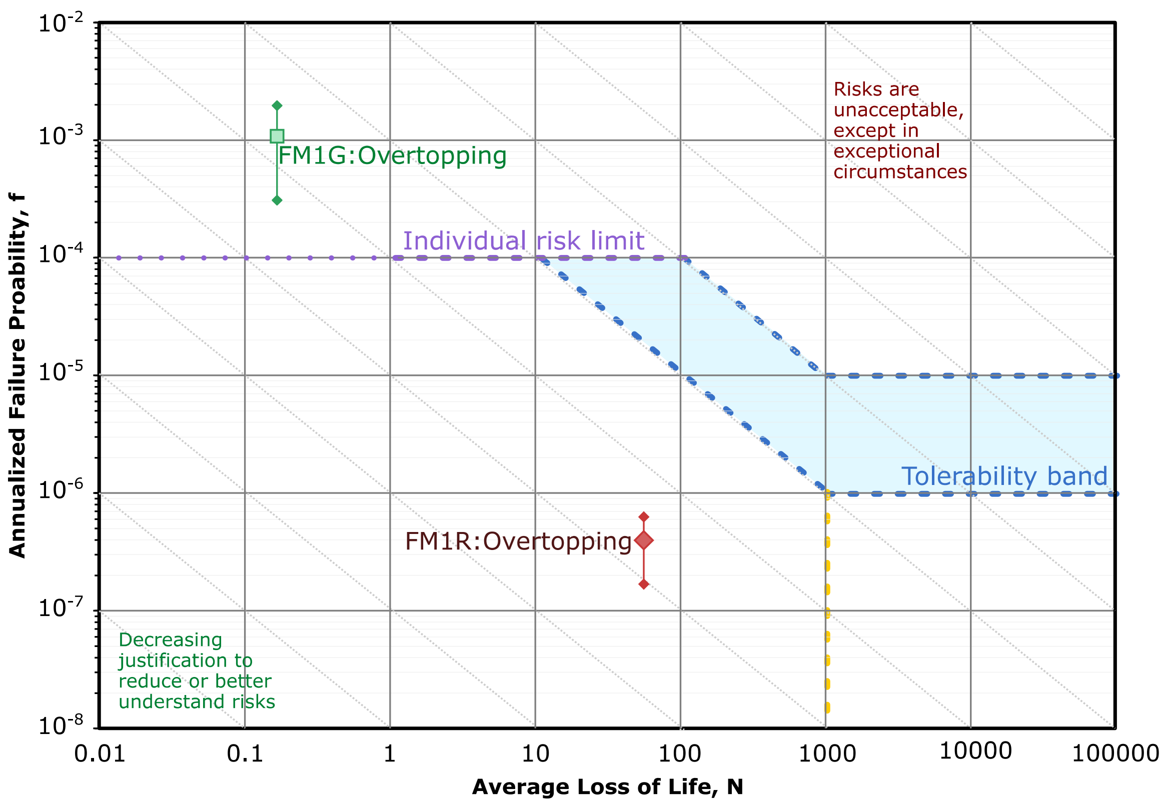
As can be observed in the evaluation graph, the Green Dam risks are above the individual risk limit for both failure modes, especially overtopping. Instead, all the failure modes in the Red Dam are aligned with the tolerability guidelines, since failure probability is much lower. In this sense, risk reduction measures that reduce failure probability of the Green Dam seem to be the most effective to achieve the proposed limits.

3.6. Uncertainty analysis

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

Method for hydrological analysis

In order to analyse uncertainty in hydrological data, two new families of inflow hydrographs were obtained by changing the methodological data applied in the hydrological model. These hydrographs were used to re-compute risk in both dams, obtaining the range of variation shown in the following figure:



Uncertainty analysis results for hydrological data.

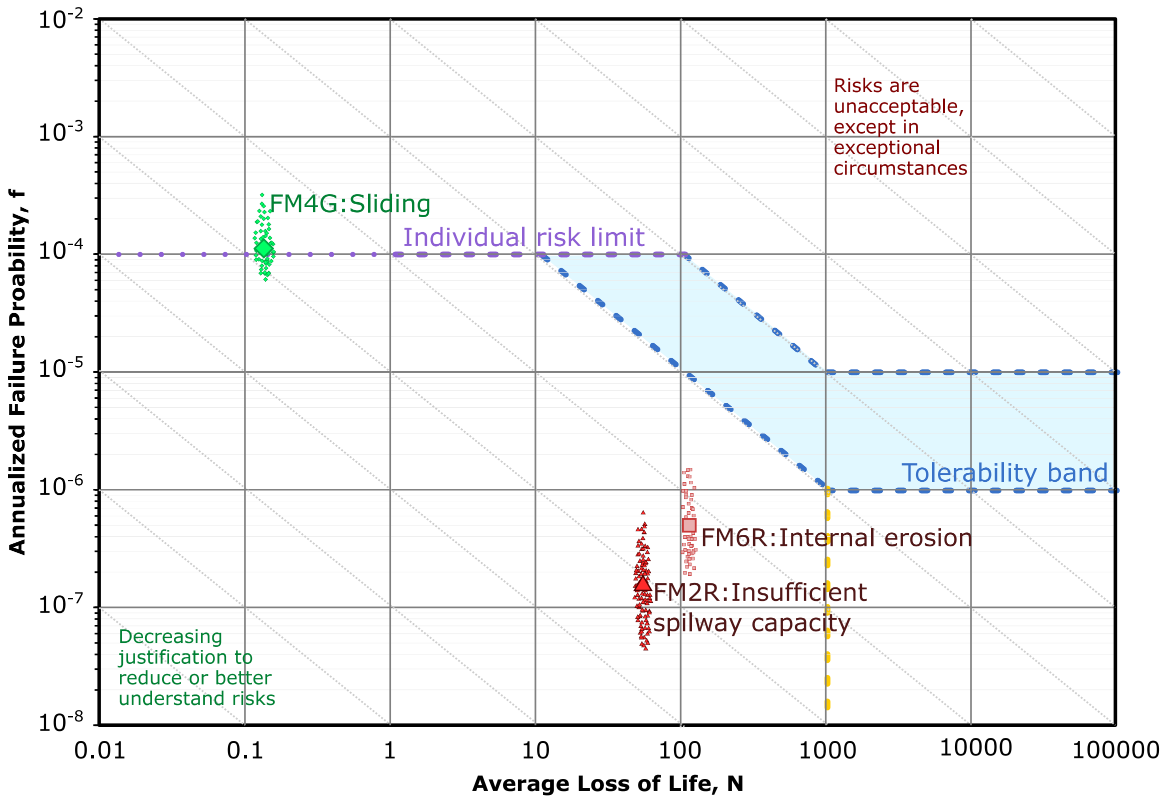
Results show how hydrological data uncertainty has a significant influence on overtopping risk results. However, in the Red Dam risk is always aligned with tolerability criteria and in Green Dam, risk is always above tolerability limits. This result shows that the accuracy of the last hydrological study is enough to promote risk reduction measures in the Green Dam, since failure probability is higher than 10^{-4} in all the cases.

Probabilities estimated by expert judgment

As explained in Section 3.3, most of the probabilities in failure modes FM4G, FM2R and FM6R were estimated by expert judgment. For each node, a better estimate of the probability was obtained and also a lower limit and an upper limit for these estimates. The best estimate was the value used to obtain the risk results shown in the previous graphs.

In order to analyse the uncertainty of these estimates, a triangular probability distribution was defined in each node. The extremes of this distribution were defined by the lower limit and the upper limit of the probability estimated in each node, while the midpoint was defined by its best estimate.

From these distributions, a Monte Carlo analysis was carried out by sampling independently 100 times each of the nodes and thus obtaining 100 different groups of probabilities. With these groups of probabilities, 100 different risk results were obtained that characterize the uncertainty in the estimates. In this way, the variation in the risk results can be analysed according to the uncertainty expressed by the participants in the failure probabilities estimation session. The 100 risk results form a point cloud that is shown in the following figures, classified by failure modes.

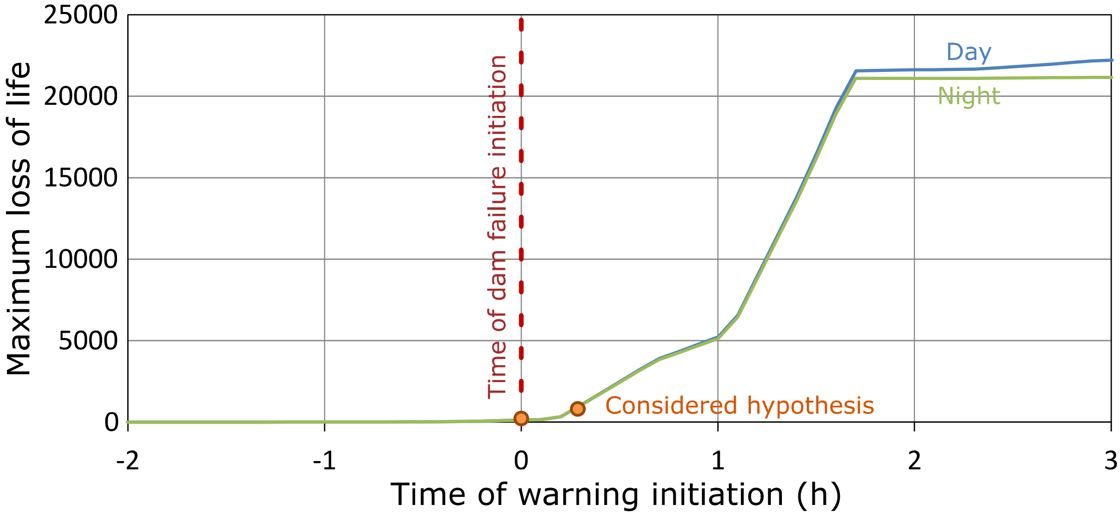


Uncertainty analysis results for probabilities estimated by expert judgement.

These results show that expert judgement uncertainty does not have a high influence on the conclusions reached based on risk results. In the Red Dam failure modes, risks are still below the tolerability limits in all the cases. In the Green Dam, the degree of variation of the sliding failure mode is not high (less than one order of magnitude), since in this dam the predominant failure mode is overtopping, this variation does not change the conclusions reached about this dam.

Warning time used to estimate loss of life

Since there are very important populations living downstream of the Red Dam, a sensitivity analysis was made to analyse how loss of life would be incremented if the time of initiation of warning to the population downstream is made some time after the failure of the dam. The results obtained are shown in the following figure:



Uncertainty results of loss of life for time of warning initiation.

These results show that loss of life could be incremented (almost two orders of magnitude) if warnings are not made properly. These results indicate the importance of warning procedures and population awareness to avoid loss of life in case of dam failure, since one of the most important cities of the region is located downstream of the dam.

3.7. Prioritization of risk reduction actions

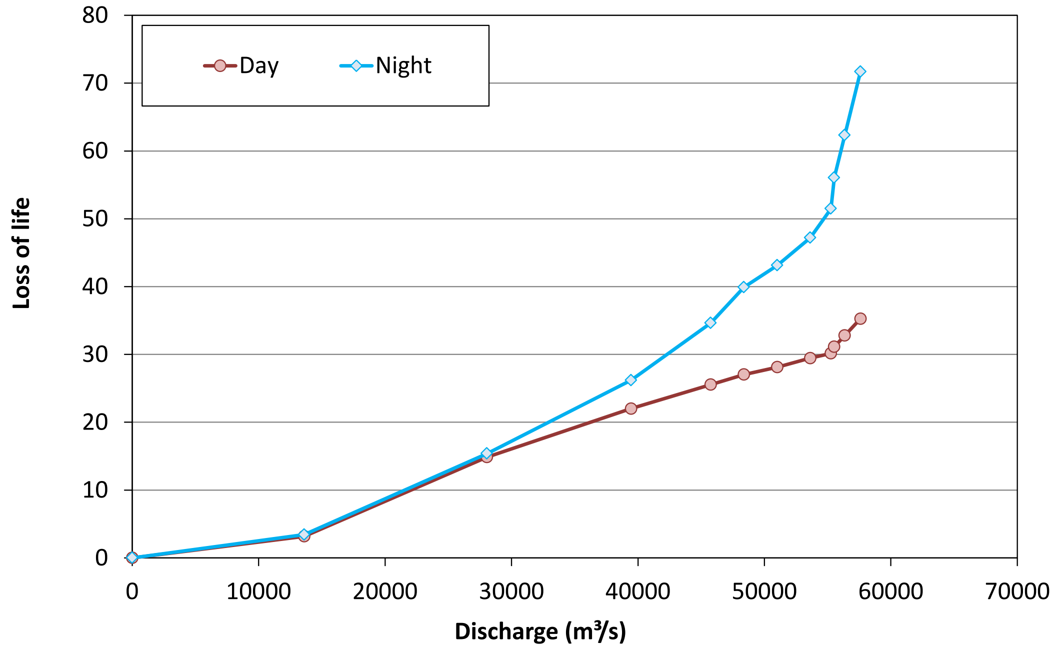
Proposed risk reduction actions

The final stage in a Quantitative Risk Assessment is the study of potential risk reduction measures. Six measures were selected from identification of failure modes recommendations (Sections 2.7 and 2.8), risk results, technical inspections and, in general, expected measures planned for each dam. Based on these inputs, the proposed measures were discussed by the team group, defining them with more detail. The proposed risk reduction actions are:

