

# **Dam Safety Management: Operational Phase of the Dam Life Cycle**

**Committee on Dam Safety  
International Commission on Large Dams (ICOLD)**

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## Foreword

*“Engineering is inherently based on weighing of risk. Traditionally, this has been drawn to a large extent from judgment reinforced by experience. As techniques of risk analysis offered in the literature have become increasingly sophisticated, practical engineers and related professionals have preferred to apply time-tested judgmental approaches rather than new techniques. Yet there is a need to improve methods of risk analysis for the engineering of dams and other structures whose safety is important to the public interest. This especially applies where funding for remedial work is limited and expenditures must be directed to achieve an optimum reduction of risk.” (US National Academy, 1983)<sup>1</sup>*

In 2003 the Committee on Dam Safety (CODS) was asked to review and assess the need to update ICOLD Bulletin 59 - Dam Safety Guidelines. Issued in 1987, the Bulletin was the first document prepared by the ICOLD Committee on Dam Safety, which was created in 1982. The primary importance of Bulletin 59 was in directly addressing the challenge posed to the Committee by ICOLD. This challenge was described in the Foreword to the Bulletin as follows:

*“The Committee on Dam Safety was established as a coordinating body to assure an integrated approach of all (ICOLD) Technical Committees to safety issues, to guide toward action where shortcomings or gaps may be perceived, to define a common safety philosophy and to prepare general guidelines on dam safety outlined along this philosophy.”*

Bulletin 59 began with the establishment of philosophical foundations of dam safety, and outlined the basic principles and requirements which should govern the development of methods and techniques ensuring that these principles and requirements are met during the entire life cycle of a dam. The Bulletin acknowledged that growing societal demand for safer dams involved an increase in expenditures and that the optimal allocation of limited resources (in the presence of conflicting objectives of economic efficiency and safety) was not possible without assessing the overall safety of the dam through an estimation of the total risk<sup>2</sup> of a dam failure. The Bulletin concluded that at that time (1987) credible estimation of such risks was not achievable, but it also encouraged the development and application of a probabilistic approach. In summary, the concepts of assessing and managing dam safety outlined in the Bulletin were predominantly of a deterministic character, and introduced various semi-probabilistic components in some areas of safety analysis.

In 2005 the CODS issued Bulletin 130 – Risk Assessment in Dam Safety Management: A Reconnaissance of Benefits, Methods and Current Applications. The new Bulletin pointed out that steadily growing societal demands for transparency and accountability in the areas of decision making which affect safety required a profound philosophical change in how the decision-making framework should be formulated. Taking into account the significant progress in the development and application of advanced risk-informed and risk-based methods in the fields of safety assessments, the Bulletin outlined a general framework of a risk-informed approach to decision making in dam safety. This new Bulletin has been perceived by some professionals in the dam engineering field as an attack on the traditional ways of assessing dam safety outlined in Bulletin 59. However, the position of the CODS on this subject is different, and the reasons are explained below.

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<sup>1</sup> Safety of Existing Dams: Evaluation and Improvement. Committee on the Safety of Existing Dams. National Research Council. National Academy Press, Washington, D.C. 1983.

<sup>2</sup> In this document the term ‘risk’ refers to the characterization of both the probability of adverse consequences resulting from dam failure and their magnitude. Detailed considerations with regard to ‘risk’ can be found in ICOLD Bulletin 130.

The traditional approach to dam safety assessment (often called standards-based) begins with the establishment of safety requirements and criteria associated with a predetermined classification system reflecting either the hazard potential or the consequences of dam failure. The uncertainty is not addressed directly and it is accounted for in an indirect manner by applying safety coefficients and conservatively safe values for resistance variables and loads.

Most of these deficiencies in the process of assessing the safety of dams can, in principle, be eliminated by an appropriate application of either the risk-based or the risk-informed approach. Bulletin 130 pointed out the major limitations of the risk approach, (quantification of probabilities, estimation of consequences, definition and societal acceptability of the tolerable risk concept), and it is encouraging to note that major progress has been made in all of these areas since the issuance of the Bulletin in 2005. Therefore, the time when the conditional term “in principle” can be dropped from the sentence above is getting closer and the expectation that a credible and comprehensive risk assessment could provide a solid basis for a transparent and effective risk management of dams is becoming more and more realistic.

At the present, the dam engineering community is divided between the slowly declining majority which insists that the traditional approach is the only one which can be trusted; a minority constituted of those who deny the validity of the traditional school concepts; and finally the third group which is slowly but constantly gaining more support, and which is of the opinion that the systematic but gradual expansion of risk techniques into the area of dam safety assessment and management is the proper way to proceed. The expansion should be conditional not only on the satisfactory progress in developing the analytic site of the risk assessment process, but also on the availability of financial and human resources. Taking into account that risk-based analyses not only cost more, both in terms of time and financial input, but also that they demand a different set of skills and knowledge than traditional dam engineering, the necessity for a gradual approach should not be surprising.

And that observation finally brings us to the main point of this foreword. Dams are structures that differ from many other engineering creations. What makes them different is the longevity of service, and thereby, the exceptional length of their economic life. The typical life cycle of a properly engineered dam can easily exceed 100 years. There are numerous examples of dams still in operation in Europe whose construction goes back to the times of the Industrial Revolution. There are also dams in Iran, built thousands years ago (Bahman Dam and Mizan Dam built in the 1<sup>st</sup> and 4<sup>th</sup> century A.D., respectively) and still in operation. Within the complete life cycle of a dam (concept – design – construction – commissioning – operation – rehab/decommissioning) the operational phase is the longest, and requires that the organization responsible for the dam has a process in place that is fully capable of addressing all aspects of dam safety. This process should be developed in such a manner that it remains effective over long periods of time and be immune from all external and internal disturbances during that period. Thus, such system should be able to identify, track and address effectively all potential and actual problems that can impact the safety of the dam.

The complexity of the task increases significantly when the organization has a portfolio of dams. The size of the portfolio can add significant complications to the prioritization of actions and the prioritization of urgency in solving numerous identified problems. In industry or in commerce, the method by which integrity of all operational activities being carried out is assured is known as a management system. Such systems establish a systematic and consistent way of translating a dam-owning organization’s principles, policies and values into the outputs of industrial or commercial activities. Since the safety impacts of dam presence or operation may affect people, property and the environment, these principles and policies have to be in agreement with the

general interest of the population. These interests are usually protected by the country's laws and government regulations.

Quite early in the initial stage of this Bulletin's development, the Working Group with the consensus of the CODS came to the conclusion that the management of dam safety in the operational phase is possibly the most challenging, and, taking into account the sheer number of existing dams, also the most urgently needed. However, what also became readily apparent during our work on this Bulletin is that another document dealing with the development and implementation of the modern safety management approach to other phases of the dam life cycle should be considered as a priority task for the CODS in the future.

This Bulletin is devoted to the development and the implementation of a dam safety management system for dams in the operational phase of their life cycle. It outlines the general structure of a systems approach to safety management, and strives to develop a system that can address all the interdependencies, and encompass all the arrangements necessary to ensure proper dam safety management. The outline is built on the principles established in Bulletins 59 and 130, as well as the general philosophy that informs them both. In that respect this Bulletin is not intended to update or replace the Bulletin 59 which although written in 1987 is still valid and should remain as a primary source of guidance for these professionals who are applying traditional approach to dam safety.

A comment is needed with respect to the decision-making processes involved in managing the safety of existing dams. Depending on the various decision-making problems which may occur during a dam's operation, the nature of this process can vary substantially. On the one hand, these decisions can be made using the approach of simply comparing the outcomes of deterministic analyzes and observed values with standards and safety requirements. On the other hand, if the risk-informed approach is to be used, then the analytic part becomes much more complex, but the resulting comparison of assessed risks provides a more complete picture of the safety status, and ensures full transparency of the decision-making process by comparing the assessed risk with the tolerable risk criteria. This Bulletin is in a way neutral with respect to which type of decision-making approach should be selected. The safety management system presented in the Bulletin allows for the use of either of the two approaches.

In conclusion, the authors and the entire Committee on Dam Safety sincerely hope that the Bulletin will be helpful in developing, implementing, reviewing and improving the management of dam safety at all organizational levels.

Przemysław A. Zielinski  
Chairman, Committee on Dam Safety

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The Committee on Dam Safety and the ICOLD Executive gratefully acknowledge the contribution of members of the Committee's Working Group and the support provided by their sponsoring organizations. The final text of the Bulletin is the result of the collective effort of the entire CODS which continued providing general guidance and valuable input during the period of 2004 to 2010. The task of converting this guidance into technical guidelines for managing dams' risks rested with the Working Group. The Group not only acted as a forum for exchange of ideas but was also instrumental in reviewing and commenting on numerous drafts. Finally, the task of writing the drafts and preparing the final text was carried out by:

1. Dr. D.N.D. Hartford, Principal Engineering Scientist, BC Hydro, Canada – financial and in kind assistance provided by BC Hydro;
2. Mr. M. Poupart, previously Dam Safety Advisor at Electricité de France, presently Independent Consultant, France - financial and in kind assistance provided by Electricité de France;
3. Dr. P. A. Zielinski, Manager Technology and Dam Safety, Ontario Power Generation, Canada - financial and in kind assistance provided by Ontario Power Generation;

The other members of the Working Group:

4. Dr. D.S. Bowles, Director, Institute for Dam Safety Risk Management and Professor, UWRL/Civil and Environmental Engineering, Utah State University, and Principal, RAC Engineers & Economists, United States of America - financial and in kind assistance provided by Utah State University;
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It needs to be stressed that the effort provided by the members of the Working Group was extensive and its work was instrumental for completion of the task. The knowledge and experience of Working Group members covered the wide spectrum of potential stakeholders of dam safety – the government, the regulators, the owners, the consultants and the academia. This breadth of perspective on regulatory, organizational, managerial and engineering aspects of dam safety management can hopefully provide the readers of this Bulletin with the help in designing and implementation of the modern comprehensive management system for managing risks of dam owning and operating organizations.

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# Chapter 1 - Introduction

Dams are instruments for the protection of the public interest, through the control and storage of water for human or agricultural consumption, hydropower generation, or for flood protection and control. Just as the public interest is protected *by* dams, it is necessary for the public to be protected *from* dam failures. Thus the management of safety of dams is an integral part of the overall sustainable management of dams.

The control of water resources is a matter of national importance to all governments. Government is responsible for creating the legal frameworks, laws and other legal instruments to control these activities through the national political and legal mechanisms. International conventions and specific treaties normally apply to water resources shared between countries.

Laws which deal with general duties of care are often supplemented by regulations that are specific to different activities. Licensing arrangements are among the instruments available to the various levels of government to control industrial and other societal activities. Governments have methods of monitoring the effectiveness of their controls over water resource management through statements of policy, setting of expectations, and establishment of oversight arrangements. These oversight arrangements can also include consideration of a broad spectrum of factors including financial, societal and environmental stewardship.

Ownership of hazardous installations and their operations, including dams, brings attendant responsibilities and liabilities, which have been laid out in various ways in different countries over the millennia. Most often, the owner can be considered to be the Responsible Entity and nominates an individual representative who is required to develop internal structures for discharging the duties as defined in the laws and regulations that govern the hazardous operation, and to demonstrate compliance with the laws and regulations. At the same time, the representative is responsible for demonstrating to the Responsible Entity that all of the other operational functions of the industrial activity are continuing as intended. More detailed discussion of responsibilities is provided in Sections 2.3 and 4.1.

The Responsible Entity typically has processes in place to enable effective operation of all dimensions of the organization both under normal and abnormal conditions including emergencies. It is also responsible for making all organizational and management arrangements to perform activities within the constraints of government regulation.

In the modern world, organizations are often expected to explain the values that underpin their operations and activities, whether they are governments, public corporations or private entities. The values include concepts such as integrity, accountability, safety, public trust, and environmental stewardship.

The values of an organization can be operationalized through statements of principle that account for the life cycle phase of the organization, the typical phases being design, construction, operational activities, and decommissioning. Societal and industrial organizations are generally established to endure over time, and in establishing the operations, the organization will consider all aspects of the life-cycle of the assets and processes.

The operational capacity and other attributes such as safety will change naturally as a result of the activity itself, ageing, or unplanned events including natural events and human acts. These changes must be managed in a way that ensures the integrity, safety and viability of the operation. Owing to the long life of most large

dams, it is not necessarily realistic to consider that the entire life-cycle will be managed by the same entity, operating to the same values and principles, over decades or centuries. Thus, if the different phases are to be managed as different entities, the correct linkages between the various stages should be made. This Bulletin provides the context and then focuses on the operational phase of the life-cycle, as shown in Figure 1.1.

Chapter 2 outlines the fundamental dam safety objective in terms of protecting people, property and the environment, and it outlines overarching principles for dam safety management that should be considered by organizations that own and operate dams. Dam ownership is diverse and the management of dams is usually carried out as part of a wider socio-economic activity.

Chapter 3 introduces management systems in the context of modern industry. It outlines the elements of a dam safety management system, and explains how they can be incorporated in the broader management system of the Responsible Entity.

Chapter 4 expands upon the elements of a dam safety management system and provides practical guidance that the Responsible Entity can apply to manage and implement a dam safety program. It seeks to embody the concepts presented in Chapter 2 within the management structure of a Responsible Entity to permit the management system process described in Chapter 3 to be effectively applied to all levels of management actions and implementation activities within the Responsible Entity. The chapter is written with the recognition that the concepts described in Chapter 3 can be applied for example by the Board of Directors of the Responsible Entity in the oversight of the executive management's arrangements to discharge the organizations responsibilities as described in Chapter 2. Thus, the early part of Chapter 4 involves a certain amount of overlap with the result that the text does not flow strictly in the linear consecutive way as is outlined in Chapter 3. Against this background, Section 4.2 addresses the enabling strategies that are required within the dam owning organization and the management direction required to achieve effective management of dam safety. Section 4.3 provides a general description as to how the management direction is achieved through deployment and distribution of roles and responsibilities and how the concepts of Chapter 3 are applied to all levels within the management hierarchy. Section 4.4 provides an outline of the types of considerations that dam owning organizations can apply in achieving the objectives with respect to dam safety within the overall operating context of the dam owning organization. Against this background, Sections 4.2 through 4.4 should be considered as enabling precursors to the implementation of the management system process of Chapter 3 as outlined in Sections 4.5, 4.6 and Chapter 5.

Chapter 5 addresses the on-site activities that are the most recognizable elements of typical dam safety programs. However, as laid out in this Bulletin, those activities at the dam must be managed with consideration of the systems and principles described in Chapters 1 to 4.

Appendix A illustrates the importance of other ICOLD Bulletins to development and implementation of modern dam safety management program. It contains review of all ICOLD Bulletins which can provide input to such endeavour.

Appendix B contains more detailed discussion of general problems in dam safety decision making using both implicit and explicit approaches to uncertainty and risk.

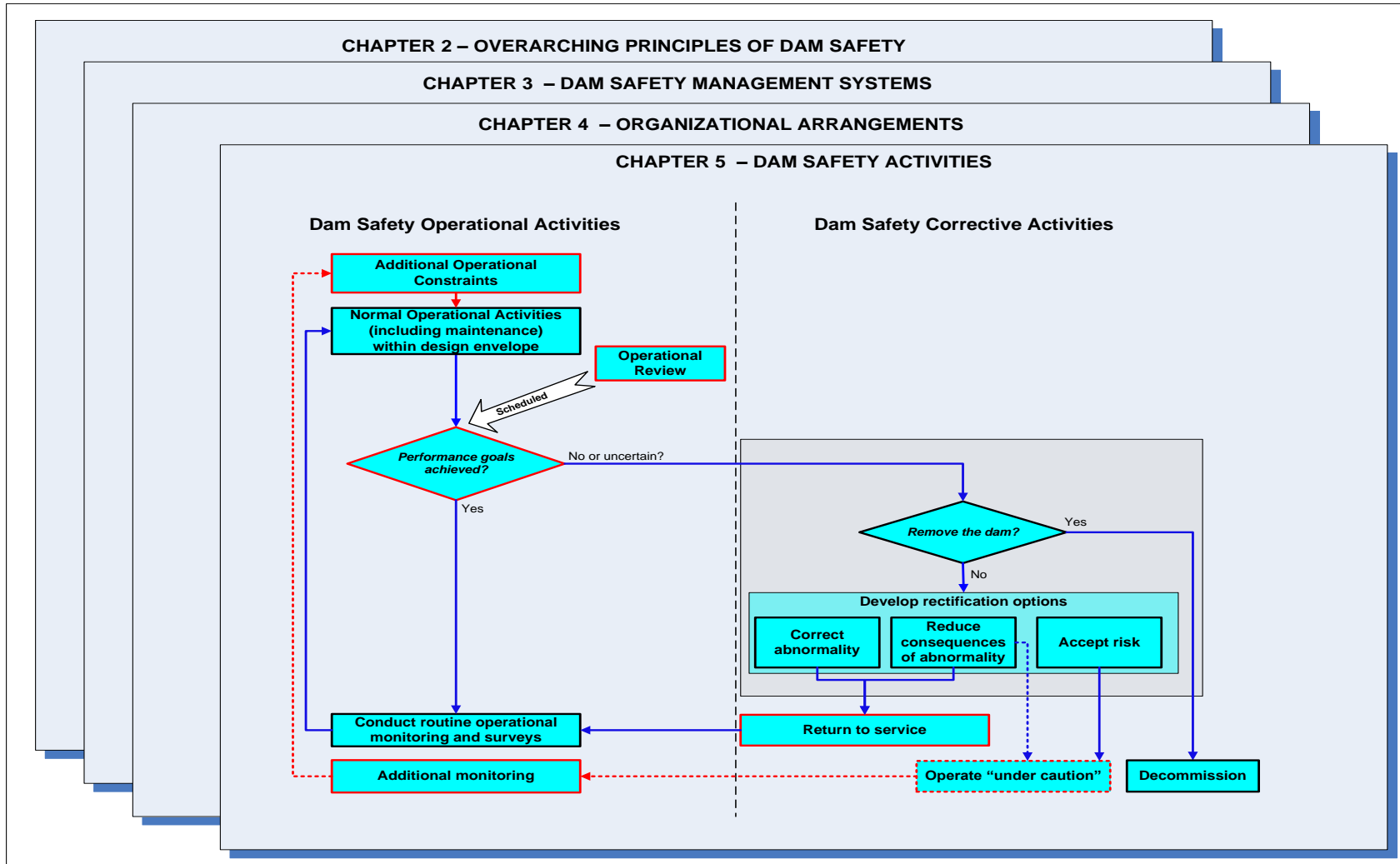
The Bulletin presents a framework for managing the safety of dams regardless of the number of dams owned or the extent to which management, engineering and operations resources are available within the Responsible Entity. The structure of the Bulletin introduces the concept of scalability, that is the framework

and embedded processes can be scaled to be applicable to meet the management needs of dam owners of any size and of dams of any size. The Bulletin takes as a premise the idea that the owner of a single relatively small dam with few resources will be faced with managing the same physical hazards and dam performance issues as the large owner of many large dams, while recognizing that the scale of the management effort to be applied and how the management activities are to be distributed will be different. In terms of this view, the individual who owns a single and a relatively small dam will have the same overall liabilities and responsibilities as the corporate or Government owner of a large number of very large dams, albeit on a considerably lesser scale.

The concept of scalability applies to the managed activities in the same way as it does to the management responsibilities with the concepts of Chapter 3 being as applicable to the management arrangements for an entire portfolio of dams as it is to the management of a single process such as the Periodic Dam Safety Review activity or the Routine Surveillance activity.

The so called 'small owners' of single dams with relatively high hazard potential may find themselves in a situation where the nature and the magnitude of hazards require that quite extensive efforts and significant financial, management and engineering resources have to be available in order to meet dam safety requirements. Lack of these cannot be used as a justification of inaction due to inaffordability because the public, property and the environment located downstream of such dam deserve the same level of protection as others exposed to similar hazards.

Figure 1.1 – Context for Dam Safety



## Chapter 2 - Overarching Principles of Dam Safety

### 2.1 Justification for Dams

**Dams should be constructed and operated only if they yield an overall benefit to society.**

The construction of a dam imposes risks on society, with the risks often distributed unevenly, so that those who benefit<sup>3</sup> from the dam are not necessarily those on whom the risk is imposed. For dam and reservoir activities to be considered justified, the benefits that they provide to society as a whole should outweigh the risks that they create. For the purposes of assessing benefit and risk, all significant consequences of the operation of dams and reservoirs have to be taken into account.

In many cases, decisions relating to benefit and risk are taken at the highest levels of government, such as a decision by a state to embark on a dam building program. In other cases, the regulatory body may either determine whether proposed dams and activities are justified or influence the decision on this matter.

### 2.2 Fundamental Dam Safety Objective

**The fundamental dam safety objective is to protect people, property and the environment from harmful effects of misoperation or failure of dams and reservoirs.**

This objective is achieved by retaining the stored volume of water and controlling all flows through and around the dam within specified limits determined through the approvals and licensing process established by government. "Misoperation" involves any departure from the design norms for safe operation of any part of the dam or its safety critical systems.

The objective of protecting people, property, and the environment from the effects of dam failure has to be achieved without unduly limiting the benefits created by operation of dams and reservoirs. To achieve the highest standards of safety that can reasonably be achieved, measures must be taken to:

1. Control the release of damaging discharges downstream of the dam through controls embedded in the normal operating regime of the dam;
2. Restrict the likelihood of events that might lead to a loss of control over the stored volume and the spillway and other discharges;
3. Mitigate through on-site accident management and/or emergency planning the consequences of such events if they were to occur.

Meeting the dam safety objective will therefore mean that:

- All reasonably practical measures have been taken to prevent dam failure and to mitigate the consequences, should it occur;

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<sup>3</sup> Benefits include all social and environmental benefits and are not restricted to quantifiable economic benefits.

- There is a high level of confidence that the likelihood of events with a potential to cause serious consequence is extremely low;
- There is a high level of confidence that, for all possible dam-failure-initiating events taken into account in safety assessment, any adverse consequence would be minor.

The fundamental safety objective applies to all dams and dam operational activities and to all stages over the lifetime of a dam, including planning, design, construction, commissioning, operation, and either the long term sustainability of the dam or decommissioning of the dam.

The principles presented in the following sections provide an overarching management framework to support achievement of the fundamental dam safety objective.<sup>4</sup>

### 2.3 Responsibility for Operational Integrity and Safety

**The prime responsibility for operational integrity and safety of a dam should rest with the Dam Owner.**

The Dam Owner is ultimately responsible for assuring the safety of the public, property and environment around and downstream of dams. However, since dams are often not owned and operated by a single individual, company or organization, the term Responsible Entity is used in this Bulletin. Usually the dam owner is the Responsible Entity. Sometimes a government institution or agency is responsible for the safety of the dam and the public, either directly or through oversight over the safety management activities of the bodies that operate the dam.

The safety arrangements established by the Responsible Entity must conform to the requirements and expectations of government and the prevailing laws, regardless of how they are established and implemented. Therefore, the Responsible Entity's values and principles that govern safety management reside within the overarching legislative and regulatory value system of the country where the dam is located.

In some instances for dams, the Responsible Entity may be a branch of government with significant internal dam engineering and safety management capability, and which is responsible for all aspects of the operational integrity and safety management of the dam over its entire life-cycle. Conversely, the Responsible Entity may have no engineering capability and, in the absence of prescriptive regulatory requirements, it will be the legislative and judicial arms of government where the safety of dams is implied by existing legislation and precedents, with all responsibility for meeting the intent of the law resting with the Responsible Entity.

In order for the Responsible Entity to be confident that it is meeting all obligations in relation to the safety of its dams, a systematic approach to dam safety management activities is needed. This means that the Responsible Entity is responsible, at a minimum, for:

1. Establishing and maintaining the necessary competencies;
2. Providing adequate training and information;
3. Establishing procedures and arrangements to maintain safety under all conditions;

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<sup>4</sup> The principles are derived from a set developed by the International Atomic Energy Agency (IAEA), which is an example of an international body with responsibility for overarching control and regulation of activities across a hazardous endeavour.

4. Verifying appropriate design and the adequate quality of facilities and activities and of their associated equipment;
5. Ensuring the safe control of all inflows, outflows and stored volumes;
6. Ensuring the safe control of all sediments and deleterious materials that arise as a result of the dam.

Dam safety management covers the full spectrum of hazardous conditions, including dam failure, which can arise from the activities of storing and discharging water. Since dam management can span many human generations, consideration should be given to the fulfillment of the responsibilities of the Responsible Entity and the regulator in relation to both present and future operation. Provision should be made for the continuity of responsibilities and the fulfillment of funding requirements in the long term.

These responsibilities should be fulfilled in accordance with applicable safety objectives and requirements, as established or approved by the regulatory body, and their fulfillment is to be ensured through the implementation of a management system.

## 2.4 Role of Government

**The legal and governmental framework for all industrial activities, including operation of dams, provides the overarching structures for operational integrity and safety assurance.**

The role of the Government includes defending the general interest of the population and, in order to do so, it writes laws and regulations specific to protection of people, property and the environment. For activities that are hazardous, laws and regulations are often enacted to protect third parties against the harmful effects of misoperation or failure of the specific activity.

In some cases within the general legal framework, specific laws and regulations may be established to protect against the misoperation or failure of dams and reservoirs. The legal and governmental framework provides for the governance of dams, reservoirs and operational activities that give rise to dam breach and other inundation risks. The framework typically includes the clear assignment of Responsibility for Operational Integrity and Safety (see Section 2.2). The government is responsible for the adoption of such legislation, regulations, and other standards and measures, within its national legal system, as may be necessary to effectively fulfill all its national responsibilities and any international obligations. In terms of the modern view of safety governance this includes establishment of an independent regulatory body to assure the safety of dams.

Government authorities should ensure that arrangements are made for reduction of risks from dams, including emergency actions, monitoring of high discharges to the environment, and disposing of reservoir silt waste. This does not require that the governments establish and maintain all arrangements, although they may choose to do so. In addition, government authorities have to address the safety of dams for which no other organization has responsibility.

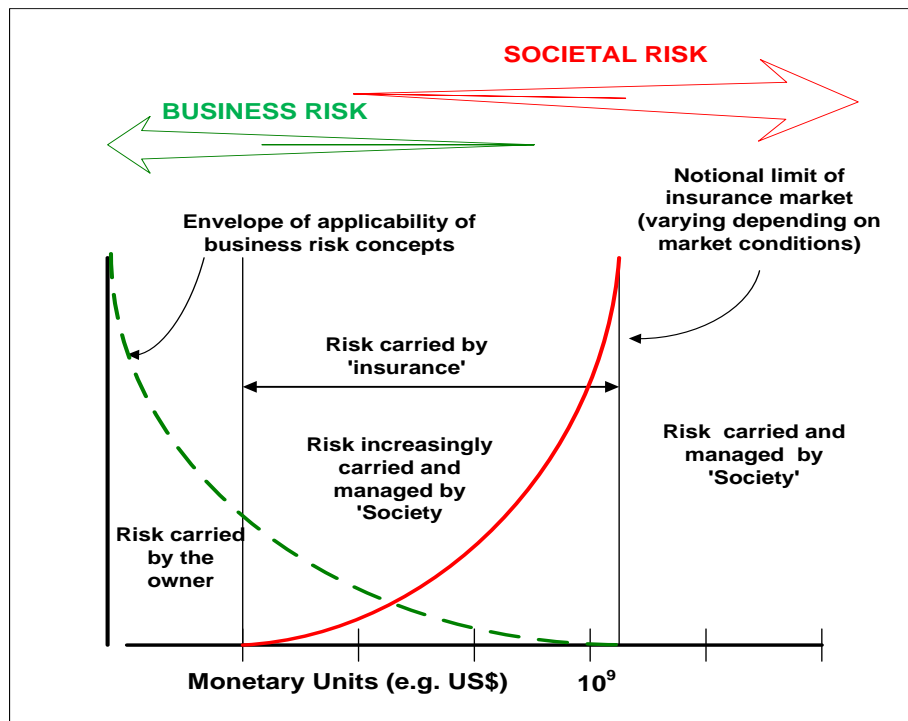
The government body with responsibility for dams should:

- Have adequate legal authority, technical and managerial competence, and human and financial resources to fulfill its responsibilities;

- Be effectively independent of the Responsible Entity and of any other body, so that it is free from any undue pressure from interested parties;
- Set up appropriate means of informing parties in the vicinity, the public and other interested parties, and information media, about the safety aspects (including health and environmental aspects) of dams and reservoirs and operational activities, and about regulatory processes;
- Consult parties in the vicinity, the public and other interested parties, as appropriate, in an open and inclusive process.

Governments and regulatory bodies thus have an important responsibility in establishing standards and establishing the regulatory framework for protecting people, property and the environment against dam safety risks.

**Figure 2.1 – Example of Distribution of Costs of Dam Failures**



If the Responsible Entity is a branch of government, this branch should be clearly identified as distinct from and effectively independent of the branches of government with responsibilities for regulatory functions.

It is now generally accepted that government or the state authority appointed by government should confront some basic issues arising from the presence of dams - most notably, the balancing of economic, social and technological progress, against a wish for "zero risk" and guaranteed safety. Thus the regulator may need to consider the following propositions.

- Risk is a necessary part of the human condition;
- Progress often depends both on incurring risk and learning from failures (i.e. accidents);



- Risks must be controlled but cannot in most circumstances be eliminated;
- Control of risks must, in the interests of technological development and societal progress, move public opinion from focusing on what is acceptable to what is tolerable<sup>5</sup>;
- "Safe enough" is the goal to be striven for in design, engineering and risk management.

This balancing function (see principle for Balancing of Protection across Competing Safety Objectives in Section 2.6) is particularly important for dams because of their essential roles in societal development over a number of generations. The government apparatus must recognize that many dams must be managed in perpetuity and that the liabilities associated with dam failure may exceed the capacity of the Responsible Entity to meet these liabilities. As illustrated in Figure 2.1, there are three loss categories:

- Risk that is carried by the owner (commonly referred to as the owner's "deductible");
- Risk that is carried by insurance;
- Risk carried and managed by society in the form of the national government.

## 2.5 Leadership and Management for Safety

**Effective leadership and management for operational integrity and safety should be established and sustained over the life cycle of the dam.**

In general, leadership in safety matters should be demonstrated at the highest levels in all organizations. Dam safety is no different. Safety has to be achieved and maintained by means of an effective management system. This system should integrate all elements of management so that requirements for safety are established and applied coherently with other requirements, including those for human performance, quality and security, and so that safety is not compromised by other requirements or demands. The management system also has to ensure the promotion of a safety culture, the regular assessment of safety performance, and the application of lessons learned from experience.

A safety culture that governs the attitudes and behaviour in relation to safety of all organizations and individuals concerned should be integrated in the management system. Safety culture includes:

- Individual and collective commitment to safety on the part of the leadership, the management and personnel at all levels;
- Accountability of organizations and of individuals at all levels for safety;
- Measures to encourage a questioning and learning attitude and to discourage complacency with regard to safety.

An important factor in a management system is recognition of the entire range of interactions of individuals at all levels, with technology and with organizations. To prevent human and organizational failures, human factors must be taken into account, and good performance and good practices supported. Despite all measures that are taken, accidents may occur. Processes should be put in place for the feedback and analysis of operating experience, including initiating events, accident precursors, near misses, accidents and unauthorized acts, so that lessons may be learned, shared and acted upon.

<sup>5</sup> Detailed discussion of tolerability and acceptability concept with respect to dam safety risks is provided in Section 4.4 and Appendix B.

Management must ensure that safety is assessed for all dams and reservoirs and for all operational activities, consistent with an approach that proportionately accounts for consequences, costs, perceptions and other significant considerations.

The design and implementation of such a management system is the subject of Chapters 3, 4 and 5 of this Bulletin.

## 2.6 Balancing of Protection across Competing Objectives

**Protection should seek to achieve a balance across competing objectives to provide the highest level of operational integrity and safety that can reasonably be achieved.**

The safety measures applied to dams are considered balanced if they provide the highest level of safety to people, property and the environment that can reasonably be achieved throughout the physical lifetime<sup>6</sup> of the dam, without unduly limiting its utilization. Balancing of protection must be considered in terms of risk to individuals and risks to future generations as described in Section 2.7 below. The balancing process necessarily involves making comparisons and trade-offs between competing interests that cannot be compared directly. Risk acceptability is a complex and, in principle, a political issue. Politics is an activity where comparing “apples and oranges” is legitimate. Even in jurisdictions where the Roman or Napoleonic legal system prevails, political considerations can overrule the results of the risk assessment,

To determine whether dam safety risks are as low as reasonably achievable, all such risks whether arising from normal operation or from abnormal or accident conditions, should be assessed (using a graded approach) *a priori* and be periodically reassessed throughout the lifetime of facilities and activities.

Where there are interdependencies between related actions or between their associated risks (for example, for different stages of the lifetime of dams and reservoirs, for risks to different groups), these should also be considered. Account also has to be taken of uncertainties in knowledge.

The balancing of protection requires judgments to be made about the relative significance of various factors, including:

- Number of people (workers and the public) who may be exposed to dam related hazards;
- Likelihood of people being exposed to the hazard;
- Dam safety risks arising from foreseeable events;
- Economic, social and environmental factors.

The balancing of protection also means using good practices and common sense to avoid dam safety risks as far as is practical in day-to-day activities.

The resources devoted to safety by the Responsible Entity, and the scope and stringency of any laws or regulations in general or specific to dams, and their application, have to be commensurate with the magnitude

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<sup>6</sup> Physical lifetime may be different from "economic life" used in economic evaluation of dams at the time of construction or evaluation of dam safety improvements.

of the dam safety risks and their amenability to control. Regulatory control may not be needed where it is not warranted by the magnitude of the dam safety risks.

## 2.7 Limitation of Risk to Individuals and Society

**Measures for controlling risks from dams should ensure that no individual bears an unacceptable risk of harm, and that the risks to society do not exceed the risk tolerance levels of society.**

Justification of risk taking and balancing of protection does not in itself guarantee that no individual (including employees and operators as well as the wider society) bears an unacceptable risk of harm. Risk limits typically represent a legal upper bound of acceptability; they are insufficient in themselves to ensure the best achievable protection under the circumstances, and they therefore have to be supplemented by the optimization of protection. Thus, both the balancing of protection and the limitation of risks to individuals are necessary to achieve the desired level of safety.

Risk acceptance in the context of risk management is a value-laden decision process that is primarily fashioned by the prevailing legal and regulatory arrangements.

Protection measures that can be established and would normally be expected to be established (either by the Responsible Entity or the local government or state according to the legal and regulatory framework existing in each country) include the following:

1. Elimination or reduction of predictable hazards or establishment of controls over them to the extent that is practicable;
2. Elimination or reduction of failure modes, if practicable and if judged to be reasonable in terms of cost and risk reduction benefit;
3. Justifying that the capacity of the system and its components exceeds the demands by sufficiently large margins to provide protection that is “as close to equivalent” to elimination of the failure mode, as is reasonably practicable;
4. Establishing and implementing the capability to intervene and avert failure in the unlikely event that a failure mode initiates;
5. Demonstration that effective evacuation to prevent loss of life given dam failure is provided;
6. Availability of funding mechanisms for the compensation of the community affected by a failure, generally financed by measures illustrated in Figure 2.1.

Once the safety management measures are established, it may be necessary to demonstrate that the risks to any affected individual or group or to the environment are within the norms accepted by society. These norms may be stated explicitly in numerical terms, more generally in terms of principles, explicitly in terms of engineering and other standards, or even implied through permitted societal activities.

The extent to which the above management activities are implemented will typically be context dependent, but fundamentally the whole process demands a balancing of costs and benefits, specifically, the cost of

maintaining safety at a particular level against the societal benefits that are derived from taking the risk associated with dam operation. These activities are explained in more detail in Section 4.4.

## 2.8 Sustainability of Dams and Reservoirs

**In order to secure the societal value, dams and reservoirs must be sustained in the long term. To ensure sustainability of dams, all reasonably practicable efforts should be made to prevent and mitigate failures and accidents.**

Due account must be taken of the fact that dam safety management generally spans many human generations, and that decisions made in the present will affect future generations. Similarly, dams are not benign with respect to the environment and the long term risks to the environment must also be considered.

The possible consequences of current and future actions have to be taken into account in judging the adequacy of measures to control risks of dam failure and reservoir release. This means that:

- Safety standards apply not only to local populations but also to populations remote from the dam and reservoir;
- Where effects of inundation damage could span generations, subsequent generations have to be adequately protected without any need for them to take significant additional actions.

Whereas the effects of exposure to flood waters on human safety and health are relatively well understood, albeit with some uncertainties, the effects of severe flood waters on the environment have been less thoroughly investigated. The general intent of measures taken for purpose of environmental protection has been to protect ecosystems against dam breach floods and damaging inundation that would have adverse consequences for populations of a species, as distinct from individual organisms.

Reservoir sediments should be managed in such a way as to avoid imposing an undue burden on future generations; that is, the generations that produce the waste should seek and apply safe, practicable and environmentally acceptable solutions for its long term management. The production of sediment waste should be kept to the minimum practicable level by means of appropriate design measures and procedures, such as the recycling and reuse of material.

The primary means of preventing and mitigating the consequences of accidents is ‘defense in depth’. Defense in depth is implemented primarily through the combination of a number of consecutive and independent levels of protection that would have to fail before harmful effects could be caused to people, property or to the environment. If one level of protection or barrier were to fail, the subsequent level or barrier would be available. When properly implemented, defense in depth ensures that no single technical, human or organizational failure could lead to harmful effects, and that the combinations of failures that could give rise to significant harmful effects are of very low probability. The independent effectiveness of the different levels of defense is a necessary element of defense in depth.

ICOLD recognizes that there are some difficulties in achieving “defense in depth” for all critical elements of dams, largely because it is not possible to ensure redundancy of physical protection systems. Therefore conservative criteria and non-physical measures as outlined below should be provided to compensate for the lack of physical redundancy.

Defense in depth is provided by an appropriate combination of:

- Effective management system with strong management commitment to safety and a strong safety culture;
- Adequate site selection and the incorporation of good design and engineering features providing safety margins, diversity and redundancy, mainly by the use of:
  - Design, technology and materials of high quality and reliability;
  - Control, limiting and protection systems and surveillance features;
  - Appropriate combination of inherent and engineered safety features;
  - Comprehensive operational procedures and practices as well as incident and accident management procedures.

Accident and incident management procedures should be developed in advance to provide the means for regaining control of the reservoir or spill in the event of a loss of control of the reservoir, and for mitigating any destructive consequences.

## 2.9 Emergency Preparedness and Response

**Appropriate arrangements should be made for emergency preparedness and response for dam failures and accidents.**

The primary goals of preparedness and response to a dam breach emergency are to ensure that for reasonably foreseeable incidents, inundation consequences would be minor, and for any incidents or failures that do occur, practical measures are taken to mitigate consequences for human life and health, property, infrastructure, and the environment.