Measure 1	Emergency Action Plan		
Introduction cost (Rs Crores)	5.3626	Maintenance cost (Rs Crores/year)	0.26813
Lifespan (years)	20	Failure Modes	All failure modes
Description			
This improvement consists of the joint implementation of the Emergency Action Plans of the Green and Red Dams, which entail the improvement of emergency response procedures and a better communication to the downstream population through warning systems. This plan is currently written but it is not implemented.			
Graphical scheme			

Effect on risk model
In this case, this measure affects the loss of life in the cases of breakage and non-breakage of the dams (Nodes 13, 14, 34, 35 and 36). To include the effect of this measure within the risk model, the loss of life has been calculated again using the Graham method. As shown in Section 3.3, within the European project SUFRI, the rates of this method have been adapted to study different degrees of understanding of the flood-severity depending on the warning systems, the existence or not of an Emergency Action Plan and the coordination between the emergency services. To do this, the mortality rates were divided into ten categories. In the case considered, category 4 has been chosen (instead of Category 3 used in the base case), which includes the implementation of the Emergency Plan for

Dams. For instance, the effect of this measure in the loss of life for the internal erosion failure mode (Node 34) is shown in the following figure:

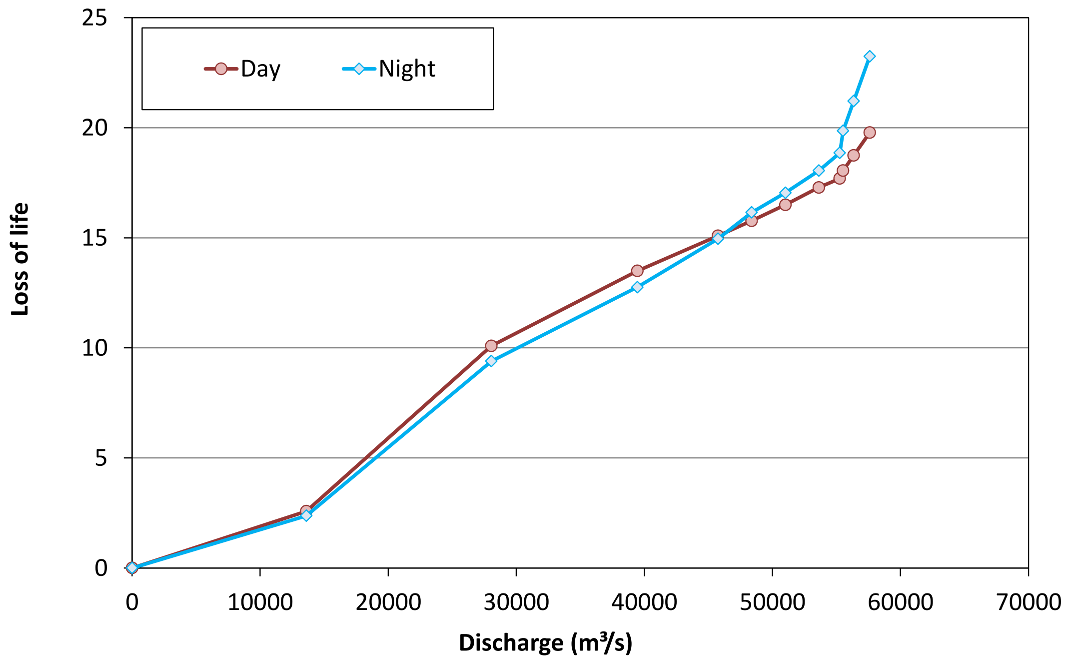


Loss of life results for FM6R downstream Red Dam (Nodes 34) after implementing Emergency Action Plan.

As can be observed, this measure has a high influence to reduce loss of life in case of failure.

Measure 2	Flood Awareness Campaigns downstream		
Introduction cost (Rs Crores)	0	Maintenance cost (Rs Crores/year)	0.26813
Lifespan (years)	20	Failure Modes	All failure modes
Description			
This measure was proposed due to fact that the uncertainty analysis resulted in high influence of warning procedures on loss of life consequences. It consists of complementing the implementation of the Emergency Plan of the two dams with Continuous Flood Awareness Campaigns to the population downstream of the Red Dam. These campaigns will be useful to improve the population behaviour and procedures in case of emergency, reducing the potential loss of life. For this, it is necessary a program of continuous training to the population, including drills, and an efficient coordination of the media, emergency services and security forces, in order to reduce the loss of life as much as possible. This measure only has sense after implementing the Emergency Action Plan for these dams.			
Effect on risk model			
Like the previous measure, this option only affects the loss of life (Nodes 13, 14, 34, 35 and 36). Therefore, the calculations made to estimate loss of life using the Graham method have been carried out again with updated mortality rates that include greater population awareness. In this case, within the ten categories developed in the methodology of the SUFRI project to apply the			

Graham method, category 10 has been chosen, which includes the situation with a greater formation of the population. For instance, the effect of this measure in the loss of life for the internal erosion failure mode (Node 34) is shown in the following figure:



Loss of life results for FM6R downstream Red Dam (Nodes 34) after implementing Emergency Action Plan and Flood Awareness Campaigns downstream.

As can be observed, this measure has a high influence to reduce loss of life in case of failure.

Measure 3	Drainage rehabilitation in Green Dam		
Introduction cost (Rs Crores)	0.911	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	20	Failure Modes	FM4G
Description			
As explained previously, during the technical visit it was observed that some foundation drains are not working properly due to its age and obstructions can be observed. Water leakage does not concentrate in the drains, but it seems to soak the whole lower part of the dam body, producing water leakage and uplift pressures dissipation in the drainage gallery. Therefore, with this measure a complete drilling of foundation drains is proposed. This measure was already foreseen by the management and maintenance team of the Green Dam.			
Effect on risk model			
This measure mainly affects the node of high uplift pressures of the sliding failure mode (Node 8) of the Green Dam, since the drilling of drains decreases the probability of high uplift pressures at the dam-foundation surface. This probability has been reduced from 5% to 2%.			

Measure 4	Reinforcement of parapet wall in Green Dam		
Introduction cost (Rs Crores)	1.9059	Maintenance cost (Rs Crores/year)	0.26813
Lifespan (years)	50	Failure Modes	FM1G

Description

This measure consists of reinforcing and maintaining the continuous parapet wall located at the crest of the Green Dam, so that it has enough strength to resist the water pressure and therefore, overtopping would not begin until the reservoir level reaches the wall crest. This parapet wall was deliberately prolonged in the right abutment until coming into contact with the abutment rock. In addition, there is structural connection between the parapet and the dam body.

Graphical scheme


Parapet wall of Green Dam to be reinforced.

Effect on risk model

This measure modifies the risk model by changing the level of coronation that goes from 1143.8 to 1145 m.a.s.l., since the parapet is 1.2 meters high. Therefore, when applying this measure, it is considered that overtopping occurs only when the water exceeds 1145 m.a.s.l., calculating the probability of overtopping failure from this level. For this reason, the Node 7 is modified with this new crest level. It also changes the flood routing results since overflow is only considered above this new crest level (1145 m.a.s.l.).

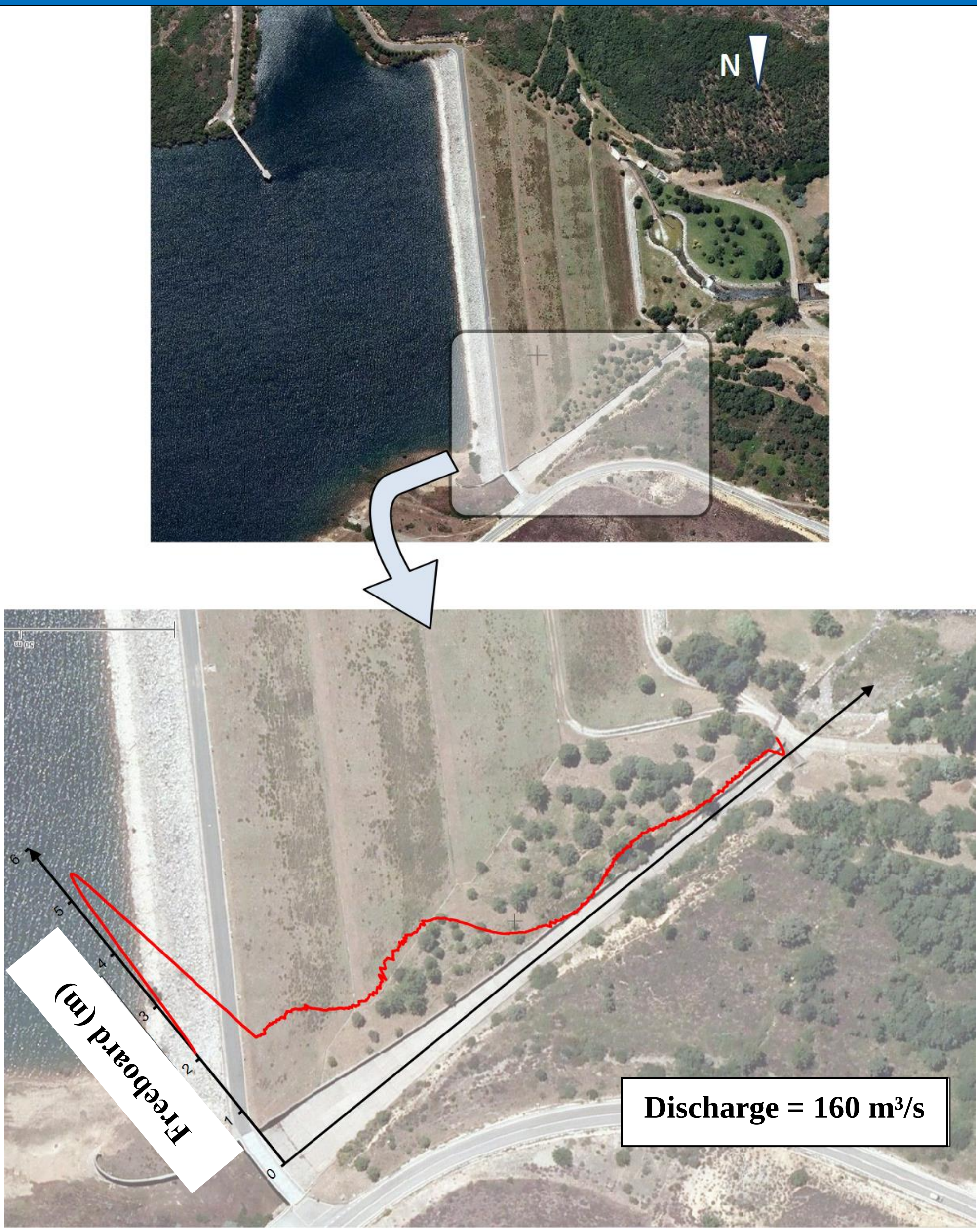
Measure 5	Improvement of Red Dam spillway		
Introduction cost (Rs Crores)	7.0154	Maintenance cost (Rs Crores/year)	0
Lifespan (years)	50	Failure Modes	FM2R

Description

This measure is based on the recommendations obtained from the Failure Modes Identification sessions and the results of the numerical analysis made of the Red Dam spillway. It consists of constructing higher walls in the lower part of the spillway and improvement of the discharge channel to ensure a good behaviour and to avoid damaging the embankment toe.

As shown in the following figure, in the lower part of the spillway the lowest freeboards are obtained, so this is the part that should be reinforced to improve spillway performance. This part is where spillway walls would be raised. In addition, the final part of the spillway would be reinforced to avoid toe erosion.

Graphical scheme



Freeboard obtained in the numerical model for each part of the spillway.

Effect on risk model

In order to introduce this measure in the risk model, it has been considered that if these improvements are executed, this overflow failure mode in the spillway (FM2R) should be removed from the risk model, since it is not considered credible anymore. Therefore, Nodes 27, 28, 29, 30 and 31 are modified.

Measure 6	Improvement of Red Dam monitoring		
Introduction cost (Rs Crores)	1.0543	Maintenance cost (Rs Crores/year)	0.0527
Lifespan (years)	30	Failure Modes	FM6R

Description

This measure arises from the recommendations of the Identification of Failure Modes sessions in order to improve knowledge about pore pressures in the Red Dam body and water seepage. In this way, the characteristics of the flow can be known and detected and avoid a possible internal erosion process. This data will also be useful to analyse sliding failure modes in the Red Dam, as explained in Section 4.3.

The main improvement proposed in the hydraulic monitoring of the Red Dam is recovering or replacing the piezometers equipment that is currently inoperative. The installation or recovery of this equipment in the downstream slope of the dam is especially recommended, so the flow characteristics in this area can be better known. In addition, in some areas water seepage can be better controlled, discretizing between the different parts of the dam and analysing potential movements of soil particles.

Effect on risk model

This measure affects the node of non-detection and/or not intervention (Node 25) in the internal erosion failure mode of the Red Dam, since the improvement of the monitoring system will help to detect and to avoid a process of this type. The probability of this node has been modified from 17% to 5%.

Effect on incremental risk results

After defining these measures, the next step was to recalculate risk by incorporating the effect of each measure into the risk model with incremental risks. Results obtained for each measure are shown in the following table:

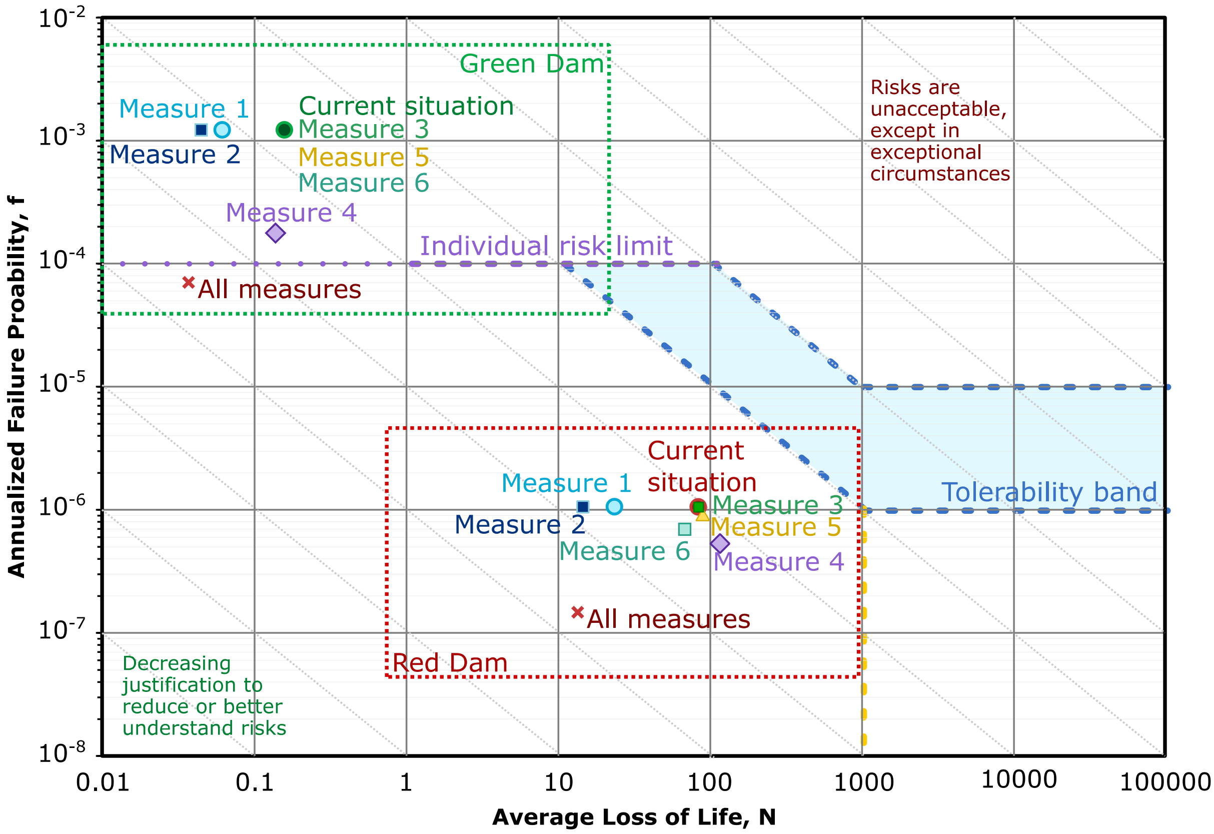
Current situation			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.108E-03	1.810E-04	4.003E-01
FM4G: Sliding	1.106E-04	1.498E-05	3.926E-02
Total	1.219E-03	1.960E-04	4.396E-01
Red Dam			
FM1R: Overtopping	3.960E-07	2.199E-05	4.003E-03
FM2R: Insufficient spillway capacity	1.598E-07	8.889E-06	1.620E-03
FM6R: Internal erosion	5.026E-07	5.816E-05	3.738E-03
Total	1.058E-06	8.904E-05	9.360E-03
Measure 1: Emergency Action Plan			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.108E-03	6.793E-05	4.003E-01
FM4G: Sliding	1.106E-04	5.596E-06	3.926E-02
Total	1.219E-03	7.353E-05	4.396E-01
Red Dam			
FM1R: Overtopping	3.960E-07	8.535E-06	4.003E-03
FM2R: Insufficient spillway capacity	1.598E-07	3.449E-06	1.620E-03
FM6R: Internal erosion	5.026E-07	1.276E-05	3.738E-03
Total	1.058E-06	2.474E-05	9.360E-03

Measure 2: Flood Awareness Campaigns downstream			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.108E-03	5.086E-05	4.003E-01
FM4G: Sliding	1.106E-04	4.203E-06	3.926E-02
Total	1.219E-03	5.506E-05	4.396E-01
Red Dam			
FM1R: Overtopping	3.960E-07	6.246E-06	4.003E-03
FM2R: Insufficient spillway capacity	1.598E-07	2.524E-06	1.620E-03
FM6R: Internal erosion	5.026E-07	6.786E-06	3.738E-03
Total	1.058E-06	1.556E-05	9.360E-03
Measure 3: Drainage rehabilitation in Green Dam			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.110E-03	1.813E-04	4.009E-01
FM4G: Sliding	4.427E-05	5.998E-06	1.572E-02
Total	1.154E-03	1.873E-04	4.166E-01
Red Dam			
FM1R: Overtopping	3.957E-07	2.198E-05	4.000E-03
FM2R: Insufficient spillway capacity	1.523E-07	8.471E-06	1.543E-03
FM6R: Internal erosion	5.026E-07	5.816E-05	3.738E-03
Total	1.051E-06	8.861E-05	9.281E-03
Measure 4: Reinforcement of parapet wall in Green Dam			
Failure mode	**Failure probability**	**Societal risk (lives/year)**	**Economic risk (Rs**

	(1/year)		Crores/year)
Green Dam			
FM1G: Overtopping	4.971E-09	2.32E-08	5.91E-06
FM4G: Sliding	1.745E-04	2.41E-05	6.21E-02
Total	1.745E-04	2.41E-05	6.21E-02
Red Dam			
FM1R: Overtopping	4.253E-09	2.36E-07	4.30E-05
FM2R: Insufficient spillway capacity	2.114E-08	1.18E-06	2.14E-04
FM6R: Internal erosion	5.027E-07	5.82E-05	3.74E-03
Total	5.281E-07	5.96E-05	4.00E-03
Measure 5: Improvement of Red Dam spillway			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.108E-03	1.729E-04	3.989E-01
FM4G: Sliding	1.106E-04	1.426E-05	3.912E-02
Total	1.219E-03	1.871E-04	4.380E-01
Red Dam			
FM1R: Overtopping	3.961E-07	2.200E-05	4.004E-03
FM2R: Insufficient spillway capacity	0.000E+00	0.000E+00	0.000E+00
FM6R: Internal erosion	5.029E-07	5.819E-05	3.741E-03
Total	8.990E-07	8.019E-05	7.744E-03
Measure 6: Improvement of Red Dam monitoring			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	1.108E-03	1.810E-04	4.003E-01

FM4G: Sliding	1.106E-04	1.498E-05	3.926E-02
Total	1.219E-03	1.960E-04	4.396E-01
Red Dam			
FM1R: Overtopping	3.960E-07	2.199E-05	4.003E-03
FM2R: Insufficient spillway capacity	1.598E-07	8.889E-06	1.620E-03
FM6R: Internal erosion	1.480E-07	1.712E-05	1.100E-03
Total	7.038E-07	4.800E-05	6.723E-03
All measures			
Failure mode	**Failure probability (1/year)**	**Societal risk (lives/year)**	**Economic risk (Rs Crores/year)**
Green Dam			
FM1G: Overtopping	9.964E-09	1.317E-08	1.182E-05
FM4G: Sliding	6.979E-05	2.565E-06	2.475E-02
Total	6.980E-05	2.578E-06	2.477E-02
Red Dam			
FM1R: Overtopping	2.010E-09	3.170E-08	2.032E-05
FM2R: Insufficient spillway capacity	0.000E+00	0.000E+00	0.000E+00
FM6R: Internal erosion	1.480E-07	1.998E-06	1.100E-03
Total	1.500E-07	2.030E-06	1.121E-03

These results can also be represented in the tolerability graph shown in the previous section:



Individual and societal risk evaluation for proposed risk reduction actions.

The following conclusions were obtained from these results:

- The Emergency Action Plan (Measure 1) has a direct effect on the loss of life. The existence of good protocols and systems for alerting and evacuating the population reduces societal risk, moving fN points toward left, although it does not change failure probability nor economic risk.
- Complementing these plans with Flood Awareness Campaigns downstream (Measure 2) help to reduce loss of life even more.
- The rehabilitation of drains in the Green Dam (Measure 3) improves the drainage system of the foundation, which decreases the probability of high uplift pressures, and therefore, reduces the probability of sliding failure in this dam. Since in this dam the predominant failure mode is overtopping, this effect is not so high on the total results but it is clear in the sliding failure mode.
- Reinforcing and maintaining the parapet wall (Measure 4) reduces significantly the overtopping failure probability in the Green Dam but also in the Red Dam, since probability of cascade failure is reduced.
- The improvement of the Red Dam spillway (Measure 5) has a limited effect on the Red Dam total risk, since this is not the predominant failure mode in this dam. Its effect on the Green Dam risk is very limited.

- Finally, the improvement of hydraulic monitoring in the Red Dam (Measure 6) reduces internal erosion failure probability in this dam. Its effect on the Green Dam risk is very limited.

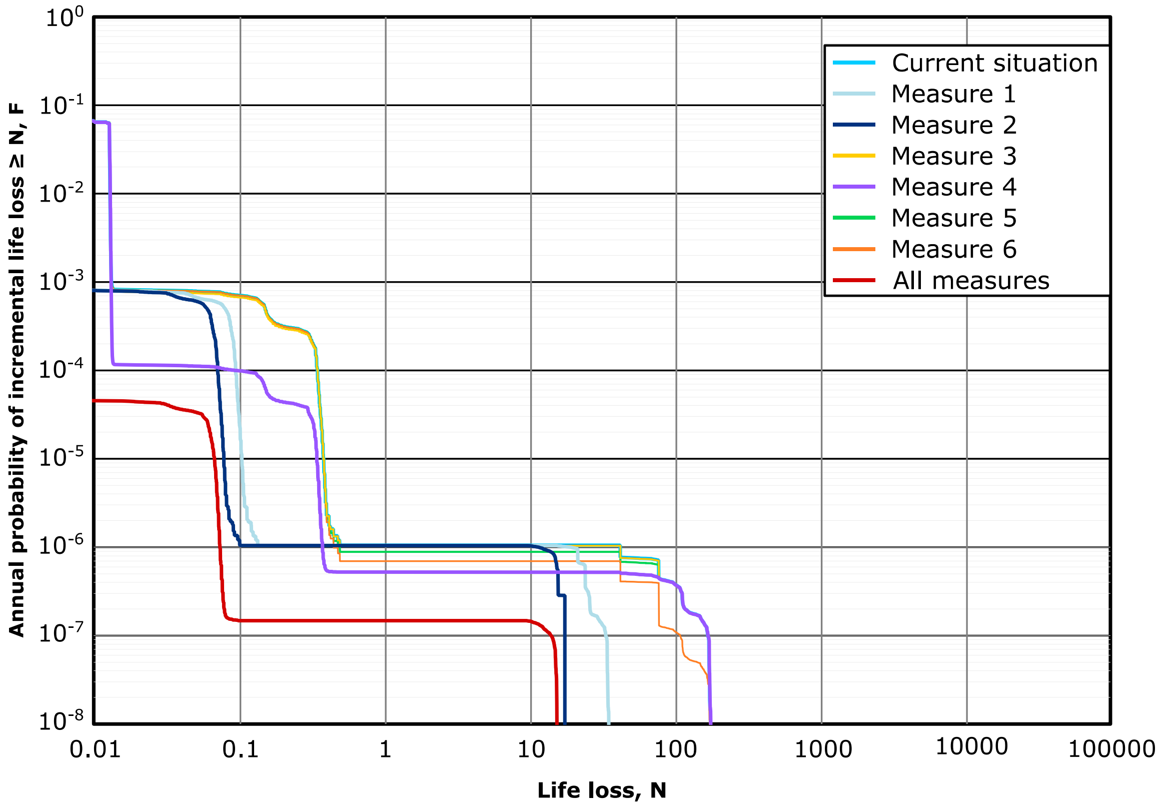
Effect on total risk results

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	1.554E-03	8.296E-01
Measure 1: Emergency Action Plan	5.707E-04	8.296E-01
Measure 2: Flood Awareness Campaigns downstream	4.262E-04	8.296E-01
Measure 3: Drainage rehabilitation in Green Dam	1.545E-03	8.066E-01
Measure 4: Reinforcement of parapet wall in the Green Dam	1.382E-03	4.515E-01
Measure 5: Improvement of the Red Dam spillway	1.545E-03	8.280E-01
Measure 6: Improvement of the Red Dam monitoring	1.513E-03	8.270E-01
All measures	3.690E-04	4.115E-01

As can be observed in this table, all the measures contribute to reduce total flood risk downstream (societal and/or economical). Measure 1 and 2 are especially effective to reduce societal risk while reinforcing the parapet wall is the most effective measure to reduce economic risk.