The Responsible Entity, employer, regulatory body, and appropriate branches of government need to establish in advance arrangements for emergency preparedness and response to a dam breach emergency. Plans may be needed at local, regional and national levels, and where agreed between countries, at the international level.

The scope and extent of emergency preparedness and response should reflect:

- Potential consequences of a dam breach emergency;
- Characteristics of the dam breach flood ;
- Nature and location of the dam, reservoir and operational activities, and their proximity to habitations and dam safety infrastructure;
- Criteria set in advance for use in determining when to take different protective actions;
- Capability to take actions to protect and inform personnel at the scene as well as the public, if necessary.

In developing the emergency response arrangements, consideration should be given to all reasonably foreseeable events. Emergency plans should be exercised periodically to ensure the preparedness of the organizations having responsibilities in emergency response.

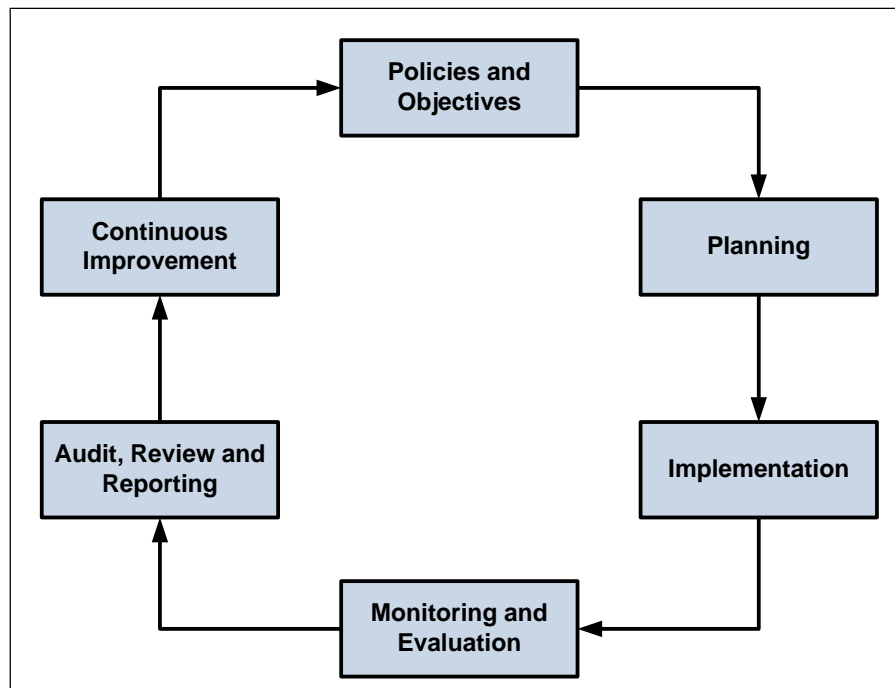
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## Chapter 3 – Dam Safety Management Systems

### 3.1 General

In most of the industrial<sup>7</sup> operations, a “management system” is the method by which operational activities are carried out and the integrity of the industrial activity is assured. Broadly, the management system establishes a systematic and consistent way of transforming an operating organization’s values, principles, policies and procedures into the products or outputs of industrial or commercial activities, through a set of linked sub-activities that achieve an appropriate balance across all activities, as illustrated in Figure 3.1.

Figure 3.1 - Elements of a Management System



**Policies and Objectives** should set a clear direction to follow in achieving all of the goals of the organization. Typically, these policies and objectives will cover strategies to accommodate competing internal objectives and provide a means to strike a balance between these objectives in a way that ensures overall success of the endeavour.

**Planning** sets objectives and targets to be achieved, develops plans for implementation, and defines performance standards. Comprehensive assessment of risks and uncertainties that could adversely impact the operation and achievement of the objectives, and the development of contingency plans, would normally

<sup>7</sup> The term “industrial” should be understood in a broad sense and not as related to only manufacturing industries

precede the implementation of the plan. This step also includes determination of resources required to achieve the objectives.

**Implementation** activities put in place an effective management structure and system of procedures that ensure that the objectives are achieved.

**Monitoring and Evaluation** of performance provides information on the effectiveness of the activity and whether the management system is maintaining operation within its defined objectives. Performance is measured against the standards established in the *Planning* step.

**Audit, Review and Reporting** provides a systematic review of performance, based on information collected by *Monitoring and Evaluation*, with additional data provided by independent audits. Performance can be assessed not only against the standards set in the planning step, but it can also be compared with external practice.

**Continual Improvement** uses the results of *Performance Monitoring and Evaluation* along with results from *Audit, Review and Reporting*, to make adjustments and improvements in the policies and processes.

Well designed management systems are scalable in the sense that the same general elements of the management process apply at all levels in the operating organization, although to different degrees and at different levels of detail.

An organization whose operation poses a risk to the public, public property and the environment should include specific management provisions for process integrity, safety assurance, and control of technological risk. The management system should define the balance between operational integrity and safety, and industrial output. It will define conditions where further control of safety and risk takes priority over other objectives.

Hazardous industrial process industries normally have elements, sometimes in the form of subsidiary management systems, that specifically address the integrity of the process to assure safety and control of risks associated with the hazardous activities. The subsidiary management system defines the ways in which these matters are dealt with in the context of the wider industrial activity.

Management systems, whether related to environmental, occupational or public safety, financial, overall quality, or other aspects of conducting a business, can be powerful tools in managing a company's internal and external requirements. In a very broad sense, a management system can be defined as a group of related and integrated processes outlining how and ensuring that all work necessary to achieve the objectives is being carried out. Management systems can provide a logical and consistent framework to ensure that the organization can efficiently manage all necessary activities and processes. In addition, certified management systems are helpful in mitigating liability aspects and stakeholder relation issues covered by these systems.

## 3.2 Life-Cycle Management

Whether the Responsible Entity is a business or a publicly owned entity, economic and financial aspects of owning and operating a dam have to be properly balanced with safety requirements in order to achieve all organizational objectives over the entire economic life of the dam. The efforts to achieve compliance with the



safety objectives usually vary within the life-cycle in proportion to increasing or decreasing dam safety risks. The optimal way of accounting for all life-cycle management issues is through the asset management, which addresses both physical (structures and equipment) and financial (dam value and profits from operation) assets. Asset management can be perceived as a business-oriented approach to monitoring and tracking the life-cycle of the assets of an organization designed and implemented in such a way that it can provide sufficient information for long- and short-term decisions. Life-cycle management is the most important component of asset management, providing the means to maximize return on investment over the economic life of the dam by:

- Optimizing the operation and maintenance over the entire life-cycle;
- Ensuring that the desired levels of performance and safety are met.

Life-cycle considerations for dams may differ from similar considerations for some other commercial or industrial assets. The most important factors in that respect are:

1. Importance of life and health safety in dam operation;
2. Political and socio-economic pressures to maintain original or adapted functions of dams beyond their economic life span or to replace dams in order to provide these functions;
3. Societal pressures to prematurely decommission dams.

Elements of life-cycle management of dams have not generally been properly addressed in the past and have usually been dealt on an *ad hoc* basis by adjusting the management approach as the dam moves through the life-cycle phases and issues emerge. Decisions taken during concept, design and construction phases can have significant impact on operating costs, management of safety, feasibility and costs of life extension and decommissioning. Decisions taken at any phase, often aimed at optimization of costs within a specific phase, may in the long term lead to a situation where the benefits lost over the entire economic life of the dam exceed the savings realized within the particular phase.

It is very important that all safety-related decisions and considerations at any phase of the dam life-cycle should address all implications for the subsequent life-cycle phases. However, characterization of phase-specific inputs is beyond the scope of this Bulletin which focuses on the operational phase.

The overarching dam safety principle of Sustainability of Dams and Reservoirs (Section 2.8) states that in order to secure the societal value, dams and reservoirs must be sustained in the long term. To ensure sustainability of dams, all reasonably practicable efforts should be made to prevent and mitigate failures and accidents. All relevant factors that might affect present and future safety of the dam should be identified, recorded and analyzed to identify potential solutions for removal, control or mitigation of adverse effects on dam safety.

### **3.3 Integrated Management Systems**

Although it has been recognized that the most effective approach in organizational management is an integrated approach, the reality generally differs from this ideal model. Quite often different systems (for environment, health, and safety, for example) are used as stand-alone control and documenting mechanisms, with independent management in the organization. The benefits of integration are enhancement of safety, reduction of duplication and costs, increased efficiency, and more effective and efficient collection and use of information, which generally improves overall business performance.

A well designed integrated management system can provide the organization with a single framework for all arrangements necessary to achieve all of the organization's goals, which usually include safety, environment, security, quality and financial concerns. Integration of management systems can provide a consistent and coherent approach to planning strategies to meet all corporate goals and objectives.

Technological innovations have radically changed the interactions between systems and humans, impacting the ways that organizations are managed. The management process, organizational and safety culture, and every day practices, are now deeply interrelated through a complex system of interconnections. Only a complete integration of all components of such system into a single management system that includes all structures, resources and processes, can provide optimal efficiency and adequacy.

If a Responsible Entity does not have an integrated management system, the areas of overlapping responsibilities, omitted or poorly defines responsibilities, and areas of potentially conflicting objectives should be carefully examined and addressed in the management system for dam safety assurance.

To be effective, dam safety management should be an integral part of the operations of the organization that manages the dam because the potential for dam incidents<sup>8</sup> and emergencies often arises as a result of operational problems of some kind. Responsible Entity should strive to have a single integrated management system in which all of the organization's goals, strategies, plans and objectives are considered collectively in a coherent manner. In terms of such a philosophy, dam safety is assured if the aims of the organization are achieved.

The public interest dimensions of dam ownership demands that the sustainability of the dam must be one of the aims of any dam-owning organization.

### **3.4 Dam Safety Management Systems**

A Dam Safety Management System (DSMS) should consist of systematic and comprehensive processes in order to ensure that the dam safety risks are properly managed and that all aspects of safety management are integrated or aligned with the organization's overall management structure.

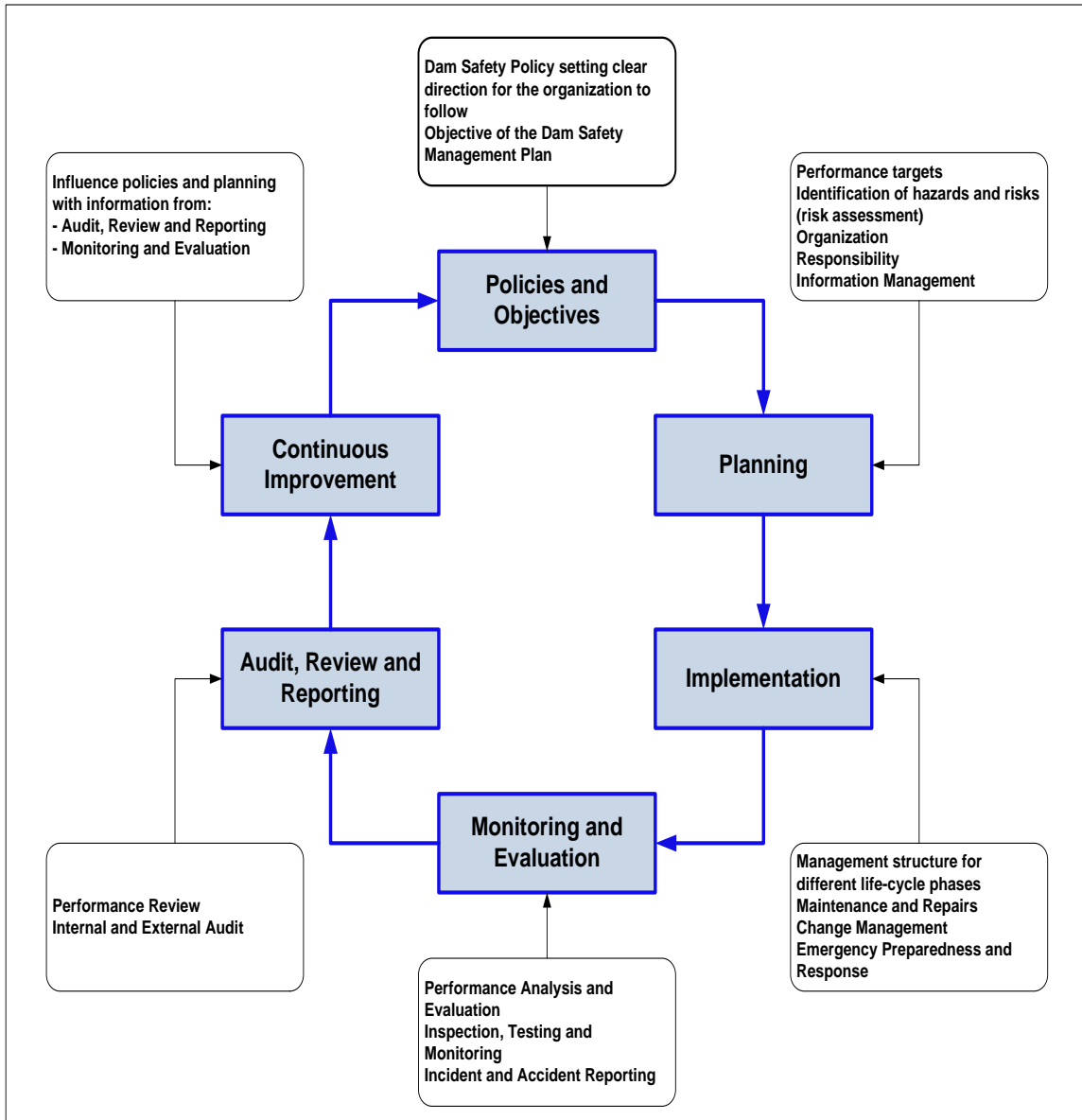
The DSMS provides a formal organized process by which safety of the dam is ensured and maintained throughout its lifetime, from the conceptual phase, through design, construction and operational stage to decommissioning. The formalization of the process is achieved by development of a series of policies, procedures, directives and instructions. The complete set of such documents has to be developed and implemented in such a way that logical and functional links between individual documents are preserved and that they are linked appropriately to the risks that the dams can pose to people, property, and the environment.

Figure 3.1 is enhanced to provide further details about the general structure of the dam safety management system, as shown in Figure 3.2. These elements are outlined in Sections 3.5 to 3.10.

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<sup>8</sup> 'Incidents' include unplanned events such as leakages, incident precursors such as signs of internal erosion, near misses such as spillway gate malfunction, accidents and unauthorized acts (including malicious and non-malicious acts).

**Figure 3.2 - Elements of Dam Safety Management System**



### 3.5 Policies and Objectives

#### 3.5.1 Dam Safety Policy

At the foundation of the DSMS is a documented set of policies that clearly indicate the commitment of senior management to setting appropriate priorities for sound management of risks posed by the dams, outline senior management goals and objectives, and lastly, underline the organizational will to strive for continual improvement.

The following aspects of the organizational mission with respect to safety of its dams should be covered by the dam safety policy:

- It should clearly indicate that the dam safety requirements have priority over any other aspect of organization's management, including business aspects and any demands arising from the production needs;
- The policy should include a commitment to the development, implementation and maintenance of a positive and progressive safety culture, with the requirement to communicate this commitment throughout the organization;
- The policy should outline the commitment to compliance with existing regulatory requirements and to appropriate management of dam safety risks;
- The policy should be current and endorsed either by the company Board of Directors and Chief Executive Officer, or by other equivalent bodies or persons with equivalent positions;
- The policy should outline the management arrangements and initiatives which are in place to ensure that the policy is discharged and maintained.

Senior management of the organization has to ensure that dam safety objectives and performance targets are established for all activities and at all levels of the organization that may affect dam safety. The safety objectives should conform to the dam safety policy and they should be measurable. Establishment of measurable objectives allows the conversion of dam safety policy into a set of operating procedures, instructions and directives for all dam safety-related processes and activities.

A model policy statement that illustrates how these principles can be applied to dams is shown Figure 3.3 below.

### **3.5.2 Governance**

The DSMS must include suitable systems to ensure that those who are responsible for oversight of the organization have access to accurate and timely information about all issues that could affect dam safety. In particular, these arrangements have to ensure that the Chief Executive Officer and the Board of Directors have adequate information to determine whether:

- All identifiable dam safety risks have been assessed and have either been eliminated or effectively controlled;
- The process of identifying and controlling dam safety risks is subject to regular reviews;
- Both processes have built-in provisions for continuous improvement;
- Adequate technical, engineering and financial management arrangements are in place to ensure that dam safety is maintained at all times and specific performance targets are met;
- Adequate resources, in terms of staffing numbers and personnel competence, are maintained in order to meet dam safety objectives.

**Figure 3.3 - Example of Dam Safety Policy Statement**

**EXAMPLE OF DAM SAFETY POLICY STATEMENT**

**Policy Statement**

The Company dams shall be designed, constructed, operated and maintained in a safe manner which will comply with all regulatory requirements.

In the absence of regulatory requirements, the dams shall be prudently managed, taking into consideration best practices as recommended in the National Dam Safety Guidelines published by National Dam Association and in other appropriate international practices.

The underlying philosophy in the practices adopted shall be that the Company will manage the residual risks associated with dams and their operation, and where appropriate, seek means to reduce those risks.

**Requirements**

The Executive Vice President (Safety) is accountable to the President and Chief Executive Officer for ensuring that the principles and objectives of this policy are implemented within the Company.

The Executive Vice President (Safety) is accountable for a Dam Safety Program that encompasses all dams owned and/or operated by the Company.

The Executive Vice President (Safety) shall ensure clear delegation of accountability and authority for management and oversight of the program, and that an effective management system is in place.

The Dam Safety Management System shall include:

- Policies, guidelines, standards and procedures
- Organization and accountabilities within the program
- Program planning and execution
- Safety assessment and risk management
- Dam design, upgrades and rehabilitation
- Documented operational and maintenance practices
- Detailed inspection and surveillance
- Emergency preparedness and response
- Incident reporting
- Staff training
- Audits and quality assurance
- Document management and control
- Public and regulatory communication
- External oversight and independent review
- Elements demonstrating continuous improvement

The Executive Vice President (Safety) shall present an annual assessment of the Dam Safety Program to the Board of Directors.

The Executive Vice President (Safety) and the President and Chief Executive Officer shall inform the Board in a timely manner of any significant dam safety incidents or emerging issues which either violate or have the potential to breach the intent of this policy.

**Policy approved by**

Board of Directors  
Chief Executive Officer

## **3.6 Planning**

### **3.6.1 Organizational Structure**

The DSMS has to effectively outline an organizational structure that enables successful discharge of all requirements for dam safety. Development of such a structure should be led by senior management with input from all levels of management of the organization. It begins with identification of the functions that are needed for safe planning, design, maintenance and operation of the organization's dams, thus ensuring that all stages of the dam life cycle are addressed.

The process of designing the operational structure has to accomplish clear allocation of tasks, responsibilities, and authorities to make decisions and execute actions to all levels of management. All levels of management must understand their roles and be in full agreement with the corresponding requirements. The design needs to provide synergy and consistency between the requirements and the responsibilities and authority allocated to each level of management.

The organizational structure has to be documented, regularly reviewed in order to ensure it continuing adequacy, and revised if necessary.

### **3.6.2 Performance Targets and Performance Measures**

The DSMS establishes and documents desired performance targets (sometimes called performance levels) related to dam safety goals and objectives. The complete set of performance targets enables senior management to identify inadequate or declining dam safety performance. Performance, targets should indicate whether:

- The current design of the dam system allows the system to be operated safely;
- Adequate resources (human, financial, etc.) are available at all times and are capable of dealing with normal and abnormal operating conditions at all stages of the dam life-cycle.

The set of performance targets should address all actions and processes affecting safety of the dam during the entire life-cycle. The overall role of the performance targets is to enable the judgment whether the risks posed by the dam system are as low as reasonably practicable.

It is important that the performance targets be measurable. Performance measures or indicators associated with specific performance targets are the primary tool in monitoring dam safety risks and overall safety performance. The DSMS needs to establish appropriate performance measures for all performance targets identified as relevant for dam safety.

Quantitative performance indicators should track both historical performance and forward-looking efforts to improve safety. These two sets of performance indicators can be subsequently used for predictive purposes to assess trends, and for assessment of adequacy of established goals and performance targets.

When developing performance indicators, the following should be kept in mind:

- The frequency of observability of performance indicators is important. A small number of observations compounded by uncertainty in the quantification may lead to incorrect trending conclusions;

- Both negative (related to failures) and positive (related to safety improvements) indicators should be considered;
- Quantitative indicators should always be subject to careful scrutiny and interpretation before being used in any decision-making process;
- The set of performance indicators should be regularly reviewed and adjusted if necessary;
- Qualitative indicators should also be considered if development of numerical indicators is not possible.

### **3.6.3 Safety Review**

#### **3.6.3.1 General Requirements**

The main purpose of the safety review is to obtain an overall view of the actual state of safety of the dam system, determine whether any modifications (organizational, managerial and structural) are necessary to ensure that the level of safety is appropriate, and ensure that the principle of continuous improvement is observed.

The safety review constitutes a comprehensive assessment of the dam system and provides answers to the following questions:

- Does the dam system conform to current regulatory requirements, current national and international standards and practices, and to current requirements with respect to acceptable and tolerable risk criteria?
- Are the managerial and organizational arrangements currently in place sufficient to maintain the levels of safety in conformance with the above requirements until the next safety review?

With reference to the Operational Activities of a dam safety organization, as shown on the left side of Figure 3.4, a safety review includes:

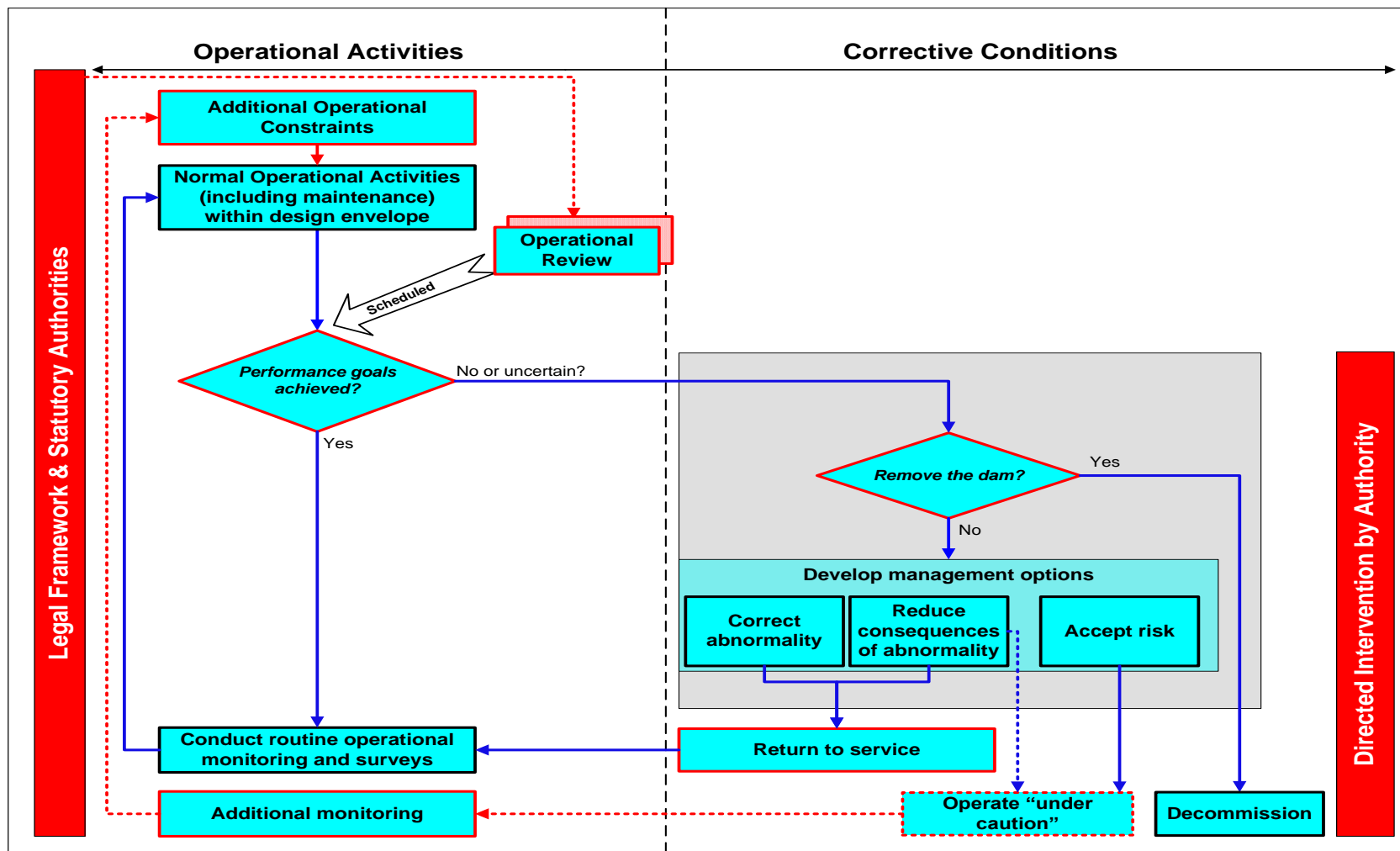
- Identification of all reasonably foreseeable dam safety risks relevant to dam operation;
- Development and implementation of a systematic and comprehensive safety analysis and assessment process ensuring that the above is accomplished;

If the actual level of safety is inappropriate, improvement options are to be developed and implemented (Corrective Conditions on the right side of Figure 3.4) through:

- Development of the comprehensive process ensuring that the proper corrective action is undertaken to address all unsatisfactory conditions of the dam system.

Safety reviews should be conducted periodically with the frequency depending on the level of risk to people, property and the environment.

Figure 3.4 - Systematic "Operation" Process





A safety review should be performed for the first time during the design phase of the dam system and be regularly updated as the dam system passes through consecutive phases of the entire life-cycle.

The DSMS must ensure that the review process is systematic and comprehensive, that the review is performed with adequate amount of skill and expertise, and that all relevant information related to the safety of the dam is available and reviewed. The review should address the following aspects:

- Assessment of risks imposed by the dam system on people, property and environment;
- Assessment of engineering aspects of safety;
- Assessment of human factors and organizational and managerial aspects of dam safety.

### **3.6.3.2 Safety Analysis and Documentation**

The safety analysis should assess expected or planned (if the assessment takes place in the design phase) performance of the dam system against the entire range of operational states and operating conditions, in order to obtain complete understanding of how the dam is expected to perform. The analysis should assess the performance of the dam under all conditions against performance goals established within the DSMS. The degree of detail should be in proportion to the magnitude of risks associated with the dam system, and the complexity of the system and its operation. The analysis should identify all external and internal hazards and potential modes of system failure and should be performed utilizing a systematic and structured approach. The analysis should identify all potential weaknesses in the design of the dam system, provide necessary design improvements, and demonstrate that the dam system meets all safety requirements and is in conformance with established risk criteria. The analysis should address all safety related aspects of organization and management with a special emphasis on human performance issues.

The safety analysis process has to be performed in such a way that the outcomes are highly credible. Credibility can be achieved by ensuring appropriate scope of the analysis, completeness, accuracy, availability of required skills and expertise and high quality and transparency of all calculations.

**The traditional approach** to dam safety analysis (often called deterministic or standards-based) begins with the potential hazard or consequence classification and follows with calculations to ensure that the dam system conforms to a deterministic set of principles, rules and requirements (traditionally called design standards). Since some aspects of dam system safety cannot be included explicitly in the analysis and all inputs are subject to varying levels of uncertainty, a considerable level of conservatism is usually built into the standards, with the expectation that it will provide adequate safety margins, and consequently an adequate level of safety. ICOLD Bulletin 59 provides a complete characterization of the approach.

**The risk-based approach** is a systematic and structured process seeking an understanding of all possible outcomes and impacts of interactions affecting the safety of a dam system. Risk, understood as a measure characterizing the likelihood of undesired events and the consequences of such events, can itself provide an objective performance measure that can be compared with established risk criteria. A probabilistic dam safety analysis, addressing all uncertainties explicitly, can thus provide a proper insight into all aspects of dam system safety, including overall system performance, reliability, impact of interactions between system components and a complete range of hazards and failure-initiating events and consequences of dam failure. ICOLD Bulletin 130, which describes the dam safety risk assessment process, also provides details of risk analysis and probabilistic analysis of dam safety.

The results and findings of the safety analysis should be documented, included in the safety review report and retained for future safety reviews. Qualitative and quantitative outcomes of dam safety analysis should be supplemented by supporting evidence (models, data and assumptions applied in modeling and calculations).

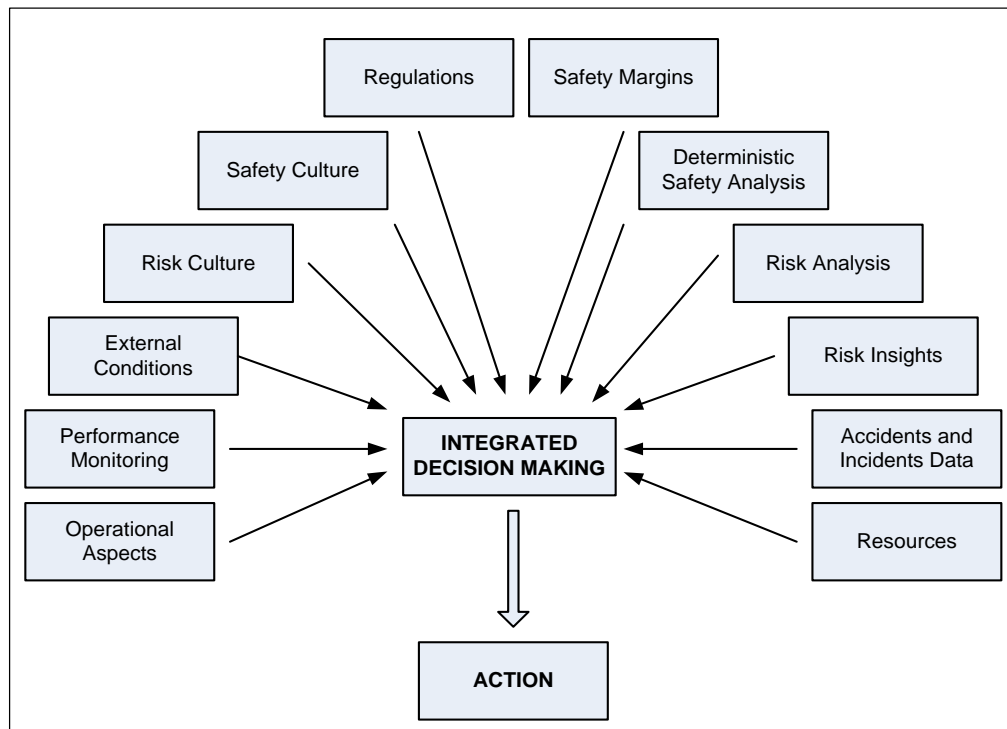
### 3.6.3.3 Decision Making

Completion of the safety analysis task provides the input to the decision-making process which is present in both sides of Figure 3.4 (Systematic “Operation” Process). Safety analysis results can be compared with the performance targets and conclusions on the acceptability of the achieved safety levels can then be reached. If all performance goals have been achieved, the DSMS should direct the process into routine activities described in the following Sections 3.6 to 3.9. If the analysis outcomes cannot support such decision, the process is re-directed into Corrective Condition activities which begin with the development of potential options (structural, non-structural or both) capable of bringing the dam safety into full conformance with performance goals. Each considered option has to undergo a complete safety analysis as described above.

In defining the decision-making model for the DSMS, all insights from the safety analysis should be taken into account. The general integrated decision-making model is conceptually illustrated on Figure 3.5.

The approach presented on Figure 3.5 combines the insights from deterministic and probabilistic safety analyzes with other requirements (such as legal, regulatory, business). The degrees to which individual components of the decision-making process are included may vary from organization to organization. However, it is important that the DSMS clearly establish the structure and parameters of the decision-making model.

**Figure 3.5 - Integrated (Risk-informed) Decision Making**



## **3.7 Implementation**

### **3.7.1 Process Management**

The DSMS must identify all processes that are needed to achieve the safety performance goals and meet safety requirements. It also has to ensure that these processes are implemented, assessed and continually improved. The DSMS should also determine methods to ensure both implementation and control of the processes.

In developing individual processes, the following aspects should be identified:

- All hazards and risks reasonably foreseeable for the current life-cycle stage of dam system;
- Sequencing and interactions with other processes;
- Process inputs and outputs;
- Measurement criteria.

If the DSMS is not a part of a fully integrated management system, special care should be taken in identifying how many other processes are in place in the organization and how they interrelate with the DSMS.

Similarly, at the lower organizational level, the DSMS has to specify how different activities between different groups involved in a single DSMS process are planned and managed in an effective manner.

The DSMS must have provisions ensuring that each process has a designated individual with responsibility and authority for:

- Developing and appropriately documenting the process;
- Ensuring that interaction between interrelating and interfacing processes is managed effectively;
- Monitoring and reporting on performance;
- Ensuring that the process is in conformance with policies, objectives and goals of the organization and that the necessary improvements are considered.

### **3.7.2 Change Management**

Management of change is aimed at managing organizational risks associated with any changes affecting dam safety. The process establishes fundamental organizational risk controls which should address responsibilities and accountabilities, management of records, interface management (with processes outside of DSMS) and physical changes to the dam system.

The DSMS must include suitable and sufficient processes for safe management of change which include the following areas of interest:

- Structural improvements to dam safety components or operational changes resulting from implementation of recommended action from Corrective Conditions (see Figure 3.4);
- Other structural changes to components of the dam system;
- Other operational changes.

- Organizational changes with a potential for staff reduction, for reassignment of responsibilities and authorities, and for realignment and interfacing with other processes of the organization

Again, if the DSMS is not part of a fully integrated management system, care must be taken to ensure that interfaces with other managed systems are closely monitored and that provisions are in place for effective communication of operational and organizational changes between different systems. If the DSMS is part of the integrated management system, potential impact of any organizational or operational changes can be assessed before changes are implemented.

Irrespective of the overall management system of the organization, the DSMS has to ensure that for all changes that potentially can impact the safety of the dam system, the following requirements are met:

- Staffing arrangements are adequate in terms of number, training, knowledge and experience;
- There is full clarity with regard to responsibilities and authorities at all levels of the organization affecting the dam safety;
- Adequate transitional arrangements are made.

### **3.7.3 Accountabilities, Responsibilities and Authorities**

The ultimate responsibility for establishment of the DSMS, its implementation, periodic assessments and continuous improvements rests with the senior management. An individual reporting directly to senior management should be given responsibility and authority to:

- Coordinate the development, implementation, regular assessments and continual improvement of the DSMS;
- Request periodic reports from those responsible for specific dam safety related activities and processes on the status of performance;
- Report on the performance of the DSMS to the senior management;
- Report any identified need for the DSMS improvements;
- Resolve potential conflicts between poorly designed requirements and activities and processes related to dam safety.

The DSMS must clearly outline assignment and delegation of responsibilities at all remaining levels of the organization for the effective implementation and maintenance of the DSMS, including compliance with existing regulations and management of risks posed by the dam system. Such an outline can be effectively developed following the organizational structure as described in Section 3.6.1. It can be carried out with the help of organizational charts describing responsibilities, accountabilities and authorities to act. The charts should also provide details related to all interdependencies and interrelations of all staff which manage or perform activities related to or affecting the safety of the dam. The outline should ensure that the arrangements provide sufficient authority to all personnel involved in dam safety activities to:

- Initiate actions aimed at prevention of safety incidents and accidents (all staff);
- Identify any safety issues and report through designated channels (all staff);
- Initiate, recommend or develop solutions to identified safety issues (all staff);
- Verify the implementation of solutions (management staff);

- Monitor and control all dam safety activities to ensure that all recognized deficiencies and unsatisfactory conditions are corrected in a timely manner (management staff);
- Provide adequate material and human resources (management staff).

The outline should describe how responsibilities for management of dam safety risks are allocated within the organizational chart and provide details on levels of authority assigned to each organizational level.

### 3.7.4 Resource Management

The DSMS must ensure that arrangements are in place to provide sufficient resources for management of dam safety risks and maintenance of the DSMS. These arrangements have to be made with respect to material and financial, as well as human resources and knowledge and information resources. The responsibility for ensuring that all resources necessary for the development and implementation of the DSMS should remain with the senior management

Resource management should address the needs for and sources of *financial resources*. Senior management should plan for, make available and control financial resources necessary to meet all dam safety objectives and targets and for maintaining and continually improving the DSMS.

Similarly, senior management should determine what the *material needs* of the DSMS are, including equipment, building materials, workspace, information and communication technology, and support and transport services. It is highly recommended that a registry of all assets linked to dam safety be maintained. The registry should include a plan defining how the asset will be maintained throughout its lifecycle and a plan for replacement at the end of its useful life. The DSMS should ensure that material inventories of spares and replacement parts for the components affecting dam safety are maintained at the levels dictated by risk management strategy only and irrespective of economic considerations.

Information and knowledge should be managed within the DSMS as a resource. Knowledge management can be defined for the purpose of the DSMS as a systematic process of identifying, collecting, processing, developing, disseminating and preserving knowledge relevant to achieving dam safety objectives and goals. All collected data should be converted to information which could subsequently be used for continual development of organizational knowledge providing a foundation for decision-making processes. The DSMS should clearly identify the following aspects of information and knowledge management:

- Organizational information needs;
- Sources of internal and external information;
- Means of converting information into knowledge and ways of using knowledge to meet the organization's dam safety objectives;
- Means for ensuring appropriate security and confidentiality;
- Preservation of organization's formal and informal knowledge.

The DSMS should define the competency requirements for staff at all levels and outline arrangements ensuring that the necessary individual and collective competence is available for carrying out all dam safety related activities and tasks. The *human resources* strategy of the organization should also ensure that immediate and long-term needs for competency are properly identified and addressed. In addressing these needs, the following should be included:

- Future needs in relation to dam system ageing process;
- Succession planning;
- Anticipated organizational changes.

The DSMS should also ensure that all necessary provisions are included for providing training to achieve and maintain required level of competence by all staff involved in carrying dam safety related activities. It also should ensure that evaluation of training effectiveness is performed on a regular basis. Training should provide all personnel with awareness of the relevance and importance of their activities for achievement of the organization's dam safety objectives.

### **3.7.5 Records and Document Control**

The DSMS must include suitable and sufficient systems for the control and management of all documents and data related to management of dam safety risks. The system has to ensure that:

- All dam safety records are identified, created and properly managed. The records should include all available dam safety related reports, rationale for delaying or not carrying actions recommended by them, and a summary report of all important data, sources of data and geotechnical parameters;
- Storage and maintenance of records provides easy retrievability and appropriate maintenance prevents loss or deterioration;
- Language is accurate and clear ensuring good quality and minimizing misunderstandings;
- Appropriate document control and release procedures are in place ensuring that current status of documents and history of changes are recorded;
- Obsolete documents are either properly identified if retained for knowledge preservation, or are removed from circulation;
- An appropriate system is in place ensuring that all staff involved in dam safety related activities is updated on changes in relevant documentation in a timely and reliable manner;
- Appropriate means of accessing the records and documents are in place, including provisions to have the access from various locations at times of emergency.

### **3.7.6 Maintenance and Repairs**

The DSMS must include suitable and sufficient processes ensuring that all components of the dam system important to the system safety remain in accordance with the conclusions and requirements of the current dam safety review. The process should ensure that a systematic approach is taken to identify which maintenance activities are to be performed and at what intervals. The process should establish how maintenance activities are initiated, managed, assessed, prioritized, planned and scheduled. The identification, selection and frequency of maintenance activities should take into account:

- Magnitude of risks involved;
- Guidelines and requirements of applicable codes and standards;
- Design and operation conditions;
- Operating experience;
- Vendor recommendations;

- Ageing management requirements.

The maintenance program should include all activities aimed at avoiding, detecting and repairing any deficiencies endangering structural integrity of dam components. In organizing the maintenance process, it may be useful to recognize that the maintenance activities can be divided into two groups that have different objectives, namely:

- Preventive maintenance whose primary role is to avoid and detect failures;
- Corrective maintenance which encompasses all activities aimed at repairing components which are already in the failed state.

Preventive maintenance should include predictive, periodic and planned activities. Preventive maintenance will also require development of a formal process to detect, assess and manage deterioration of dam components as a result of ageing effects.

Corrective maintenance will require development of a process for controlling and performing temporary repairs. The process should address all aspects related to a proper approval system, adequacy assessment and time period until the permanent repairs can be implemented.

All maintenance activities should be performed in accordance with written approved procedures and the DSMS should ensure that all maintenance activities are carried out in an adequate and timely manner.

### **3.8 Performance Monitoring and Evaluation**

The DSMS should establish a monitoring, measuring, analysis and evaluation system for routine measurement and assessment of dam safety performance and the assessment of effectiveness of all processes of the DSMS. This is to ensure that all planned safety performance targets and requirements (Section 3.6.2) are fulfilled, and the safety of the dam system is maintained at the desired level.

Adequate monitoring processes should be developed and implemented to ensure conformance with the established safety targets for all elements of the dam system, and to provide early warnings of inadequate performance. In general, the monitoring and evaluation process should have the capability to determine whether the overall safety performance is constant, deteriorating or improving. The outcomes of the process should be sufficient to identify the underlying causes of unsatisfactory performance and to provide the basis for identification of corrective measures.

### **3.9 Audit, Review and Reporting**

The effectiveness of the DSMS should be evaluated to confirm its ability to achieve the dam safety objectives and to identify opportunities for improvement. This evaluation is closely aligned with the components described in Sections 3.7 and 3.8, as illustrated in Figure 3.6.

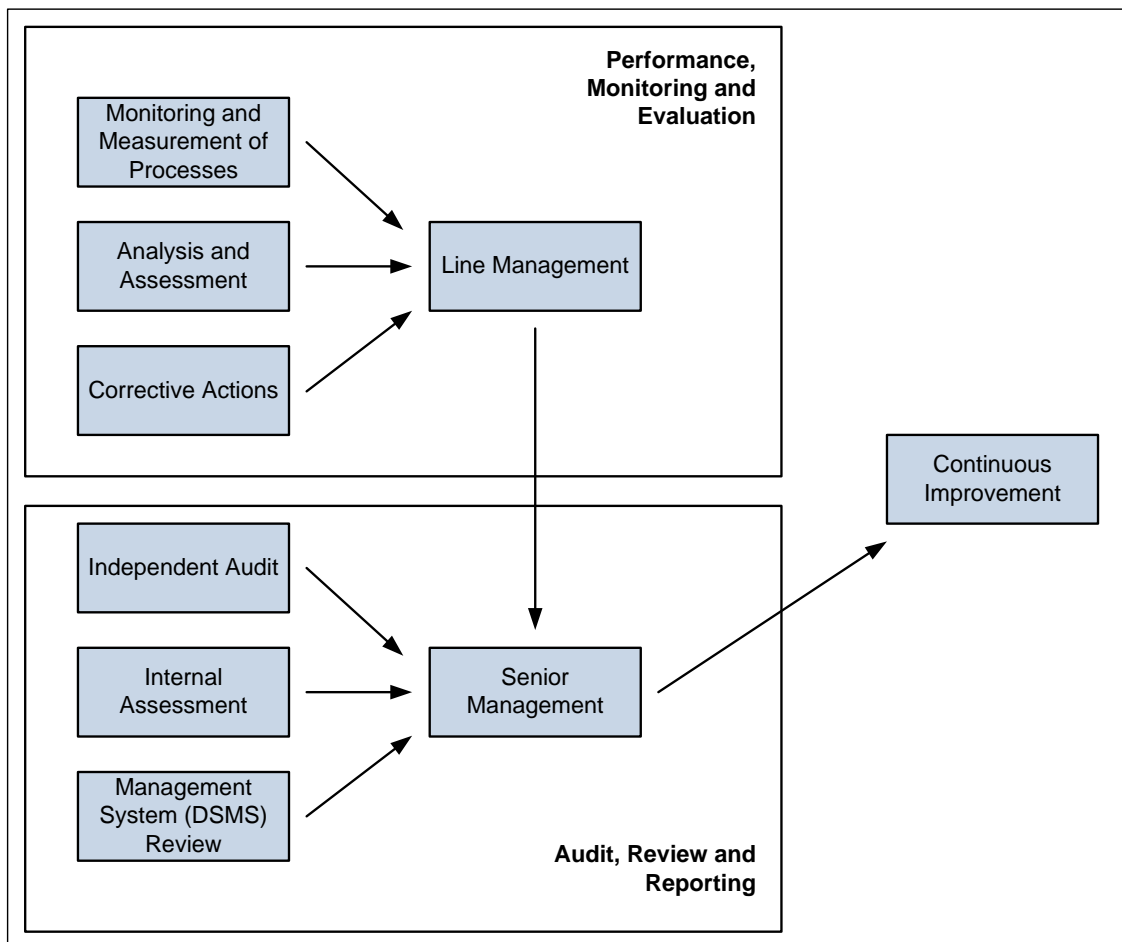
The purpose of internal assessment carried out by the senior management is to detect, correct and prevent management problems that can prevent the organization from meeting its dam safety objectives. The assessment should address the broad range of issues that may include:

- Validity and appropriateness of current objectives and goals;
- Effectiveness of monitoring at all levels of the DSMS;
- Opportunities to enhance safety;
- Performance trends.

The DSMS should ensure that independent audits are carried out according to the schedule established by senior management. The audits should identify any deviations from the expected safety performance, evaluate appropriateness of corrective actions and identify opportunities for improvement.

The DSMS should also have provisions ensuring that senior management develops a process for management system review. The process should address not only effectiveness of the DSMP but should also examine all interfaces and interrelations with other managed systems.

**Figure 3.6 - Relationships within Dam Safety Management System**





### **3.10 Continuous Improvement**

Continuous improvement of all processes constituting the DSMS should be one of the objectives of the DSMS. Opportunities for improvement should be identified on the basis of:

- Management system review;
- Internal assessment and independent audit;
- Input from line management.

Input from these three activities can relate improvement opportunities with the unique perspectives of different levels of the organization. Improvements can be identified and implemented at several levels:

- Level of the management system by revision of the management structure, revision of existing individual processes, or by implementation of new processes;
- Process level;
- Working level by improvement of activities conducted within the existing processes.

Continuous improvement processes should include the following elements:

- Reason for improvement;
- Evaluation of the effectiveness of the existing structure/processes;
- Causes of inefficiencies and inadequacies;
- Identification of possible options;
- Evaluation of anticipated effectiveness.

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# Chapter 4 - Organizational Arrangements

## 4.1 Introduction

Chapter 4 integrates the principles and concepts outlined in Chapters 1, 2 and 3 and describes how they can be transformed to operational activities. The chapter outlines the management arrangements that enable the implementation of dam safety activities to achieve the objectives. The systematic way the safety of dams is managed by an organization (the management system) is typically documented in a manual or internal controlled website. The structure and content of the manual is based on the Responsible Entity's operational management system framework, policies, and standards that are approved by the appropriate executives.

The Responsible Entity typically appoints a specific individual to be responsible for directing and overseeing the management (or carrying out the management, in the case of a small dam owning organization) of all activities necessary for dam safety. The level of authority of this individual will typically depend on the overall risk profile - the contribution of the dams to the total risk profile and the importance of dam safety to the organization. For owners of large dams, the individual with ultimate responsibility is normally a senior executive and in some instances could be a member of the Board of Directors.

The management system should be capable of revealing the inevitable tension between "dam safety activities" and "production activities" in the management of the functions of dams. While there is no doubt that the production function pays for the safety function and **delivers** the overall operating objectives of the Responsible Entity, the safety function is intended to protect the production function and **protect** against the major liabilities of the Responsible Entity. Thus the production objectives and safety objectives are not fully aligned.

The Directors of the Responsible Entity should be able to see these tensions in the organization and satisfy themselves that management is dealing with the trade-offs between these somewhat competing objectives properly.

The applicable laws, regulations and other legally binding requirements are normally stated in the management system, with the actual text provided either in the relevant section of the management system or in an Annex to the management system manual. The operation of a dam involves more than adherence to general laws and dam specific licensing arrangements which would normally be laid out in the management system.

Other legal requirements, duties and regulations also pertain to matters such as worker safety, environmental flow requirements and many other societal regulations and duties that go along with the privilege of dam ownership. These wider duties and how they relate to the safe operation of an individual dam would also normally be described in the management system, and their influences over the safe operation of the dam would be incorporated in the operational arrangements.

The arrangements and reporting relationships with the regulatory authorities will normally be described at this point, with the detailed procedures for regulatory reporting dealt with in the section of the management system dealing with Communications and Records.

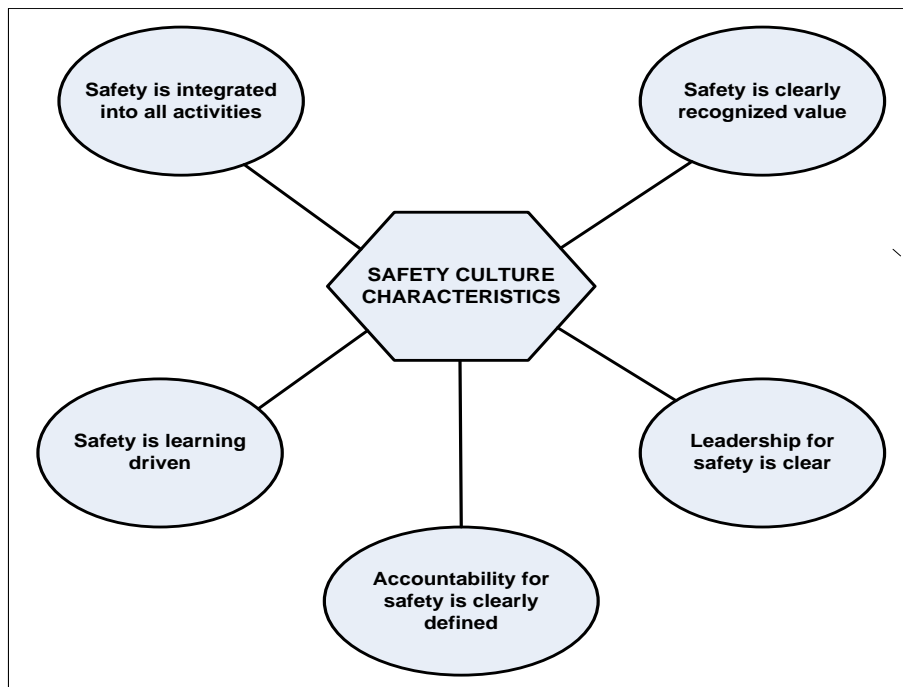
## 4.2 Owner's Values and Structure

### 4.2.1 Safety Culture

In the modern context, companies are explicit about the values and principles that govern the decision-making processes. Government and companies in general may operate in terms of many values and principles, but usually a small number will predominate. These values and principles are increasingly stated in publicly available Social Responsibility Reports. For example, a company may value the environment and may require specific consideration of environmental impacts in its operations and in its evaluation of options. Responsible Entities value their dams and as a matter of principle often assign expenditures on dam safety a higher priority than other operational expenditures in order to protect the operations and to prevent catastrophic losses.

One of the cornerstones of the organization's system of values and principles is the presence of a proper safety culture. The organization should recognize the enormous value of a strong and robust safety culture in achieving its objectives and should ensure that the basic elements (see Figure 4.1) are in place.

Figure 4.1 – Characteristics of Strong Safety Culture  
(from Management System for Nuclear Installations, IAEA Safety Guide GS-G-3.5, 2009)



**Leadership for safety** requires that all levels of management, especially senior management, be clearly committed to safety. Involvement of management in all safety aspects is clearly visible and the organization ensures that the necessary skills are available. The organization strives for relationships built on trust, full openness, good communication and efficient conflict resolution mechanisms.

That **safety is a clearly recognized value** can be reflected by high priority given to safety in allocation of resources and in business plans. High priority to safety also has to be clearly shown in communication and decision making. The entire staff has to be convinced that safety is at least as important as production and management at levels should reinforce safety conscious behaviour and encourage social acceptance.

**Clear accountability for safety** requires that ownership of the safety concept be evident at all levels of the organization and refer to the entire workforce. Roles and responsibilities are clearly defined and understood, and delegation of responsibility and authority is carried out in a way that ensures clear accountabilities at all levels. Level of compliance with regulations and internal safety procedures is high.

**Full integration of safety into all activities** can be achieved by ensuring good working conditions (elimination or control of time pressures, excessive workload and stress) and by providing high work motivation and job satisfaction. Quality of processes from planning to implementation and review, quality of documentation and all procedures, cross-functional and inter-departmental cooperation and teamwork are other essential factors.

**Learning driven attribute** of a healthy safety culture encourages constructive and questioning attitudes and open reporting of deficiencies. All safety performance indicators are tracked, evaluated and used in development of individual competencies. Operating experience should be highly valued. Training, benchmarking and self-assessment should be used to stimulate learning and improve performance.

Senior management of the organization should have a good understanding that these key characteristics are indispensable in achieving a strong safety culture. It should also provide the guidance and reinforce behavioural patterns that promote sustainability and continual development of a strong safety culture.

The implementation of this core value requires considerable effort at all levels of the organization and can be achieved by addressing the five attributes depicted on Figure 4.1.

In accepting that a proper safety culture is one of the indispensable values of a successful organization, it is important that the organization:

- Continually improves the safety culture and strives to fully match the characteristics described above. The improvements should start with the assessment of the present state and the identification of the desired future state. After the gap between the actual and the desired state is known a necessary change process can be identified;
- Put in place a mechanism for timely detection of warning signs of a decline in safety culture, so that potential problems may be identified in sufficient time and corrective action undertaken to prevent any adverse consequences;

- Recognize that human factors in the organization are critical for safe operation, that they should not be separated from technical aspects, and that ultimately safety depends heavily on successful interaction of individuals with the technology and the organization.

#### 4.2.2 Policy Development

Company policies are typically well crafted general statements that cover all facets of the organizations operations. These policies may or may not go beyond the primary focus of the operational activities and include social responsibility and environmental stewardship. Safety is one such area where specific policy statements are common. In some cases the policy will be specific to safety, in others the policy could be more general and apply to the protection of people, property and the environment.

Dam safety policy, as all other company's policies, should be developed by senior management of the organization and as a minimum should provide the direction for the entire organization by:

- Demonstrating senior management commitment to the safety of organization's dams;
- Setting the policy in context with organizations business objectives;
- Committing to continuing improvement in performance of dam safety.

##### **EXAMPLE OF OVERARCHING POLICY STATEMENT FOR PROTECTION OF PEOPLE, PROPERTY AND ENVIRONMENT**

We believe that protecting people, property and the environment against the hazards inherent to our operations and our operating environment is of paramount importance to our success. Excellence in safety performance is an integral part of our business and is essential to our commercial and social success.

Our policy is to achieve and maintain excellence in safety and operational performance through elimination of accidents and operational incidents that present a threat to people, property and the environment.

#### EXAMPLE OF POLICY EXPLANATION IN TERMS OF DAM SAFETY

Large dams involve risk, risk which is accepted for the benefits that accrue from relatively inexpensive and environmentally sustainable electricity and from flood control.

Our dams have been, and are, built on the basis of best practice existing at the time of their construction and a proven approach ensuring that they are as strong and as safe as it is practicable to make them.

Though ageing and normal wear and tear present constant challenges, and new threats sometimes emerge, our **aim** is to manage the whole fleet of dams so that there is no significant deterioration in the risk position and that the overall level of risk is kept well within limits of tolerability. To exclude risk altogether is impossible, for this or for any important hazard.

Our **method** is to keep the condition of the dams and the risks they present under constant review, to identify, and so far as possible to measure any new threats, and to make any necessary improvements and repairs as soon as it is practicable.

Our **approach** takes account of economy and cost. Whenever it is possible to make improvements or necessary to take remedial measures, we seek to achieve as big an increment to safety as possible without compromising the overall benefit of electricity at an affordable price, and at the very minimum, not to accept any reduction in the standard of safety. We therefore seek to balance the cost of each possible improvement against the added safety it would achieve, erring always on the side of safety, and subject to the over-riding condition that if the resulting risk level is less than fully acceptable, the dam would be taken out of service.

The whole approach involves constant monitoring and estimation of risks and threats, taking advantage of lessons learned worldwide. It implies an ongoing program of review, with improvements, and remedial actions where necessary prioritized according to

- Size and significance of the added safety that can be achieved, and the cost
- Wherever remedial action is needed, the degree of urgency
- Need to ensure the application of the best possible expertise.

The type of general policy statement and explanation of a dam owning agency usually require more detailed statements of policy specific to the safe management of dams that transforms the governance objective into parameters that the Responsible Entity's engineers and managers can transform into operational objectives, as illustrated in the Model Statement below.

The statement of policy may make specific reference to "all applicable laws and regulations" within the body of the policy itself, alternatively it may make general reference to laws and regulations, with the specific details being dealt with in the "policy implementation.

For dams in the modern context, explicit policies with respect to the performance of dams affected by extreme natural hazards and other factors are necessary to make the broad statement made at the policy level relevant to the dam safety assurance activities.

It is important that the dam safety policy of the organization be presented as a clear, precise and short statement, thus allowing effective understanding and communication.

#### **EXAMPLE STATEMENT OF POLICY ON CONTROL OF RISKS FROM DAM FAILURE**

1. This (model) Policy Statement amplifies the general policy on protecting People, Property and the Environment in respect of risks to the public from a dam failure.
2. Individual members of the public are provided a level of protection from the consequences of dam failure and operation such that there is no significant additional risk to the life and health of individuals; and; Societal risks to life and health from dam and hydropower plant operation are comparable to or less than the risks associated with (e.g. of generating electricity) by viable alternative activities, and should not significantly add to other societal risks.
3. The safety performance of all dams is periodically reviewed independently for conformity to established engineering practices, and the safety standards of the dam engineering profession and regulators, both nationally and internationally. Ongoing surveillance is carried out to detect both temporary and permanent changes in dam performance.
4. Any potential or actual deficiencies identified by these reviews and surveillance, or by a safety incident, are reported. Corrective actions will be rigorously evaluated using external expert and peer reviews where appropriate. Implementation of improvements will be decided in accordance with the principle that risks to the public are reduced to a level that is as low as reasonably practicable.
5. The practical interpretation of this principle is that the engineering of the dam must, at a minimum, conform to practices and standards that are authoritative and up to date. Beyond this, any improvements that are cost effective in further reducing the risk must also be implemented up to the point that additional measures to further reduce the risk are grossly disproportionate to the risk reduction achieved. The residual risk, after all improvements have been made, must always be less than “1 in x” per year for the most exposed member of the public, and will typically be less than “1 in << x” per year.
6. The residual risk will be controlled through adoption of best safety management practices that include a combination of monitoring and intervention. The consequences of a dam failure, should such an event occur, will be mitigated by emergency actions in accordance with a prepared plan. The plan will be subject to periodic testing for effectiveness.
7. We will continue to develop and maintain world-class capability in safety assessment and dam safety engineering to ensure that risks are properly controlled and that the maximum safety benefit is achieved from expenditure on improving dam performance.

#### **4.2.3 Governance**

Responsible Entities are generally strictly liable for the damages that would result from dam failure and the Board of Directors of the Entity has liabilities in this regard. Accordingly, the Board of Directors is ultimately accountable to the shareholders (Government, or private owner) for all liabilities that accrue to the organization. Because of the catastrophic consequences of dam failure and the destruction of lives and livelihood, these liabilities may be enormous. Thus, the Board of Directors of a Responsible Entity has a very great responsibility for dam safety that is discharged through establishment of appropriate structures to enable implementation of the dam safety activities at the operational level.

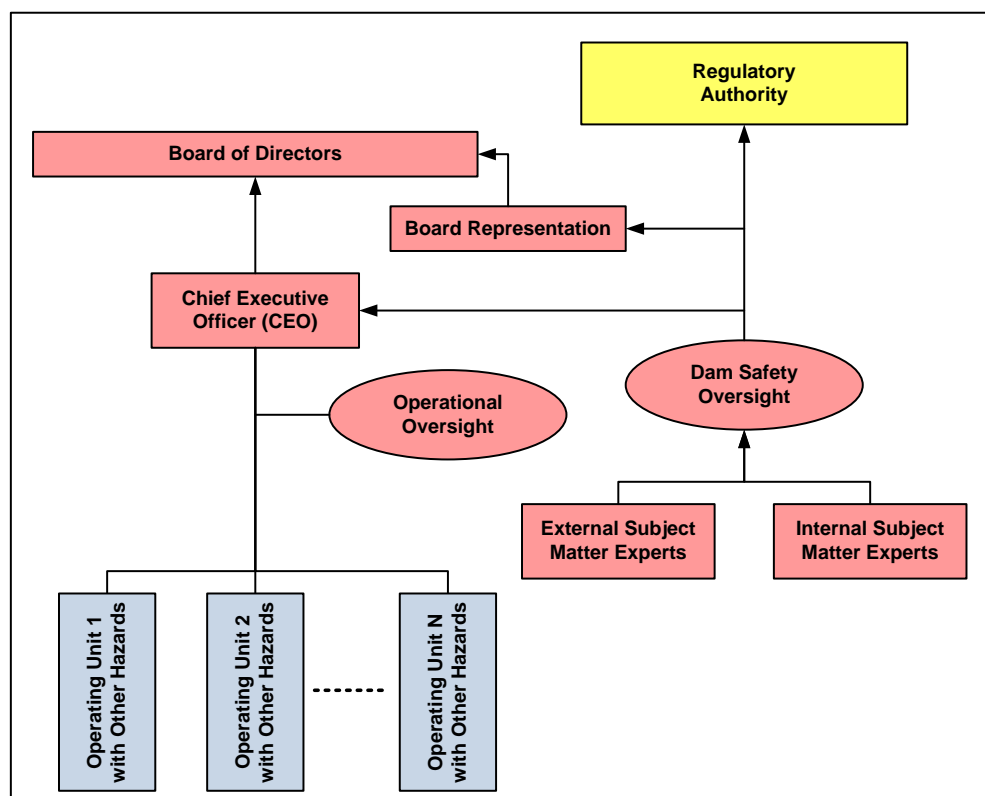
Since Dam Safety Assessment and Management is a managed engineering and scientific activity, responsibility for demonstrating that dams are operated safely is normally delegated by the Boards of Directors to an appropriately qualified (in the engineering and scientific sense) senior executive or manager. The Board of Directors should ensure that structures are in place for the organization to perform two separate principal functions; determining what level of dam safety is appropriate and how it might be achieved; and, implementation of activities to achieve and demonstrate the adequacy of



safety performance. Fundamentally, the two principal functions should complement each other. However, commercial pressures and market forces often combine in a way that can result in conflict between these two fundamental functions. Typically, the implementation phase is the responsibility of the group that operates the dam whereas the determination of what level of safety is appropriate is best established independently of the operational management but in consultation with the Board of Directors (this does not preclude prior consultation with the operational management).

A general but by no means unique form of a governance structure which shows a line of oversight and reporting for dam safety that is independent of operational activities is shown in Figure 4.2.

**Figure 4.2 - Example of a Governance Structure**



The implementation of the actual dam safety activities occurs in the operational unit. Another model structure could absorb the dam safety oversight role into the operational unit with a slightly different reporting arrangement. A third model could have the implementation of dam safety activities independent of the operational unit.

It should be noted that the inventory of dams is key to implementation of dam safety policies, and it must be clearly defined and maintained. The type of information included (but not necessarily publicly accessible) may be at the discretion of the Responsible Entity or under regulatory prescription. The inventory typically forms part of the “asset register” of the organization and may be a subset of a much

larger portfolio of assets, for which an overarching Asset Management System may have been established.

<b>EXAMPLE OF INFORMATION INCLUDED IN DAM INVENTORY</b>
<b>Technical Information</b>
<ul style="list-style-type: none"><li>- Name of dam</li><li>- Location</li><li>- Type of dam</li><li>- Height of dam</li><li>- Crest length</li><li>- Reservoir volume</li><li>- Year of construction</li></ul>
<b>Safety Information</b>
<ul style="list-style-type: none"><li>- Consequence or Hazard Potential Class</li><li>- Performance goals</li><li>- Emergency Preparedness Plan</li><li>- Population at risk; infrastructure at risk; ecological system at risk; culture and heritage at risk; operational functions at risk (forecasts of losses may also be included)</li><li>- Safety reports</li></ul>
<b>Financial Information</b>
<ul style="list-style-type: none"><li>- Contribution of dam to operation</li><li>- Total cost of dam failure (third party losses at a minimum)</li><li>- Post accident repair or reconstruction costs</li></ul>

## **4.3 Dam Safety Functions, Roles and Responsibilities**

### **4.3.1 Policy Implementation**

The process for implementing dam safety policies involves making fully operational the functions outlined in Figure 1.1 (and repeated again with more detail on Figure 4.3) in order to achieve the policy objectives.

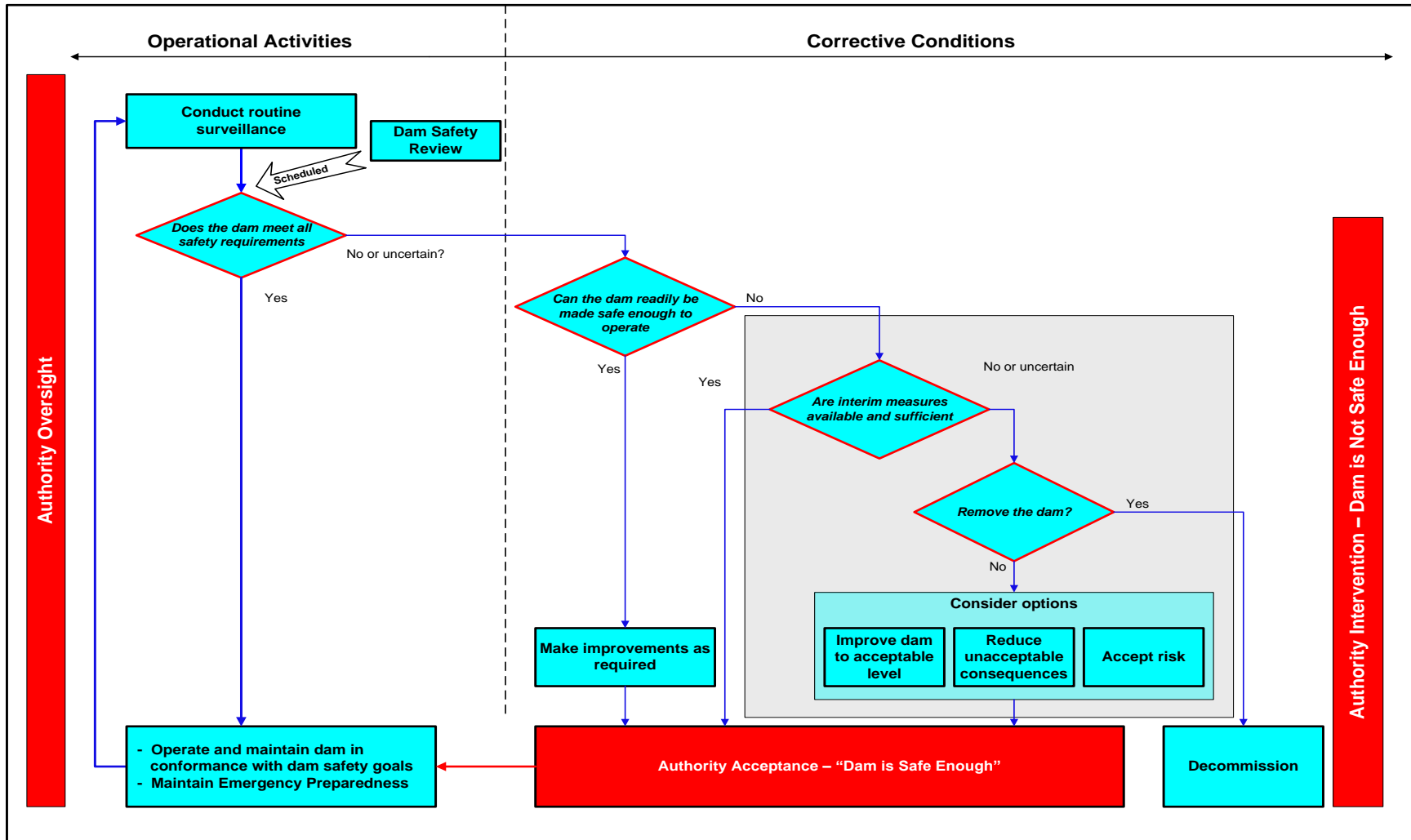
When the performance of a dam indicates that there are actual or potential performance deficiencies, the process of transitioning from dam safety oversight activities to developing dam safety improvement activities can be extremely complex, highly iterative and highly resource-intensive - to first confirm that there is an actual performance concern, and then to properly define the range of practicable options to restore the performance capacity.

Notwithstanding the possible complexity involved in defining options, the implementation of Figure 1.1 is more straightforward for a single dam than for a portfolio of dams, where a wider range of management activities is required.

Implementation of the dam safety policy begins with establishment of organization strategies, plans, goals and objectives by the senior management in such a way that they are consistent with other policies of the organization. Typically, the roadmap for policy implementation should be developed by the senior management and consider the following:

- Strategy to ensure integration into general business activities;;
- Structure for planning and assessing the policy, policy implementation, systematic progress reviews and continual improvements;
- Means of pursuing policy objectives by establishing measurable objectives for implementation of organization goals, strategies and plans.

Figure 4.3 - Dam Safety Activities to be Managed



How the policy is to be implemented can be stated first in general terms in the management system and then amplified in subsequent text and in site-specific documents. This amplification may be part of the statement of implementation (the “what”), or it may follow in subsequent explanatory text. This bulletin has chosen the latter because the laws regulations and policies will differ from one jurisdiction to the next. The actual activities become increasingly similar between owners as the management system transitions through the management arrangements down to the actual dam safety activities carried out for the dams. The most important aspect of this phase of organizing a dam safety program is that the process for implementation and the functional structure within which the policy is implemented should be clear, and the organization’s personnel should know exactly what their relevant roles and responsibilities are. These requirements are necessary for the staff to understand what risks exist in the operation of the dam, and how they can be effectively controlled.

The essential elements of the functions involved in managing and demonstrating the adequacy of operational arrangements required for dam safety as detailed in the management system manual are introduced below.

The management system as described in general terms in Chapter 3 can be further developed to meet the needs of any particular organization, as for example outlined in Figure 4.4.

The activities that are carried out by the manager responsible for dam safety would normally be expected to be outlined in a general way in the management system without focusing on specific details that apply in the implementation of dam safety activities at a particular dam. The latter would normally be in the documents on the management controls for the individual dam. The overall responsibility for the dam safety management system should remain with the senior management which should ensure that the management system is established, implemented, periodically assessed and improved.

The manager responsible for dam safety reporting directly to senior management should have the following general responsibilities and authorities:

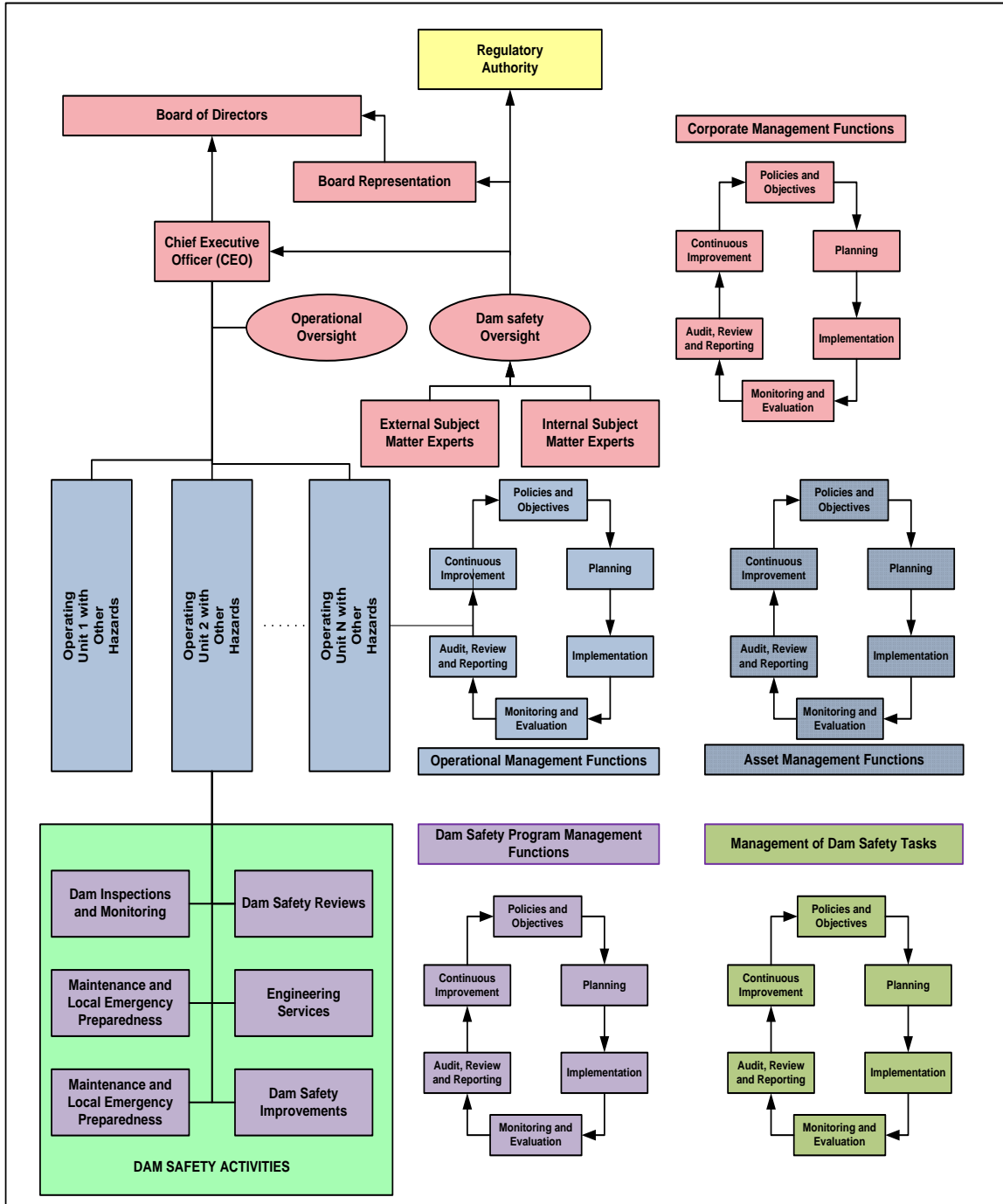
- Coordination of the development and implementation of the management system;
- Assessment and continual improvement of the management system;
- Reporting on the performance of the management system and any needs for improvement;
- Resolving any potential conflicts between various processes and within the various processes of the management system.

The manager responsible for dam safety must ensure that there is absolute clarity on accountabilities and responsibilities for all of key dam safety management functions and processes (Section 4.3.4).

In terms of an integrated management system of the type illustrated in Figure 3.1, the six elements apply at all levels of the governance structure, although in different ways. The management system structure is scalable and while the details of the activities vary, the fundamental concepts are the same. For example, dam safety performance monitoring at the dam is planned, scheduled, implemented and reported in much the same way as the independent audit of dam safety functions as directed by the Board of Directors. Similarly the activities across a dam safety program for a portfolio of dams are planned, scheduled and implemented in terms of the policies and objectives set by the Responsible Entity.

At each level of implementation, the overarching policy of the dam-owning organization may be augmented by more specific policy application procedures or by auxiliary policies or sub-policies (e.g. “policy application document for dam surveillance”).

**Figure 4.4 - Hierarchy of System Management Functions**



The dam management functions and processes that require a dam safety management plan are of the following general form:

#### **4.3.2.1 Dam Safety Implementation**

Implementation of the Dam Safety Functions at a dam broadly includes:

1. Safety assessment;
2. Asset (including dam) portfolio management;
3. Safety improvements and risk reduction measures.

In the following, the general management system arrangements and activities for those who are responsible for Dam Safety implementation are broken down as follows:

- Application of policies and securing objectives:
  - Engineering and operational standards and other guidelines;
  - Roles and responsibilities.
- Implementation of planning:
  - Definition of urgency, prioritization and planning.
- Implementation of task activities:
  - Operation, maintenance and testing;
  - Monitoring and surveillance;
  - Dam Safety Reviews;
  - Interim safety management improvements for identified concerns;
  - Investigations and rectification of deficiencies in dam performance;
  - Emergency Planning and Response.
- Review and Reporting:
  - External advice and management reviews.
- Continuous Improvement (of the safety management process)

#### **4.3.2.2 Principles of Safety Demonstration**

How the scientific and engineering activities support the management processes and the adherence to legal principles and requirements together with the general framework for demonstrating safety would normally be laid out as part of the management system. At the implementation level, these principles will be quite detailed and cover the whole life-cycle of the dam. Broadly, and as is the case in the nuclear field, these principles might be considered in terms of:

- Dam safety design principles:
  - Site selection and layout;
  - Investigations and design;
  - Construction;
  - Commissioning, testing, maintenance and inspection;

- Performance and operation;
- Decommissioning.
- Dam safety assessment principles:
  - Dam safety classification and standards;
  - Identification of hazards, loadings and performance demands;
  - Assessment of integrity and performance reliability;
  - Achievement of design capability and performance capacity;
  - Fault and failure analysis;
  - Human factors.
- Dam safety management principles for:
  - Design;
  - Commissioning;
  - Operation;
  - Repair/refurbishment/replacement or decommissioning.