Effect of risks reduction measures was also represented in an FN graph for total risk:



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

As can be observed, Measures 1 and 2 reduce risk (moving the curves toward left) in failure and non-failure cases, while the rest of measures only change the failure part.

Prioritization of risk reduction actions

Finally, proposed risk reduction actions were prioritized according to incremental risk and the EWACSLS indicator (with n = 1) to combine equity and efficiency criteria. The discount rate considered is 5%. 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	0.678	3.63E+03	3.63E+03
Measure 2: Flood Awareness Campaigns downstream	0.268	9.70E+03	9.70E+03
Measure 3: Drainage rehabilitation in the Green Dam	0.070	5.11E+03	4.84E+03
Measure 4: Reinforcement of parapet wall in the Green Dam	0.099	<0	<0

Measure 5: Improvement of the Red Dam spillway	0.366	2.05E+04	2.05E+04
Measure 6: Improvement of the Red Dam monitoring	0.118	2.81E+03	2.81E+03

ACSLS of Measure 4 is negative, which indicates that this measure is 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 are used in an iterative process to obtain a sequence of risk reduction actions. The steps of the obtained sequence are:

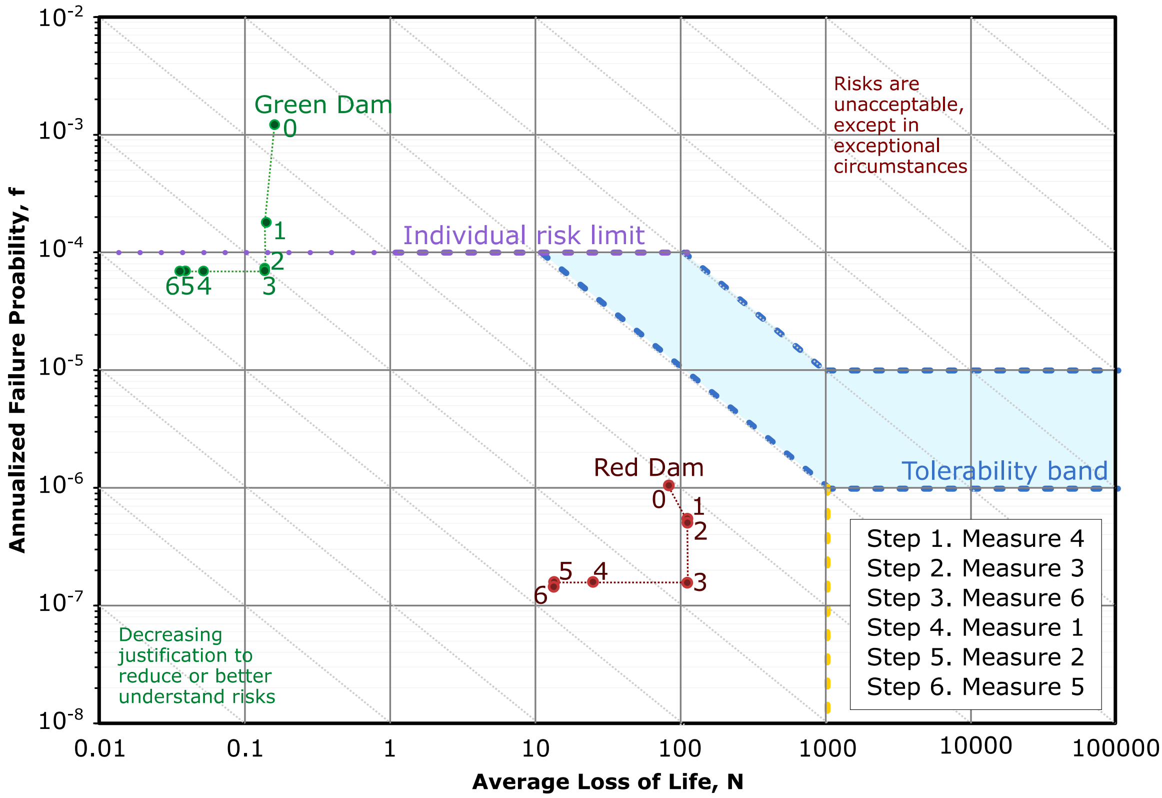
Step	Measure	Societal risk (lives/year)	Economic risk (Rs Crores /year)	ACSLS (Rs Crores /life)	EWACSLS (Rs Crores/life)
1	Measure 4: Reinforcement of parapet wall in the Green Dam	2.850E-04	4.490E-01	< 0	< 0
2	Measure 3: Drainage rehabilitation in the Green Dam	2.440E-04	4.463E-01	2.11E+03	1.20E+03
3	Measure 6: Improvement of Red Dam monitoring	4.266E-05	6.347E-02	2.81E+03	2.81E+03
4	Measure 1: Emergency Action Plan	2.738E-05	2.606E-02	3.43E+04	3.43E+04
5	Measure 2: Flood Awareness Campaigns downstream	7.594E-06	2.606E-02	9.86E+04	9.86E+04
6	Measure 5: Improvement of Red Dam spillway	4.875E-06	2.606E-02	1.37E+06	1.37E+06

As can be observed in this table, when all the proposed measures are implemented, societal risk is reduced in $2.8 \cdot 10^{-4}$ lives/year and economic risk is reduced in 0.423 Rs Crores/year. The total introduction cost of these measures is 16.25 Rs Crores and the total annualized (including implementation and maintenance) is 1.6 Rs Crores/year.

As can be observed, the measure with the lowest ACSLS and EWACSLS values is Measure 3. Therefore, it is the first step of the recommended sequence of measures. These results are logic since it is not very expensive and it is the measure that has the highest influence on reducing failure probability in the Green Dam. Next, drainage rehabilitation reduces the Green Dam risk results to be aligned with tolerability guidelines. Next, the following measures will help to reduce failure probability and risks in the tolerable area. These risk results are useful to prioritize these risk reduction actions within the Dams Portfolio management.

It can be observed that ACSLS and EWACSLS after Step 3, when failure probability of both dams is lower than 10^{-4}.

This itinerary can also be represented in the risk tolerability graph:

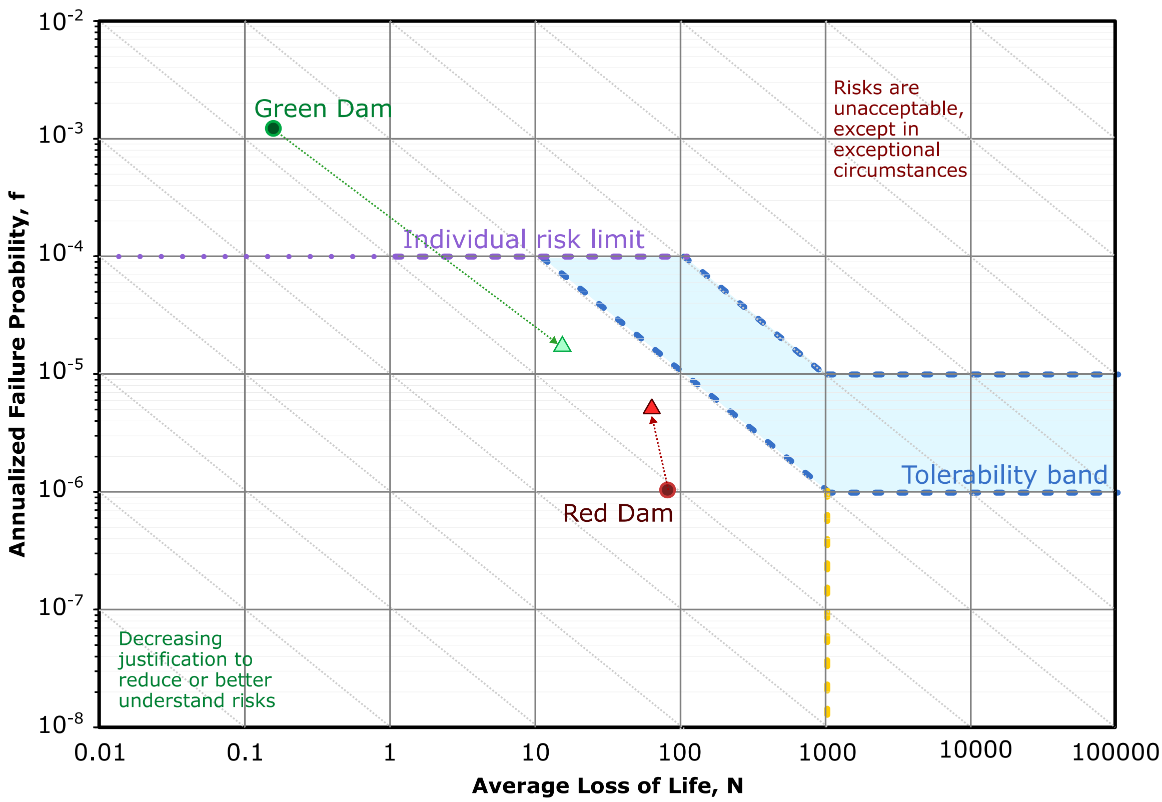


Itinerary followed by implementing the proposed sequence of actions in risk tolerability graph.

3.8. Analysis of freeboard requirements

This measure consists in distributing the seasonal freeboard requirements that are currently being applied only in the Red Dam, between the two dams. In this way, it is also possible to protect the Green Dam, which has a higher overtopping failure probability that the Red Dam. The total freeboard volume (10 hm³) would remain the same but it would be distributed between dams. This distribution has been made proportional to the volume of each reservoir, being 2.3 hm³ in the Green Dam and 7.7 hm³ in the Red Dam.

This analysis was proposed in the Failure Modes Identification sessions, to use the risk model to check if a more optimal freeboards distribution would reduce societal risk in the system. The obtained results for both dams after this change is shown in the following figure:

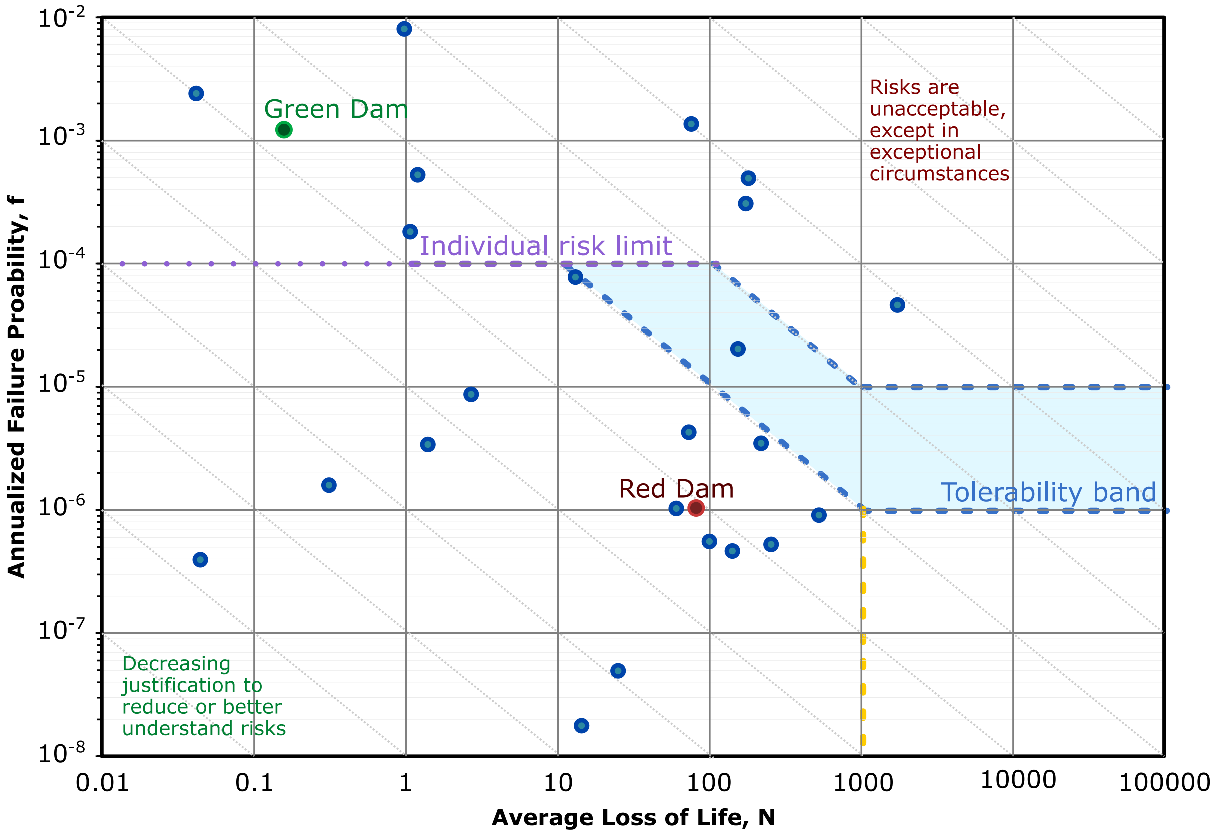


Effect of modifying exiting freeboard requirements in risk tolerability graph.

As can be observed in this figure, this change in freeboard requirements has an effect on the two dams. On the one hand, it reduces the Green Dam failure probability, since the new freeboard requirements reduce the probability of high levels and overtopping in the reservoir. On the other hand, failure probability and risks in the Red Dam increases, as the freeboard requirements in this reservoir are lower. In this case, as the loss of life due to the Red Dam failure is much greater, the sum of the societal risk of the whole system increases, due to the fact that the increase in risk in the Red Dam is more important than the decrease in the Green Dam. This change in the freeboard requirements does not reduce the societal risk in the system, and therefore, it is not recommended.

3.9. Portfolio Results

Finally, risk results of Green and Red Dams were compared with the risk results of the rest of dams managed by the Blue River Authority. This comparison is useful to understand the current state of the Green and Red Dams within the Portfolio of dams of this authority. Risk results of the Portfolio are represented in the following figure:



Risk results in the Portfolio of Blue River Authority.

As can be observed, even though Green Dam risk is above tolerability guidelines, there are other dams in the Portfolio with clearly higher risks (almost three orders of magnitude higher). Hence, it is expected that the risk reduction measures proposed in this report will not be the first ones in the prioritization queue of actions in the Portfolio.

4. SEMI-QUANTITATIVE RISK ANALYSIS

4.1. Introduction

In a Semi-Quantitative Risk Analysis, a preliminary estimation of risk is made based on 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 C Failure Modes** to prioritize new studies and new instrumentation in the Portfolio of dams. In addition, **Class B 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, no additional studies are recommended from uncertainty analysis.

Therefore, the failure modes included in this analysis (Class C) were:

- FM4R: Downstream sliding of the Red Dam.
- FM5R: Upstream sliding of the Red Dam.

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
AAAA BBBB	Engineer in charge of the Red Dam	ZZZZ
CCCC DDDD	Engineer in charge of the Green Dam	ZZZZ
EEEE FFFF	Risk Analysis expert	YYYY
GGGG HHHH	Risk Analysis expert	YYYY
IIII JJJJ	Dam engineer	ZZZZ

Semi-Quantitative Risk Analysis was coordinated and supervised by AAAA BBBB who has proven experience in this type of analysis applied to dam safety.

4.2. 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 popula-

tion 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's importance for the regional economy. In these cases, consequences category can be assigned based on economic consequences.

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

FM4R: Downstream sliding of Red Dam	
Failure probability category	**Remote**
Justification	
As discussed in the FMI sessions, it is expected that this failure mode has a lower probability than internal erosion and overtopping. The following factors were taken into account to assign this probability: • This dam is relatively new and built under good quality standards. • Measures in the drains that discharge in the perimeter gallery do not show any pressure. • No clear (or important) signs observed regarding embankment instability. • During the construction of the dam, special care was taken in the quality control and placement of the materials.	
Consequences category	**3**
Justification	
This category was assigned following the results of consequences estimation made for the risk model. According to these results, complete failure of the Red Dam would produce an estimated loss of life between 10 and 100.	

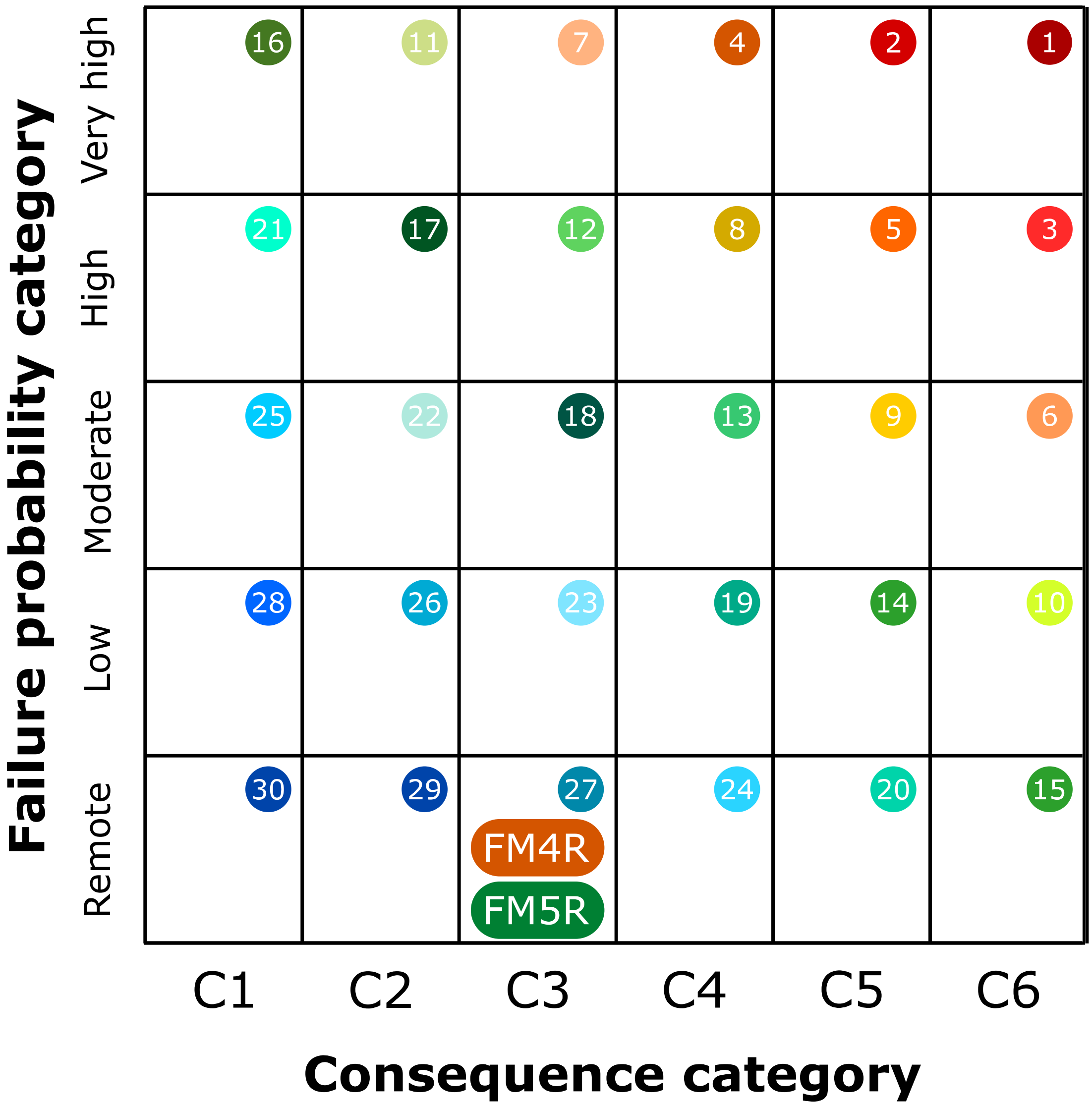
FM5R: Upstream sliding of Red Dam	
Failure probability category	**Remote**
Justification	
As discussed in the IFM sessions, it is expected that this failure mode has a lower probability	

than internal erosion and overtopping. The following factors were taken into account to assign this probability:

- This dam is relatively new and built under good quality standards.
- In the upstream slope, there are horizontal draining layers at different levels, which would avoid the permanence of pore pressures in the embankment material.
- No clear (or important) signs observed regarding embankment instability.
- During the construction of the dam, special care was taken in the quality control and placement of the materials.

Consequences category	**3**
Justification	
This category was assigned following the results of consequences estimation made for the risk model. According to these results, complete failure of the Red Dam would produce an estimated loss of life between 10 and 100.	

The results of this Semi-Quantitative Risk Analysis are represented for each failure mode in the following matrix:



Semi-Quantitative Risk Analysis results.

4.3. Prioritization of new studies or instrumentation

Once the risk of each Class C failure mode 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 C 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 B Failure Modes can also be introduced in this prioritization if they are recommended after quantitative risk evaluation and uncertainty analysis.

In this case, the following new studies and instrumentation are proposed:

Study 1	Stability analysis of Red Dam
Failure Modes	FM4R and FM5R
Description	
Dam stability has not been checked numerically since the dam's design (last 80s). For the calculation of stability, certain geotechnical parameters of the dam and foundation body materials were used, but no precise information is available on the geotechnical parameters of the materials actually used in each area. During the IFM working sessions, it was recommended to check the hypothesis followed and the computations made in this project with a new stability analysis, using new available numerical tools and software. This numerical analysis will be based on new geotechnical tests, which will be used to estimate resistance parameters in the dam body. Therefore, this study consists of a detailed studied on the Red Dam stability with numerical models to analyse instability in upstream and downstream slopes.	

Study 2	Improvement of Red Dam hydraulic monitoring
Failure Modes	FM4R
Description	
This measure is already included in the risk reduction actions list since it is also directly related with a Class B Failure Mode (FM6R). It arises from the recommendations of the Failure modes identification sessions in order to improve knowledge about pore pressures in the Red Dam body and water seepage. In this way, pore pressures can be known, which they are valuable information for dam stability assessment. The main improvement proposed in the hydraulic monitoring of the Red Dam is the recover or re-placement of the piezometers equipment that is currently inoperative. The installation or recovery of this equipment in the downstream slope of the dam is especially recommended, to improve the knowledge of flow characteristics in this area. In addition, in some areas water seepage can be better controlled, discretizing between the different parts of the dam and analysing potential movements of soil particles.	

Second, based on the priority level of each failure mode, new studies and instrumentation are prioritized. Priority level of failure modes depend on their cell in the SQRA matrix, as shown in the previous matrix. As can be observed in this matrix, failure modes closer to the upper-right corner (higher failure probability and higher consequences) have a higher priority level. Following this procedure, the priority levels of the proposed studies are:

Studies	Priority level
Study 1: Stability analysis of Red Dam	27
Study 2: Improvement of Red Dam hydraulic monitoring	27

These results show the same priority level for both actions, since they are both related with the same failure modes. In this case, it is recommended to make a first stability analysis of the Red Dam with available data and to check this study with the results of pore pressures after some years of measurements. The prioritization of these studies and instrumentation will depend on the priority of the rest of studies prioritized in the Portfolio Management.

5. CONCLUSIONS

The risk assessment process applied to the Green and Red Dams involved a number of positive effects derived from its own nature and structure, due to the participation of technical personnel from the dam management and regulation entities and risk analysis experts. Results obtained can be used to guide and define future activities of dam response reporting and actions to improve dam safety and reduce uncertainty.

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:

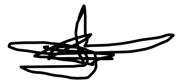
- The process for identification of failure modes allowed a comprehensive safety review of both dams with a complete group of experts and it provided recommendations for risk reduction actions and new studies. These sessions were the key to develop the Risk Assessment process.
- Failure Modes will be a better guide for future monitoring actions and technical inspections with the aim of detecting potential failures processes.
- Existing risk in this system of dams was reasonably characterized by a quantitative risk model with 5 failure modes (2 for the Green Dam and 3 for the Red Dam) and a semi-quantitative risk analysis for 2 failure modes.
- The process for elaborating this quantitative risk model was useful to make a comprehensive review of available information in both dams and performing detailed analysis on key aspects like sliding failure of the Green Dam and potential consequences downstream.
- Quantitative risk results show that failure probability is clearly higher for the Green Dam than for the Red Dam, mainly due to overtopping failure mode. These results indicate that the Red Dam does not fail in most of the cases that the Green Dam fails, since this reservoir is able to manage the failure flood wave. However, societal risk is higher for the Red Dam, since loss of life is much higher when this dam fails, due to the importance of the populations located downstream. The three failure modes in the Red Dam have low probability with similar values.
- Risk evaluation shows that the Green Dam risks are above individual risk limit for both failure modes, especially overtopping. Instead, all the failure modes in the Red Dam are aligned with the tolerability guidelines, since failure probability is much lower.
- Based on results of the risk model, six risk reduction measures were analysed for both dams. A prioritization sequence was obtained for these measures, combining efficiency and equity principles.
- The first measure of this sequence is reinforcing the Green Dam parapet wall to avoid overtopping. This measure is not very expensive and it is the measure that has the highest influence on reducing failure probability in the Green Dam. Next, drainage rehabilitation reduces the Green Dam's risk results to be aligned with tolerability guidelines. The following measures will help to reduce failure probability and risks in the tolerable area in both dams. These prioritization results are useful to prioritize the proposed risk reduction actions within the Dams Portfolio management.
- In this case, high uncertainties in risk results were not detected, so further studies are not suggested before implementing these actions.
- Sensitivity analysis shows a very high dependence on the loss of life with respect to the warn-

ing time to the population. This fact is due to the proximity of the province's capital city to the dam, where the Red Dam's failure without enough alert time to evacuate the population would be catastrophic. So in this system of dams, warning and coordination procedures are especially important. The result highlights the importance of a proper Emergency Action Plan, even though it is not in the first steps of the prioritization sequence.