#### **4.3.2.3 Standards (Performance Goals and Safety Standards)**

To avoid ambiguity, confusion and misunderstandings, the detailed technical requirements, standards and performance goals that are to be met should be stated for each dam. There would normally also be a statement to the effect that dam safety standards reflect good engineering practice and the safety standards of national and international dam engineering professionals, including the principles of the National Dam Safety Organization (National Committee) within ICOLD, and all other relevant good practices. Bulletin 59 also provides some general directions in this respect. Other standards may include risk criteria in those jurisdictions where consideration of risk is an explicit element of the government approved safety management process. Discussion of general risk criteria can be found in Bulletin 130 and in Appendix B.

#### **4.3.2 Roles and Responsibilities**

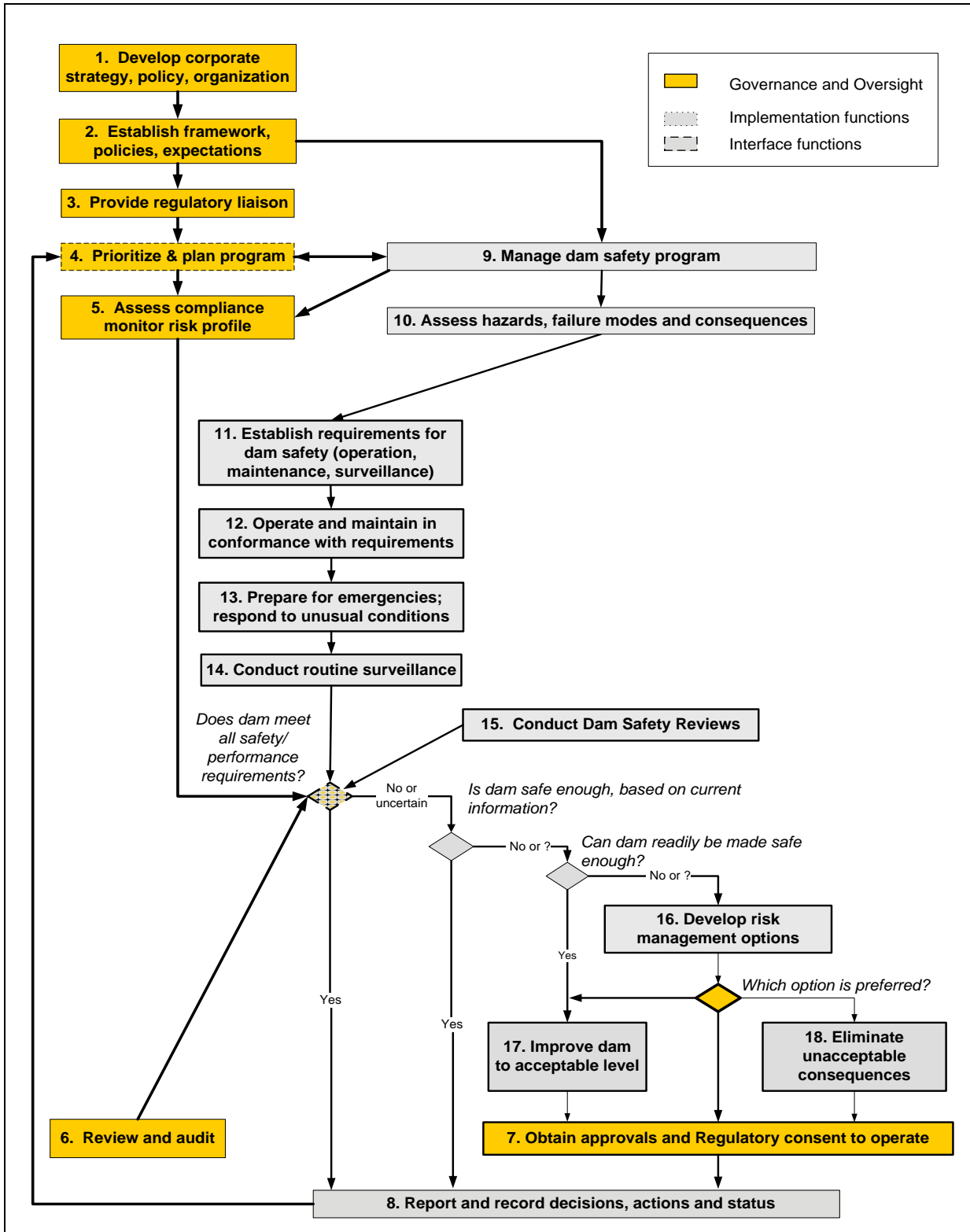
Assignment of roles and responsibilities needs to relate directly to the required functions. This is illustrated in Table 4.1, which is a so called responsibility matrix that is linked to the process diagram of Figure 4.5. Additional detail is provided in the matrix to show different roles during the same process step.

In this example, the organization defines six management positions with roles and responsibilities:

RE-D:	Dam Safety Responsible Executive
DSA:	Responsible Executive's Dam Safety Advisor
RE-S:	Responsible Executive's Support
A&OM:	Manager Asset and Operational Dam Safety
Op-M:	Manager of (Production) Operation
Op-Dir:	Director, Operation and Asset



Figure 4.5 - Detailed Dam Safety Management Functions



Further, the matrix includes up to five types of involvement in each step. The following definitions will give rise to considerable debate, and an organization may choose to use a simpler approach. However, the discussion that takes place during development and communication of this type of matrix is considered to be very beneficial. A review of the matrix is recommended annually, and whenever new staff is brought into the picture.

Accountable (A) – One person is ultimately *Accountable* for a task, objective or decision, and has veto power over it. The Accountable must get the job done, either by doing it or assigning Responsibility to others.

Responsible (R) – A *Responsible* person does the actual work. Responsibility may be shared, but the Accountable must clearly assign the scope to the Responsible persons. (On the matrix it is preferable to define activities such that only 1 person is Responsible for each activity. Shared responsibility for a single activity creates the opportunity for administrative gaps and associated management weaknesses to occur.

Consulted (C) – These are people who need to be *Consulted*, as they bring expertise or are impacted by completion of the work. This is two-way communication. This refers to consultation which is a required procedure, rather than informal seeking of ideas.

Informed (I) – These people need to be *Informed* after a decision or action is taken. This is one-way communication. This refers to provision of information that is a required procedure that should be documented.

The Responsible Entity would normally state that all dam safety functions are carried out in terms of the dam safety management system which, to be effectively embodied into the operational activities should be an integral part of the organization's overall operational management system.

Roles, responsibilities and competencies of staff involved in assuring dam safety would normally be specified in the management system documentation. Each organization must determine the most appropriate hierarchy and structure for these documents. Oversight and management functions may be addressed in detail in different parts of the overall system documentation.

**Table 4.1 - Roles and Responsibilities (RACI) Matrix**

Step	Functional Activity	RE-D	DSA	RE-S	A&OM	Op-M	Op-Dir
1	Establish Ownership Structures	C					
2	Establish dam safety governance framework, policies, oversight processes and expectations. Approve Dam Safety Management Manual.	AR					
2	Establish dam safety inventory and consequence classifications	AR	C		C		
2	Oversee development of technical guidelines and methodologies for implementation in dam safety program		AR		CI		
2	Establish requirements for reporting and review	AR			I		
3	Provide leadership to wider dam safety community		AR				
3	Maintain knowledge of international practices		AR		CI		
3	Liaise with regulator; confirm interpretation of Regulation; obtain acceptance of dam safety goals;	AR	C		CI		
3	Monitor & report regulatory compliance; submit compliance documents	A		R			
3	Oversee corporate security and emergency mgmt			AR	C		
3	Approve external communications re security and emergency management			AR			
3	Approve external communications re dam safety	A			R		
4	Prioritize dam safety projects and propose program for risk reduction		C		R	C	A
4	Approve prioritization methods; review proposed risk reduction program		AR				
4	Approve proposed plan for risk reductions	AR					
4	Maintain portfolio risk profile (i.e. risk matrix)	A	C		R		
4	Measure risk reduction performance vs. forecast				R		A
5	Assess compliance with Dam Safety Management System	A		R			
6	Manage Independent Advisory Boards	A	C		R		
6	Assist periodic corporate audit of dam safety	AR					
6	Implement corrective action to address audit/review results	A			R	C	
7	Provide jurisdictional approvals to dam safety projects	AR			CI		
7	Obtain regulatory consent to operate	AR			CI		
8	Manage dam safety records				AR		
8	Liaise with Corporate Communications and approve dam safety	C		C	AR		
8	Report quarterly to Director on dam safety program implementation	I		I	R		A
8	Report quarterly to Board on dam safety status and governance	AR		C	CI		I
8	Prepare annual report on dam performance				R		A
8	Inform Director of Dam Safety before submitting dam safety project briefings to Board of Directors						AR
9	Establish procedures & standards for implementation of dam safety program		C		R		A
10	Assess hazards, failure modes and consequences for all dams		C		AR		
11	Develop & document OMS requirements for each dam				AR		
11	Plan and implement portfolio OMS strategies & goals				R		A
12	Operate and maintain dam sites to meet requirements and goals					R	A
12	Manage security at dam sites consistent with Corporate requirements				S	R	A
12	Manage public safety at dam sites consistent with Corporate requirements				S	R	A
13	Manage emergency preparedness and maintain response plans for all dams				R	A	
13	Maintain emergency response capability for dam facilities				R		A
13	Respond to unusual conditions and incidents at the dam	I			C	R	A
13	Report emergencies to regulator	AR			C		
13	Provide direction for managed response to dam safety incidents	AR			C		I
14	Plan and implement surveillance program				AR		
15	Manage program of Dam Safety Reviews (DSR) and follow-up		C	C	AR		
16	Identify, assess, monitor actual & potential deficiencies; determine action		C		AR		
16	Plan and implement deficiency investigations and safety assessments		C		R		A
16	Approve safety assessment methods and results	A	R		C		
16	Develop dam safety options and recommend requirements for projects				R		A
16	Choose preferred safety management measure	AR			C		C
17	Plan and implement safety improvement projects		C		R		A
17	Identify planned alteration to dam (regulatory); provide information to support			CI	R		A
17	Obtain regulatory approval for alteration to dam	A		R	CI		
17	Confirm if dam meets project requirements		C	I	R		A
18	Eliminate unacceptable consequences				R		A

## **EXAMPLE OF DEFINITION OF KEY ROLES AND RESPONSIBILITIES**

### **Executive Responsible for Dam Safety [EX in Table 4.1]**

- Determine corporate strategic direction for ensuring the safety of the Organization's dams.
- Advise the Executive and Board of Directors regarding emergent risks, decisions, and actions to be taken.
- Establish dam safety governance framework, policies and goals. Approve Dam Safety Management Processes and Documentation. Approve changes in dam inventory and consequence classification.
- Provide jurisdictional approval for dam safety projects or delegate to Manager of Dam Safety.
- Interact regularly with the dam safety regulator.
- Report quarterly to the Chief Executive Officer and the Board of Directors.
- In case of dam safety incident or emergency, notify Regulator, and provide direction to managed response.

### **Dam Safety Advisor [DSA]**

- Advise Executive Responsible for Dam Safety on decisions, policy implications and safety demonstrations.
- Recommend individuals to be auditors, advisors, and members of advisory council or boards.
- Ensure effective implementation of dam safety risk assessment requirements.
- Assess operational safety cases and prepare risk acceptance safety cases.
- Oversee prioritization of dam safety and dam risk management initiatives.
- Provide guidance and direction for scientific and technical aspects of dam safety program, including standards.

### **Responsible Executive's Support [EX-S]**

- Develop, review and update dam safety risk management system framework, policies, oversight and governance procedures and guidelines. Maintain Dam Safety Management System.
- Implement dam safety oversight processes and controls; report non-compliances.
- Coordinate preparation and assist Executive Responsible for Dam Safety for all reporting requirements.
- Maintain good relationship with regulatory staff; monitor and report on compliance.
- Submit documentation for compliance.

### **Manager Asset and Operational Dam Safety [MAO]**

- Manage dam safety process so decisions are made at appropriate levels, based on policies set by Executive.
- Develop Dam Safety Program objectives, quality assurance standards, strategies for continual improvement, maintenance and advancement of dam safety state-of-practice.
- Issue instructions to operation and facilities on operational requirements for dam safety.
- Provide program of ongoing performance assessment of dams, including management of Dam Safety Engineers. Report, track, evaluate and prioritize dam safety concerns until resolution.
- Implement and audit dam surveillance activities.
- Report hazardous conditions and provide follow-up action as appropriate.
- Initiate Performance Assessments, Deficiency Investigations and Dam Safety Improvement projects. Provide technical and financial oversight to projects, consistent with policies, goals and standards set by Executive.
- Ensure that emergency preparedness and response plans are maintained (including testing and training) for each dam. Establish and maintain a system to provide continuous safety support capability.
- Ensure that dam sites have appropriate security and public safety measures to ensure safe functioning of dams.
- Manage program of external Dam Safety Reviews; follow up results and recommendations.
- Prepare, for Executive Responsible for Dam Safety approval, an Annual Dam Safety Program Plan.
- Report quarterly to Executive Responsible for Dam Safety on status and initiatives at all dams.
- Ensure that dam safety records are maintained for regulatory compliance and due diligence.

The roles and responsibilities as described in Table 4.1 are characteristic for a top-down organization where decision making is highly centralized at the upper levels of the management system. In some circumstances (for example, when the dam inventory is spread over a large geographical area) a distributed model can be considered as more effective in implementation of a dam safety program. The diagram depicted on Figure 4.5 remains still valid but some arrangements with regard to roles, responsibilities, accountabilities and reporting may change resulting in a simpler model as described below.

**EXAMPLE OF DEFINITION OF KEY ROLES AND RESPONSIBILITIES**

**Manager of (Production) Operations**

- Responsible for managing the implementation of all aspects of production operations within the Responsible Entity

**Operations Director**

- Responsible for the strategic and general business policies, planning functions, activities and processes of the Responsible Entity.

## **EXAMPLE OF AN ALTERNATIVE MANAGEMENT AND OVERSIGHT ARRANGEMENT**

The responsibility for the safety of the Organization dams rests with the Board of Directors and the accountability to execute the Dam Safety Policy (as adopted by the Board of Directors) is delegated to the Chief Executive Officer.

**Chief Executive Officer** shall ensure a clear delegation of the accountability and authority for the management and oversight of the program to the **Director - Dam Safety**.

**Director - Dam Safety** is accountable for:

- Development of the Dam Safety Program
- Development and maintenance of a management system that includes all elements of the Program
- Providing Program direction, assessments, plans and advice in the areas of resource allocation, regulatory inputs, training, research and development, and Program improvement opportunities
- Development of policies and procedures as necessary for the management and administration of the Program
- Approval of all dam safety technical standards and procedures as dam safety governing documents.
- Liaison with regulators and stakeholders on policies, issues and future directions related to dam safety management that could impact the Organization
- Coordination of dam safety activities across the Organization
- Monitoring of the execution of the Program
- Annual reporting on the Program to the Board of Directors
- Periodic reporting on dam safety activities to the Chief Executive Officer.

**Operational Group Managers** - Stewards of the facilities and are accountable for the safe operation and maintenance of the dams belonging to each individual Group. They shall be accountable for the execution of all dam safety program elements that pertain to them including:

- Ensuring that all applicable dam safety program elements are executed according to plan as established in the Project Execution Plans
- Informing the Director - Dam Safety of the plans, schedules and costs of all Dam Safety work
- Reporting all dam safety incidents as soon as possible to the Director- Dam Safety
- Planning, scheduling and tracking all dam safety related follow-up work activities that have resulted from the Dam Safety Program for each dam site.

**Director – Water Resource Engineering** - Provides resources and technical expertise in support of the Dam Safety Program in the following areas:

- Dam Safety Periodic Reviews (DSPR)
- Technical validation of preliminary Periodic Review conclusions and recommendations
- Dam Safety General Inspections (DSGI) for dams classified as High or Very High
- Dam Safety Surveillance Training for Plant Group staff
- Dam instrumentation, performance monitoring, reporting and training
- Dam performance database management
- Hydrotechnical studies and associated work in support of DSPRs
- Failure Modes and Effects Analysis (FMEA) and Dam Risk Assessment
- Dam Safety standards and procedures – development and updating as requested by the Director – Dam Safety

**The Vice President – Developments**, shall support the Dam Safety Program in the following areas as they relate to the dam safety portion of projects assigned to Water Resource Developments for execution:

- In consultation with Director Dam Safety, Director Water Resource Engineering, and Operational Group Managers, ensures that design and operational requirements conveyed to consultants performing work on behalf of Owner conform to all regulatory requirements, and Owner standards, procedures and guidelines.
- Ensure that commissioning procedures developed by the consultants are reviewed by the Owner's stakeholders (e.g. Dam Safety, Water Resource Engineering and the Production Groups) prior to the work taking place.
- Ensure that all as-built documentation is conveyed to the Owner upon completion of the project.

### 4.3.3 Planning

In terms of the management system approach, dam safety programs, projects and activities are systematically planned and may be prioritized; works are ordered and properly planned to effectively utilize available resources to provide an acceptable level of protection to the public and the Responsible Entity. The prioritization and planning process is not simply a management arrangement to balance resources; it should also include explicit consideration of completion of mandatory and routine dam safety activities (shown on the left side of Figure 1.1); the duration that a safety concern can remain; the rate or urgency at which safety is to be improved (rate of risk reduction); and, implementation of dam safety improvements (shown on the right side of Figure 1.1).

The planning process covers planning of routine and periodic safety activities at individual dams, as well as investigations into actual or potential dam safety concerns and subsequent improvements which may need to be prioritized to maximise the utilization of resources. The planning process normally addresses the portfolio as a whole first, followed by a similar subsidiary process for each dam. Priorities may be assigned to activities within individual initiatives and projects.

The details of how and when dam safety activities are prioritized and a process for planning the various activities would normally be laid out in the management system. It is at this point that resourcing and other constraints are applied to the management endeavour to finally develop the scope, schedule and budget of the activities to be managed. A clear distinction would be expected between those expenditures necessary to control known dam safety hazards and risks under normal operational conditions as well as those expenditures necessary to correct identified performance anomalies; and those expenditures that are desirable to further reduce “residual risk”.

Prioritization schemes for applicable operational activities are intended to provide a rational means of organizing operational activities and distributing resources. In addition, a rational scheme should assist those responsible for managing all of the operational activities (which includes aspects of safety) with part of a due diligence defence against charges of negligence in the event of incidents or accidents materializing. Typically, at the operational level of a Responsible Entity, all investments and operational activities that compete for financial and human resources are considered. However, having a prioritization scheme is, by itself, insufficient to provide a due diligence defence. The prioritization scheme must be logically sound and arrange risk reduction activities in the “right” order, and the rate of implementation of risk reduction activities must be appropriate, i.e. commensurate with the risk.

Clearly, for prioritized activities, from a due diligence perspective two questions must be answered:

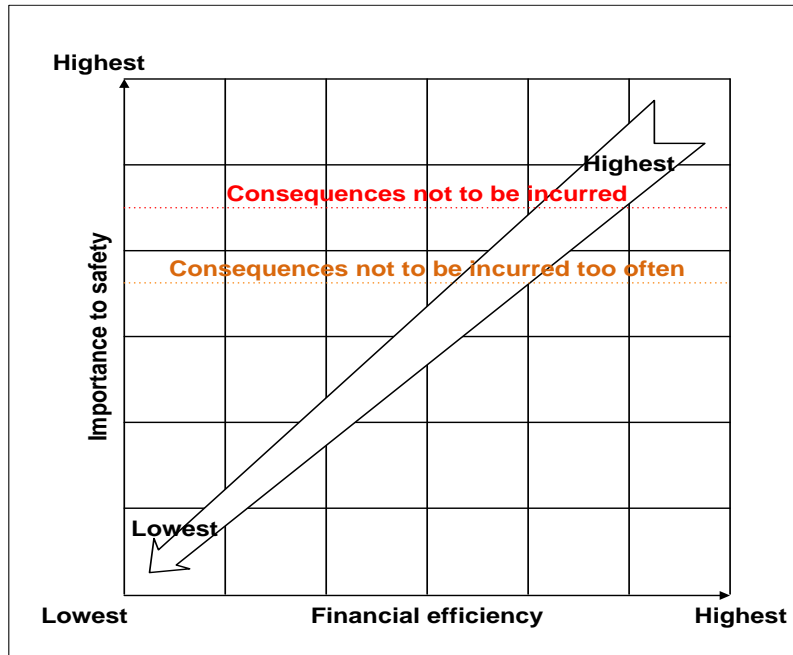
- Is the priority order reasonable?
- What constitutes (in terms of funding, schedule and competence) “appropriate resources”?

All of this suggests that prioritization of operational activities (including dam safety improvement activities) in terms of quantified risk is a logical thing to do. However, quantified risk analysis and the generation of priority orders in terms of quantified risk do not form part of traditional dam safety prioritization practices, although quasi-quantitative risk-based schemes have been implemented by Responsible Entities since the mid 1990’s (refer to ICOLD Bulletin 130). However, it is fair to say that risk concepts, while not explicitly described, are ever present in prioritization schemes as applied in traditional dam safety practice.

Principles of prioritization should be established and laid out in the management system.

One principle of prioritization could be that one should concentrate on those issues that are inherently most important to safety and/or performance and where capital investments are likely to have the most effect subject to all statutory regulatory and policy requirements and risk boundary considerations having been met. The basic notion is illustrated in Figure 4.6.

**Figure 4.6 - (Some) Dimensions of a Prioritization Framework**



Typically at the operational level of a Responsible Entity, all investments and operational activities that compete for resources are considered for prioritization. This involves making trade-offs between operational activities and related expenditures and dam safety expenditures. Once the trade-offs have been made, the dam safety activities that are to be funded and resourced would be reprioritized by the manager responsible for implementation of dam safety activities. Normally, it is most efficient to prioritize the inventory of desirable dam safety activities in advance of the operational level prioritization and then re-prioritize after the resources have been allocated.

One straightforward way to prioritize dam safety initiatives is in terms of the risk expressed as Expected Value (Probability x Consequences) but this is not the best way as expected value does not discriminate between “Low Probability – High Consequence” events and “High Probability – Low Consequence” events. Risk scores, which are a somewhat unsatisfactory substitute for expected value (the extent to which they are satisfactory varies across a spectrum from “a reasonable approximation” to “dangerously misleading”), might also be used provided the necessary care is taken with their interpretation.

The first step, for both safety/risk and for performance issues, often involves the use of a (discretionary) critical items list (which may be summarised and ranked in a comprehensive risk framework) to focus the



prioritization process (Figure 4.5). The highest risks across the system can be plotted highest on one axis and the most financially efficient initiatives are plotted on the other axis. Priorities are simply set from top right corner to the bottom left.

However, in reality, things are not straightforward as there are a number of statutory, regulatory societal and business constraints that must be imposed before financial efficiency become important. Consequences “not to be incurred” are those where the consequences of failure exceed the loss absorption capacity of the Responsible Entity. Consequences “not to be incurred too often” challenge the loss absorption capacity of the organization in a way that would mean that a succession of such losses would quickly exceed the loss absorption capacity of the Responsible Entity. A properly designed prioritization scheme for a portfolio of dams can also be applied to the activities at a single dam.

Once the trade-offs within the brief of operational expenditures has been completed, the dam safety activities and associated expenditures for a particular period are defined.

#### **4.3.4 Management of Dam Safety Activities**

##### **4.3.4.1 Operation, Maintenance and Testing**

Dams, hydraulic infrastructure (including power stations) and reservoirs should be operated and maintained within the specified constraints. For each dam, reservoir, and production system, operation, maintenance and testing requirements for ensuring the adequacy of the functionality of the entire system for safety should be developed and documented in an up-to-date Operation, Maintenance and Testing (OMT) Manual for Dam Safety. The OMT manual serves as one of the standards against which the dam safety activities carried out by the operational groups responsible for the dams can be audited against.

##### **4.3.4.2 Surveillance, Technical Data and Performance Monitoring**

Surveillance comprises: Inspections (visual or remote observation); Monitoring (measurements and readings) and Analysis and Interpretations (investigation of integrity of data and interpretations of measurements and readings) of dams. These activities are central to the detection of deviations from normal performance conditions and other signs of deterioration and performance deficiencies. Adequate surveillance should be carried out with due consideration of consequences of failure, potential failure modes, and key performance indicators. Surveillance includes data analysis and data management activities:

- Analysis of changes in performance, deviation from expected performance, and conditions that might threaten dam safety;
- Tracking compliance of reservoir operation and adequacy of conformance with dam safety requirements;
- Adequate quality assurance to maintain the integrity of data, inspection information, dam safety recommendations, training, and response to unusual conditions;
- Comparison of actual performance with design expectations;
- Quality assurance.

Deployment of monitoring equipment and the development of surveillance plans and interpretation techniques are amongst the most important tasks in dam safety management. These arrangements, both

physical and procedures should be designed and documented and the relevant data and interpretations recorded in a technical data book. The monitoring, inspection and technical data as well as interpretations are recorded and preserved. The surveillance records would normally contain all of the instrument specifications and calibrations as well as the raw data, quality controlled data and all of the interpretations.

#### **4.3.4.3 Dam Safety Reviews**

The arrangements for periodic independent Dam Safety Reviews, and the standards and guidelines against which the safety of dams is assessed are normally described in the management system. These reviews are carried out to determine if the safety and management of the dams and associated facilities is current and adequate. Determination that certain dam safety management controls are no longer current and/or adequate normally initiates a detailed investigation and review. At the implementation level in the management system, the arrangements pertain to managing the review process.

#### **4.3.4.4 Performance Concerns and Deficiencies in Dam Performance**

All performance concerns and actual deficiencies in dam performance should be characterized, prioritized and monitored until they have been resolved in terms of the arrangements defined in the dam safety management system. Performance Investigations (PI) and Deficiency Investigations (DI) should be carried out to support risk management decisions. Dam Safety Improvement projects (capital investments) should be carried out when performance criteria are not met and when prudent or beneficial.

#### **4.3.4.5 Internal Emergency Planning and Response**

No matter how unlikely the possibility of a dam incident or failure, Internal Emergency Planning and Response procedures to prevent the dam from failing should be prepared and maintained current for dams. The arrangements for emergency exercises and tests of the robustness of plans and responses would also normally be described in the management system.

The Responsible Entity would normally establish arrangements to deal with the escalation of dam incidents to emergencies in order to ensure that the responsibility for decision making is raised to the appropriate level in the management structure as the seriousness of the emergency increases. The management arrangements would normally recognise that dam emergencies may be potentially catastrophic with sometimes enormous societal impacts. In emergency mode, any business interests would normally be focused on prevention of dam failure and prevention of societal losses without consideration of cost because what was previously “at risk” will have transitioned to a state of “being in peril”.

#### **4.3.4.6 External Emergency Planning and Testing**

Notwithstanding the efforts to prevent dam failure, Responsible Entities should always have arrangements in place and functioning in order to warn the public downstream of dams that may be affected by dam failure or flooding associated with dam incidents.

Typically the warning and evacuation is organised and implemented by the responsible civil authorities with the role of Responsible Entity to provide the responding authority with sufficient information to effectively protect the public through evacuation and other means. Exercises and tests of the plans and equipment that

form part of the external emergency plan are normally carried out to ensure that the responders are adequately equipped and trained to effectively carry out their emergency duties.

#### **4.3.4.7 External Advice and Management Reviews**

The management system should describe the circumstances when it is advisable to seek independent external advice. The type of advice should be specified as should the level of reporting of the external review. Typically these external reviews are focused either on the highest levels of management responsibility in the Responsible Entity or on individual dams, particularly those where deficiencies have been identified or safety improvements are planned or ongoing.

#### **4.3.4.8 Continuous Improvement**

The specific procedures for reviewing dam safety standards, performance goals for periodically updating them to ensure they are up-to-date and appropriate would normally be the responsibility of the manager responsible for dam safety. Often, the continuous improvement process also applies to the local manager and staff involved in ensuring the safety of dams.

Typically continuous improvement will involve consideration of changes in engineering practices and safety standards as endorsed by national and international dam engineering professionals, including the principles of the National Dam Safety Organization (National Committee) within ICOLD, and all other relevant good practices, including practices from other industries.

#### **4.3.4.9 Audit, Review and Reporting**

The Management System provides a basis for auditing actual management performance against intended management performance. Audits are normally carried out with the view to providing the Board of Directors and senior management with the means to demonstrate that they have exercised due diligence in the discharge of their responsibilities with respect to dam safety and that the activities as directed are being implemented. The arrangements for and frequency of audits would be defined in the management system. The management system audit is not a technical assessment of the safety of the dam which is outlined in the Section 4.3.2 above, it is an audit of the Responsible Entity's structures and processes that enable the safety assessments to be carried out properly.

#### **4.3.4.10 Communications and Records**

Internal and external communications protocols are normally described in the management system including the authorities for documenting and disseminating information about dam safety.

Records management is a very important aspect of dam safety and the records management system should be structured in a way such that all relevant records are readily accessible and are retained for appropriate periods of time. These arrangements would be contained in this part of the management system.

Two types of records, administrative and scientific/technical, are normally controlled by the management system. Together, these records are required to demonstrate the safety of the dam. The specific controls to ensure the integrity of these two types of documents may be different as the administrative documents do not typically contain specific technical or scientific information.

## 4.4 Decision Making

### 4.4.1 Decision Principles

The following is intended to assist the national associations, committees and societies of ICOLD to establish more specific dam safety decision guidance appropriate for the traditions and legal, regulatory, economic and social structures that prevail in their countries.

Fundamentally, the decisions that have to be made in the broad area of dam safety can be separated into two major categories:

1. **Safety decisions** related to clear confirmation whether dam performance is satisfactory. If a dam meets the safety requirements it can be operated without additional conditions;
2. **Programmatic decisions** aimed at supporting safety decisions through development of prioritization schemes, which may differ depending on the objectives and goals of prioritization.

General decision-making principles should provide sufficient guidance for developing a single framework for all arrangements, processes and activities to address the safety goals of the organization. These principles are listed below.

In the modern context and consistent with the report of the World Commission on Dams (2001), the basic principles of decision making are that the process can be and should be:

- Comprehensive;
- Fair and equitable;
- Transparent;
- Consultative;
- Defensible.

The extent to which each of these basic principles applies depends on the nature of the decision and the objective of the assessment. In the context of safety and the risk-informed approach, regulators and those responsible for hazardous installations such as dams and reservoirs must be able to explain the hazard, the characteristics of the risk involved, the degree of uncertainty in that quantification, the methods used to make those assessments, and the confidence limits that can be placed on them. Clear and unambiguous characterization of the problem is essential. It is also necessary to demonstrate the independence of the people raising questions, the adoption of an interdisciplinary approach, application of established good practice, and that conclusions have been fully tested and evaluated. It is necessary to demonstrate that these conclusions have been peer-reviewed and that the data and evidence used, and the methodology applied, are appropriate in the view of the peer reviewers.

ICOLD Bulletin 130 on Risk Assessment frames the decision-making process in terms of the generalised “analytic-deliberative” approach which would comprise the following major steps leading up to a decision recommendation and then onto a decision and implementation:

1. **Define the decision issue(s)** including technical aspects, decision context, stakeholders, and any legal, regulatory, corporate, or other goals or constraints (including risk evaluation criteria);

2. **Identify the decision options** including doing nothing, or decommissioning, if appropriate;
3. **Determine the decision bases and their relative importance**, ranging from purely technical to quantitative risk assessment and to value-based judgements, through consideration of the decision context;
4. **Examine the decision options**, rejecting any that do not meet any constraints (identified in step 1) and assessing the others based on the degree to which they meet the goals (identified in step 1 and the relative importance of these goals (indicated in step 3) and with appropriate consideration given to uncertainties;
5. **Calibrate the decision bases** to build confidence in the bases for decision making by ensuring that they are properly assessed with adequate information. Revise any earlier steps as necessary to complete calibration;
6. **Make and document the decision recommendation** with the involvement of the appropriate stakeholders;
7. **Make and document decision** with the involvement of the appropriate stakeholders;
8. **Implement, communicate and review the effectiveness of the decision.**

In the case of dams, these general considerations can be implemented as follows.

The “decision context” should be determined for each safety management decision, and decision-specific principles, frameworks and decision processes should be selected that are appropriate for the decision-context. A means of achieving this are outlined below.

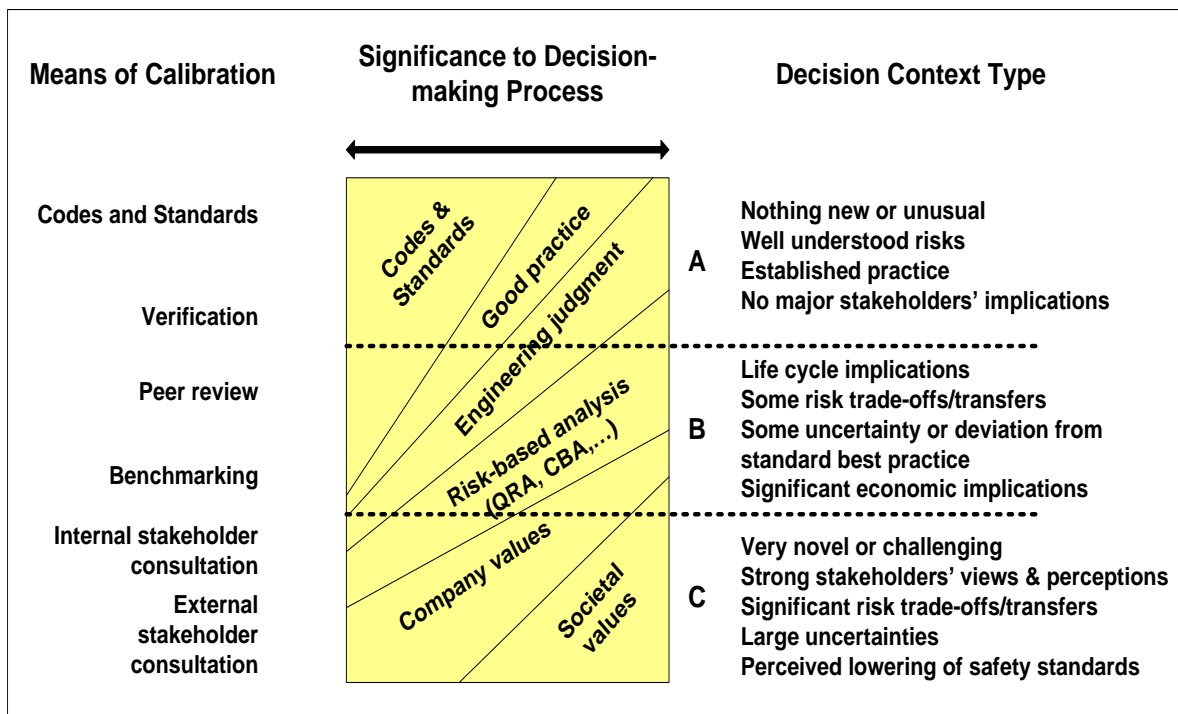
1. All dam safety related activities (understood as individual processes of the management system) that are necessary to achieve dam safety objectives and provide means to meet all safety objectives should be first identified and then their development should be planned, implemented and assessed periodically for effectiveness and continuous improvement.
2. The sequence and interactions of all safety management activities should be determined.
3. The methods ensuring effectiveness of implementation and control of the safety management activities should be determined and implemented.
4. The development of each safety management activity should ensure that:
  - All regulatory, statutory, legal, safety and business requirements are specified and addressed;
  - All interactions with interfacing safety management activities are identified;
  - Inputs to and outputs from (results) each safety management activity are clearly defined.
5. All safety management activities involving interactions between different individuals or groups carrying out an activity should be planned, controlled and managed in such a way that effective communication and clear assignment of responsibilities is achieved.
6. For each safety management activity a designated individual should have the authority and responsibility for:
  - Developing and maintaining functions, activities and solutions together with supporting documentation consistent with the management system documentation;
  - Ensuring effective interaction with interfacing activities;
  - Monitoring, reporting and promoting improvements.

7. All safety management activities that include elements of inspection, testing, verification and validation should have the responsibilities for carrying out the activity and the acceptance criteria clearly specified.
8. Each safety management activity should be periodically evaluated to ensure that it remains current and effective.
9. All work performed within any safety management activity should be carried out using approved procedures and instructions that are periodically reviewed to ensure that they remain valid and effective.

#### 4.4.2 Decision Context

ICOLD Bulletin 130, Risk Assessment in Dam Safety Management, presented the framework for setting the decision context developed by the UK Offshore Operators Association (UKOOA, 1999). The framework is depicted on Figure 4.7.

**Figure 4.7 - Framework for Setting Decision Context (UKOOA, 1999)**



As shown in Figure 4.7, the decision context defines the nature of the decision to be made. Traditionally, the decision context for dams has been related to avoidance of structural collapse and catastrophic release of the stored volume. In terms of the risk-informed approach, it is necessary to determine the spectrum of interests affected by the decision to set the decision context. The notional extents to which the various processes (codes and standards, good practice, engineering judgement, etc.) influence the decision can be read from left to right across the diagram, with the novelty and complexity of the decision stated on the vertical axis. The

design of small buildings would normally be of Type A decision context, whereas the design of small dams would be Type B decision context, with large dams, nuclear power stations and large flood protection barriers such as the sea defences at London, Rotterdam and Venice, being Type C. This framework can be readily adapted for developing the decision context for structural safety decisions. Typically, major dam safety decisions pertain to the questions: "Avoid by how much?" "What constitutes adequate? How limited? How safe is the dam?" and "How safe should the dam be?" These can be considered to be in the lower part of Type B decision context and frequently entirely in Type C. This is in stark contrast to the traditional rules-based approach to dam safety decision making, which has all of the attributes of the Type B decision context.

### 4.4.3 Uncertainty

The term "*uncertainty*" means different things to different people. A clear statement of what the term is intended to mean with respect to the safety of dams should be made in the management system documentation. This Bulletin recommends that appropriate definitions be developed at a national level or, at a minimum, be defined by the Responsible Entity guided by the authoritative literature of ICOLD and national committees.

Traditionally, in dam engineering, natural hazards such as floods and earthquakes are considered to be unpredictable or random events in space and time. Such events are unpredictable because it is impossible to know when, where, or how large the events will be at some time in the future. Characterization of such random events in terms of probabilistic properties is common in many jurisdictions, with the probabilities of exceedance of the physical parameters used to characterise the hazards expressed in numerical terms. In other jurisdictions there is a preference to account for this same unpredictability through conservative estimation of the "probable maximum" values of the physical parameters.