- Quantitative risk results show that trespassing part of the freeboard requirements to the Green Dam (currently all freeboard requirements are implemented in the Red Dam) could produce an increment of societal risk downstream.
- Semi-Quantitative Risk Assessment was used to prioritize new studies and instrumentation in both dams. After this analysis, it is recommended to make a first stability analysis of Red Dam with available data and to check this study with the results of pore pressures after some years of measurements. Priority levels obtained for these studies are useful to prioritize new studies within the Dams Portfolio management.

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

The elaboration of this Risk Assessment Dam Safety Report was coordinated by:



EEEE FFFF, Technical Director of YYYY Company

15/05/2015

APPENDIX D – GLOSSARY

Abutment - That part of the valley side against which the dam is constructed. An artificial abutment is sometimes constructed, as a concrete gravity section, to take the thrust of an arch dam where there is no suitable natural abutment. The left and right abutments of dams are defined with the observer viewing the dam looking in the downstream direction unless otherwise indicated.

Acceptable risk - A broadly acceptable risk is in general one that may be considered as negligible and properly controlled. However, risks associated with dams will rarely be classified into this category due to the huge destructive potential of this infrastructure.

ALARP - The ALARP (As Low As Reasonably Possible) is a concept related to tolerable risks. It means that to accept a risk as tolerable, all mitigation measures must be applied if their cost is not disproportionably high regarding the risks they reduce.

Alert - A notification category that provides urgent information and indicates that system action may be necessary. An alert can be used for initial notification that incident activation is likely, and for ongoing notification throughout an incident to convey incident information and directed or recommended actions.

Analysis - A method of study on the nature of something, or for assessing its essential features and their relationships.

Annual Exceedance Probability (AEP) - The likelihood that a natural event (e.g. storm/flood) will occur in any given year, reported as a percent. Calculated as the reciprocal of the Return Period.

Arch Dam - A concrete, masonry, or timber dam with the alignment curved upstream to transmit the major part of the water load to the abutments.

Attenuation - A decrease in amplitude of the seismic waves with distance due to geometric spreading, energy absorption, and scattering, or decrease in the amplitude of a flood wave due to channel geometry and energy loss.

Basin - The area of land that drains to a river. The official name of the basin in which the river or stream on which the dam is built is located. It may also be the main river on which the dam is built.

Benchmarks – Working sessions with the purpose of identifying best practices indicating superior performance. Benchmarks are adopted as targets for optimal organizational performance and may include standards or environmental management processes.

Binomial Distribution - Discrete probability distribution of the number of successes in a sequence of *n* independent experiments. In dam risk models, it is typically used to estimate the probability of a number of gates working properly when the flood arrives.

Breach - An opening through a dam that allows the uncontrolled draining of a reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening caused by discharge from the reservoir. A breach is generally associated with the partial or total failure of the dam.

Conditional Probability – The probability of an outcome, given the occurrence of some event. For example, given that a flood has reached the crest of an embankment dam, the probability of the dam failing is a conditional probability.

Consensus - When a group of individuals in a decision-making process work towards a general agreement by all involved.

Consequences - Negative impacts that may result from the failure of a dam. The key consequences are typically the loss of human life, economic loss (including property damage), lifeline disruption, and environmental impact.

Core - A zone of low permeability material in an embankment dam. The core is sometimes referred to as the central core, inclined core, puddle clay core, rolled clay core, or impervious zone.

Core wall - A wall built of relatively impervious material, usually of concrete or asphaltic concrete in the body of an embankment dam to prevent seepage.

Crest Gate (Spillway Gate) - A gate on the crest of a spillway to control the discharge or reservoir water level.

Crest Length - The measured length of the dam along the crest or top of the dam.

Cross Section - An elevation view of a dam formed by passing a plane through the dam perpendicular to the axis.

Dam – Any artificial barrier including appurtenant works constructed across rivers or tributaries thereof with a view to impound or divert water; includes barrage, weir and similar water impounding structures but does not include water conveyance structures such as canal, aqueduct and navigation channel and flow regulation structures such as flood embankment, dyke and guide bund.

Dam Crest Elevation / Top of the Bank Level - The lowest elevation at which water can flow over the top of the dam, not including flow through the spillway. If crest elevations for the masonry/concrete and earthen sections are different, it may be recorded accordingly.

Dam failure – Typical, dam failure characterized by the sudden, rapid, and uncontrolled release of impounded water or the likelihood of such an uncontrolled release. It is recognized that there are lesser degrees of failure and that any malfunction or abnormality outside the design assumptions and parameters that adversely affect a dam's primary function of impounding water is properly considered a failure. These lesser degrees of failure can progressively lead to or heighten the risk of a catastrophic failure.

Dam Inspection – On-site examination of all components of dam and its appurtenances by one or more persons trained in this respect and includes examination of non-overflow portion, spillways, abutments, stilling basin, piers, bridge, downstream toe, drainage galleries, operation of mechanical systems (including gates and its components, drive units, cranes), interior of outlet conduits, instrumentation records and record-keeping arrangements of instruments.

Dam Safety - Dam safety is the art and science of ensuring the integrity and viability of dams such that they do not present unacceptable risks to the public, property, and the environment. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe function is not explicitly determined by its original design and construction. It also includes all actions taken to identify or predict deficiencies and consequences related to failure and to document, publicize, and reduce, eliminate, or remediate to the extent reasonably possible, any unacceptable risks.

Dam Safety Program Purposes - The purposes of a dam safety program are to protect life, property, and the environment by ensuring that all dams are designed, constructed, operated, and maintained as safely and as effectively as is reasonably possible. Accomplishing these purposes requires commitments to continually inspect, evaluate, and document the design, construction, operation, maintenance, rehabilitation, and emergency preparedness of each dam and the associated public. It also requires the archiving of documents on the inspections and histories of dams and the training of personnel who inspect, evaluate, operate, and maintain them. Programs must instil an awareness of dams and the hazards that they may present to the owners, the users, the public, and the local and national decision-makers. On both local and national scales, program purposes also include periodic reporting on the degree of program implementation. Key to accomplishing these purposes is to attract, train, and retain a staff proficient in the art and science of dam design.

Dam Type - Type of dam, viz., Earth, Rockfill, Gravity, Buttress, Arch, Multi-Arch, Concrete, Masonry, Stone, Roller-Compacted Concrete.

Deterministic Methodology - A method in which the chance of occurrence of the variable involved is ignored and the method or model used is considered to follow a definite law of certainty and not probability.

Dike (Levee) - A long low embankment dam. The term is usually applied to auxiliary dams used to close off areas that would otherwise be flooded by a reservoir.

Discharge - Refers generally to the outflow and is used as a measure of the rate at which a volume of water passes a given point. Therefore, the use of this term is not restricted as to course or location, and it can be used to describe the flow of water from a pipe or a drainage basin.

Drainage Area - The area that drains to a point on a river or stream.

Direct Economic Consequences - Direct economic consequences are the costs of lost project benefits, downstream property damages, and repair/replacement costs produced directly by the flood wave.

Earth Dam/ Earth-fill Dam - An embankment dam in which more than 50% of the total volume is formed of compacted earth layers with particles that are generally smaller than 75-millimetre size.

Earthquake - A sudden motion or trembling in the earth caused by the abrupt release of accumulated stress along a fault.

Economic Consequences - Economic consequences are the direct and indirect economic impacts associated with a dam failure measured in economic terms.

Economic Efficiency - When what is analysed is economic risk reduction, that is, the searched strategy is the most advantageous from an economic point of view.

Ecosystem - A community of interdependent organisms together with the environment they inhabit and with which they interact.

Efficiency - This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first.

Embankment Dam – Any dam constructed of excavated natural materials, such as both earth-fill and rock-fill dams, or of industrial waste materials, such as a tailings dam.

Emergency - A condition that develops unexpectedly, which endangers the structural integrity of a dam and/or downstream human life or property and requires immediate action.

Emergency action plan (EAP) – A plan of action to be taken to reduce the potential for property damage and loss of life in an area affected by a dam failure or large flood. A written document prepared by the dam owner or the owner's professional engineer describing a detailed plan to prevent or lessen the effects of a failure of the dam or appurtenant structures.

Emergency Alert System - A network of radio stations that voluntarily provide official emergency instructions or directions to the public during an emergency.

Environment - The components of the earth, including air, land, and water, all layers of the atmosphere, organic and inorganic matter, living organisms, and their interacting natural systems.

Epistemic uncertainty - Epistemic uncertainty is related to the lack of knowledge resulting from either insufficient data or from the incapacity to understand the operating mechanisms of a given phenomenon. This uncertainty may be reduced through the collection of additional information, the gathering of more data and an increase of knowledge. On the contrary, this uncertainty is very difficult to quantify. This is commonly addressed as uncertainty.

Equity - In the context of critical infra-structure safety management, this principle arises from the premise that all individuals have unconditional rights to certain levels of protection. This principle is applied through the individual risk.

Erosion - The natural breakdown and movement of soil and rock by water, wind, or ice. The wearing off a surface (bank, streambed, embankment, or another surface) by floods, waves, wind, or any other natural process. The process may be accelerated by human activities.

Evacuation - Organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and their reception and care in safe areas.

Event tree - An event tree is a representation of a logical model that includes all the possible chains of events resulting from an initiating event. As its name indicates it is based on the mathematical structure known as a tree that is widely used in many other contexts.

Expert - An individual who meets some defined level of knowledge, skills, and abilities that usually have been demonstrated by his experiences.

Expert judgment - Information and data are given by qualified individuals in response to technical questions. It is generally used when test/observational data are difficult or expensive to obtain and when other sources of information are sparse, poorly understood, open to differing interpretations, or requiring synthesis. It may be an integral part of most problem solving and analysis.

Extreme event - A term used commonly in the field of risk management for collectively describing emergencies and disasters. These are events with low probability and high consequence.

Failure mode - A failure mode is the sequence of events that may cause failure or disrupt the function of the dam-reservoir system or part of it. This series of events is associated with a determined loading scenario and has a logical sequence, which starts with a main initial triggering event, is followed by a chain of development or propagation events and culminates in dam failure. A potential failure mode is a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which may lead to an uncontrolled release of the reservoir.

Failure hydrograph - A flood hydrograph resulting from a dam breach. It describes water releases downstream.

Failure probability – Likelihood of dam failure. Within the scope of Risk Analysis applied to dam safety, the concept failure is not limited exclusively to the catastrophic breakage of the dam but includes any event that might produce adverse consequences. In this sense, the terms failure and breakage are interchangeable.

Fault tree – A fault tree is a top-down, deductive logical tool in which a major undesired event (failure) is postulated and then analysed systematically. The goal of Fault Tree Analysis is to develop all events or combination of events that might cause failure. These events may be of any nature: mechanical faults, human faults, external conditions, etc. The failure or undesirable event analysed in the tree is called top event and it is drawn in the top part of the diagram. Under it, all the events that might induce the top event to happen are drawn. This is done successively until reaching the lowest level where the basic events are found.

Flood - An overflow of water onto lands that are used or usable by man and not normally covered by water. Floods have two essential characteristics: it is temporary; and the land is adjacent to and inundated by overflow from a river, stream, lake, or ocean. A temporary rise in water surface elevation resulting in inundation of areas not normally covered by water. Hypothetical floods may be expressed in terms of average probability of exceedance per year such as one-percent-chance-flood or expressed as a fraction of the probable maximum flood or another reference flood.

Flood damage - The tangible (direct and indirect) and intangible costs (financial, opportunity costs, clean-up) of flooding. Tangible costs are quantified in monetary terms (e.g. damage to goods and possessions, loss of income or services in the flood aftermath). Intangible damages are difficult to quantify in monetary terms and include the increased levels of physical, emotional and psychological health problems suffered by flood-affected people that are attributed to a flooding episode.

Flood risk - The potential risk of flooding to people, their social setting, and their built and natural environment. The degree of risk varies with circumstances across the full range of floods. Flood risk is divided into three types – existing, future and residual.

Flood routing - A process of determining progressively over time the amplitude of a flood wave as it moves past a dam or downstream to successive points along a river or stream. In reservoirs, flood routing study analyses inflow and outflow in the reservoir.

Flood storage - The retention of water or delay of runoff either by the planned operation, as in a reservoir, or by the temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel. Storage space available in a reservoir between the normal pool elevation and the maximum operating pool elevation (top of active storage).

Fluvial - Of or pertaining to rivers and streams; growing or living in streams ponds; produced the action of a river or stream.

fN graph or fD graph - An fN graph is a way of representing risk. In this graph, the probability of failure is represented in the vertical axis (f) and its consequences are represented in the horizontal one (loss of life (N) or economic consequences (D)). Thus, risk will be the dimension that combines both axes. In this way risk would be smaller in the lower left corner (orthogonal sense) and would grow towards the upper right corner. The di- agonal lines in an orthogonal sense to the one depicted would be the iso-risk lines (lines made of combinations of equal risk value). Logarithmic scales are usually used in this kind of graphs.

FN graph or FD graph - One of the most extended representations of risk is the FN graph, which is simply the cumulated form of fN graphs. In this way a curve is obtained instead of discreet points. In this curve, the horizontal axis represents the consequences (loss of life (N) or economic consequences (D)) and the vertical axis the probability that these consequences (F) are exceeded.

Foundation - The portion of the valley floor that underlies and supports the dam structure. The material upon which dam is founded.

Fragility Curve – A function that defines the probability of failure as a function of an applied load level. A form of the more general 'system response'.

Framework - An organized structure of policies, legislation, programs, and tasks created to achieve a specific outcome. There can be frameworks for broad policies and strategic initiatives at various scales (e.g. provincial, regional, sector, media); programs and program delivery; and short-term tasks and projects.

Freeboard – Vertical distance between a specified Stillwater (or other) reservoir surface elevation and the top of the dam, without camber. For example, freeboard above maximum surface or freeboard above normal reservoir level.

Frequency - The measure of likelihood expressed as the number of occurrences of a specified event in a given time. For example, the frequency of occurrence of a 20% annual exceedance probability or five-year average recurrence interval flood event is once every five years on average.

Gate - A movable water barrier for the control of water.

Gravity Dam – A dam constructed of concrete and/or masonry that relies on its weight and internal strength for stability.

Geographic Information System - A computerized system for the capture, storage, analysis and display of geographically/ spatially related information. Commonly, GIS shows a portion of the surface of the earth in the form of a map on which this information is overlaid.

Guideline - A specific performance measure that is not legally binding unless designated in legislation. It is a guide or indication of a future course of action. It describes how something will be accomplished. It may contain numerical performance measures and may deal with multiple uses of water.

Hazard - A situation that creates the potential for adverse consequences such as loss of life, property damage, or other adverse impacts.

Hazard Potential – The possible adverse incremental consequences that result from the release of water or stored contents because of failure or incorrect operation of the dam or appurtenances. Impacts may be for a defined area downstream of a dam from flood waters released through spillways and outlet works of the dam or waters released by partial or complete failure of the dam. There may also be impacts for an area upstream of the dam from effects of backwater flooding or landslides around the reservoir perimeter.

Hazard Potential Classification – A measure of the potential for loss of life, property damage, or economic impact in the area downstream of the dam in the event of a failure or malfunction of the dam or appurtenant structures. The hazard classification does not represent the physical condition of the dam.

Height of Dam – The difference in elevation between the natural bed of the watercourse or the lowest point on the downstream toe of the dam, whichever is lower, and the effective crest of the dam.

High Hazard Potential - Dams assigned the high hazard potential classification are those where failure or mis-operation results will probably cause huge loss of human life.

Hydrograph - A graph showing, for a given point on a stream, the discharge, height, or another characteristic of a flood with respect to time.

Hydrology - One of the earth sciences that encompasses the natural occurrence, distribution, movement, and properties of the waters of the earth and their environmental relationships. The science dealing with the waters of Earth - their distribution and movement on the surface and underground; and the cycle involving evaporation and precipitation.

Hydro-mechanical Equipment - Gates, valves, hoists, and elevators.

Impervious Surfaces - Land where water cannot infiltrate back into the ground such as roofs, driveways, streets, and parking lots. Total imperviousness means the actual amount of land surface taken up with impervious surfaces, often stated as a percentage.

Incremental Consequences- Under the same conditions (e.g., flood, earthquake, or another event), the difference in impacts that would occur due to failure or mis-operation of the dam over those that would have occurred without failure or mis-operation of the dam and related structures.

Incremental Risk - It is the part of risk exclusively due to the dam failure. It is obtained by subtracting from the consequences of the dam failure the ones that would have happened anyway, that is, even if the dam had not failed.

Indirect Economic Consequences - Indirect economic consequences, which are also known as indirect impacts, refer to the changes in the valuation of business output, interruption of the economy and changes in employment from a failure scenario.

Individual Risk - The increment of risk imposed on a particular individual by the existence of a dam. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the facility did not exist.

Inflow Design Flood – The flood hydrograph used in the design of a dam and its appurtenant works particularly for sizing the spillway and outlet works and for determining maximum storage, the height of the dam, and freeboard requirements.

Influence diagram - The influence diagrams are compact conceptual representations of the logic of a system. On its most generic form, an influence diagram is any representation including the relations between possible events, states of the environment, states of the system or subsystems, and consequences. An influence diagram offers a visual representation of a risk model. Each variable of the system is represented as a node and each relation as a connector or arc.

Instrumentation - An arrangement of devices installed into or near dams that provide for measurements that can be used to evaluate the structural behaviour and performance parameters of the structure.

Intensity - Refers to the attributes of a hazard that causes damage (e.g., water depth and velocity are commonly used measures of the intensity of a flood).

Intensity, Seismic - A numerical index describing the effects of an earthquake on man, manmade structures, or other features of the earth's surface.

Intolerable risk - A risk that, when compared with tolerability guidelines, is so high that it requires consideration of implementation of treatments or actions to improve understanding, avoid, transfer or reduce the risk.

Inundation Map – A map showing areas that would be affected by flooding from releases from a dam's reservoir. The flooding may be from either controlled or uncontrolled releases or because of a dam failure. A series of maps for a dam could show the incremental areas flooded by larger flood releases. For breach analyses, this map should also show the time to flood arrival, and maximum water-surface elevations and flow rates.

Leakage - Uncontrolled loss of water by flow through a hole or crack.

Length of Dam - The length along the top of the dam. This also includes the spillway, power plant, navigation lock, fish pass, etc., where these form part of the length of the dam. If detached from the dam, these structures should not be included.

Loading scenario - To obtain the risk associated with a dam, the calculation is usually disaggregated into various scenarios, depending on the event that originates failure. For instance, a dam may fail when subjected to a flooding or to an earthquake, and it is convenient to do those calculations in a separate way, each situation being called loading scenario.

Lognormal distribution - A two-parameter probability distribution defined by the mean and standard deviation. An asymmetrical distribution applicable to many kinds of data sets where the majority (more than half) of values are less than the mean, but values greater than the mean may be extreme, such as that with streamflow data.

Loss of life – Human fatalities that would result due to floods, considering the mitigation of loss of life that could occur with evacuation or other emergency actions.

Management - Decision making and decision-implementation to direct and coordinate activities to achieve a common goal. This is achieved by establishing objectives, assigning resources to the objectives and defining the parameters within which the resources are to achieve the objectives.

Maintenance – Those tasks that are generally recurring and are necessary to keep the dam and appurtenant structures in a sound condition and free from defect or damage that could hinder the dam's functions as designed, including adjacent areas that also could affect the function and operation of the dam.

Maintenance Inspection – Visual inspection of the dam and appurtenant structures by the owner or owner's representative to detect apparent signs of deterioration, other deficiencies, or any other areas of concern.

Masonry Dam – Any dam constructed mainly of stone, brick, or concrete blocks pointed with mortar. A dam having only a masonry facing should not be referred to as a masonry dam.

Maximum Operating Pool Elevation or Maximum Operation Level - The upper limit or top of active storage. This is the reservoir elevation that would be attained when the reservoir is fully utilized for all purposes, including flood control. It represents the highest elevation achieved in the reservoir under normal operating conditions.

Maximum Storage Capacity – The volume, in cubic hectometres (hm^3), of the impoundment created by the dam at the effective crest of the dam; only water that can be stored above natural ground level or that could be released by failure of the dam is considered in assessing the storage volume; the maximum storage capacity may decrease over time due to sedimentation or increase if the reservoir is dredged.

Mathematical and computer models - The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.

Mitigation - All activities that reduce or eliminate the probability of a hazard occurrence or eliminate or reduce the impact of the hazard in case of its occurrence. Mitigation activities are undertaken during the period prior to an imminent or actual hazard. Once the hazard impact is recognized, subsequent actions are considered response actions and not mitigation.

Modified Puls Method – A method of flood routing through a reservoir that ignores the slope of the water surface in the reservoir.

Monte Carlo analysis - A method that produces a statistical estimate of a quantity by considering many random samples from an assumed probability distribution, such as a normal distribution. The method is used when experimentation is infeasible or when the actual input values are difficult or impossible to obtain.

Multipurpose Project - A project designed for irrigation, power, flood control, municipal and industrial, recreation, and fish and wildlife benefits, in any combinations of two or more. In contrast to single-purpose projects serving only one need.

National/State Disaster Management Authority - The national and state agencies responsible for emergency operations, planning, mitigation, preparedness, response, and recovery from all hazards.

Natural uncertainty - Uncertainty arising from variations inherent in the behaviour of natural phenomena (e.g., the severity of the maximum flood in a year). It is also called randomness or natural variability. In risk models, it is usually addressed within risk model probabilities.

Non-structural measures - Measures such as raising, relocating, flood proofing and regulatory and emergency actions associated with structures and damageable property that modify the existing and/or future damage susceptibility. Non-structural measures are not designed to directly affect the flow of floodwaters.

Normal distribution - A two-parameter probability distribution defined by the mean and standard deviation. Symmetrical "bell-shaped" curve applicable to many kinds of data sets where values are equally as likely to be greater than and less than the mean. Also called the Gaussian distribution.

Normal operation level / Maximum Operating Level- The normal operating water elevation when storage is at its maximum level (without any flood surcharge).

Other damages - Related to environmental damage, social disturbing, loss of reputation, attachment to historical or cultural heritage, etc. All these aspects are difficult to quantify thereby they are usually treated in a qualitative way.

Outlet - An opening for releasing discharge that is lower than the spillway crest. Designed to release reservoir water through or around a dam. An opening through which water can be freely discharged from a reservoir to the river for a purpose. A conduit or pipe controlled by a gate or valve, or a siphon, that is used to release impounded water from the reservoir.

Outlet Gate – A gate controlling the flow of water through a reservoir outlet.

Outlet Works – A dam appurtenance that provides release of water (generally controlled) from a reservoir.

Overtopping failure - A hydrologic dam failure that occurs because of the water level in the reservoir exceeding the height of the dam.

Parapet wall – A solid wall built along the top of a dam (upstream or downstream edge) used for ornamentation, for the safety of vehicles and pedestrians, or to prevent overtopping caused by wave run-up.

Peak flow – The maximum instantaneous discharge that occurs during a flood. It is coincident with the peak of a flood hydrograph.

Performance Assessment - The linkage of inputs (e.g., funding, staff, equipment, supplies), actions (e.g., advice, projects, programs, services) and outputs (e.g., reports, plans, policies) to outcomes or results (e.g., an increase in awareness, a change in behaviour, or the achievement of an outcome or result, such as a healthy environment).

Piping failure - Dam failure caused when concentrated seepage develops within an embankment dam and erodes to form a "pipe." Piping typically occurs in two phases: formation of the "pipe" and the subsequent collapse of the dam crest. It is possible for the reservoir to drain before the dam crest collapses.

Policy - A governing principle, plan, or consistent course of action developed to meet recognized needs and to achieve specific measurable outcomes. Policies are normally broad, conceptual documents that outline approaches and/or considerations to be considered by decision makers. Policies do not act as constraints but provide information. A statement of intent that is not legally binding. It sets direction and expectations for activities.

Population At Risk - People living (or working) within the potential flooded area in an undesired event.

Prioritization – To define priorities between proposed risk reduction actions or proposed new studies or instrumentation.

Probability - The likelihood of an event occurring.

Probable - Likely to occur; reasonably expected; realistic.

Probable maximum flood (PMF) - The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that is reasonably possible in the drainage basin under study.

Probable maximum precipitation (PMP) - Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a geographical location during a certain time of the year.

Public and Stakeholder Involvement - The process used by the government to obtain advice or recommendations from a community and engage them in decision-making. Public and stakeholder involvement is an umbrella term that includes a range of interactive approaches including information and education, consultation, collaboration, partnerships, and delegated authority.

Quantitative Risk Analysis – An analysis based on numerical values of the potential consequences and likelihood, the intention being that such values are a valid representation of the actual magnitude of the consequences and the probability of the various scenarios which are examined.

Random Variable – A quantity, the magnitude of which is not exactly fixed, but rather the quantity may assume any of the number of values described by a probability density function.

Regulator - An entity delegated the power to regulate a specific activity or set of activities.

Regulatory Instruments - Rules-based tools that focus on enforcing compliance with minimum standards. Their goal is compliance with the law and their driving mechanism is deterrence. Regulatory tools include laws and regulations.

Reliability – For gate and mechanical systems reliability is defined as the likelihood of successful performance of a given project element. It may be measured on an annual basis or for some specified period of interest or, for example, in the case of spillway gates, on a per demand basis. Mathematically, Reliability = 1 - Probability of unsatisfactory operation.