Beyond natural flood and earthquake hazards, other factors that enter into the dam safety management process such as variability in foundation characteristics, fill and concrete properties, etc., are characterized in terms of exceedance frequency or conservative upper (or lower) bound parameters.

Such unpredictable occurrences are known as *aleatory* uncertainties. The term *probability*, when applied to such random events, is taken to mean the frequency of occurrence in a long or infinite series of similar trials. This frequency is a property of nature, independent of anyone's knowledge of it. It is innate, and has a "true" value. Two observers, given the same evidence, and enough of it, should eventually converge to the same numerical value for this frequency.

The term "uncertain" applies in a different way to matters involving lack of knowledge: where uncertainty is a lack of sureness or a lack of confidence about someone or something, ranging from falling just short of complete sureness or confidence, to an almost complete lack of conviction about an outcome or result. In dam safety assessment it is not possible to have complete and perfect knowledge of the condition of a dam or its performance and, as such, knowledge uncertainties permeate the dam safety assessment and management processes. Such unknown things have been called *epistemic*, after the Greek for "knowledge." This term, too, is now widely used to distinguish imperfect knowledge from randomness.

The term *probability*, when applied to imperfect knowledge, is usually taken to mean the degree of belief in the occurrence of an event or the truth of a proposition. In this sense, probability is a property of the individual. We may or may not know what the value of the probability is, but the probability in question can be learned by self-interrogation. There is, by definition, no "true" value of this probability. Probability is a

mental state, and therefore unique to the individual. Given the same evidence, two observers may arrive at different probabilities and both are right.

Three facets of uncertainty have been identified with respect to the safety of dams:

- *Uncertainty* with respect to the world means that an outcome or result is unknown or not established and therefore in question;
- *Uncertainty* with respect to the state of knowledge means that a conclusion is not proven or is supported by questionable information;
- *Uncertainty* with respect to a course of action means that a plan is not determined or is undecided. The term uncertainty has various nuances. Each of these expresses an aspect of uncertainty that must be addressed in dam safety assessment and management.

In recent years, financial pressures and the emergence of consideration of societal interest and transparency of decision making concerning societal risks associated with dams and other hazardous installations has resulted in considerable emphasis on explicit treatment of uncertainty in dam safety assessment and management. The dam safety decision-making environment of today and of the future is starkly different to that of the past when the safety of dams was determined by engineers (individually or as professional and learned societies) thereby determining the level of cost and risk carried by the owner and the level of risk imposed on society.

Dam safety management and therefore the dam safety management system have to acknowledge the many scientific issues that exist in relation to safety of dams, and that uncertainty will inevitably permeate all considerations; it cannot be removed. In this regard, the management system would be expected to define what is meant by uncertainty and how uncertainty is to be handled in the dam safety management process.

#### **4.4.4 Role of Judgment**

Dam behaviour, being governed by the laws of physics, is best characterized using physical parameters that are measurable; such measurements through inspections, instrument readings and surveillance, are the cornerstone of ongoing dam safety management (left hand side of Figure 1-1). However, measurements by themselves are not sufficient as it is necessary to relate the data to the physical behaviour of the dam itself to assess its safety. The physical behaviour is normally expressed in terms of idealized models of the dam, how it functions, and how it might fail to function. Together, given complete data and comprehensive models that reflect all aspects of performance, it is theoretically possible to analyze the safety of a dam in quantitative terms. However, human cognitive processes must be brought to bear on both the collection and verification of the data and in the construction of the behavioural models. Therefore, despite their numerical characteristics, the results of the analysis are not absolute but reflective of a mix of physical data, cognitive analysis and the judgement of the engineers involved. Being human judgements, it is impossible for the engineers to separate their analytical judgements from the personal values that govern their practice. Thus, in reality, it is impossible to obtain the “complete data set”, to have accurate and precise comprehensive behavioural models, and to eliminate the human element from the analysis process.

All approaches to dam safety, be they the deterministic approach or risk approach, incorporate in different ways strong elements of judgment, and all reflect in different degrees the need to bridge inadequacies or absences of data. Thus dam safety assessment is not the same as conducting an academic scientific



investigation, although the process must be founded on proper scientific principles and the deployment so far as feasible, of scientific method.

Throughout the dam safety management process, there are some uncertainties that are simply not amenable to quantitative estimation based on data and models. These may reflect unique situations that are not found in the historical record of experience with dams. They may reflect uncertainties associated with poorly understood physical phenomena. They may reflect conditions for which data could, in principle, be collected but only at a prohibitive price, and so forth. Formerly incorporating such uncertainties in a dam safety assessment relies on professional judgment. In most cases, this judgment has to do with tacit rather than explicit knowledge. It is based on intuition, qualitative theory, anecdotal experience, and other sources that are not easily amenable to mathematical representation. Yet, this judgment of experts is important information in analyzing safety.

The role of judgement in dam safety management is even broader than that of dam safety analysis as it must also embody the prevailing laws, customs and societal values of the jurisdiction involved and also the values of the dam owning organization as they apply given the operating constraints. Against this background, there is a compelling case for the dam safety management system to describe how judgement pervades the management process, the conditions for which expert opinion is sought, and the processes for identifying selecting appropriately qualified experts.

#### **4.4.5 Decision Frameworks**

##### **4.4.5.1 Standards-Based Framework**

Approved engineering standards and codes of practice for engineered facilities where they exist, and especially when they are enshrined in legislation, provide a convenient means of dam safety decision making in some jurisdictions. However, the uniqueness of each site severely restricts the extent to which prescriptive codes and standards can be applied. Inevitably, judgment will be required both in the engineering analysis and the decision process, with the result that experienced engineers have an essential role in safety assessment and decision making.

The question as to “Who sets the safety standards” arises because these standards are normally stated in engineering terms such as factor of safety, whereas the question “How safe is safe enough?” is a political question with societal implications. There is also the issue of designers setting safety standards, as designers normally adopt a cautious, conservative approach such that their dams will not fail, yet all safety measures come at a cost which in the case of dams can be a very significant cost. The standards-based approach does not provide a means of balancing costs and benefits in term of compatible metrics. Thus while designers and engineers might gain comfort and protection working in terms of approved standards, the problem of how to set appropriate standards remains.

##### **4.4.5.2 Generally Accepted Framework**

ICOLD Bulletin 61, Dam Design Criteria, defines two objectives for dam safety decision making stated in terms of a philosophy. The philosophy of design criteria, stated in terms of two basic criteria is that the objective is to create a “structural form together with the foundation and environment [that] will, most economically:

- Perform satisfactorily its function without appreciable deterioration during the conditions **expected normally** to occur in the life of the structure and,
- Will not fail catastrophically during the **most unlikely but possible** conditions which may be imposed.”

Bulletin 61 stops short of specifying criteria *“for two reasons:*

1. Much study and discussion is needed to establish generally applicable values even for well-established parameters.
2. Many parameters (such as those describing the constitutive properties of materials for instance).”

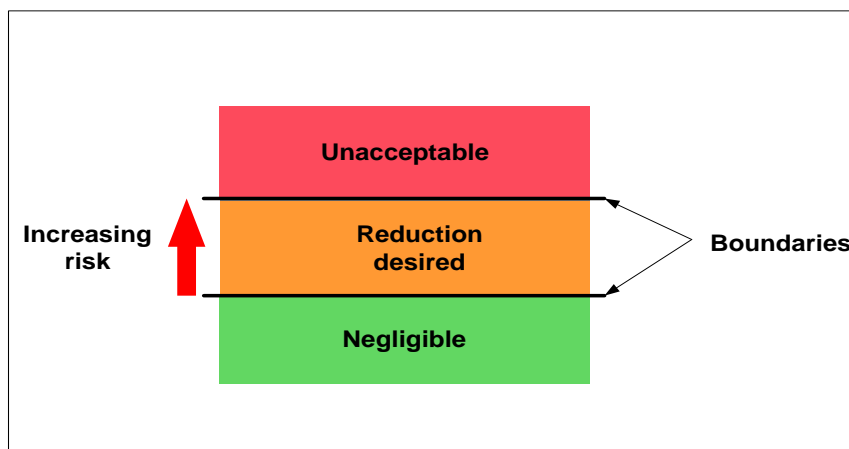
The established approach is to consider two conditions: operational integrity under “normal conditions” and avoidance of catastrophic collapse under “extreme conditions.” However, while Bulletin 61 provides a comprehensive treatment of the considerations that should be incorporated in the decision process, it falls short of integrating all of these considerations into a single framework.

There is nothing new or unusual in such an approach as even the ancient Code of Hammurabi did not specify how safety was to be assured; rather the consequences to the owner of a dam whose failure caused flood damage were defined. Thus in terms of this approach, neither of the questions “How safe is safe enough?” and “How is achievement of safety demonstrated?” are addressed explicitly. In addition, the same limitations with respect to achieving a balance between costs and benefits of safety and the role of judgment by suitably qualified engineers increase over that of the standards-based approach.

#### 4.4.5.3 Risk-Based Framework

In jurisdictions with a codified legal system, decision rules provide the basis for establishing the extent to which people, property and the environment are to be protected. In such jurisdictions, there is scope for numerical risk acceptance criteria where the decisions are based on pre-determined criteria and the quantum of risk associated with each specific case. The framework that has been used since the time of Napoleon is illustrated in Figure 4.8.

**Figure 4.8 - General Form of Risk Acceptance Criteria (the Netherlands)**



#### 4.4.5.4 Risk-Informed Framework

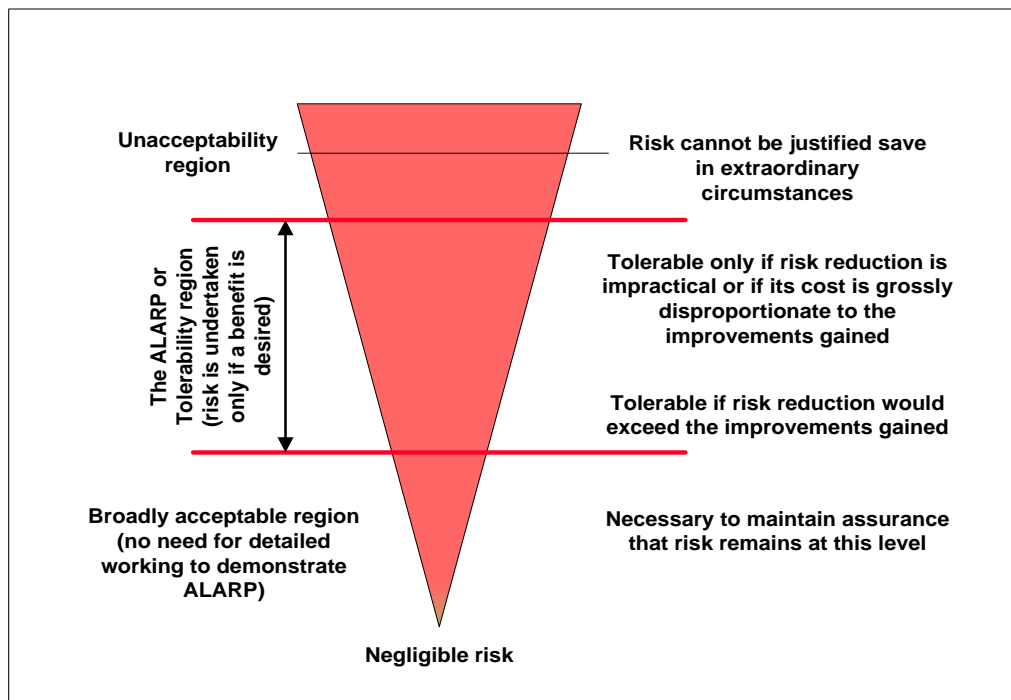
Under the common law system, which operates in a different way to the Codified (Napoleonic) system, the idea that levels of risk may be acceptable or unacceptable to the public, Responsible Entities, and regulators has long been present in an implicit form in dam safety considerations, although only in recent times are explicit forms being developed. The most comprehensive approach to date (Rimington et al. 2003) recognizes the following risk categories (Figure 4.9):

- **Broadly acceptable risk** - An annual risk of casualty significantly lower than  $10^{-6}$  arising from any particular source, generally taken as negligible risk;
- **Unacceptable risk** - An annual risk of casualty in excess of  $10^{-4}$  deemed to be intolerable under normal circumstances. This does not preclude individuals from voluntary participation in recreational activities involving higher levels of risk, often in the range  $10^{-3}$  to  $10^{-2}$  fatalities per annum;
- **Tolerable risk** - An annual risk of casualty between the values  $10^{-6}$  and  $10^{-4}$ .

The key component is risk to life safety. With respect to this, NSW Dam Safety Committee (2006) proposes two principles:

- With respect to individual risk, the increment of risk imposed on an individual by a dam should not exceed a small fraction of the average background risk that the population lives with on a daily basis;
- With respect to societal risk, the probability of an event that could result in multiple casualties should not exceed a value which is a function of the number of possible casualties (i.e. an expectation) and which is declining as the number of casualties increases.

Figure 4.9 - Tolerability of Risk Framework

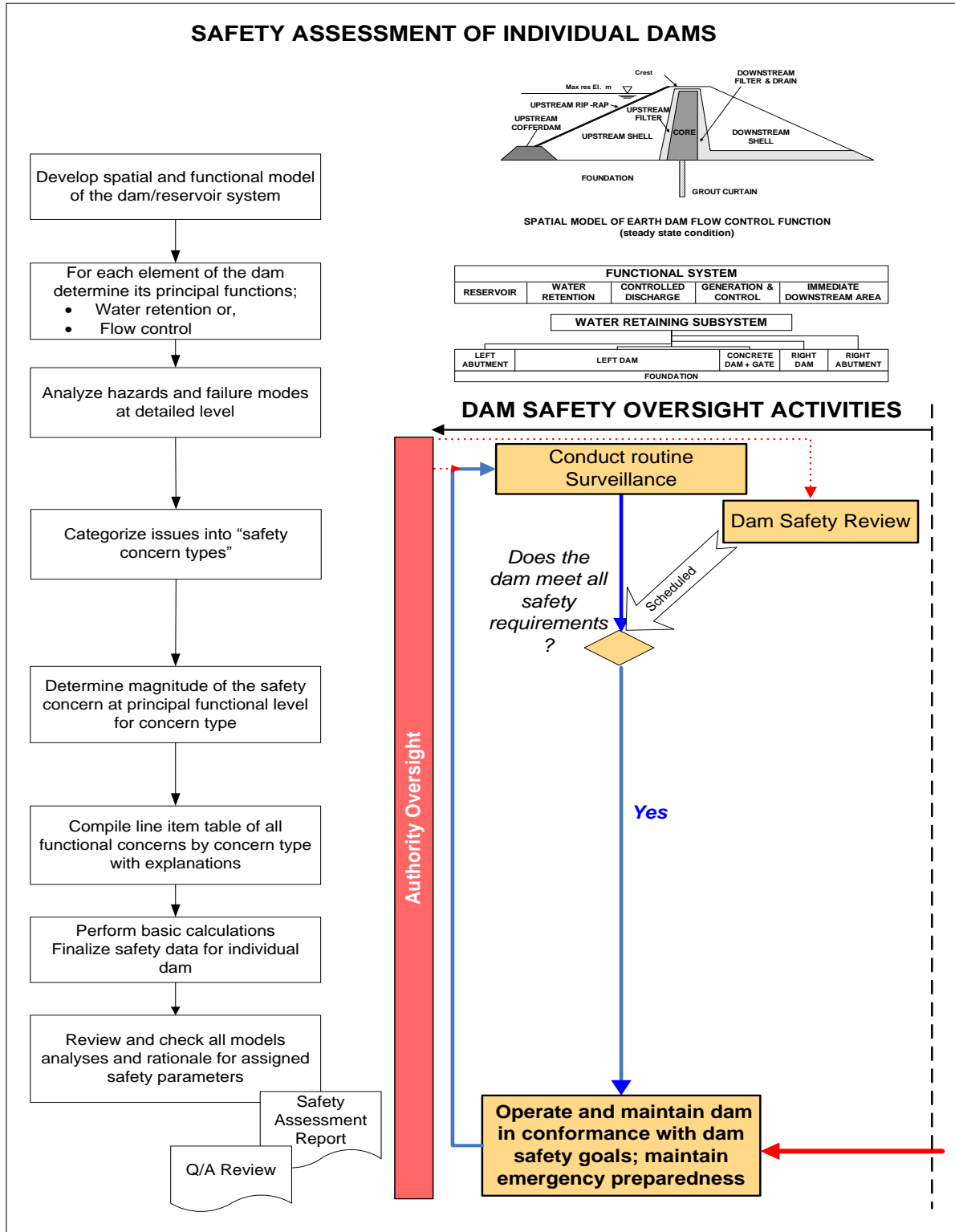


## 4.5 Overall Program Planning

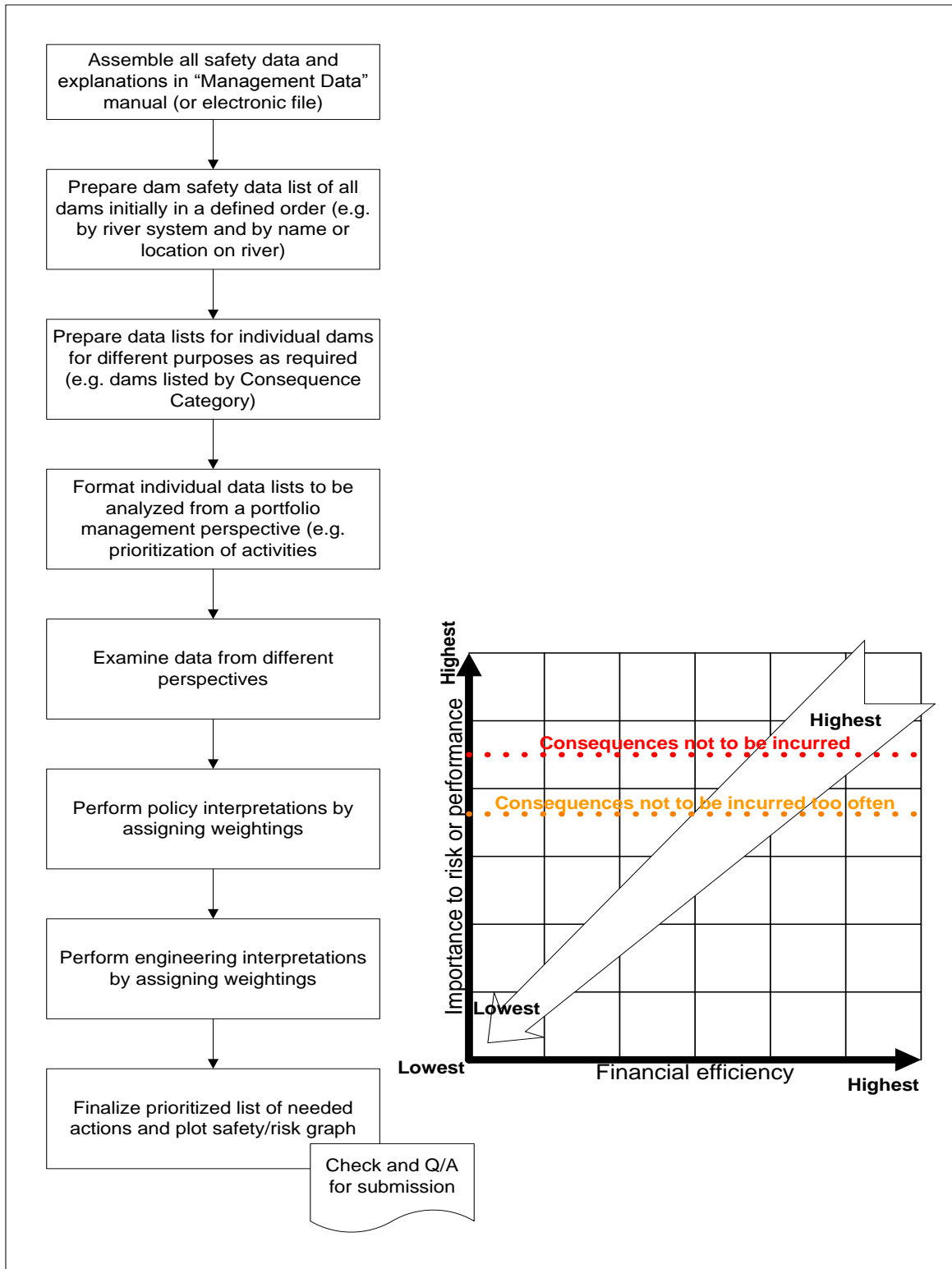
The following illustrates the planning activities for a portfolio of dams.

The actual work to be done can be divided into three parts; the first and third parts follow directly from Figure 1.1 (Figure 4.5), with the second intermediate part involving balancing resources between dams and between the dam safety demands and all of the other operational demands. As noted previously, trade-offs must be made between dam safety activities and other operational activities and the notion that all dam safety activities must be funded because “they are dam safety activities” is no longer tenable. In reality, even if all funding requirements are available, implementation of dam safety work is best carried out in a systematic and prioritized way with the result that the same underlying management controls are required regardless of the funding situation. Thus the following, as illustrated in Figures 4.10 – 4.12, applies regardless of the funding situation.

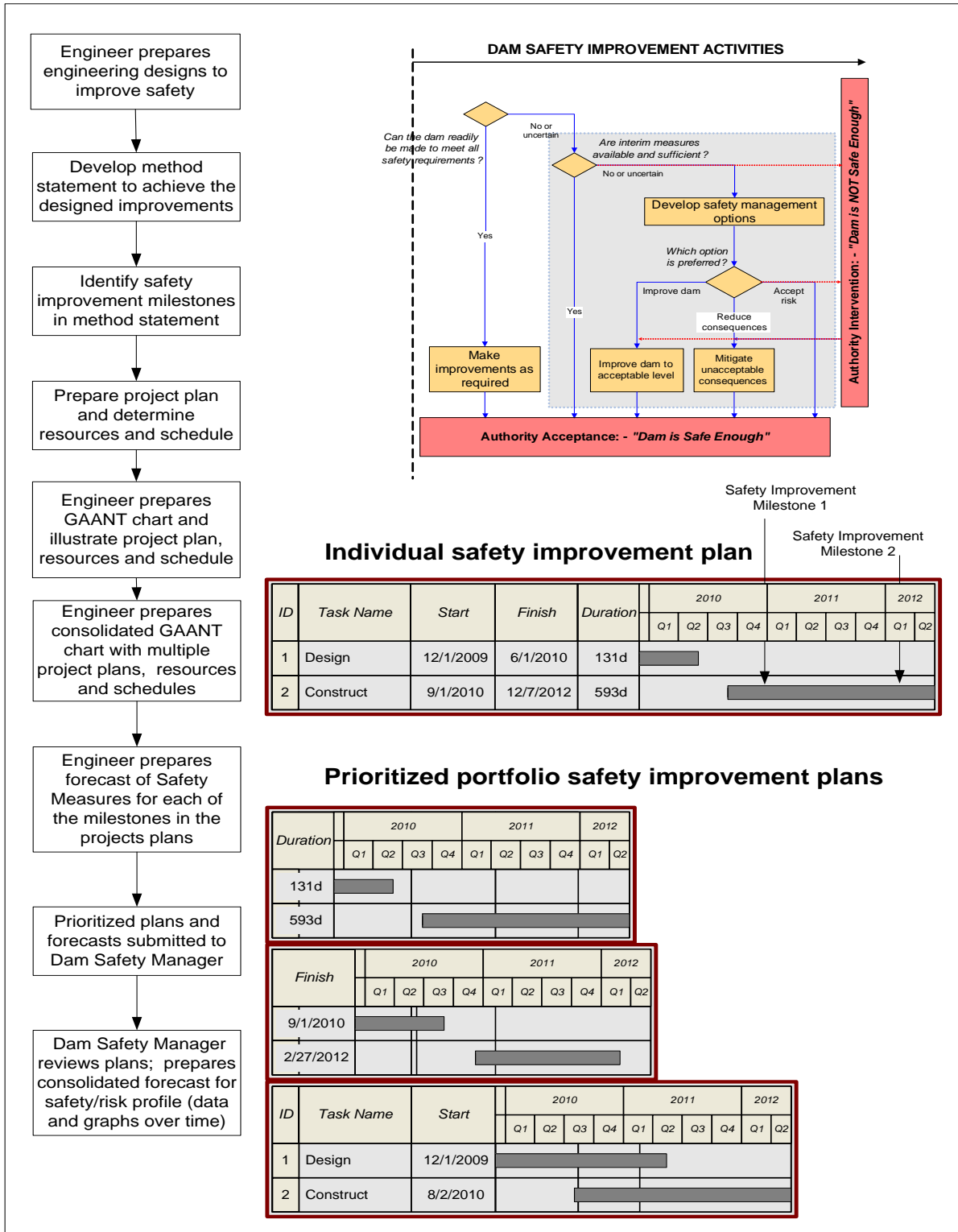
Figure 4.10 - Systematic Safety Assessment Process



**Figure 4.11 - Preliminary Planning and Prioritization**



**Figure 4.12 - Finalization of Plans and Implementation of Dam Safety Improvements**



## **4.6 Implementation of Management Arrangements for Dam Safety**

### **4.6.1 Activities at a Dam**

Dam safety activities are very well known by many dam operators and owners around the world. They are the result of experience and sound judgment accumulated over more than a century. However, it is not always clear why and to what extent these activities are necessary, how they may be adapted to the dam type and behaviour, how much effort must be devoted to do them. Decisions or procedures were often written years ago, quite often without much by way of explanation or justification, and dam surveillance may then be considered as a routine activity, without sound understanding of the underlying basis. Furthermore, these activities have often been considered separately, depending on their objectives; dam surveillance, flood routing, maintenance, emergency planning, etc., and, also separately the management and practical arrangements aspects that are not easily included in the activities themselves.

The activities carried out at a dam are primarily focused on detection of changes in performance of the dam and changes in the influences and environment around the dam and typically involve:

- Visual observations and inspections;
- Measurements and surveys;
- Reading of instruments (manual and/or automatic);
- Maintenance of surveillance infrastructure;
- Testing of safety systems;
- Documentary records.

The activities at a dam should be designed in a way that produces meaningful data for analysis. Thus, the activities at a dam should be focused on identification of; Hazards, Failure Modes and Indicators of Undesirable Performance (Failure Effects). This means that the designer of the monitoring and surveillance program for a dam must understand the general performance characteristics of the type of dam involved, as well as the details of specific (and sometimes controlling) features of an individual dam.

### **4.6.2 Identification of Hazards, Failure Modes and Failure Effects**

Fundamentally, the safety assurance process involves formal consideration of:

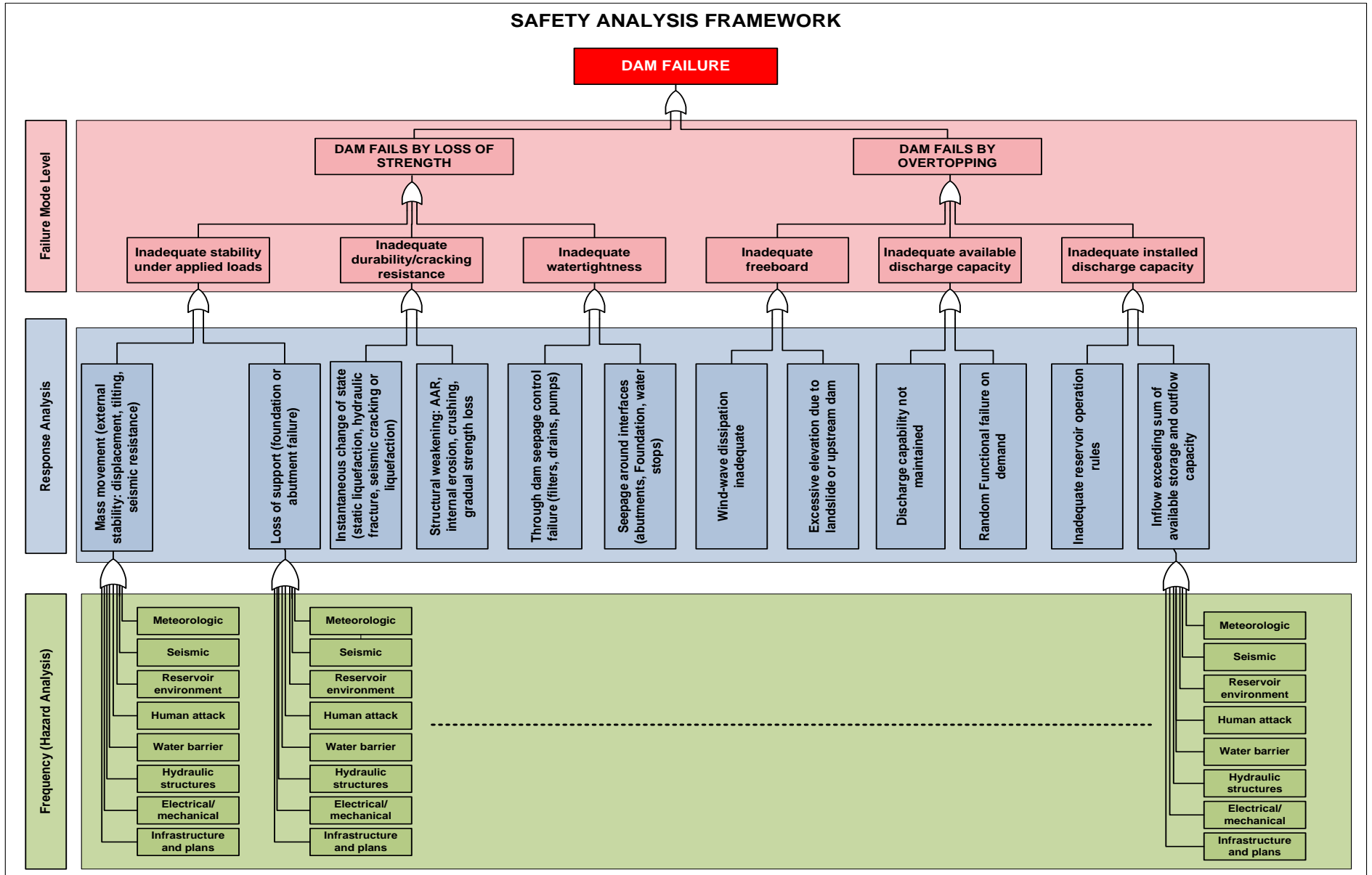
1. Hazards, broadly subdivided into two parts:
  - External (outside the control of the Responsible Entity) hazards such as floods, earthquakes, reservoir environment hazards, and human agency.
  - Internal (within the control of the Responsible Entity) hazards such as design errors; construction flaws, maintenance arrangements, operating procedures etc.
2. Failure modes; specifically the various ways that dam failure processes manifest themselves.
3. Consequences of dam failure.



Now a new and very powerful tool, often referred to as the “bow-tie” model, which combines Fault Tree Analysis and Event Tree Analysis can provide answers to these questions, giving at the same time sound arguments; assessment of hazards, failure modes and potential failure, and resulting consequences. This methodology is based on the identification of all failure modes, affecting the dam and its appurtenant works, potentially resulting in uncontrolled leakage or water level, and, more generally, in possible accident for people or property. Each failure scenario is described in a fault tree model (Figure 4.12), which comprises the left hand side of the bow-tie model (Figure 4.13).

Figure 4.13 provides a means of mapping the activities described in many existing ICOLD Bulletins to the management activities described in this Bulletin in Appendix A.

Figure 4.13 - Fault tree Model of Hazards and Failure Modes



### 4.6.3 Safety Engineering Philosophy

Once the risks are analyzed and the sequences between hazards, undesirable events, failure modes, and consequences are determined, risk management measures can be identified to prevent or reduce the possibility of the development of the failure scenario. Typically, these dam safety activities involve:

**PREVENTION** of the occurrence of undesirable events through for example:

- Elimination or control of the hazard whenever possible;
- Elimination of failure modes.

Provision of the ability to retain **CONTROL** of the system such that any failure sequence that initiates can be brought back under control before the undesirable state (event: hydraulic functionality compromised) is reached through for example:

- Provision of adequate margins of safety between the magnitude of the hazard and the undesired response of the system;
- Design features that result in the system defaulting to a safe condition given the initiation of a safety (failure) sequence.

**MITIGATION** measures that eliminate or minimise the potential for the undesirable event to cause harm through for example:

- Suppression of stored energy through controlled drawdown and warning systems;
- Emergency responses and evacuation.

These measures, **Prevention, Control and Mitigation (PCM)**, can be illustrated in the bow-tie risk analysis model as shown in Figure 4.14. These measures may relate to engineering, maintenance and operational activities.

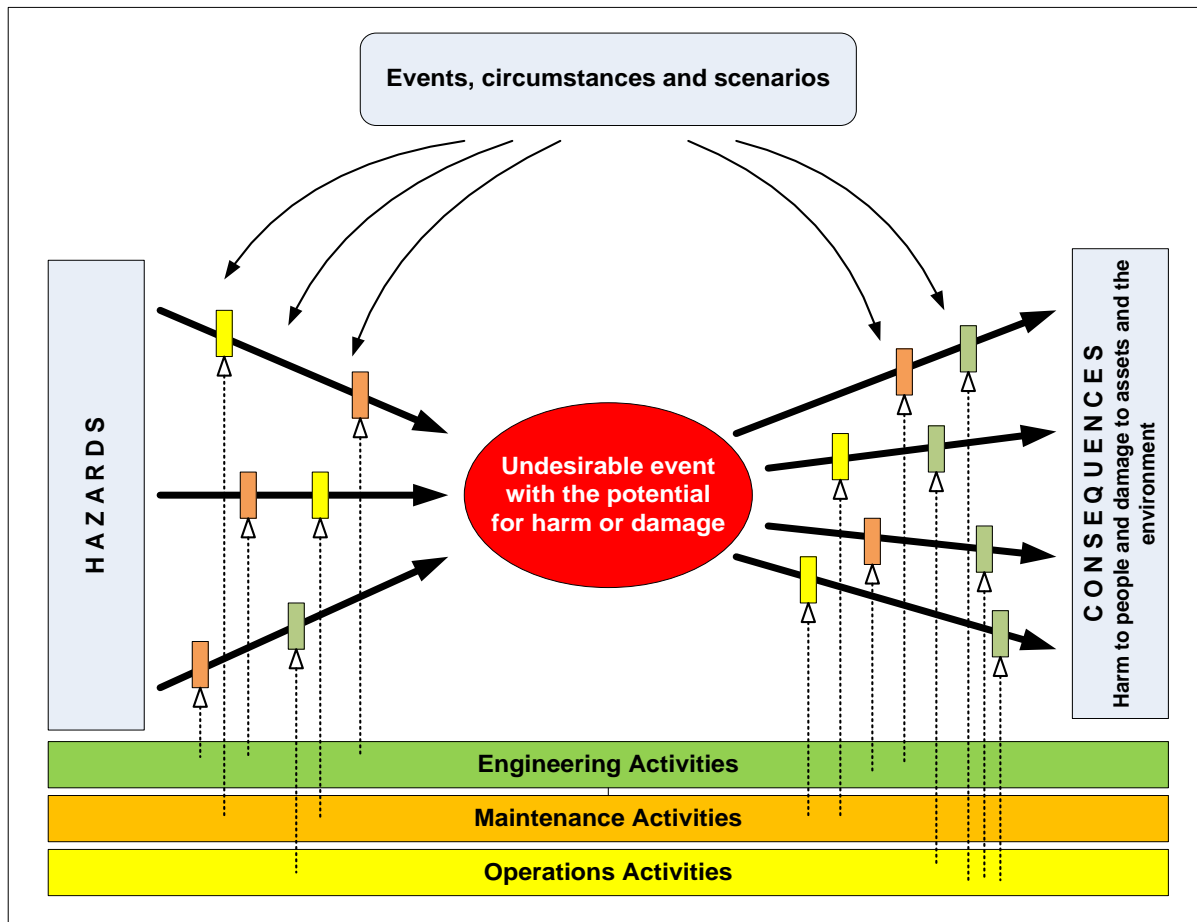
Since it is not possible to ensure that all risks can be eliminated or completely controlled through engineering, maintenance and operation activities, risk assessment concepts can be applied to the residual risk that remains. The point at which the residual risk becomes tolerable or subsequently acceptable will vary depending on the jurisdiction where the dam is situated and where the adverse consequences would materialise.

As a result of this analysis of failure scenarios, the risk management measures or barriers can be divided in three main groups:

- Prevention - Activities necessary to ensure the structural safety of the dam - Design and calculations applying to new or existing dams, dam construction or rehabilitation, dam deconstruction. These activities aim to minimize the risk by optimal design.
- Control - Operational activities during all of the dam life to maintain the safety of the dam: surveillance (monitoring, visual inspection, equipment tests), flood routing, maintenance, activities ensuring public safety.
- Mitigation - Emergency preparedness and response.

These two last categories of activity aim to controlling the residual risk. The PCM scheme is also a hierarchy of effectiveness of the controls with Prevention being at the top of the hierarchy and Mitigation at the bottom. Prevention is always superior to the other types of control and will always be the preferred type of control. In terms of the hierarchical philosophy, mitigation measures are never an equivalent alternative to preventive controls.

**Figure 4.14 - Bow-Tie Risk Management Model**



All the management arrangements, at all levels of the Responsible Entity, as described in Chapter 1 to 3 and sections 4.1 to 4.4., are included in the barriers. Among these barriers, structural safety, being preventive, is the most important one and it relies upon expert and engineering techniques along with the knowledge of causes of deficiencies in dams.

These "bow-tie" models or risk analysis and risk management clearly illustrate the relationship between accepted and well proven practices, and risk assessment and risk management methods. In particular, the three categories of activities listed above can be found as barriers in this analysis. These "bow tie" models apply to the entire life stage of a dam.

#### 4.6.4 Engineering Principles for Safety Assurance

The engineering principles that underpin an organization's safety assessment process would normally be described in the management system, although the principles would need to be applied specifically on a site-by-site basis. The list of principles will normally be quite extensive. However, there are a number of fundamental principles to guide safety assessment as follows:

1. Redundancy: more than one way to achieve the desired performance;
2. Diversity: different ways to achieve the same function for a dam system;
3. Segregation: function served from different locations and directions;
4. Defence in depth: large margins of capacity over demand (in all systems, including redundant systems);
5. Fault tolerant (include human fault tolerant): a single fault will not cause loss of dam system function;
6. Fail to a safe condition: if a part of the dam system does fail, it will render the dam to a harmless condition.

There will be inevitably some situations where it is not possible to meet all of these features and there may be cases where it is impossible to meet more than one of these principles. In such cases, the quality of the engineering design, fabrication, operation, maintenance and replacement will govern the safety and reliability of the system. In general, the fewer the principles that are achieved, the greater is the dependence on the quality and robustness of the engineering and system management.