Reservoir – Any water spread which contains impounded water. A body of water impounded by a dam and in which water can be stored. A man-made lake that collects and stores water for future use. During periods of low river flow, reservoirs can release additional flow if water is available.

Reservoir Area - The total surface of a reservoir measured in a horizontal plane at an elevation corresponding to the full supply level of the reservoir. The area that would be flooded due to backwater elevations or surcharge is not included.

Reservoir Capacity – The total volume of water a reservoir can hold when filled up to the full supply or normal water level. Storage derived from temporary flashboards, surcharge, or backwater curve is not included. Reservoir capacity usually is reported as of the date of construction of the dam. The sum of the dead and live storage of the reservoir.

Return period - The average time interval between occurrences of a hydrological event of a given magnitude or greater, usually expressed in years.

Risk - Risk is the combination of three concepts: what can happen, how likely it is to happen and what are the consequences in the case it happens. In Risk Assessment applied to dam safety, what can happen refers to dam failure, how likely it is to happen is related with the failure probability of the dam and the consequences are the facts resulting from the failure of the dam, including economic consequences and loss of life. Numerically, risk is estimated combining the likelihood of occurrence of loads (e.g., flood, earthquake, etc.), the likelihood of dam failure due to these loads and the failure consequences.

Risk Analysis – A procedure to identify and quantify risks by establishing potential failure modes, providing numerical estimates of the likelihood of an event and estimating the magnitude of the consequences.

Risk Assessment – The process of deciding whether existing risks are tolerable and present risk control measures are adequate and, if not, whether alternative risk control measures are justified. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk Communication - The process of providing concise, comprehensible, credible information for making effective decisions about risks. Risk communication is considered as a service to those outside the command system, with the objective of influencing behaviour.

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.

Risk Governance - The process of risk-informed decision making and the process by which risk-informed decisions are implemented.

Risk Informed – This term implies that decisions are made considering risk estimates and many other contributing factors that might include confidence in the risk estimates, risk uncertainty, deterministic analyses, and the overall dam safety case in addition to other local or regional considerations. Risk will play a key role in decisions related to dam safety but will not be the only information to influence the final decisions.

Risk Management - The systematic application of management policies, procedures, and practices to the tasks of identifying, analysing, assessing, treating and monitoring dam safety risks.

Rock Fill Dam – An embankment dam in which more than 50% of the total volume is comprised of compacted or dumped cobbles, boulders, rock fragments, or quarried rock generally larger than 75-millimetre size.

Risk of Failure - It is the part of total risk due to the dam failure.

Risk of Non-Failure - It concerns the situations of downstream flooding when the dam has not failed.

Risk Reduction Actions - Long-term measures to reduce the magnitude/ scale/ duration of adverse effects due to disaster hazards on a society at risk. In dam safety, typical measures may include improved dam safety body or foundation, floodplain zoning and land-use planning, monitoring and surveillance etc. They may be classified into structural and non-structural measures.

Roller Compacted Concrete Dam – A concrete gravity dam constructed using a dry mix concrete transported by conventional construction equipment and compacted by rolling, usually with vibratory rollers.

Saddle Dam (or Dyke) – A subsidiary dam of any type constructed across a saddle or low point on the perimeter of a reservoir.

Sedimentation - The process of material settling out of the water.

Semi-Quantitative Risk Analysis – An analysis that uses numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Sensitivity Analysis - An analysis in which the relative importance of one or more of the variables thought to have an influence on the phenomenon under consideration is determined.

Screening Analysis - Screening analysis is a semi-quantitative analysis based on risk principles. Sieving analysis is usually applied to a portfolio of dams. This analysis, instead of estimating each of the probabilities considered in the risk equation, assigns risk indexes based on the available information and provides in the end a risk index for each of the studied dams. This method- ology is useful to do a preliminary ordering of the dams according to their importance in terms of safety, thus helping to determine how to focus ulterior efforts.

Societal Efficiency - When what is analysed is societal risk reduction, that is, the first prioritized strategy is the most efficient from a societal risk point of view.

Spillway - A structure over or through which flow is discharged from a reservoir. If the rate of flow is controlled by mechanical means, such as gates, it is considered a controlled spillway. If the geometry of the spillway is the only control, it is considered an uncontrolled spillway. A chute, weir, conduit, tunnel, channel, or other structure designed to permit discharges from a reservoir. The primary purpose of a spillway is to discharge flood flows safely past a dam, but they may also be used to release water for other purposes. A spillway may be gated (controlled) or not. Gates are used to regulating the level of the reservoir above the spillway crest. In an un-gated (uncontrolled) spillway, the discharge occurs automatically when the water level rises above the level of the spillway crest.

Spillway Capacity - The maximum flow a spillway is capable of discharging when the reservoir is at its highest water surface elevation. The maximum spillway outflow that a dam can safely pass through the reservoir at its maximum level.

Spillway Crest - The lowest level at which water can flow over or through the spillway.

Spillway Type - Type of spillway – controlled or uncontrolled.

Stability - The condition of a structure or a mass of material when it can support the applied stress for a long time without suffering any significant deformation or movement that is not reversed by the release of the stress.

Stakeholder - An individual, organization, or government with a direct interest in a process or outcome.

Standard - A definite rule established by authority. They are legally enforceable numerical limits or narrative statements found in a regulation, statute, contract, or another legally binding document, which have been adopted from a criterion or objective. Environmental standards often take the form of prescribed numerical values that must be met.

Stilling Basin - A basin constructed to dissipate the energy of rapidly flowing water, e.g., from a spillway or outlet, and to protect the riverbed from erosion. A pond or reservoir, riprapped or in a natural state, formed downstream of a dam, usually by means of a small auxiliary dam or weir. Its purpose is to protect the streambed from scouring caused by spillway and outlet discharges. The basin serves to dissipate energy.

Storage - The retention of water or delay of runoff either by the planned operation, as in a reservoir, or by the temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel. Definitions of specific types of storage in reservoirs are:

Storm - A disturbance of the ordinary, average conditions of the atmosphere which, unless specifically qualified, may include any or all meteorological disturbances, such as wind, rain, snow, hail, or thunder.

Suffosion - Internal erosion mechanism that can occur with internally unstable soils. It is a similar process to suffusion, but results in volume change (voids leading to sinkholes) because the coarser particles are not in point-to-point contact. Suffosion is less likely than suffusion under the stress conditions and gradients typically found in embankment dams.

Suffusion - Internal erosion mechanism that can occur with internally unstable soils. It involves selective erosion of finer particles from the matrix of coarser particles (that are in point-to-point contact) in such a manner that the finer particles are removed through the voids between the larger particles by seepage flow, leaving behind a soil skeleton formed by the coarser particles. With suffusion there is typically little or no volume change.

Technical assistance - Support provided to States, and local governments/ organizations who have the resources but lack the complete knowledge and skills needed to perform a difficult activity.

Tolerable risk - A tolerable risk is one society is ready to live with, in exchange for certain benefits as compensation. This risk is not considered negligible and therefore cannot be ignored. It must be managed, periodically reviewed and reduced if possible.

Total risk - It is the total risk of flooding downstream of the dam. It is produced by both the cases in which the dam fails and the ones it does not.

Uncertainty - The process of Risk Analysis incorporates a series of uncertainties that have a relevant impact in the understanding and interpretation of the probability results of the model. The term uncertainty encompasses mainly two concepts of the different essence: natural uncertainty and epistemological uncertainty.

Vulnerability - The degree of susceptibility and resilience of a community, it's social setting, and the natural and built environments to flood hazards. The vulnerability is assessed in terms of the ability of the community and environment to anticipate, cope and recover from flood events. Flood awareness is an important indicator of vulnerability.

Warning - Dissemination of notification message signalling imminent hazard that may include advice on protective measures (e.g., warning issued by the IMD for fishermen cautioning them not to venture out into the sea when a cyclone is expected).

Warning time - In general, warning time is defined as the time elapsed between the moment the population is warned about the arriving flood and the moment the flood wave reaches the first person of the population at risk. With enough time, the inhabitants of the flooded area may organize their belongings and move them to higher places or away from the affected areas.

KEY CONTRIBUTORS

Dr. Ignacio Escuder-Bueno

Ignacio Escuder-Bueno has his doctorate's degree in Civil Engineering from Universidad Politécnica de Valencia (UPV, Spain), holds a Master's degree of Science in Civil Engineering from the University of Wisconsin-Milwaukee (UWM, USA), and he has been a member of the Spanish Institution of Civil Engineers since 1996.

He is professor at UPV and is both founder and senior partner of iPresas (a technology based SPIN-OFF company from UPV). He has been a visiting professor at the University of Maryland (USA, 2014), at Utah State University (USA, 2006).

He is the President of the Spanish National Committee on Large Dams (SPANCOLD) since October 2017, and also is member of the Spanish Commission of Legal Codes for Large Dams since 2016. He has been Chairman of the International Committee of Dams Computational Aspects of the International Commission of Large Dams (ICOLD) from 2011 to 2017 and Secretary-General of ICOLD European Club from 2010 to 2017.

He is the author or co-author of more than 100 publications and he has lectured in over 20 conferences hosted in several countries. Among others, he has been the coordinator and co-author of the SPANCOLD's Guideline N.8., T.1 "Risk analysis applied to dam and reservoir safety management (2012)".

He has over 20 years' experience as a consultant in multiple projects related with safety studies, design and risk analysis of more than 70 dams (hydroelectric, supply, irrigation, etc.). He also works as a consultant for the design of strategies for governance of natural risks, critical infrastructures and security of dams for private operators, government agencies and multilateral organizations.

Eric C. Halpin

Eric Halpin holds a Masters Degree in Civil Engineering from Oklahoma State University (1989), a Bachelors Degree in Civil Engineering from Clemson University (1983), and the Army Management Staff College (2001). He is a registered Professional Engineer since 1989 (Georgia).

In 2019 Mr. Halpin retired from the US Army Corps of Engineers after almost 40 years of service and now works as an international dam and levee expert with Halpin Consultants LLC. He has planning, design, construction, operation, and management experience with thousands of dam and levee systems worldwide including New Orleans Levee System (Louisiana), Guajataca Dam (Puerto Rico), Wolf Creek Dam (Kentucky), Oroville Dam (California), and Mosul Dam (Iraq). His focus has been the incorporation of risk methods into infrastructure decisions.

He is associated with and a member of a number industry organizations including the US Society on Dams (board member 2013-2019), the American Association of State Dam Safety Officials, the Deep Foundations Institute, and the International Commission on Large Dams. He has authored and presented dozens on dozens of topics relevant to industry. He has been a driving force behind the incorporation of risk methods into design, construction, and management policies and processes in the United States.

Dr. Adrián Morales-Torres

Adrián Morales Torres holds a degree as Civil Engineer, a MSc in Hydraulic Engineering and Environment and a PhD in Civil Engineering from the Polytechnic University of Valencia (UPV, Spain).

He has 10 years of experience in the field of dam safety and hydraulic structures, working on the application of risk analysis methodology for dam safety management for more than 50 dams, owned by public and private entities. He has work experience applying this methodology in countries such as Spain, India, Argentina, Colombia, Albania and Uruguay.

Currently, he is Chief Technical Officer of the spin-off company iPresas Risk Analysis. In addition, he is responsible for iPresas software development, and he has worked on developing other Decision Support Tools for water infrastructures.

He is member of the Spanish National Committee on Large Dams (SPANCOLD) within the dam safety committee and coordinator of the risk analysis subcommittee. He is also member of the ICOLD (International Commission of Large Dams) Technical Committee on Prospective and new challenges for dams and reservoirs.

He is author or co-author of more than 65 publications, including indexed journal papers, books, chapters, conference papers and guidelines for dam safety and sustainable water management.

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Central Dam Safety Organisation

Central Water Commission

Vision

To remain as a premier organisation with best technical and managerial expertise for providing advisory services on matters relating to dam safety.

Mission

To provide expert services to State Dam Safety Organisations, dam owners, dam operating agencies and others concerned for ensuring safe functioning of dams with a view to protect human life, property and the environment.

Values

Integrity: Act with integrity and honesty in all our actions and practices.

Commitment: Ensure good working conditions for employees and encourage professional excellence.

Transparency: Ensure clear, accurate and complete information in communications with stakeholders and take all decisions openly based on reliable information.

Quality of service: Provide state-of-the-art technical and managerial services within agreed time frame.

Striving towards excellence: Promote continual improvement as an integral part of our working and strive towards excellence in all our endeavours.

Quality Policy

We provide technical and managerial assistance to dam owners and State Dam Safety Organizations for proper surveillance, inspection, operation and maintenance of all dams and appurtenant works in India to ensure safe functioning of dams and protecting human life, property and the environment.

We develop and nurture competent manpower and equip ourselves with state of the art technical infrastructure to provide expert services to all stakeholders.

We continually improve our systems, processes and services to ensure satisfaction of our customers.

Dam Rehabilitation & Improvement Project