A system with:

- **Redundancy** will have more than one way to achieve the function available to be brought into service at any time.
- **Diversity** will achieve the same function in different ways;
- **Segregation** will achieve the same function from two separate paths;
- **Defence in depth** will have large margins of capacity over demand;
- **Fault tolerance** will not fail as a result of a single fault/failure;
- **"Fail to a Safe Condition"** features will be benign if it does fail.

A system with:

- **Redundancy** and **Diversity** will have more than one and different ways to achieve the same function;
- **Redundancy, Diversity** and **Segregation** will have more than one and different ways to achieve the same function derived from different paths;
- **Redundancy, Diversity, Segregation** and **Defence in Depth** will have more than one and different ways to achieve the same function derived from different paths operating normally (as opposed to under stress);
- **Redundancy, Diversity, Segregation** and **Defence in Depth** and **Fail to a Safe Condition** features will have more than one and different ways to achieve the same function derived from different paths operating normally (as opposed to under stress) that will fail to a harmless state.

In general, a system with these features can be expected to be safer, more productive (in terms of more available, more reliable, more resilient, more maintainable, more repairable) more removable, more insurable, more risk free and usually more expensive to build than a system with none of them. It will not necessarily be more expensive over the whole life-cycle, and any liability associated with the residual risk will be lower.

The elements in a system with **Redundancy** and **Diversity** may be able to perform under a wider spectrum of conditions because the differences in the failure modes of the two different elements. These features complement each other and typically contribute to more than one of the above system qualities. For example, Fail to a Safe Condition contributes to “reparability”.

# Chapter 5 - Dam Safety Activities

## 5.1 Management Arrangements for Dam Safety Activities

Dam safety is ensured, in the end, by the operational activities which have been introduced in the previous chapter as the barriers in the bow tie model. These activities can be divided in two main categories, shown in Figure 1.1.

- **Oversight activities** including operational activities during the entire dam life to maintain the safety of the dam: surveillance (monitoring, visual inspection, equipment tests); flood routing; maintenance; activities ensuring public safety, emergency preparedness system and procedures; and safety reviews to periodically assess the safety level of the dam. If a deficiency is detected, either by routine surveillance, inspection following an extreme event, or in a safety review, dam safety improvements necessarily must be considered, and lead to “dam safety improvements activities” as outlined below.
- **Dam safety corrective activities** begin with a safety assessment of the dam, and could then include investigations and thorough analysis; they can lead to interim or long term remedial actions, or, depending on the degree of urgency, activation of the emergency plan.

### 5.1.1 Management Arrangements - General Considerations

Roles and responsibilities of staff ensuring dam safety are defined in Chapter 4. Some complementary operational comments are presented hereafter. The “Manager Asset and Operational Dam Safety” and dam staff operators are often in charge of the whole facility, including the installations such as hydroelectric powerhouse, water treatment and distribution, etc. Furthermore, several dams and facilities could be assigned to one Manager. Therefore, the activities specifically intended for dam safety are quite often managed together with many other activities. It is therefore the responsibility of the Managers of operational dam safety to give these activities the higher priority and attention.

Very often, the dam site is not permanently staffed. This can be acceptable as long as the operating personnel can access the dam with little or no delay. An acceptable delay for proceeding to an urgent inspection in the case of a detected anomaly or following an external threat (earthquake) could be from one to several hours and depends mainly on the dam type.

The operating staff is usually managed directly by either Operation Manager or the Dam Safety Manager. For specialized inspections or measurements (topographic survey) it is often not the case, and the responsible Manager then has to arrange the contracts with required specialists to ensure that they will be available on demand if an inspection or measurement analysis needs to be performed urgently. If these specialized resources belong to the owner organization, it is simpler to manage, but it still must be formalized.

### 5.1.2 Documentation, Records and Reporting

Proper documentation of the dam characteristics, current condition and past performance is necessary to assess the adequacy of operation, maintenance and proposed corrective actions. Documentation related to

each individual dam must be available both on the dam site, in a secured area, and in the owner offices, with a clear registration plan. This documentation includes:

- Design documents: topography, hydrologic, geologic, and seismologic studies, soil and rock mechanics laboratory tests, stability and hydraulic calculations, preliminary design, final design.
- Construction documents: specifications, tender documents, detail drawings, analysis reports, investigation reports and as built drawings.
- Monograph of the dam.
- Reports related to the surveillance, operation and maintenance of the dam: survey and inspection reports, all monitoring data and its interpretation (behaviour report), flood reports, all documents about maintenance works (on a routine basis or rehabilitation).
- Operations and Maintenance Log (also sometimes referred as “dam register”) should be provided (as part of the database/book) at all dams, and entries should be periodically verified by the regulator and the Responsible Entity or a suitably qualified representative to ensure compliance with authorized procedures and instructions.
- Operating procedures (see below 5.1.3)
- Maintenance procedures (see below 5.1.4)
- Safety review and report on assessment of hazards, failure modes and consequences of potential failure (see below 5.2.5)
- Emergency preparedness procedures (see below 5.2.6)

### **5.1.3 Operating Procedures**

The Operating Procedures should contain the detailed information required by a dam operator to ensure proper and safe operation of the dam and its associated structures and equipment. Operating procedures should be developed and documented by the Responsible Entity for the safe operation of a dam under adverse (even worst case) scenarios as well as normal conditions. These operating procedures should include:

- Dam surveillance and monitoring procedures: Description of visual inspection routes and frequency, description of monitoring sensor location and frequency of their readings (either manual or automated), procedure and frequency of sensor maintenance and calibration. The data acquisition and local treatment should be defined in these procedures, along with the relationship between local staff and specialized staff in case of non standard results.
- Flood routing procedures: They describe first the states of the dam under flood condition: particular upstream areas which will be affected by a rising water level, and downstream areas where discharges from the spillway will create impacts. Then the flood routing procedures define the general approach adopted to route the flood, taking into account these upstream and downstream constraints, along with dam safety which will be given the highest priority. Finally, technical instructions give all the detailed activities for the gates operations, etc. Periodic tests and functional tests of the safety equipment (gates, outlet, power supply, etc.) are also defined in these procedures.
- Standard operation procedures: Public safety is of paramount importance at all dams and reservoirs. In many cases now, a risk analysis specific to these aspects is carried out, resulting in identification of mitigation measures designed to avoid or minimize the risk for the public. These measures can include particular operating modes (progressive start up of the turbines, precautions to be taken before water releases), describe the barriers (booms, fences, etc.) and public information devices (warning signs, leaflets, etc.) and communication, etc. All these aspects are described in detail in



appropriate procedures, along with the maintenance and evaluation of the effectiveness of these barriers based on analysis of incident report.

#### **5.1.4 Maintenance Procedures**

Maintenance work can be described as preventive, corrective or emergency.

Preventive maintenance can be either routine (e.g. time based operations such as operating and lubricating gates, cleaning pressure relief drains) or condition based (e.g. repairing concrete, painting). Routine maintenance should be scheduled in the maintenance procedures and in the owner's maintenance management system if applicable. It should also be properly controlled and recorded in a data book or database.

Condition based maintenance should be identified, scheduled and budgeted for, annually. Where the owner's resources are limited, condition based maintenance may be prioritized according to a risk assessment across the owner's dam portfolio and other assets.

Financial provisions should be made for corrective and emergency maintenance to cover the unforeseeable repair of assets that have suddenly deteriorated or failed (e.g. blockage of a piezometer, flood damage).

#### **5.1.5 Planning and Scheduling**

The onsite activities are easy to plan and schedule, as long as they are described in sufficient detail in the operational procedures. As for all industrial activities, the dam engineer has to plan for all the activities and allocate the staff to undertake them. Annual planning is generally an appropriate time span to consider. As dams are operated according to the water use requirement (hydroelectricity, irrigation, water supply, etc.), and are dependent on natural water input, some of these activities will have to be modified on that basis. Some provision for planning adaptation should be provided, to be able to take into account natural event as flood, drought, the occurrence of which may modify the scheduled activities.

The activities for the specialized teams are planned for a longer span of time, often about several years. This planning has to comply with the regulatory requirements which often set the frequency for the standard report (annually) and for activities such as in-depth inspection and behaviour analysis of the dam (safety review), which may done every five to ten years (or more) depending on the dam category.

#### **5.1.6 Assessment and Tracking of Dam Safety Issues and Deficiencies**

It is of the highest importance to detect and analyze all the deficiencies related to the dam behaviour, along with the sensors, energy supply, etc. which contribute to safe dam surveillance and operation. Each event must be analyzed in order to determine the causes of the deficiencies and measures taken to avoid them in the future. A global analysis of these deficiencies and the effectiveness of the measures taken is a part of the dam annual report.

### **5.1.7 Incident and Accident Reporting**

Incidents and accidents are particular deficiencies where the consequences have been observable impacts on operations, the public or the environment around the dam and river area. For example, an incident or accident could be:

- Bad calibration of a sensors, resulting in wrong data used to analyze dam behaviour
- Undetected failure of a reservoir water level sensor used as a flood warning and for flood operation
- Wrong gate calibration curves (discharge versus opening rate and water level) resulting in an inappropriate discharge
- Unexpected water level
- Unexpected water discharge value
- Public stranded in the downstream river
- Public injured or killed as a result of the dam operation,

As for the dam and equipment deficiencies, these events must be identified, registered in a data base, and analyzed to determine the causes and implement the mitigating measures. The system used can be the same as the one used for dam and equipment deficiencies, where these events can be given a specific code in order to sort them easily. Depending on the regulation in the country, these events have to be reported to the government representatives within a time period that depends on the gravity of consequences. In some data base systems, each event is given attributes according to the gravity of consequences and the category of the event, etc. which makes it easier to sort all these events for global cause analysis, and multi-annual overview giving an excellent indicator of efficiency of the measures taken.

### **5.1.8 Skill Development and Training, Knowledge Retention and Maintenance**

It is important to have competent and trained personnel for all the activities mentioned in the previous sections. Two components must be considered: formal education (academic, professional schools, etc.) and experience. Academic courses relevant to dams can be found widely: civil engineering, mechanic, hydraulic, hydrology, metrology, etc. It is current practice to define in the quality assurance documents, the initial level of education needed for each job.

However, for some activities, the additional knowledge that is needed can only be acquired through experience. This can be done in specialized training schools, but more often is done by learning directly from skilled engineers and workers. In some countries, engineers must be authorized by a governmental agency or a professional association, in order to carry out specific studies. On a dam site, some activities can be performed only by workers with several years of experience in this activity (e.g. gates operation, monitoring reading analysis, etc.)

To maintain a competent and experienced workforce into the future, given departures and retirements, it is the responsibility of the owner or its representative, and this must be indicated in the relevant quality assurance documents.

## **5.2 Dam Safety Operational Activities**

After the first filling and the first years in operation, dam safety is mainly ensured by operational activities, which are dam surveillance and maintenance, flood routing, and maintaining emergency preparedness plans. The aim of dam surveillance is to detect any discrepancies between the actual condition and behaviour of the dam, and the expected condition and behaviour. As a result, corrective actions may need to be conducted. Dam surveillance must also cope with unexpected events such as earthquakes. Operation of the dam and its facilities is mainly done under normal hydrological condition, but a flood period may occur and all the arrangements to safely pass the inflow must be prepared. Finally, the emergency preparedness plans, which will never be applied for the majority of dams, must nevertheless be maintained due to the possibility of an incident or failure.

### **5.2.1 Flood Routing**

Flood risk is one of the major concerns for dams, as it is an important cause of dam failures after the first filling. Parameters controlling this risk are:

- The capacity to pass extreme floods, and thus the choice of a design and safety check flood and the design of a spillway suitable for safe routing of these floods. It should be noted at this point that the discharge capacity is not the only criterion for a good design. It is also important to have hydraulic design of means to allow for passing of debris, power supply, and sensor redundancies. These aspects are addressed in ICOLD bulletins 82, 125 and 131.
- The reliability of flood routing, including the hydrologic forecast network, the flood routing procedures, tests and inspections, maintenance, and operator training. These last aspects are the key ones in the operational phase of the dam and are addressed in ICOLD bulletins 49 and 142. Some considerations are given below.

#### **5.2.1.1 Hydrological Forecast**

Operators will be able to properly manage the dam during flood periods if they have at their disposal appropriate tools for forecasting the inflow into the reservoir. Responsible Entity should make arrangements for this ability, either in their organization or by contracting with hydrological agencies. It should be stressed that inflow forecasts will very often be unavailable during extreme flood periods due to the telecommunications problems. Thus, if the reliability of these forecasts is not sufficient, operators must have access to standalone tools for evaluating the inflow.

#### **5.2.1.2 Operational Flood Routing**

When the spillway is a free overflow weir, the role of operators is limited to the surveillance of the facility during the flood and to taking appropriate action if debris clogging occurs. For gated spillways, their role is essential for equipment operations. Indeed, remote control of spillway facilities cannot be suitable for safe flood routing. The extreme weather conditions resulting in extreme floods will often cause malfunction or failure of remote control systems and thus justify operators' presence at the dam site during these flood periods. To provide the necessary direction when it is needed, the operations to be performed, and particularly manual gates opening, must be defined and written in flood procedures (see Chapter 4).

### **5.2.1.3 Surveillance and Tests**

Spillways and their appurtenant equipment – power supply, sensors, and acting mechanisms - must be surveyed and maintained to ensure good condition. This surveillance is done by periodic visual inspections and equipment tests as described in ICOLD Bulletin 49.

### **5.2.1.4 Operator Training**

Periods of flood, especially major ones, can be very stressful to the operators. As the operator's decisions could have an important effect on the safe routing of the flood, it is useful to organize periodical emergency exercises. Additionally, it could be useful to have a flood routing simulator, typically running on a desktop computer, which can be used to have the operators faced with events they have never experienced - including extreme flood conditions, gate malfunction, etc.

## **5.2.2 Surveillance and Monitoring**

Dam surveillance is based on the experience learned from dam incidents and accidents for more than one hundred years. With the exception of accidents due to floods, most of the other accidents are preceded by visible and/or measurable physical phenomena. The main objective of surveillance is then to detect and analyze these phenomena which are the physical confirmations of the dam behaviour. Timely detection of anomalies is important because it allows operators and specialized engineers to be quickly aware of any changes and to take adequate measures when necessary. Surveillance also provides knowledge about long term trends of the dam behaviour, and may then give indication with regard to long term issues which consequently have to be fixed.

Two complementary activities contribute to this surveillance: visual inspection and monitoring. The main difference between these two activities is:

- Visual inspections can be exhaustive for the visible parts of the dam, but give only qualitative results;
- Monitoring gives quantitative results of phenomena measured at some points of the dam, either on its surface or inside its body.

General considerations about objectives and principles, recommendations and examples of international practices are developed in ICOLD bulletins 60, 68, 87, 118 and 138. For seismic surveillance and instrumentation bulletins 62 and 113 are relevant. The subsequent sections give an overview of these along with some criteria to determine their frequency.

### **5.2.2.1 Visual inspection**

Visual inspection is absolutely mandatory for all dams, as it is often the only means to detect anomalies. A visual inspection activity can be defined as searching for abnormal visible phenomena on the surface and inside of the dam. There are generally several levels of visual inspection: routine inspection, carried on regularly by on site operators, and specialized inspection carried on by experienced civil engineers. All these inspections are defined in procedures and must conclude with a written report, even when nothing of significance was observed. For new dams, the scope of the inspection procedures should be developed by the design engineer. Visual inspection is not a static process. Events occurring at the dam and monitoring results, for example, may lead to modifications of inspection scope and frequency.

### 5.2.2.2 Monitoring

Visual inspections lead to a qualitative knowledge about the visible part of the dam. For many dams, quantitative information about some important physical parameters (displacements, strains, water pressure, and leakage) is equally important in order to detect any deficiencies in the dam behaviour.

**Readings of the sensors:** According to the frequency defined in the surveillance procedures, operators on site carry out the readings of each instrument at the defined frequency. They report the readings in writing or, more usually nowadays, with the help of an electronic portable data collector.

**Remote monitoring:** A remote monitoring system must be seen as a tool which allows automatic readings of sensors. All principles about the monitoring system design and the quality of sensors remain valid. With respect to the sensors, it must be always possible to read sensors locally in case of malfunctions in the automatic system. At times it requires setting of manual sensors beside the automated ones. It must be clear that remote monitoring does not automatically mean less human presence at the dam site. On the contrary, relieving the operators from the sensor reading task gives them opportunity to concentrate on visual inspections.

**Sensors calibration and maintenance:** As all sensors used in industrial processes, monitoring instruments are maintained and regularly controlled.

- Maintenance is scheduled on a regular basis and on demand when a sensor is out of order. This activity is carried out by applying internal procedures or recommendations from the manufacturer.
- Calibration is an activity where the operator verifies that the difference between the “true” physical value and the measured one is smaller than the defined accuracy requested for the sensor. When remote monitoring is installed the entire functional chain is controlled. It should be kept in mind that sometimes calibration may have negative effects; for example, removing a sensor in order to calibrate it in a laboratory setting may negatively impact data series quality. Very often on site checks without removing sensors are then the option even if the calibration is not as perfect as required by the ISO standard.

**Readings and inspection frequency:** Some principles can help to define inspection and readings frequency:

- The first one is the anticipated failure rate: monitoring must detect the measurable effects of a possible appearing failure mode. Therefore, the frequency must be scheduled in such a way that the significant physical occurrence is not missed between two measurements. It is clear that this may lead to different frequency for each physical phenomenon and according to the dam type. It can also lead to varying frequency along the year according to the level of the reservoir.
- The second one is the phase of the dam life cycle. During construction and first impounding, the sensors reading and visual inspections frequencies are higher than during the operational life cycle.
- The third one is the behaviour of the dam. When a dam exhibits particular behaviour readings are usually more frequent, at least for some sensors, and must be defined by the dam specialist on a case by case basis.

The consequence of a dam failure, which is often linked to the size of the dam, is a criterion for the size of monitoring system, more than for readings frequency.

**Specific inspections and monitoring sensors readings:** In case of extreme event as earthquake, flood, unusual behaviour, etc., specific inspections and monitoring should be performed.

- Extreme flood - when the operator anticipates that the reservoir level will reach a level above the maximum water level, he must alert the upper management level, according to the procedures. It can result in the activation of the EPP. After all significant floods specific inspection and monitoring of the dam and gates should be carried out.
- Earthquakes - ICOLD bulletin 62 explains how the operators should be informed (national network or local instrumentation), the surveillance activities to be carried out, and how they should be scheduled according to the intensity of the earthquake.
- Dam performance - from the results of routine surveillance and data analysis it is often not obvious how to formulate the criteria characterizing the importance of an unexpected behaviour. Usually, the different actions to be taken by the order of importance and the degree of urgency are as follows:
  - New readings and inspections by civil engineers;
  - Enhancement of monitoring system;
  - Increase of measurements and inspection frequency, investigations and analysis;
  - Lowering of the reservoir;
  - EPP activation.

**Data storage:** A properly organized and implemented data storage system is not as simple task as it seems to be. Some principles can help to carry out this activity correctly:

- Raw readings from sensors and parameters are the data to be stored in priority. Permanent access to raw data enables re-calculation of physical parameters values at any time, even many years later (for example, if some mistakes have been found in the parameters or for any other reason);
- A reading must never be deleted, even if it seems wrong. The value should be marked as “error” and kept it in the database with an appropriate commentary;
- The best tool to store data is a computer database with reliable mechanism to input data, parameters, etc. Each data is linked to the measurement date, the reservoir level, the set of parameters to be used and commentaries on the sensor condition, observed events during the readings, etc. Database is a far superior tool than spreadsheets for which alteration of data is possible due to involuntary operator mistake.

Visual inspection results must be recorded, but usually, it is more practical to do it in a “classical” report. Annual report by dam engineer must then incorporate the results of these periodic visits made by on site operators.

### **5.2.3 Analysis and Interpretation of Data**

Data analysis should follow immediately (no more than one or two days) after the reading process is completed. The final outcome result of the data analysis process is a safely stored validated data set. The important objective is to get a reliable database because bad data may lead to wrong interpretation and decisions. This analysis is performed on a sensor by sensor basis, and can be based on the analyst judgment.

Data interpretation must be performed periodically (once a year to several years, according to the dam category). This includes a thorough analysis by a dam engineer of all the data collected and visual inspections results, the interpretation and consistent explanation of the dam behaviour.

#### **5.2.4 Maintenance and Testing**

Dams are not the type of structures for which a preventive or systematic maintenance is usually relevant. The size of these structures and their constitutive materials are the main reasons. However, some types of dams do need systematic or preventive maintenance, for example, a very thin concrete arch of a multi arch dam may need periodic paintings or clearing of their structural joints.

On the other hand, quite all appurtenant equipment requires maintenance on a periodic basis. For example, sensors used in the monitoring system or for the flood control operation need periodic systematic maintenance (cleaning, control, calibration).

All equipment related to spillways and bottom outlets and more generally all equipment with a potential impact on the dam safety needs also a careful maintenance. As all industrial heavy mechanics, spillway gates must be maintain by classical means : lubricating moving apparatus, painting surfaces exposed to air and water corrosion effects, etc. Periodical functional testing must be performed on gates and their appurtenant equipment. The power supply and controlling devices must be maintained and tested following the supplier recommendations.

All dams do have conditional maintenance requirements. After several years in operation it can be often observed that some deviations in the behaviour or the condition of the dam are occurring and that may require specific maintenance when certain conditions are present. A classical example is the cleaning of drainage holes which is linked to the measured water pressure and leakage.

Corrective maintenance is the more frequent type of maintenance for dams, and it is designed based on the observed condition and behaviour of the dam or its appurtenant structures, or after a safety review. The maintenance works could be very heavy and costly, and generally need specific investigations and in depth comprehensive studies. The decision-making process is an important part of these maintenance works, and the decisions must be carefully recorded.

It is not the aim of this bulletin to present all possible maintenance works according to the type of dams and their pathologies. Specific questions of ICOLD congress (Q65) have addressed these issues and constitute a sound technical basis for these specific works design and realizations.

#### **5.2.5 Dam Safety Reviews**

A Safety Review is a procedure for assessing the safety of a dam, and comprises, where relevant, a detailed study of structural, hydraulic, hydrological and geotechnical design aspects and of the records and reports from surveillance activities.

A Safety Review should assess the integrity of a dam against known failure modes and mechanisms for the various types of dams in terms of safety acceptance criteria (engineering standards, dam safety guidelines) or risk management criteria.

Background information should first be collected. This includes all relevant historical investigations, design, construction, commissioning, remedial operation and maintenance, monitoring and inspection data. The performance of the dam is then compared with the standards and criteria set by the dam designer and the relevant safety standards and guidelines existing at the time of review. If a design standard is not available or known for the dam, the Review should include a prediction or assessment of the theoretical performance of the dam. Updating of risk assessment studies should also be undertaken as part of the Review.

Periodic Safety Reviews at 10 to 20-years intervals (depending on risk level, hazard category and technological changes) are considered appropriate. An unscheduled Safety Review may be required at short notice if any inspections, monitoring results or unusual events such as flooding, earthquake or landslide indicate that an adverse trend or condition exists.

The personnel engaged in such Reviews should be qualified dams engineers suitably experienced in dam technology. Where necessary, the services of suitably experienced geologists, hydrologists, risk assessment analysts and other specialists should be utilized.

A report is produced to document the Safety Review and to recommend remedial or maintenance work. Responsible Entities may use risk assessment techniques with Safety Reviews to determine the urgency and extent of works and to priorities remedial works within their portfolio of dams.

Conclusions should be drawn, where relevant, regarding the adequacy of the main features of the dam (i.e. foundations, main wall, spillway, outlet works, associated equipment and monitoring system). Comments should also be made regarding the frequency of inspections, surveillance program, and operation and maintenance procedures.

Such comments and conclusions should take into account modern developments in hydrology, hydraulics, geotechnical engineering, engineering geology, and structural analysis and design criteria relating to dams. Details of the Review should be outlined in a report. The report should include a summarized statement on the safety of the dam indicating whether or not the dam is in a satisfactory condition, its risk status, and what remedial or emergency action should be carried out and when to rectify any deficiencies in the dam.

## **5.2.6 Emergency Planning Preparedness and Response**

### **5.2.6.1 Preventive and Precautionary Measures**

Two types of emergency plans are usually required:

A Dam Safety Emergency Plan developed by Responsible Entity; and a separate Disaster Plan developed by appropriate state or local emergency management agencies to provide protection for downstream communities in the event of a dam safety emergency.

It is important that these two plans be linked in a compatible way. In the following, when the word “plan” is used, it refers to one of these plans, as it could be differently arranged according to each country’s regulations.



The emergency action plan should be established for each dam within the drainage area or the operating system (operating company, power system, etc.), as well as for the system as a whole. If there is more than one system operating within the same drainage area, the emergency plans should be coordinated by a joint committee on emergency operation composed of representatives of all operating organizations. The plan should take into account the possible effects of the failure of upstream dams.

Although some jurisdictions require that all emergency action plans should be approved by the government agency the specific arrangements may differ from country to country.

Risks and hardships that may be caused by possible dam accident increase with the development of the river valley. Emergency action plans should, therefore, be reviewed at regular intervals for the need of updating and for adaptation to alterations of the physical and social environment, if necessary. Appropriate intervals for the review may be periods of not more than five years in fast developing regions, and about 10 years in all other cases.

Consideration should be given to the extent of inundation, the development and occupation of the land that would be flooded, and the time available for emergency action. Information regarding risks from failure of the dam should be developed and released to disaster relief organizations if so required by circumstances. Organizations and agencies in charge of public planning in the river valley should have access to the results of flooding risk analyzes.

Emergency operation in river basins crossing boundaries should be established and maintained under the joint co-ordination of the government agencies of the riparian entities. The compatibility of the emergency requirements and precautions of each of the riparian entities should be checked periodically. Emergency operation should not be hindered by entity boundaries.

Emergency action plans should deal with, but not be limited to, the following activities, conducted either Responsible Entity or the emergency governmental agencies.

***Activities to be conducted by Responsible Entity:***

- Hydrographical observation and flood warning schemes;
- Drawdown and flood control operation of reservoir or reservoirs;
- Emergency communication inside the organization and with external emergency agencies;
- Regular reviews and exercising of emergency plans through table-top exercises and functional drills;
- For each failure scenarios, identification of warning phenomenon and several warning threshold values;
- Emergency drawdown of the reservoir or reservoirs;
- Inundation maps for flows up to the design flood, and for the catastrophic conditions caused by dam failure, inclusive of the corresponding risk analyzes;
- Environmental accidents (for instance : oil spills, contamination by hazardous substances);
- Equipment, material and support available for emergency relief;
- Emergency operation of power plant, water supply or irrigation scheme, locks, etc., associated with the dam or dams;
- Emergency warning

***Activities under responsibility of emergency agencies:***

- Emergency communication toward public;
- Co-ordination of emergency relief actions with third parties (for instance: civil defense, police, hospitals, etc.);
- Regular reviews and exercising of emergency plans through table-top exercises and functional drills that include all stakeholders and involved parties.
- Emergency standby of public utilities;
- Evacuation of flood-threatened areas;
- Rescue operations and other emergency provisions, as well as definition of responsibility for such operations and provisions;
- Emergency transportation;
- Emergency access to remote sites;
- Emergency decision-making process and procedures

Planning of emergency actions may be done for several types and modes of emergency but should include the analysis of the most severe possibility; that is, the instantaneous (concrete or masonry structures) or almost instantaneous (embankment) failure of the dam (war, sabotage).

The plan should cope with emergency precautions and possible emergency repair measures at the dam site and with warning and emergency relief action downstream of the dam. Where there are several dams on the same river, the hazard analysis should consider the possibility of progressive failure in series of the dams.

Flood warning and emergency warning schemes should be checked for reliability and efficiency periodically or before the beginning of every flood season.

Preventive measures and safety precautions should be prepared for possible emergency situations caused by riots, terrorism, sabotage or war.

The emergency plan should include instructions to be followed by the local operating staff in the event of loss of communications with the central control unit.

**5.2.6.2 Emergency Operations Requirements**

In case of an imminent danger or of a major accident corrective action must be taken immediately and independently of normal administrative procedures. Enough authority should be vested in the operator's top level technical personnel to order emergency preventive or repair measures without asking for special authorization from management.

Clear and easily understandable emergency instructions should be issued to all operating units and stations. These emergency instructions, which must include a definition of the supervising units authorized or obliged to issue orders under emergency conditions, should be easily accessible. The need for updating should be checked periodically and always after institutional, operational and administrative changes. Copies of emergency instructions should be available in the office and home of each person involved in an emergency operation assignment.

Operating staff should be trained and periodically retrained in emergency operations. Training programs and procedures should be updated in accordance with advancing technology and alterations introduced in the emergency plan.

## **5.3 Dam Safety Improvement Activities**

### **5.3.1 Introduction**

Dam safety improvements (i.e. risk reduction) are required at a dam when it no longer meets an acceptable level of safety. The remedial actions evaluation process should select a timely and cost effective course of action, which could include interim or long-term remedial works, maintenance, changes to operating procedures, or decommissioning.

Dam remedial actions are initiated by the recognition of the existence of a dam safety problem. These problems are usually discovered during surveillance programs, evaluations, or safety reviews.

Deficiencies can result from a variety of causes such as:

- Inappropriate or deficient design or construction;
- Changes to safety criteria (e.g. design, regulation);
- Changes to Hazard Potential Category;
- Ageing or breakdown of materials;

Maintenance related problems:

- Inappropriate operating techniques;
- Interpretation of updated knowledge (e.g. analytical techniques, material properties) and data;
- Inadequate surveillance procedures ; or
- Damage from natural incidents (e.g. earthquakes, landslides, debris).
- Damage due to human agency

Deficiencies can vary in severity from mild uncertainty about documentation to those with imminent potential for dam failure. The type of remedial action required, and its urgency, is determined by the nature of the deficiency, the associated risks to the dam and the dam's Hazard Potential Category.

### **5.3.2 Deficiency Assessment Process**

On detection of a dam safety deficiency it should be promptly investigated and information gathered for analysis. This may involve geotechnical investigations, site monitoring and document reviews relevant to the particular deficiency. An assessment should be made of the consequences of a worsening situation and its likelihood. The outcomes of the investigations could be a resolution that there is indeed no deficiency or that further investigations are required. In acute cases where time is critical, and the risks are high, or where high hazard situations are associated with considerable uncertainty, Dam Safety Emergency Plans should be activated and immediate risk reduction measures expedited (e.g. lower the reservoir). This assessment process is represented in the figure 3.4 by the diamond on the left hand side.

In most cases it is usual to undertake a safety assessment (i.e. evaluation against prescriptive and/or risk based criteria) to determine the severity of the deficiency and whether maintenance, or a more appropriate solution, is required. An extensive decision analysis and Safety Review may not be necessary in all dam deficiency studies and a degree of judgment is required.

For remedial action to be considered in response to a dam deficiency a determination must be made based on technically sound engineering principles. Decision analysis techniques should be used in the process of studying dam deficiency problems to enhance the quality, consistency and equity of solutions or remedial actions. These techniques may involve both quantitative and qualitative methods to provide structured and systematic ways to make decisions.

The following matters need to be undertaken in the deficiency review process:

#### **Determination of Likelihood of Dam Failure**

Dam safety deficiencies are situations, or conditions, which suggest that dam failure scenarios are possible under certain conditions. The likelihood of each scenario should be determined in the review and compared with acceptance criteria or case histories.

#### **Hazard Potential (Consequence) Assessment**

Justifying remedial actions require examining the consequences due to a dam failure. If it has not previously been undertaken, the review should include a hazard potential assessment to demonstrate whether dam failure substantially increases the loss of life and damage to property, and the environment, beyond that caused by the failure-initiating event (i.e. flooding or earthquake) if failure did not occur.

#### **Risk Evaluation**

The review may include a risk evaluation to compare the estimated risks with tolerable risk criteria in determining whether the existing risks are tolerable. While the risk to life should be the predominant consideration, the risk assessment should include other aspects of quantitative risk assessment (e.g. an Economic Risk Assessment). This is accomplished using reasonable estimates of loading frequencies, failure response probabilities and damage values. Responsible Entities should also consider other relevant matters such as the ALARP principle, regulatory requirements and business interests in their assessment.

#### **Reporting**

A summary of the deficiency review should be documented in a report to management or the Responsible Entity. The report should:

- Indicate the dam deficiencies causing the problems and their severity against acceptable criteria (risk or standards based);
- Clearly demonstrate whether there is an unacceptable risk of dam failure;
- Recommend remedial actions. These should primarily be the reduction of risk to human life from a dam failure to tolerable levels; or otherwise demonstrate, on the basis of an economic risk assessment that the economic benefits exceed the cost of the remedial works;
- Indicate the degree of urgency or priority for remedial action. For dam portfolios, or dams with multiple identified deficiencies, those posing the greatest public hazard together with those having the

highest risk of failure, or greatest deviation from acceptable risk criteria, are usually given priority for further study or remedial action.

### **5.3.3 Dam Safety Improvement Actions Study**

A remedial action study may be required to develop alternative risk reduction options for a dam deficiency (structural, non-structural or combinations of both). These options may also include traditional standards based engineering options. It is also required to evaluate the effectiveness (i.e. level of risk reduction) and costs of these alternatives and to present information on them to the Responsible Entity in a manner such that a preferred option may be identified and implemented.

The study should be undertaken by a dam engineer, and other appropriate specialists, with all available information reviewed. Where information deficiencies are determined, action should be instigated at an early stage to obtain the additional information required.

Both interim and long-term remedial measures should be postulated and examined. Interim measures can be modified as the understanding of the deficiency and its implications becomes clearer. Staged and prioritized implementation of remedial measures may be necessary for practical reasons.

The alternatives should be compared primarily on the basis of reduction in risk to life, followed by other damage costs and risk costs. All impacts should be identified and described including those which are difficult to give a monetary value to (i.e. social, environmental, legal). Costs should also include future expenditure to make the measures effective. Indirect costs may also be involved.

An optimum remedial option should be recommended and suitable detailed investigations should have been undertaken to determine that the solution proposed is practical and will not create other problems. It may not necessarily be the least cost solution.

Any report on proposed remedial action should demonstrate that the proposed action is aimed at reducing risks to the public, from dam failure, to tolerable levels. Ideally, it should also demonstrate that any proposed risk reduction action is cost effective and consistent with technical, environmental and publicly accepted standards.

#### **5.3.3.1 Interim remedial Actions**

Interim remedial actions are those required when a deficiency has been identified at a dam, to provide an early reduction in the risk or consequence of a dam failure. These actions may include but are not limited to implementation of:

- Dam Safety Emergency Plans, and Disaster Plans, which could involve evacuation of persons at risk in the event of a dam emergency;
- Warning Systems based on actual dam failure or, preferably, on conditions which could result in a dam failure;
- Modifications to the dam operation including controlled release of the storage to lower storage levels;
- Increased surveillance.

Interim remedial actions are undertaken as temporary measures prior to the determination of the final long-term solution to the problem. In some cases the interim remedial action may be adopted as the long-term solution, or as an adjunct to it.

#### **5.3.3.2 Long Term Remedial Works**

Long-term remedial works are those works required at a dam to reduce the risk of a dam failure to an acceptable level for the continuing life of the dam. They may also be included in overall augmentation of the dam undertaken for other reasons such as increased storage.

Dam remedial works vary considerably and no listing of possible remedial works could be exhaustive. It is not the aim of this bulletin to present all the possible maintenance works according to the type of dams and their pathologies. Specific questions of ICOLD congress have addressed these issues and constitute a sound technical basis for these specific works design and realizations. Moreover, many ICOLD technical bulletins address the topics of dam design, performance assessment, pathologies and rehabilitation. Other bulletins give recommendation for design criteria, either for flood design, seismic design, calculation methods, etc.

# **Appendix A: Review of ICOLD Bulletins**

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It is not the objective of this bulletin to describe the operational activities or to characterize how they should be carried out, as it is the subject of quite large number of existing ICOLD Technical Bulletins. Nevertheless, it was judged as useful to provide a link between these ICOLD Technical Bulletins and the safety management concepts developed in this bulletin. In this respect, a review of all relevant ICOLD bulletins was performed, starting from 1985 (all bulletins issued prior to 1985 are either obsolete or have already been replaced/updated).

The review addressed the following (see the Box 1 below for explanation of terms):

- Which **general areas of dam safety activities** and **specific types of activities** are covered in the bulletin to a degree that makes it useful for planning, developing and implementing the dam safety management system/program?
- Which **hazards** to dam safety are related to these activities? Some activities are of a general nature and are not related to any specific hazards (see Box 2 which illustrates the conceptual framework for the review and has a separate designation **General** for such cases).

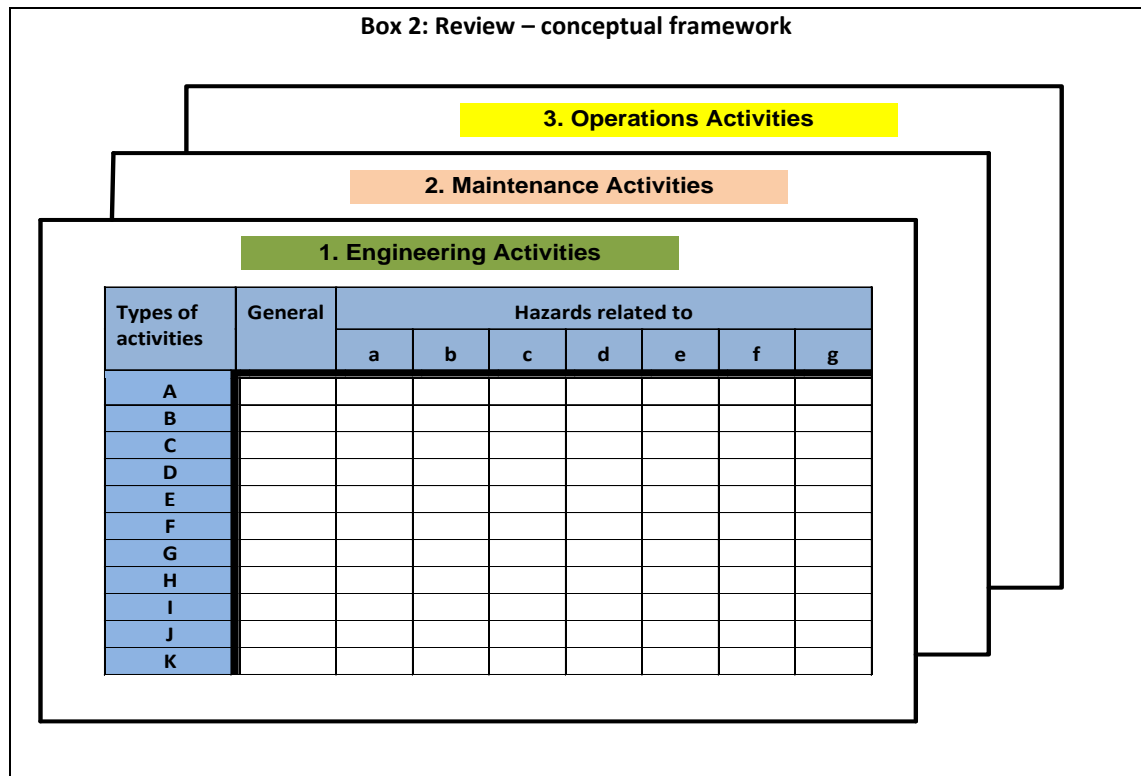
It was not the purpose of the review to provide detailed information on the activities but rather to have a screening-type review formalized by a short description of the bulletin content and the main safety issues addressed by the bulletins. The bulletins were also classified according to the activities and the hazards (see Box 1 below) in order to obtain a synthesis of all the reviewed bulletins.

**Box 1: Explanation of terms – activities and hazards**

**General areas of dam safety activities:**

1. Engineering
2. Maintenance
3. Operation

<p><b><u>Types of activities:</u></b></p> <ol style="list-style-type: none"> <li>A. Prioritization and planning</li> <li>B. Operation</li> <li>C. Maintenance</li> <li>D. Testing</li> <li>E. Inspection, monitoring and surveillance</li> <li>F. Dam safety reviews</li> <li>G. Investigation and rectification of deficiencies</li> <li>H. Emergency planning and response</li> <li>I. External Advice and management reviews</li> <li>J. Communication and records</li> <li>K. Continuous improvement</li> </ol>	<p><b><u>Consideration of hazards related to:</u></b></p> <ol style="list-style-type: none"> <li>a. Weather</li> <li>b. Seismic events</li> <li>c. Reservoir environment</li> <li>d. Water barriers</li> <li>e. Hydraulic structures</li> <li>f. Electrical/mechanical</li> <li>g. Infrastructure and plans</li> <li>h. other</li> </ol>
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The main findings are reported in three tables, respectively for engineering, maintenance and operational activities. The numbers in each cell correspond to the number of occurrences of the hazard and the activity encountered in the ICOLD technical bulletins. The analysis of these tables may lead to the following observations:

1. There are clearly significant differences between the number of occurrences attributed to activities and hazards, which would show that ICOLD bulletins do not address different fields of dam safety in a balanced way. On the other hand it is not clear that every aspect of safety (activities and hazard) must be addressed by a strictly identical number of bulletins. Therefore the question is: is it possible to define, and what could be an objective target bulletin repartition for different activities and hazards? For example, it is obvious that each category of dam needs to be addressed by a different bulletin, when some generic issue (flood, EPP, etc.) are treated in few bulletins
2. The engineering activities are by far the most comprehensively addressed in ICOLD bulletins. The number of their occurrences is superior to those of maintenance and operational activities together. Proportionally, the maintenance and operational activities are given an importance respectively of 40% and 55% of the importance devoted to engineering activities. It indicates clearly that ICOLD community is mostly focused on new dam design, as all these bulletins deal with different aspects of dam type design, technology, etc.
3. For engineering activities, not surprisingly, water barriers hazard gather most of attention. With respect to activities, the three main activities addressed are, in quite equal proportions, inspection monitoring and surveillance, dam safety reviews, and investigation and rectification of deficiencies.

4. For maintenance activities, water barrier is the most important hazard addressed. With respect to activities, surprisingly, dam safety reviews receive less attention than inspection monitoring and surveillance, and investigation and rectification of deficiencies.
5. For operation activities, water barriers, seismic events and environment are the most often addressed hazards. It is not surprising to find that inspection monitoring and surveillance is the activity which is by far the most often addressed in ICOLD Bulletins.

Table A.1 - Number of ICOLD Bulletins Addressing Engineering Activities

Types of Activities	General	Hazards related to							
		a. Weather	b. Seismic events	c. Reservoir environment	d. Water barriers	e. Hydraulic structures	f. Electrical/ mechanical	g. Infrastructure and plans	h. other
A. Prioritization and planning	3	4	5	6	11	6	2	5	2
B. Operation		3	4	6	6	6	3	2	2
C. Maintenance		2	3	6	11	10	3	1	1
D. Testing		1	5	6	16	7	2	1	1
E. Inspection, monitoring and surveillance		5	13	11	35	14	5	1	1
F. Dam safety reviews		6	16	10	36	14	3	2	1
G. Investigation and rectification of deficiencies	2	7	16	12	39	18	6	3	1
H. Emergency planning and response		3	3	4	4	2	1	2	1
I. External Advice and management reviews		2	5	4	4	1	1	1	1
J. Communication and records		1	5	3	3	1	1	2	1
K. Continuous improvement		1	7	2	5	1	1		



Table A.2 - Number of ICOLD Bulletins Addressing Maintenance Activities

Types of Activities	General	Hazards related to							
		a. Weather	b. Seismic events	c. Reservoir environment	d. Water barriers	e. Hydraulic structures	f. Electrical/ mechanical	g. Infrastructure and plans	h. other
A. Prioritization and planning		1	2	2	1	1	1	1	1
B. Operation			1	1					
C. Maintenance		3	4	9	20	12	4	2	
D. Testing			2	4	5	3			
E. Inspection, monitoring and surveillance		4	6	7	12	5	2	1	1
F. Dam safety reviews			2	3	4	2			
G. Investigation and rectification of deficiencies			2	3	10	8	1		
H. Emergency planning and response		1	1	2	1				
I. External Advice and management reviews		1	2	2	1	1	1	1	1
J. Communication and records		1	2	2	1	1	1	1	1
K. Continuous improvement		1	2	2	1	1	1	1	1

Table A.3 - Number of ICOLD Bulletins Addressing Operation Activities

Types of Activities	General	Hazards related to							
		a. Weather	b. Seismic events	c. Reservoir environment	d. Water barriers	e. Hydraulic structures	f. Electrical/ mechanical	g. Infrastructure and plans	h. other
A. Prioritization and planning	1	2	3	4	3	2	1	2	1
B. Operation	1	7	8	8	10	13	4	2	1
C. Maintenance		2	4	5	4	3	2	1	1
D. Testing		1	2	4	4	4	3		
E. Inspection, monitoring and surveillance		2	14	5	23	7	2	3	1
F. Dam safety reviews		2	3	4	5	1	1	1	1
G. Investigation and rectification of deficiencies			2	3	4	2			
H. Emergency planning and response		2	3	4	4	1	1	1	1
I. External Advice and management reviews		1	2	2	1	1	1	1	1
J. Communication and records		2	11	4	8	1	2	1	1
K. Continuous improvement		1	3	3	2	1	1	1	1

## REVIEWED BULLETINS

### 1. Bulletin 49a: Operation of Hydraulic Structures of Dams (1986)

The bulletin gives consideration to design, operation, inspection and testing of hydraulic structures in dams. Based on a survey, information from 128 dams is summarised and discussed. Recommendations are added and some case examples are described. Much emphasis is put on a reliable and timely response when action is needed (floods, monitoring results, etc.). The focus however is on the protection of the dam and the unnecessary spillage of water and less on risk reduction for people and property.

Several staffing models are described: from full attendance to partial attendance and centralized monitoring with warning and alert functions.

The important role of inspection and testing is stressed. Inspection of underwater parts and inspection and testing for discharge structures (spillways, bottom outlets) is treated.

Current practice and recommendations for operational rules during the flood season, including the driving parameters for decisions, are given. Special attention is given to the role of automation in monitoring and operation of hydraulic structures in dams. More automation requires adequate monitoring of the control system, adequate monitoring and testing of the hydraulic structures and more redundancy.

### 2. Bulletin 51: Filling Materials for Watertight Cut-off Walls (1985)

The bulletin sets out the general requirements for thick diaphragm walls made from rigid concrete, plastic concrete and bentonite grout. It does not describe all known techniques and materials for thick diaphragm walls, but sets out to provide an improved general understanding of the nature of and requirements for design and construction of the walls. In this regard the bulletin is not a “do-it-yourself” guide.

Guidance is given of the general design requirements that each type of wall should meet, the materials used and construction and quality control techniques, including instrumentation.

### 3. Bulletin 53: Static Analysis of Embankment Dams (1986)

The bulletin outlines the analytical techniques available for embankment dams both for the purposes of design and for subsequent monitoring of dam performance. Both finite element and limit equilibrium methods are described, but with greater attention to finite element, because it provides an understanding of stresses and movement of dams under working conditions.

The bulletin provides details of how to set up finite element modelling for the construction conditions, reservoir filling, steady seepage, rapid drawdown and consolidation. Case studies are also provided.

#### **4. Bulletin 54: Soil Cement for Embankment Dams (1986)**

This short bulletin (41 pages plus references, appendices and figures) gives general information and orientation on the use of compacted soil cement in dams and embankments.

The document refers to data related to 136 dams constructed between 1962 and 1986. Nearly all cases correspond to USA dams and institutional experiences (Bureau of Reclamation, Corps of Engineers, Portland Cement Association, AASHTO, ASTM) for slope protection applications. Material properties, design concepts, construction performance and control procedures, research and development, are aspects considered in the bulletin. For testing the document refers to ASTM procedures.

New experience and information is now available since this bulletin has been published.

#### **5. Bulletin 55: Geotextiles as Filters and Transitions in Fill Dams (1986)**

The bulletin is a state-of-the-art review of the use of geotextiles as filters in fill dams.

The potential applications of geotextiles are discussed and performance requirements for use of geotextiles as filters are set out within a framework of "principles of filtration". Differences between geotextiles and granular filters are described and filter design criteria for geotextiles are provided.

The conclusions are that early uses were in non-critical locations where general principles were established for design, but that considerable caution is required in using geotextiles to prevent erosion at interfaces which are subject to seepage from the reservoir as it had not been proven that they can provide an equivalent function to a properly designed granular filter.

#### **6. Bulletin 56: Quality Control for Fill Dams (1986)**

The bulletin contains guidelines on how the quality control of earth and rockfill materials is to be carried out in order to achieve intended performance in the construction of fill dams. The scope of the Bulletin is restricted to applications of quality control programs during construction and at the construction site. Three major parts of the Bulletin are:

- Considerations of quality control aspects during investigation and design phase.
- Principles of quality control and quality control plan at the construction site.
- Quality control process organization and responsibilities.

The Bulletin briefly discusses reporting and recording requirements for all fill construction operations and characterizes required frequency and extent of reporting. This aspect of quality control during construction is of the utmost importance for dam safety reviews during operating phase.



## **7. Bulletin 57: Materials for Joints (1986)**

This bulletin provides a reference to the properties, treatment and installation of the various materials that may be used for joint sealing (waterstops) in concrete dams.

The types of joints in concrete dams, or the concrete elements of any dam are explained. The necessary properties of seals for joints are described and the properties of the various alternative materials given along with technical specifications for each.

Finally, information for the correct preparation and installation of the materials is provided and test methods are described.

## **8. Bulletin 58: Spillways for Dams (1987)**

The Bulletin provides a review of experience with design and construction of outlet works for large dams prepared on the basis of a questionnaire sent to ICOLD members. It contains a summary of major considerations for spillway design and construction arising from the recent (prior to 1987) dam projects.

The content of the bulletin can be summarized as follows:

1. Brief characterization of spillway types and guidance on selection of a particular type;
2. Energy dissipation and physical modeling;
3. Surface and submerged spillways – specific problems and critical features;
4. Characterization of potential problems due to damage, abrasion, cavitation and nitrogen release;
5. Maintenance and repair.

Issues presented and discussed in items 4 and 5 can provide relevant information for the operation and maintenance of existing dams

## **9. Bulletin 59: Dam Safety – Guidelines (1987)**

The Bulletin provides a comprehensive general account of activities involved in assuring the safety of dams as it was understood in terms of practices in the mid 1980's. Much of the content remains valid to-day, although certain aspects that were less developed at that time have subsequently been resolved and are dealt with in other Bulletins (e.g. the role of Risk was addressed in Bulletin 130).

The Bulletin comprises: A Philosophy for the Safety of Dams and five principal parts; General Aspects, Design, Construction, Operation, and Abandonment which together provide a complete life-cycle perspective on dam safety assurance.

The Bulletin was "prepared with the intent to compile the basic principles and requirements which govern the philosophy, methods and procedures of the management, surveillance and evaluation of the safety of dams and reservoirs." The guidelines are presented in the form of recommendations rather than binding requirements, and the details are purposely developed only to the extent necessary to make the principles

understandable. The guidelines were mainly intended to stimulate and facilitate the development of national dam safety regulations.

The Bulletin recognizes that probability, risk and uncertainty have a role in dam safety assurance and also recognizes the limitations due to the level of understanding of these matters as they applied to dams at that time.

The Bulletin makes the following statement about dam safety assurance: *“we have only a few uncertainties about the way to achieve maximum dam safety; namely, by having all levels of personnel assigned to a dam project apply the utmost care and competence to every aspect and phase of its design, construction, operation and maintenance.”* While such a goal remains admirable in the modern context, its achievement and sustainment of the resources to maintain such a high state of expertise is challenging.

- 10. Bulletin 60: Dam Monitoring - General Considerations (1988)**
- 11. Bulletin 68: Monitoring of Dams and their Foundations – State of the Art (1989)**
- 12. Bulletin 87: Improvement of Existing Dams Monitoring – Review and Recommendations (1992)**
- 13. Bulletin 118: Automated Dam Monitoring System – Guidelines and Case Histories (2000)**
- 14. Bulletin 138: General Approach to Dam Surveillance (2009)**

All five bulletins address the topic of dam monitoring, with the primary focus on existing dams monitoring systems rehabilitation (Bulletin 87) and remote monitoring (Bulletin 118). Similar topics are found in each of the Bulletins, with more or less details depending on a bulletin. No specific rules are given and the Bulletins usually refer to existing practices in different countries. These practices could be quite different and the Bulletins simply indicate that selection of specific design should be guided by experienced engineers; no evaluation with regard to presented solutions is provided and the evaluation is left to the readers.

The more general view on dam surveillance objectives and tools are addressed in Bulletin 138, where monitoring, visual inspections and equipment tests are described. Monitoring objectives are defined in all five Bulletins, always in a qualitative way as it seems to be difficult to give exact rules to design of monitoring systems. Bulletins 87 and 118 indicate that these systems should encompass short term objectives (quick detection of anomalies) and long term objectives (understanding of dam behaviour and evolution trends). These two objectives may result in different sensors, readings frequency, etc.

Bulletins 60 and 87 present the general design principles for a monitoring system and for the choice of sensors according to the type of the physical phenomenon that need to be measured. Some guidance on the number of sensors and their quality is also provided.

Few indications are given on the operation of this system, except in the Bulletin 118. General indications of frequency for sensors readings are proposed in Bulletin 60. Maintenance of monitoring system is addressed in Bulletins 87 and 118.

The basic data analysis principle requires comparison of measured data with a model, which could be statistical (classically based on multiple regression) or deterministic (numerical models). The discrepancies between the measured values and the values given by these models are the indicators of a non-standard

behaviour and should be analyzed by experienced engineers in order to decide what are the correct decisions and actions to be taken to ensure dam safety.

In Bulletin 87 general principles of dam behaviour analysis are given based on the surveillance (including monitoring). No criteria or guidance for this analysis are given with engineering judgment being the right way to assess the dam safety conditions.

## 15. Bulletin 61: Dam Design Criteria – Philosophy of Choice (1988)

This bulletin includes seven principal parts as follows:

1. Preliminaries and Philosophy;
2. Scenarios (Normal and extreme conditions);
3. Special recommendations;
4. Analysis in the context of acceptance criteria;
5. Non-structural criteria;
6. Instrumentation and Monitoring considerations;
7. Other considerations.

The philosophy of design criteria, stated in terms of two basic criteria is that the objective is to create a “structural form [that] together with the foundation and environment will, most economically:

- a) *perform satisfactorily its function without appreciable deterioration during the conditions **expected normally** to occur in the life of the structure and,*
- b) *will not fail catastrophically during the **most unlikely but possible** conditions which may be imposed.”*

The Bulletin stops short of specifying criteria for two following two reasons:

- *More study and discussion is needed to establish generally applicable values even for well-established parameters,*
- *Large number of parameters (such as those describing the constitutive properties of materials for instance).”*

In the remainder of the Bulletin the reader can find comprehensive consideration of many relevant factors, including human factors and operational aspects that should be considered in dam design as generally understood in the mid to late 1980's. It recognizes numerous challenges that need to be addressed by the designer and the role of uncertainty in the design process.

## 16. Bulletin 62 A: Inspections of Dams Following Earthquake – Guidelines (1988)

This bulletin comprises of three parts:

- Recommendations for the **earthquake detection and warning**. The detection could be made either by a specific network or by networks operated by national agencies. A simple rule for the necessity of

inspections is given - according to the magnitude of the earthquake and the distance of the epicentre to the dam. Three examples (USA, Australia and Japan) of networks and inspections procedures are given.

- **Specific EAP procedures** should be prepared, providing dam operators with the guidance on actions to be undertaken - criteria and delays to launch post seismic inspections and scope of these inspections. The procedures should also define: how the required qualified personal is informed and made available, and the means to be used for transmission and power supply as the likelihood of potential failure of standard transmission links and power supply is high in the case of an extreme event.
- The scope of **post-earthquake inspections** depends of each specific dam and should be based on a failure mode analysis. A detailed list of possible damages is given along with some generic advice based on the type of dams and the appurtenant works.

### 17. Bulletin 66: Dams and Environment – The Zuiderzee Damming (1988)

The Bulletin describes the history of the closure and land reclamation project in the Zuiderzee (the Netherlands). It concentrates on characterization of broad environmental impacts of the project. It does not consider any aspects of dam safety in relation to the project.

### 18. Bulletin 67: Sedimentation Control of Reservoirs (1988)

This Bulletin is a guideline for sedimentation control related to design of new dams or reservoirs and operation, maintenance for existing ones. Four topics are considered: sediment yield, sediment deposits, sediment control and secondary effects. Many empirical relationships are discussed.

*Sediment yield:* factors relevant for the sediment load coming to the reservoir are described and practical methods to determine the load in the design period are given, varying from surveys to empirical relationships and modelling.

*Sediment deposits:* based on surveys and data on sediment deposits empirical relationships for reservoir sediment trap efficiencies, density of sediment deposits, sediment distribution patterns and depth of sediments at the dam are provided for the design of dams.

*Sedimentation control:* various measures intended to control reservoir sedimentation are described (trapping upstream, bypassing, passing through and, flushing and mechanical removal).

*Secondary effects:* this refers to deformation of river channels (aggradation) due to the backwater effect on sediment transport capability, the changes in water quality upstream and downstream of the reservoir, ecological effects, downstream channel changes and sediment disposal.

### 19. Bulletin 69: Moraine as Embankment and Foundation Material - State of the Art (1988)

The Bulletin provides a comprehensive review of the (then) current knowledge and experience of moraine as a dam foundation and fill material.

The general physical properties of moraine material are given and details for design and specification requirements for the embankment and foundation detailed. Previous construction practices are described including methods to deal with wet material and winter construction. General performance characteristics of moraine embankments and foundations are also given.

The bulletin includes detailed case histories for each aspect of placement, seepage, sinkholes, deformations and foundation treatment.

The Bulletin concludes with closing remarks supporting the use of moraine as a good construction material, but pointing out that great care is required with site investigations due to the lack of homogeneity and isotropy in the material. This also requires care in selection and placement of the core and appropriate filter design is critical to prevent piping. Differences in placing techniques between countries are described without comment on their effectiveness.

## **20. Bulletin 70: Rockfill Dams with Concrete Facing (1989)**

The Bulletin is presented as “state-of-the-art”. It was prepared by the Colombian National Committee to share Colombia’s experience at that time.

The Bulletin is very detailed, providing much information regarding developments in the design and construction of CFR dams over time and presenting the current practice.

Most information relates to the design detailing, material selection and construction practices appropriate for each element of: the embankment, the concrete face and the foundation. A discussion on the seismic performance of CFR dams is included.

Some information is provided regarding instrumentation.

## **21. Bulletin 71: Exposure of Dam Concrete to Special Aggressive Waters (1989)**

This is a very comprehensive guideline describing what chemicals can affect concrete, means of investigation, testing for chemicals, likely impacts and preventative measures.

Types of attacks are categorised according to chemical type and factors contributing to high risk identified through geographic locations as a source of chemical and also particularly vulnerable structural locations. Requirements for water analyses are detailed.

Methods for investigations are given along with potential preventive measures and remedial works. An extensive collection of case studies is provided.

## 22. Bulletin 72: Selecting Seismic Parameters for Large Dams (1989)

The Bulletin gives guidance and criteria for the choice of the seismic input, analysis method and relevant parameters for seismic design or evaluation of dams. Three earthquakes are then defined:

- SEE (safety evaluation earthquake) for which major damage to the dam is possible but without any significant uncontrolled water release;
- OBE (operating basis earthquake) for which some minor damages could be accepted but the dam and the safety equipments being fully operational;
- RTE (reservoir triggered earthquake) the likelihood of which should be assessed before dam building and reservoir impounding.

Two approaches, namely deterministic and probabilistic, are briefly described. In deterministic approach the MCE (Maximum Credible Earthquake) is evaluated from seismological, geological and historical analysis. In probabilistic approach all known earthquakes are used to evaluate the probability of an earthquake greater than a given intensity at the dam site. It is recommended to use both approaches and to rely on engineering judgment to make the assessment for SEE and OBE. Based on the potential dam failure consequences some indications are given how to select the return period (for the probabilistic approach).

With regard to the choice of analysis methods (pseudo static, response spectra, and acceleration time histories) the Bulletin proposes three levels ranking based on:

- Hazard class (four classes from low to extreme depending on PGA);
- Risk factor based on dam height, reservoir volume and socio-economic consequences (with weighting parameters);
- Type of dam (concrete and earthfill dams are considered).

## 23. Bulletin 77: Dispersive Soils in Embankment Dams (1990)

The Bulletin sets out background information relating to dispersive soils and explaining the differences between dispersive clays and ordinary erosion resistant clays.

Piping failure mechanisms and erosion by rainfall are described and experience with dams constructed from dispersive soils is discussed. It is concluded from this experience that for small dams the dispersive soils can be used with the usual good practice of careful construction control and well designed filters. However, for higher hazard dams, caution is advised based on in-depth specific studies on filter effectiveness and for thin cores extreme caution is advised in the use of such soils in the core.

Methods for field and laboratory identification of dispersive soils are described.

Engineering considerations for use of dispersive soils are described, including careful initial testing for dispersion, potential hazard, placement (fill, contact, structures, and low stress zones), chemical treatment and the importance of high quality filter design.

## **24. Bulletin 78: Watertight Geomembranes for Dams**

The bulletin gives the state-of-the-art (1991) of the use of geomembranes in dam construction. Different material properties for geomembranes are discussed together with testing procedures and ageing of the material. Design aspects for the use of geomembranes as a watertight facing for different dam types are described. Special attention is given to the possibility of leakage caused by ruptures in the membrane. Appropriate design measures are described to reduce the risk (filter layers and drainage). Practical construction recommendations are given. Rehabilitation and repair with geomembranes of concrete faced dams is treated with practical construction recommendations.

## **25. Bulletin 79: Alkali Aggregate Reaction in Concrete Dams (1991)**

The Bulletin provides a very detailed explanation of the causes, effects and treatment of alkali aggregate reaction.

The types of chemical reaction are described, along with the reaction mechanisms and damage caused. Prevention of AAR is presented in detail, with emphasis on selection of concrete materials, mixtures and construction practices. Where aggregate containing reactive constituents cannot be avoided, the types of cement and pozzolanic materials that can be used to limit AAR are described.

Where AAR is suspected to have occurred, techniques for site inspections, sampling and testing are provided. Importantly, it is stated that AAR cannot be positively identified by visual inspection alone.

For damaged structures, maintenance and repair techniques are described through to the alternatives of permanent modification or replacement. Many examples of AAR in dams are given.

The Bulletin concludes that there are no potentially catastrophic or rapid failure safety issues raised by AAR in dams because of the slowly developing mechanism. However cases of spillway gates jamming and equipment failing to operate because of misalignment are given. So, provided that good surveillance and monitoring and testing are in place (e.g. spillway gates) major safety issues may be avoided, but perhaps a serious dam safety issue cannot be discounted.

## **26. Bulletin 81: Spillways, Shockwaves and Air Entrainment – Review and Recommendations (1992)**

This Bulletin is a design guideline for high velocity (supercritical) flow spillways like spillways with bottom outlets and steep chutes. Features related to these spillways are shock waves (standing waves), aeration, and cavitation. All topics are treated theoretically and practical design guidelines and examples are given for simple spillway layouts.

In supercritical flow shock waves are related to changes in flow direction. These changes may be introduced by deflection walls, bends or junctions. Shock waves result in standing waves of considerable height and require additional freeboard.

The Bulletin provides description of preventive measures for reduction of the standing wave height.

Aeration of the chute flow occurs naturally but can also be induced artificially to reduce the very destructive phenomenon of cavitation. In high velocity flows cavitation may already occur from minor construction irregularities (e.g. joints) and is almost inevitable. The bulletin gives some practical solutions for aeration.

**27. Bulletin 82: Selection of Design Flood – Current Methods (1992)**

**28. Bulletin 125: Dams and Floods -Guidelines and Cases Histories (2003)**

**29. Bulletin 131: Role of Dams in Flood Mitigation (2006)**

These three Bulletins address in a comprehensive manner these topics of dam design which are to ensure that the dam can safely withstand and route extreme floods. Bulletin 82 presents several case histories of dam failures caused by overtopping of the crest. These overtopping were mainly caused by inadequacy between actual flood versus designed flood, sometimes magnified by misoperation or malfunction of gated spillways. The commonly used extreme flood estimation methods are described addressing the issues related to flow estimation, rainfall estimation and tools used to derive flow from rainfall. Both deterministic (PMP, PMF) and statistical methods are addressed. Critical analysis of methods and recommendations for the choice of an appropriate one are given. The selection of design flood is then developed, with the emphasis put on consequences of the dam failure, leading to engineering standard function of the hazard ranking of dams. Information is provided on the use of design flood and safety check flood in some countries.

These notions are developed in much more details in the Bulletin 125 and are complemented by the full description of the risk analysis (RA) approach to the choice of the extreme floods. RA method makes it possible to take into account several failure scenarios, including malfunction of spillways, human errors, reliability of data, etc., associated with extreme hydrological events. Analysis can then investigate the causes, the consequences, the possible remedial actions, etc. and lead to a selection of the safety check flood and the design flood that is better justified than the selection based solely on engineering standards.

Bulletin 125 deals also with different operating rules available for gated spillways.

Bulletins 125 and 131 develop considerations with regard to the importance of floods in natural disasters among the world and explain how dams can contribute to mitigation of human and economic impacts of such extreme events. Bulletin 125 presents examples of case histories where dams have reduced the potential impact of floods for people and the environment. Bulletin gives principles and examples for non-structural and structural measures for flood mitigation in a watershed.

**30. Bulletin 83: Cost Impact on Future Dam Design – Analysis and Proposals (1992)**

The Bulletin provides a review of potential changes in dam construction that could be useful in optimizing costs. Chapter 2 considers some traditional safety requirements that are often difficult to justify but increase the construction costs. In Chapter 5 comparison of typical and novel design concepts in terms of both costs and safety is presented and discussed. The dominant thought of the bulletin is that the progress in developing new technologies, design and construction methods in the area of dam engineering is significantly slower than in other areas of civil engineering. It notices that safety considerations play important role in general



reluctance to adopt new and better methods but it indicates that other area of civil engineering have improved safety performance while at the same time bringing the costs down.

### **31. Bulletin 84: Bituminous Cores for Fill Dams (1992)**

This Bulletin is effectively a supplement to Bulletin 42 (1982) on the same subject. It does not replace Bulletin 42 but continues dealing with developments in this technique over the ensuing decade.

The benefits of asphaltic concrete cores are discussed along with the design methods and construction guidelines and methods.

A detailed summary of dams constructed with bituminous cores is included and also some more detailed information about relevant projects is provided.

Finally, tests to determine the suitability of materials and for quality control of asphaltic concrete and transition materials are provided.

### **32. Bulletin 86: Dams and Environment (1992)**

This is a very short Bulletin (16 pages of text) which concentrates on these socio-economic impacts of large dams that are typical for developing economies. It provides a brief characterization of general philosophy for assessment and management of socio-economic impacts caused by construction and operation of dams. The introduction to the Bulletin discusses briefly methods of assessing the impacts, legal and political context and institutional arrangements and powers. Two following parts of the bulletin consider impacts during the implementation of the project (including conceptual studies, planning, design and construction) and then during dam operation. Some of the impacts discussed in the bulletin may be linked to operational activities of dam safety but the link is rather weak.

### **33. Bulletin 88: Rock Foundations for Dams (1993)**

The Bulletin provides a review of the rock foundation problems in concrete and embankment dams up to 1993.

Foundation investigations, as design and treatment aspects, are considered extensively throughout the Bulletin.

Foundation investigations methods include in situ measurements, laboratory tests, rock mass monitoring and interpretation of results. Monitoring equipment and procedures (geodetic, pendulums, wires, clinometers, piezometers and drains) as other instruments and measurements are described with many examples of applications.

The Bulletin presents a critical review of the “factor of safety” and “failure probability” concepts, recognizing the inadequacies of the deterministic approach and the advantages of the probabilistic approach. However it

also points out to various limitations to assessment of uncertainties in numerical terms. The Bulletin finally refers to the well known parametric analyses for the stability of rock masses (traditional and accepted practice still at the present)

Deformation analyses and mechanical effects of seepage, as foundation treatment methods, are also considered in detail throughout the Bulletin, with many examples of problems and solutions.

This Bulletin still provides a valuable reference and guidance for the design, construction and operational phases of dam life cycle .The Bulletin should be helpful in investigations and evaluation of landslides problems.

Dam Foundations Bulletin 129 (2005 edition) is complementary to, and an important advance over this Bulletin 88.

### **34. Bulletin 89: Reinforced Rockfill and Reinforced Fill for Dams (1993)**

The purpose of this Bulletin is to provide owners and designers with information allowing them to better understand the capabilities of this technology.

The Bulletin provides very detailed information on both reinforced rockfill and reinforced fill in two separate sections. The reinforced fill section principally discusses the use of the proprietary “reinforced earth” methods.

Details for the consideration of operating conditions, design and construction are provided. For completed structures, details of performance expectations and monitoring during operation are given.

A comprehensive section on previous projects constructed using reinforced rockfill or earthfill is included.

### **35. Bulletin 91: Embankment Dams. Upstream Slope Protection Reviews and Recommendations (1993)**

The Bulletin describes various methods used to protect the upstream slope of fill dams, with abundant examples of applications. It is intended to convey an overall idea of the state-of-the-art in the field, up to the date of the document edition. It covers in detail design criteria, quality materials, and different construction methods (dumped stones, hand placed stones, soil cement, concrete paving, bituminous, gabions, steel and timber facings, and roller compacted concrete facings)

The Bulletin also presents several case histories.

Valuable experience on rip rap behaviour, as new design and construction approaches, are available since this Bulletin has been published.

### **36. Bulletin 92: Rock Materials for Rockfill Dams (1993)**

Rockfill dams are defined as an embankment dams that depend on rockfill as its major structural element. Two major types of rockfill dams are described as those with earth cores with fill material zoning and those with man-made seepage control features such as diaphragms, reinforced concrete and asphaltic concrete faces.

Detailed information is provided on the relevant details for 113 rockfill dams, most of which were constructed during the 15 years leading to 1993.

General requirements for rockfill are described along with methods for determination of physical and mechanical properties, predicting settlement and general design information regarding the various types of rockfill dams.

A comment is made that all earth-core rockfill dams of dumped rockfill have performed well.

An interesting variation is described as “Blasted Dams” where the dam is constructed using a blast fill method.

General details of construction methods and Instrumentation requirements for construction and long term monitoring are provided along with the expected settlement behaviour for rockfill dams.

### **37. Bulletin 93: Ageing of Dams and Appurtenant Works (1994)**

The Bulletin gives a fairly complete treatment of the ageing of dams and appurtenant works related to design, construction and operation for those who are responsible for the safety and performance of these structures. Methods to detect, investigate and evaluate ageing are given together with simple remedial measures. For this 1105 case studies were used.

Ageing concerns the entire life cycle of the dam and is defined here as the class of deterioration associated with time-related changes in structure material properties. Three types of structures are distinguished: 1) concrete and masonry dams, 2) earth and rock fill dams, and 3) appurtenant works. Many failure mechanisms are described qualitatively and illustrated by practical case descriptions. For all failure mechanisms recommendations are given for detection, control or mitigation of the ageing problems.

### **38. Bulletin 94: Computer Software for Dams. Validation - Comments and Proposals (1994)**

The Bulletin addresses the issues revolving around proper development, verification and use of computer software for dams. It is not stated precisely in the text but it can be inferred that the software in question is related to general area of structural response of dam bodies to loadings. Three general aspects of computer modeling are discussed:

- Justification (underlying methodology and computer code give reasonable approximation of real behaviour);
- Validation;
- Quality assurance. A detailed guidance how these three processes should be conducted is provided in the bulletin.

The second part of the Bulletin is devoted to the concept and organization of benchmark workshops which can provide a mechanism for new software validation. The concept is illustrated by proposed themes for such workshops and examples of presentation of results.

The large area of meteorological, hydrological and hydraulic modeling as well as the software related to operation (dispatch decision making), remote control and data collection is not covered by this Bulletin.

### **39. Bulletin 95: Embankment Dams, Granular Filters and Drains (1994)**

This Bulletin considers design and construction of filters and drains in earth, earth-rock and rock fill dams. For these dams filter constructions are vital. With the help of survey information from 70 organizations and individuals was gathered and summarised to give the state of the art to engineers involved in dam design and construction. Best practises and some case histories are described.

The main function of a filter is to prevent migration of material (soil particles) from the foundation or fill layers (retention function). Another important function is to allow seepage without the build up of excessive hydraulic pressure (permeability function). Filter rules that provide these functions are given. Also rules and practical advises are given to retain the integrity of the filter (segregation, contamination). The Bulletin is still the state-of-the-art with the only exception being the part on geotextiles that could be updated with recent experience.

### **40. Bulletin 99: Dam Failures - Statistical Analysis (1995)**

This Bulletin presents a statistical analysis of dam failures, through the answers to a questionnaire sent in 1986-1988 to all the members of ICOLD. The bulletin includes 179 failures cases, and the main lessons are as follows:

- A comparison between the percentage of failures by the type of dams and the same percentage for existing dams seems to show that the failure rate is not really influenced by the type of the dam;
- Percentage of failures of large dams has been decreasing over the last four decades (from 2.2% before 1950 to 0.5% since 1950);
- Most failures involve newly built dams: 70% of the failures occur in the first ten years.

Some more detailed information is given about the failure causes for concrete dams, earthfill and rockfill dams, masonry dams and appurtenant works. For example, it is indicated that the main causes of concrete dam failures are the foundations, and that overtopping, internal erosion and foundations problems are the main causes for earthfill and rockfill dams. A quite detailed list of the different possible causes of failures is given in an appendix. These causes include design, foundations, dam materials, and misoperations.

The authors recognized that unfortunately not all countries have reported their failure events and thus the results presented should be analyzed with caution.

#### **41. Bulletin 102: Vibration of Hydraulic Equipment for Dams - Review and Recommendations (1996)**

The purpose of this Bulletin was:

- To describe problems of equipment vibrations;
- To describe and analyze the flow and structural characteristics which can cause or contribute to vibrations, and
- To present design guidelines which will help the designers to minimize the possibility of dangerous vibration.

#### **42. Bulletin 105: Dams and Related Structures in Cold Climate – Design Guidelines and Case Studies (1996)**

The purpose of the Bulletin was to provide guidance for the planning, design and operation of dams in cold regions. It begins with description of thermal regimes and processes governing ice formation and break up on lakes, reservoirs and rivers (Chapter 2). Chapter (3) provides concise characterization of ice mechanics and detailed discussion of ice related forces induced by (a) thermal expansion of ice cover, (b) fluctuating water levels, and (c) drifting ice. This chapter also provides detailed characterization of ice action on dam slopes. Operation and design guidelines for gates (Chapter 4) discuss design requirements for spillway gates and icing prevention measures. Chapter 5 begins with characterization of permafrost covering: (a) distribution and properties, (b) ground temperatures, (c) frost penetration, heat flow and ice formation, and (d) freezing and thawing. It ends with the discussion of potential problems for various dam components in permafrost areas.

Dam components include embankment dams, spillways and outlet systems, pipelines and tunnels, and submerged inlets and outlets. The final chapter is devoted to operational experience and case studies for dams in cold regions.

#### **43. Bulletin 107. Concrete Dams. Control and Treatment of Cracks - Review and Case Histories (1997)**

This Bulletin provides a comprehensive treatise on the control, accommodation and repair of cracks, and guidance on how to avoid cracking in concrete dams.

A detailed description of several sources of cracks (thermal, excess loading, foundation movements, shrinkage, chemical reactions, freezing and thawing) is presented. Mapping techniques for individual and pattern cracks, advantages and disadvantages of monitoring methods, different procedures for cracking repair (grouting methods, post tensioning techniques, options for sealing upstream face deterioration, other) are also thoroughly treated in the bulletin.

Avoidance of cracking includes prevention against chemical reactions, as structural design measures, thermal control methods, and construction practice.

The Bulletin presents interesting and valuable references of nine case histories, with analyses of problems, remedial works and performance results.

The Bulletin is an important reference and guidance for design and construction stages. It also provides useful information for investigation, evaluation, long term monitoring and corrective measures, during the operational phase of dam life cycle.

#### **44. Bulletin 108: Cost of Flood Control in Dams (1997)**

The goal of the Bulletin is “to examine ... cost factors of flood control and to recommend measures that will eliminate or reduce unnecessary and costly conservatism in discharge facilities”. The bulletin contains variety of statistical information on dam failures due to overtopping and types of spillways and their capacities developed with the help of data on 306 dams received from 8 ICOLD countries. Analysis of the data in terms of cost of outlet works is separated into two parts – spillways and outlet works and temporary diversions.

The section on Flood Control in Operating Dams begins with a very brief discussion on Design Flood and Safety Check Flood with some recommendations on selection criteria. This subject is possibly covered in a much more comprehensive manner elsewhere (Bulletins 142 and 125). Sub-sections on Control of Design Flood and on Control of Extreme Floods contain material that can provide valuable input to:

- Identification of failure modes for spillways and outlet works;
- Development of measures to rectify deficiencies;
- Improvements to operation of spillways and outlet works.

#### **45. Bulletin 109: Dams Less than Thirty Meters High – Cost Savings and Safety Improvements (1998)**

The purpose of the Bulletin was to provide general guidance on design criteria and practical solutions for reduction of costs in construction for dams that are smaller than large dams as defined by ICOLD. The Bulletin begins with a review of history, design and construction approaches in both developed and developing countries and characterization of causes and consequences of failures. Some general observations on relationship between costs and required safety levels for smaller dams follow in Chapter 2. Chapter 3 is devoted to characterization of improvements to existing dams (embankment, concrete and masonry) in terms of: (a) improving safety of these structures, (b) increasing storage capacity, and (c) improving quality of stored water and reducing environmental impacts.

With respect to safety, two major failure causes were considered, namely internal erosion and overtopping. Chapter 5 begins with a detailed discussion on inadequacy of older design criteria and practices developed for large dams to currently build smaller dams and on the need to apply risk assessment and probability-based safety criteria in developing better design criteria and methods for future dams. The main body of the chapter provides the guidance on various aspects of design for concrete arch and gravity, and embankment dams. It ends with discussion on flood control aspects and design and construction control.

#### **46. Bulletin 110: Cost Impact of Rules, Criteria and Specifications – Review and Recommendations (1997)**

The motto of the Bulletin is to select and implement the most cost effective overall design for the level of safety required. Chapter 2 on cost-effective design philosophy provides brief discussion on usefulness of risk analysis in improving the design and some comments on the need for development of risk criteria. Chapter 3 provides detailed discussion of novel design and construction methods for earthfill, concrete, masonry, and roller compacted dams, on the application of precast units, dam foundations and outlet works. This part of the bulletin may find its use in identifying risk reduction options for existing dams not meeting safety requirements. Chapters 4, 5 and 6 deal with construction specifications, changes in the design requirements for new construction and commercial contracting arrangements. In Chapter 7 there are two short sub-sections devoted to regulations of dam safety and to cost implications of dam safety regulations.

#### **47. Bulletin 111: Dam-Break Flood Analysis: Review and Recommendations (1998)**

The primary purpose of the Bulletin is the review of the state-of-the-art in the area of dam-break analysis. The mechanism of dam breach chapter contains very useful information available from field tests and historical cases of failures. The Bulletin provides an in-depth review of methodology of 1-D and 2-D hydraulic routing of dam-break waves in terms of both analytic and numerical approaches. The largest chapter on practical aspects of dam-break wave computation has an in-depth discussion on selection of modeling parameters, establishment of initial and boundary conditions, special applications, testing, calibration, validation and sensitivity analyzes. Short discussion is devoted to emerging capabilities related to GIS, remote sensing, novel data retrieving capabilities and other imaging and mapping techniques that could enhance the modeling and visualization. The bulletin ends with the summary information on existing (at that time - 1995) models in terms of their availability and capabilities.

Considering that the area of dam-breach modeling, physical modeling and breach-wave routing has been studied extensively in Europe in the last decade (results of this research are available on the FLOODSite website) the information contained in the bulletin should always be supplemented by additional capabilities developed post 1995.

#### **48. Bulletin 112: Neotectonics and Dams (1998)**

The Bulletin addresses the topic of potential crustal movements (creep or fault failure) and their consequences for dams. These consequences could include triggered seismicity, slope stability problem, creep phenomenon or fault break in the dam foundation. The different methodologies available for qualification of active faults and crustal movements are presented. The objectives of these investigation methods are the means to detect active faults and to date their most recent movements. The effects of these crustal movements on dams are discussed. Creep movements are generally acceptable, especially for earth fill dams; for concrete dams some precautions should be taken to cope with the imposed displacements. If significant fault movements are expected in the dam foundation, the advice is to abandon the site.

Several case histories are presented at the end of the bulletin, giving actual examples of dams submitted to creep movements, and the design considerations and repairs which have been undertaken.

#### **49. Bulletin 113: Seismic Observation of Dams**

A specific monitoring network for seismic observation of dams is a necessity for large dams where seismic activity is potentially high (the criteria are defined only on a qualitative basis). The objectives for such instrumentation are mainly:

1. Safety diagnosis of the dam after an earthquake, and opportunity to generate alarm signal. Contributions of the standard monitoring network and visual inspections are important tools for this diagnosis;
2. Improvement of knowledge on seismic waves propagation and dam response. Dam response can be also studied with vibration tests (but mainly for concrete dams).

The Bulletin gives detailed indications and advices for the design of a seismic instrumentation network - number and location of the sensors (depending on the objectives assigned to the network), types of sensors and their installations, calibration and maintenance, data loggers and supervision system, data processing. Nowadays, digital sensors are almost always used, and most of the data analysis for ground motion is performed by the supervision system. Dam response analysis requires more sophisticated tools.

The Bulletin presents several examples of utilization of seismic monitoring networks: vibration tests (Talvacchia dam) and data processing and results obtained after earthquakes (Kurobe, Aswan, Lower Crystal Springs, Lower Van Norman, Pacoima, Long Valley, San Justo).

#### **50. Bulletin 114: Embankment Dams with Bituminous Concrete Facing (1999)**

This is a revised edition of Bulletins 32 and 39. The Bulletin covers the state-of-the-art of current practice. This includes a review of the main elements of a facing system, a presentation of records from the practice, a description of materials used in composite facings, typical designs of a facing system, and details at the interface with other elements of the dam, joints, and some construction details, recommendations on testing, performance records, and repair techniques. A record of constructed dams and reservoirs is also provided.

Most of the dams this type have been built in Europe and they are up to 90 metres in height. The impervious layer is typically 5cm to 10cm thick with double lining used mostly for dams and single lining system for the bottom of reservoirs.

The facings are thin structural elements, exposed to very high hydraulic gradients and are susceptible to damage by external actions. Therefore the facings and the dams that they protect must be carefully designed, constructed and operated.

#### **51. Bulletin 115: Dealing with Reservoir Sedimentation**

This Bulletin deals with the management of sediment in reservoirs. Four management practices are treated for the sediment load: prevention, passing, removal and compensation.



- Prevention: watershed management activities (vegetation practices, engineering measures and agricultural practices) are treated to prevent (reduce) the sediment load.
- Passing the reservoir: two practices are treated, (1) to pass the sediment by sluicing action before settlement and (2) to use density currents (possible only in very specific cases). Calculation procedures and examples are given. The outlet design for sluicing is treated separately.
- Removal: once the sediment has settled in the reservoir it can be removed by flushing using the scouring mechanism or by excavation. Calculation procedures and examples are given.
- Compensation: sedimentation reduces the effectiveness of the reservoir. Engineering solutions are given: dam raising (where dam safety aspects are mentioned), a new dam, and overdimensioning the reservoir for sedimentation.

## **52. Bulletin 117: The Gravity Dam: A Dam for the Future - Review and Recommendations (2000)**

This Bulletin presents key aspects of gravity dams, with their design, materials used, and construction methods under the historical aspect. Then it compares the gravity dams (conventional concrete and RCC dams) to fill and arch dams, from the perspective of safety and costs. It concludes that, due to the global world-wide trend on labour costs and recent innovations as RCC and new dam profiles, gravity dams have a promising future. A statistical analysis of gravity dams failures highlights the fact that the major causes are poor foundations, the poor quality of masonry, too thin profiles and, for existing dams, floods. But none of the concrete gravity dams built after 1930 have failed. With regard to ageing - the major factor is the water percolation through the dam with three main consequences: decrease of density, of shear strength, and of permeability. Masonry dams are more sensitive to these phenomena. The Bulletin indicates that watertight facing on the upstream face is the best design features to prevent this percolation.

For the future, the bulletin proposes some perspectives on the following:

- Thickening of the profile, with the concept of Faced Symmetrical Hardfill Dam (FSHD) which provides better resistance to overtopping, to seismic loading, with no traction on upstream toe;
- upstream face watertight with concrete slabs, membrane, steel,.. ;
- allowing overtopping of the crest during extreme flood, and therefore a reduction of freeboard.

The Bulletin discusses also the cases of small dams (<30m.), of flood control dams, composite profile dams (earth and concrete) and proposes some design considerations for these particular cases.

At the end some recommendations are given concerning the construction control, surveillance by monitoring and visual inspections, and emergency plans.

## **53. Bulletin 119: Rehabilitation of Dams and Appurtenant Works (2000)**

The primary objective of the Bulletin is to summarize current international experience with rehabilitation works for dams and to provide reference for design and management of rehabilitation projects. The main emphasis of the Bulletin is on dealing with material effects of ageing processes including decay and degradation, wear, loss of serviceability, damage from natural event or vandalism. However the Bulletin also

addresses these aspects of rehabilitation works which are related to evolution and changes in modern technology including new design and construction methods and better understanding of natural hazards and physics of the dam behaviour. The focus of the Bulletin is mostly on the methodology of the rehabilitation works and less on the factors causing the need for rehabilitation.

The main chapter of the Bulletin include:

- Management of rehabilitation (legal and organizational aspects, design and construction, risk management);
- Rehabilitation of concrete dams (foundation and dam itself, stability aspects);
- Earth and rockfill dams (detection and assessment of deterioration process, rehabilitation works for foundation, abutments, embankment, upstream faces, seismic aspects);
- Appurtenant works (causes of deterioration, rehabilitation of outlet works, spillways and discharge equipment).

The Bulletin ends with a separate chapter clearly outlining the needs for research activities necessary to support improvements in rehabilitation of dams that include: better understanding of the dam behaviour and deterioration processes (monitoring and surveillance, testing, modeling), development of methodologies for assessment of performance and reliability and development of new rehabilitation methods.

#### **54. Bulletin 120: Guidelines on Design Features of Dams to Effectively Resist Seismic Ground Motion (2001)**

This Bulletin comprises two main parts:

- Description of observed performance of dams subjected to earthquake with numerous examples of case histories in appendix B (which constitutes the major part of the Bulletin);
- Outline of structural considerations required to effectively resist seismic ground motions, taking into account the geology, the topographical features of the site, and the dam type.

It provides valuable information of experience feedback about failures modes of dams subjected to seismic loading, and recommendations for design features.

#### **55. Bulletin 122 Computational Procedures for Dam Engineering – Reliability and Applicability (2001)**

Bulletin 122 continues the topics discussed previously by Bulletin 94. The main purpose of the bulletin is a critical review of the potential role and effectiveness of existing mathematical models in assessing dam response to different loading conditions. Secondary goal is to discuss reference solutions achieved through a series of benchmark workshops recommended by Bulletin 94.

The review of the models is summarized in 6 tables (3 each for concrete and embankment dams). Computer modeling capabilities for different phenomena affecting the dams at different stages of their lives have usefulness indices (called Reliability Indices) assigned and displayed in the tables. There are 4 indices defined, namely:

1. Existing models can be used with confidence;

2. Phenomena related to dam safety can be analyzed with the help of models but with some limitations;
3. Only qualitative and comparative analysis possible;
4. Existing numerical models are incapable to provide correct and accurate answers.

The Bulletin has some 'interesting' discussion related to the definition and interpretation of the concept of dam safety assessment not in agreement with the present position of CODS (*the concept of probability of failure should be taken only as a conventional index allowing relative grading*). Its understanding of mathematical models includes also empirical or rule-of-thumb rules *that are to be considered as reliable on the strength of a long practice and frequent successful applications*.

#### **56. Bulletin 123: Seismic Design and Evaluation of Structures Appurtenant to Dams (2002)**

The Bulletin gives guidance to the selection of an appropriate earthquake input and an appropriate method of analysis for the seismic evaluation of appurtenant structures. It defines allowable stress criteria based on the location of these structures and the consequences of their failures for safety.

The Bulletin defines the "critical structures" whose failures may lead to the dam failure, and "non-critical structures". Critical structures should be designed to withstand the Maximum Credible Earthquake (MCE), when the non critical structures should withstand the Operational Basis Earthquake (OBE).

Three methods of analysis are defined (pseudo-static analysis, response spectrum, time history). Selection of the appropriate method of analysis should be done according to the type of structure. Load combinations and criteria for allowable stress and displacements are proposed.

These global principles and criteria are then applied to five types of appurtenant structures: spillways, water conduits gates and valves, intake towers, navigation locks and bridges. Five chapters give detailed advice for seismic design and seismic evaluation of different kinds of structures.

#### **57. Bulletin 124: Reservoir Landslides: Investigation and Management. Guidelines and case histories (2002)**

The Bulletin examines the interaction between reservoirs and slope stability, and the effects of unstable slopes on reservoirs and their operation. It refers principally to soil and rock movements. Ice, snow avalanches and lahars are not treated in detail.

The Bulletin intends to inform about the range of hazards and risks associated with landslides. It provides guidance to the developers and owners on how reservoirs landslides risks can be identified, treated and managed to control risks.

Concepts presented are particularly important to reservoir projects in the planning stage, and to the safety evaluation of existing dams and their reservoirs.

This Bulletin provides an extensive and thorough treatment of the landslides problems and their consequences. It also summarizes the lessons learned from international experience during a period of 30

years, as illustrated by four major reservoir landslide case histories (Vaiont, Italy; Tablachaca, Peru; Dutchman Ridge, Canada; Cromwell Gorge, NZ)

Risk Management treatment and definitions in this Bulletin, are aligned with CODS DSM Bulletin concepts and Risk Assessment approach.

### **58. Bulletin 126: Roller Compacted Concrete Dams – State-of-the-Art and Case Histories (2003)**

This Bulletin presents the technology of roller compacted concrete dams. It deals mainly with gravity dams (RCC and RCD) but also addresses briefly arch dams and hardfill dams. The major parameter for these dams is the cement content, the trend being nowadays toward a high cementitious content. The upstream tightness can be ensured either by classical concrete or by high cement content RCC placed upstream.

The design of RCC gravity dams is similar to the classical concrete gravity dams, except for two main points, coming from the specificity of RCC dams: horizontal joints due to the placement of concrete in layers, and the absence of vertical joints between blocks which can cause vertical cracks. Therefore, two aspects should be particularly taken into account during the design and construction stage: shear strength and temperature control.

The other parameters which should be also considered are density, permeability and segregation. Recommendations about materials (cement, aggregate, admixtures), mixture proportion and design methods are given in this respect. Specific construction methodologies, for transportation and placement of concrete layers, joints between layers, forming of contraction joints and of upstream and downstream faces, galleries inside the dam body are indicated. Full scale trials are recommended to test the design criteria and construction specifications.

At the end, several history cases are given, for gravity and arch dams.

### **59. Bulletin 129. Dam Foundations Geologic Considerations. Investigation Methods. Treatment. Monitoring (2005)**

The Bulletin is an updated enlarged edition of Bulletin 88 of 1993.

It is a very extensive Bulletin (471 pages) devoted entirely to the dam foundations problems. It considers the following:

- Significance and influence of foundation with respect to the type of dam;
- Geologic and geotechnical characteristics of the foundation;
- Adverse conditions;
- Dam foundation interaction (stability, deformation and seepage analyzes); instability scenarios;
- Computational methods.

It also covers thoroughly:

- Investigation plans and procedures (hydro geological, geophysical and geotechnical);
- Foundation treatments (excavation, sealing measures, grouting methods, cut-offs, other);

- Drainage and strengthening measures;
- Foundation monitoring and behaviour.

The Bulletin also presents several instructive case histories and lessons learned on foundation treatment and performance, on limitations of investigations, and adjustments that were necessary to made during construction.

The Bulletin provides a valuable reference and guidance for design, construction and operation phases. Due to the unique characteristics and conditions of each site and project, it is clear that Bulletin recommendations must be applied with prudence according the prevailing situation.

### **60. Bulletin 130: Risk Assessment in Dam Safety Management. A Reconnaissance (2005)**

This bulletin comprises four principal parts as follows:

1. Context and rationale;
2. Outline of the risk assessment process;
3. Survey of current applications;
4. References.

This Bulletin provides an “introduction to risk assessment in dam safety management” as understood during the period 1998 - 2003, together with a summary of emerging risk assessment practices in member nations of ICOLD.

Risk assessment provides a generalized framework for managing the safety of dams and a basis for integrating across all disciplines and associated ICOLD Bulletins relevant to dam safety assurance, and this Bulletin provides a broad and superficial illustration of the elements of risk assessment. The Bulletin provides a limited but realistic example of the analytical techniques of Failure Modes and Effects Analysis, Event Tree Analysis and Fault Tree Analysis as are applicable to dams. The bulletin also provides information on how results of risk analysis can be presented in risk assessments; considerations in judging the significance of risks associated with dams; and risk-informed decision making.

The survey of current applications is also relevant to the period 1998 – 2003 as are the references.

The Bulletin did not provide Guidance of Implementation, and does not allude to the areas requiring further development, some of which has occurred since the Bulletin was published, or other challenges to be addressed.

### **61. Bulletin 132: Shared Rivers: Principles and Practices (2008)**

This Bulletin presents the state of practice in relation to shared rivers based on the analysis of the existing treaties among concerned countries. The focus is primarily on the aspects of water sharing and respect for the environment, among the countries where these transboundary rivers flow. The most critical aspect for the management of shared watercourses is for all of the basin states to participate in dialogue on the topic. The

exchange of data and information even at technical level is normally a useful method to initiate the process of dialogue as it builds confidence amongst the parties. Some urgent situations may occur, as flood, drought, spillage of toxic materials, dam failure, etc. and the organization set up to monitor treaties and agreements, must also address these emergencies. The measures to mitigate these risks should be data exchange and common practices on hydrological forecasts, emergency plans, preparation of evacuation, monitoring and maintenance of dams, preparation of reservoir operation rules and preventive anti-flood measures.

#### **62. Bulletin 133: Embankment Dams on Permafrost - A Review of Russian Experience (2008)**

This Bulletin presents an analysis of natural conditions in cryolitic zones of Russia, the special features of the layout, type and structure of fill dams, the ice and water discharged through the spilling structures and the special parameters of fill dam technology. Typical examples are given of dam deformation, repair and reconstruction, as well as operation in a severe climate.

#### **63. Bulletin 134: Weak Rocks and Shales in Dams (2008)**

The Bulletin provides technical background on the behaviour of shale and weak rocks as fill in dams. It includes examples of the use of weak rock, particularly on the means of excavating and compacting shoulders and core fills.

The Bulletin aims to assist dam engineers in developing sites on weak rocks effectively, considering the uncertainties and difficulties of constructing dams on weak foundations and of weak rock fills.

This document refers mainly to the use of weak rocks and shale as dam building materials. Some reference is made to shale present in dam foundation.

It includes a good summary of construction practice based on an international sample of dams.

It is not a fully comprehensive manual. Many aspects of the problem will need further investigations.

#### **64. Bulletin 136: The Specification and Quality Control of Concrete for Dams (2009)**

This Bulletin addresses all aspects of the relationship between the specification of concrete, construction procedures, and the properties of the hardened concrete and of how quality control is used. It recognizes the interdependence of the design, transport, and placement process. It gives precise and detailed recommendations on the methodology of control tests (primarily strength test). In the chapter 6, it summarises the bulletin 107 (concrete dams – control and treatments of cracks), focusing on recommendations on how to avoid thermal cracks. Chapter 7 deals with mixture composition and quality control for concrete resistance to high velocity water flows.

The roles of both designers and contractors in the production of functional, durable and economic concrete are discussed. Case histories are presented for a gravity dam of conventional vibrated concrete (CVC), a roller

compacted concrete (RCC) dam, and a CVC arch dam. Appendices give tables of typical test frequencies and a sample table of contents listing for a complete specification.

#### **65. Bulletin 137: Reservoirs and seismicity – State of Knowledge (Draft 2008)**

Reservoir triggered seismicity (RTS) are seismic events manifested during and after impounding, due to interaction of the added weight of the water stored and the pore pressure diffusion with the critically stressed faults. Dam designers are obligated to assess the risk arising from RTS for each large dam on the basis of existing knowledge. Deploying a local seismic monitoring network adapted to the prevailing seismic conditions is a requirement for each large dam built in a tectonically seismic area. However, the triggered seismicity cannot increase the seismic hazard at the dam site and, therefore, dams correctly designed on the basis of ascertained level of seismic influences are fully covered against possible triggered phenomena. This could not be the case for existing structures and facilities in the vicinity of the storage.

The state of knowledge about RTS is presented in the bulletin, along with case histories. This knowledge need still to be improved, and researches in this field are necessary and should be encouraged.

#### **66. Bulletin 140: Sedimentation and Sustainable Use of Reservoirs and River Systems (Draft 2008)**

This Bulletin deals with reservoir sedimentation and downstream ecological impacts of a dam related to the fluvial morphology.

Reservoir sedimentation is a major threat to the sustainable use of reservoir capacity. The analysis of several reservoir sedimentation data bases reveals that currently one third of the worldwide reservoir capacity is already filled with sediment. Based on predicted sedimentation rates this ratio could increase to two third within the next 50 years if no preventive measures are taken. The bulletin also provides regional predictions of storage capacity in the next 50 years.

The main downstream fluvial morphological impact of a dam relates to depth, width and bed material of the river. These effects are described qualitatively. Mitigating measures are treated: environmental flood releases and flood flushing of sediment.

Empirical regime equations are described to determine the impact of a dam and the changes in driving forces (discharge, slope and sediment diameter) on the downstream river characteristics. These equations can be used to predict approximately the equilibrium characteristics of the downstream river.

The Bulletin treats the assessment of downstream ecological impact related to changes in fluvial morphology. Also measures are described to prevent these changes. Guidelines are proposed to determine and limit the impact on downstream morphology and an economic model based on a life cycle approach (RESCON) is treated to determine a sustainable management of dam projects.

## **67. Bulletin 142: Report on Safe Passage of Extreme Floods (Draft 2008)**

This Bulletin deals with the safe passage of floods higher than the design flood. Both structural and non structural measures are described (additional spillway capacity or attenuation of flood peaks, flood forecasting, flood warning systems and emergency measures). To determine the magnitude of the extreme flood special attention is paid to confidence levels for the design flood related to record length of hydraulic data and the life time of the dam. Also other causes for increased flood levels are treated like changes in design methods/criteria or climate change.

The bulletin gives design considerations for the safe passage of extreme floods. This includes considering future changes to the project or to the hydraulic system and malfunctioning of the spillway system. To provide additional spillway capacity to the operational spillway, auxiliary and emergency spillways are distinguished.

For several dam types the sensitivity to overtopping is treated to illustrate the risk associated with insufficient spillway capacity. Several operational spillway types are treated qualitatively. Also solutions for the auxiliary and emergency spillways are treated like erodible fuse plugs, earthcut spillways, geomembranes, low-level outlets and several low cost solutions (sand bags, fuseplates, stoplogs, fuse plugs, etc).

The Bulletin briefly describes operational procedures to maintain the control of safe flood passage by maintenance, operation and training of personnel. Also some characteristics of flood warning systems are treated shortly. The bulletin ends with case descriptions of extreme floods in China, Canada and Brazil.

## **68. Bulletin 144: Cost Savings in Dams (2008 Draft)**

The Bulletin was build on works of previous 2 general bulletins (73 and 83) and 6 specific bulletins (85, 108, 109, 110, 117 and E02) and its primary purpose was: (i) identification and mitigation of existing non-technical factors detrimental to cost savings, (ii) identification of technical opportunities for innovation and cost savings in design and construction of dams. This bulletin (similarly to Bulletins 83 and 110 reviewed by CODS) is dealing with technical and non-technical issues related to the design and construction phase of life-cycle. However, some ideas presented there may be useful in identifying and examining risk reduction options for existing dams.



## **Appendix B: Decision Making in Dam Safety**

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Fundamentally, the decisions that have to be made in the broad area of dam safety can be separated into two major categories:

1. **Safety decisions** related to clear establishment whether dam performance is satisfactory. If the dam in question meets safety requirements it can be operated without meeting additional conditions.
2. **Programmatic decisions** aimed at supporting safety decisions by developing prioritization schemes. The schemes may differ depending on the objectives and goals of the prioritization.

A general framework for decision making with respect to **safety decisions** depends ultimately on whether the consideration of risks involved is explicit or implicit. The most important and difficult problem that needs to be addressed with respect to the **safety decisions** is what should be a rational basis for making societal choices for life safety decisions. Traditionally, these decisions have been made by defining more or less conservative safety standards and by using considerable amount of judgment and experience. The philosophy applied by traditional engineering, also known as a “factor of safety” approach, relied on designing the structures to survive under some extreme loads resulting from so called “maximum credible events”. While some of the uncertainties in the analysis are commonly addressed in this approach by applying conservative loads, safety factors, etc., others are disregarded entirely or only partially addressed. The management of risk created by dam existence and operation is thus addressed by imposing standards that are progressively more stringent with the higher classification. The classifications are based either on potential consequences of dam failure or on the hazard potential of the dam. The outcome of the safety analysis is always binary: either the requirements are met or they are not. In the latter case potential solutions to the problem have to be identified and since all of them have to meet the same target an economic analysis can help in selecting the preferred option. At the implementation phase of the option some prioritization may be necessary.

Explicit consideration of risk can be helpful in establishing a better, rational basis for decisions involving life safety but the road to effective and efficient decision-making mechanism requires significant effort in identifying and quantifying all risks present. Discussion in this section does not attempt to address all the complex problems of risk estimation and concentrates instead on development of risk assessment criteria and supporting attributes that are necessary if the proposed framework is to be fully operational. Thus, the aspects of *risk measuring* that aim at the assessment of consequences to life safety and their probabilities will not be discussed here. The main topic however is the *judgment of acceptability of identified risks (judgment of safety)* which is strictly a matter of personal, societal and political value judgment.

Programmatic decisions typically follow the safety decisions. They can relate to a portfolio of dams or a single structure. With respect to the portfolio of dams, most often the need of the prioritization process is the identification of those dams within a large inventory that present the biggest threat to safety and which most urgently need attention. The prioritization problems related to a single dam have usually different objective which can be characterized as the identification of the ‘best alternative’ to fix the dam safety deficiency. Scheduling and timing issues may also require help in prioritizing.

## 1. Safety Decision Making – Implicit Consideration of Risk

For some of the safety issues identified during traditional dam safety analysis and assessment the decision-making process is quite simple. If the safety requirements expressed as design standards are not met structural or non-structural improvements have to be implemented in order to bring the dam in compliance with the requirements. The degree of non-compliance is in some sense irrelevant; ultimately all deficiencies have to be fixed. If the magnitude of the safety issue can be measured (for example, by measuring the gap

between the actual performance and the design standard) this information can then be utilized in making programmatic decisions, improving the prioritizing and scheduling process.

However not all of the potential safety issues can be examined by comparing the actual performance with the design standards for a very simple reason – the standards do not exist and the problem is not amenable to such kind of comparative analysis. Thus not only the magnitude of any potential deficiency cannot be effectively measured but also even the existence of the deficiency may be difficult to establish since it can be opened to conflicting interpretations and judgments. The conflicts can arise both in the course of carrying engineering analyzes and in interpreting degrees of risk involved without any formal and structured procedures available.

The standards and other requirements are an integral part of the decision-making framework and thus a brief background<sup>1</sup> on the general philosophy of formulating standards in the dam safety area is necessary. Inflow Design Flood (IDF) as a design requirement for the discharge capacity can serve here as an example. Probable Maximum Flood (PMF)<sup>2</sup> has been in use as the IDF in many countries around the world for these dams which potentially threaten human life.

Alternative approach, most popular in Europe, has been based on floods with pre-specified return periods (with 10,000 years being used as an upper limit) obtained through flood frequency analyzes. The PMF as the IDF concept originated from a very strict interpretation of precautionary principle<sup>3</sup> and was aimed at providing the complete protection against the possible failure of the dam from overtopping. It originated from a cliché notion that any human risk is intolerable. Such notion is equivalent to putting an infinite value on human life, which is contrary to how limited resources are being allocated in modern societies.

The notion of ‘putting infinite value of human life’ is a crucial one because the engineering community has always been extremely reluctant to pursue the estimates of a monetary value that society would be willing to spend in order to prevent fatalities from human-created hazardous installations. Treating life as ‘priceless’ is an important symbol of society’s commitment to human values but any policy decision always places a value on life, either implicitly or explicitly. As an example Mendeloff, (1988) questioned whether 50 US States highway departments which had to make intelligent decisions about the worthwhileness of thousands of safety investment decisions each year could do that without some sense how much should be spent to prevent a fatality. Lave et al. (1990) argued that such decisions are being made routinely across different industries and regulatory agencies. They point out that there is a definite advantage in making implicit figures explicit because it is a necessary first step to achieve consistency across the full spectrum of decisions affecting public health and safety. Following the consistency argument, Dubler (1996) pointed out that the concept of using upper limits of natural adverse events as a basis for defining criteria for public safety is not used elsewhere in society. Such criteria can possibly require spending of much more on fatality prevention resulting from dam overtopping and breach than what is spent in achieving similar goals in most of the other societal decisions.

Early critique of promoting PMF as an appropriate IDF standard provided by Benson (1973) has remained almost entirely ignored by the engineering community, it should be recognized that it was the first one which identified important ethical and moral issues with the foundation of the decision-making framework based on

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<sup>1</sup> See Zielinski (2009) for more comprehensive information on the subject.

<sup>2</sup> The Probable Maximum Flood (PMF) is usually defined as the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular watershed.

<sup>3</sup> The principle requires caution when in presence of uncertainty.

arbitrarily imposed design criteria. Benson warned that the serious ethical dilemma it created was caused by the implied message that the design was virtually free of risk.

## 2. Safety Decision Making – Explicit Consideration of Risk

### 2.1 General Concept

At the foundation of risk-based frameworks is the principle that ultimately all decisions about safety are risk management decisions. As zero-risk decisions are not practicable and most of the time simply not affordable some tradeoffs between the costs of reducing risk and the benefits from risk reduction are unavoidable. The entity managing the dam is thus faced with a complex decision making, which concentrates around the following questions:

- When is the spending on risk reduction becoming disproportionate to the benefits of managing this risk?
- How far should the spending on risk reduction continue, if at all, beyond the point where the risk deemed to be not longer unacceptable?
- When can the risk be declared as insignificant?

Health and Safety Executive (HSE, 2002), the United Kingdom safety regulator, proposed a universal framework for making safety decisions, which since its introduction has been adopted by various hazardous industries around the world. The framework has also been adopted for regulation of dam safety in some jurisdictions and is being considered in others.

A Responsible Entity who elects to demonstrate dam safety with the help of this framework has to conduct the safety assessment in such a way as to ensure that all measures necessary to avert the risk must be taken until the cost of these measures is disproportionate to the risk which would be averted. As a result, the risk must be reduced to a level, which is ALARP (As Low as Reasonably Practicable). The concept of ALARP was explicitly formulated for the first time as a result of a court case (Edwards versus The National Coal Board) in United Kingdom, in 1949. The court:

*...established that a computation must be made in which the **quantum of risk** is placed in one scale and the **sacrifice, whether in money, time or trouble**, involved in the measures necessary to avert the risk is placed in the other; and that, if it be shown that there is a gross disproportion between them, the risk being insignificant in relation to the sacrifice, the person on whom the duty is laid discharges the burden of proving that compliance was not reasonably practicable.*

The Court of Appeal also stated “...in every case, it is the risk that has to be weighed against the measures necessary to eliminate the risk. The greater the risk, no doubt, the less will be the weight to be given to the factor of cost”. The same court also characterized a key term commonly applied in the demonstration of ALARP in the following manner:

*‘Reasonably practicable’ is a narrower term than ‘physically possible’...*

Thus the concept of ALARP is in its essence based on a legal principle that is aimed at controlling the level of risk associated with a hazardous activity. The ALARP principle provides practical means for assessing the

tolerability of risk by establishing that if the cost of reducing a risk outweighs the benefit, then the risk may be considered tolerable. Thus, in simple terms, the determination that risk has been reduced ALARP involves:

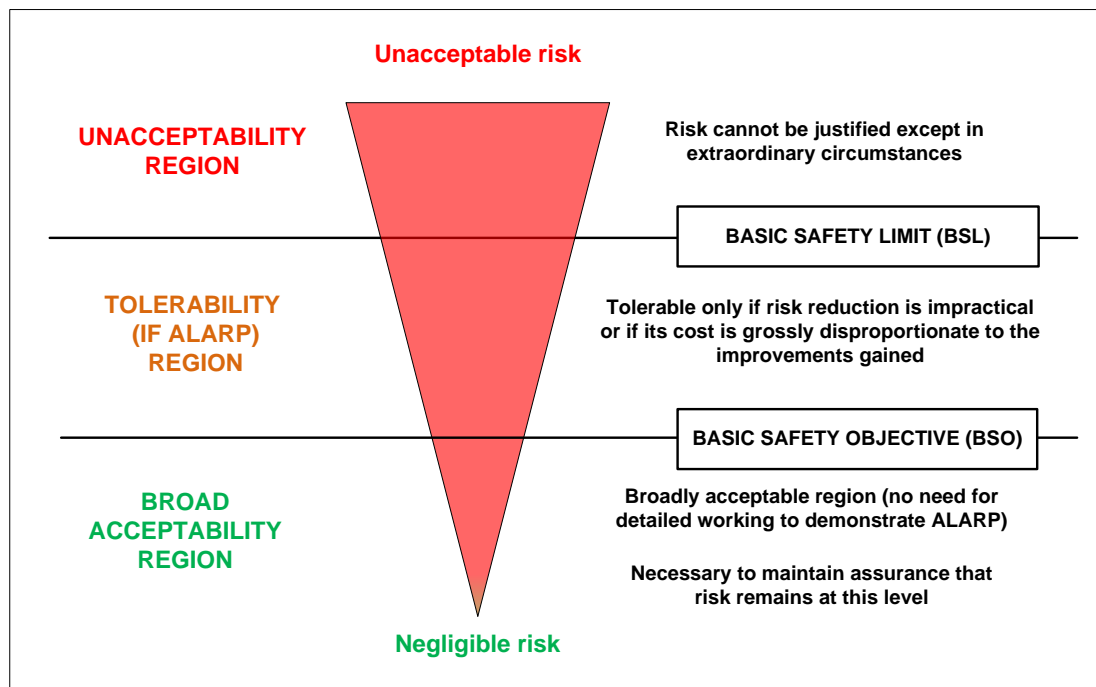
- An assessment of the risk to be avoided.
- An assessment of the sacrifice (either in money or time and trouble) cause by implementing measures to reduce or avoid the risk.
- Comparison of the two.

The proper framing of the issue of how to interpret and apply the ALARP principle when life safety is being considered begins with the realization that any decision on proportionality of action requires the characterization of risks involved. The risk has to be characterized either qualitatively or quantitatively in order to describe how it arises and how it impacts those who may be affected.

Risk can be interpreted as intolerable, tolerable or acceptable (Figure 1), where:

- An intolerable (or unacceptable) level of risk has to be reduced to a tolerable level regardless of the cost (the risk is so high that it is intolerable)
- An acceptable level of risk is regarded as insignificant (the risk is so low that can be considered negligible).
- A tolerable level of risk (that is the risk between the intolerable and acceptable regions) has to be reduced to the ALARP level.

**Figure B1 - Levels of Risk and the ALARP Principle (HSE, 2001)**



The triangle in Figure 1 represents increasing levels of risk moving from bottom to top.

Within this tolerability of risk framework introduced by HSE (2001), it is recognized that there are levels of risk that cannot be tolerated and which would be found unacceptable by the public. These risks have to be reduced regardless of the costs involved in risk reduction and the benefits from the presence of the dam, unless there are exceptional reasons to continue the operation. The risks within this zone are considered as so high that the continuing operation of the dam cannot be allowed. The Zone R1 at the top of the triangle represents this unacceptable region.

The Zone R3 at the bottom represents the region of broadly acceptable risks. These risks are generally regarded as insignificant and are comparable to the risks people face in their daily lives and consider as trivial. Further reduction of broadly acceptable risks is not required although the Responsible Entity may decide that reduction is reasonably practicable and may implement additional measures reducing the risks to even lower levels. As noted in (Hartford, 2009), HSE's definition of Zone 3 (no further reduction of risk required) may not pass the legal test if adopted in another country.

The middle Zone R2 is separated from the Zones R1 and R3 by thresholds also called the Basic Safety Limit (BSL) and Basic Safety Objective (BSO). The Zone R2 represents these risks that people are prepared to tolerate in order to receive certain benefits. The benefits can be numerous and may include employment opportunities, maintenance of general social infrastructure (electricity production, water supply), recreation, etc. The willingness to tolerate the risks is however conditional and the conditions can be derived from the following principles (HSE, 2001):

- It is expected that all suitable controls be in place to address all significant hazards. These controls, as a minimum, have to implement authoritative good practice irrespective of the risk estimates.
- The middle zone R2 of risks between intolerable and broadly acceptable regions is the tolerable region. Risks in that region are typically tolerated by the public in order to secure benefits but with the expectation that:
  - The nature and magnitude of risks can be properly assessed and the results used properly to determine control measures. The assessment of risks has to be based on the best available scientific methodology and evidence.
  - The residual risks remaining after control measures have been implemented are not unduly high and are kept ALARP
  - An adequate safety management system is in place to ensure that risks are maintained ALARP at all times. The risks have to be periodically reviewed to determine whether further or new controls need to be implemented to account for new knowledge about the risks or the availability of new risk reducing methods.
- Both the level of individual risks and societal concerns caused by the presence of the dam has to be taken into account when deciding whether risks are acceptable, tolerable or intolerable.
- The application of ALARP can only involve these risks that are controlled or mitigated by the Responsible Entity. The risks that arise from external events over which the Responsible Entity has no control but whose consequences can be mitigated should be included in the assessment.
- Affordability in examining available risk reduction measures is not a factor in the ALARP argument.

- ALARP demonstration has to consider all options, which could reduce the risk and should implement this option (or combination of options), which reduces residual risk to the lowest level. It is not appropriate to initiate the demonstration with the least costly option and only consider more expensive options for the additional margin of risk reduction.
- Extent and depth of ALARP demonstration has to be proportional to the risk being considered. Higher risk will require more rigorous and extensive demonstration than lower ones. The extent of analysis and its rigour should be increased when consequences are higher, with lower weight applied to probability estimates.

A comment needs to be made here which summarizes the ALARP approach and compares it to the framework described in the previous section. HSE framework can be characterized as a modified and more reasonable precautionary approach. In the presence of risk a test of 'gross disproportion' has to be applied which means that the risk reduction measure must be implemented unless the costs of the measure are 'grossly disproportionate' to benefits resulting from implementation.

## 2.2 Tolerability and Acceptability Criteria

The idea that levels of risk may be acceptable or unacceptable to the public, Responsible Entities, and regulators has long been present in an implicit form in dam safety considerations although only in recent times explicit forms are being developed. The most comprehensive approach to date (Rimington et al., 2003) recognizes the following risk categories:

- **Broadly acceptable risk:** An annual risk of casualty significantly lower than  $10^{-6}$  arising from any particular source, generally taken as negligible risk;
- **Unacceptable risk:** An annual risk of casualty in excess of  $10^{-4}$  deemed to be intolerable under normal circumstances. This does not preclude individuals from voluntary participation in recreational activities involving higher levels of risk, often in the range  $10^{-3}$  to  $10^{-2}$  fatalities per annum;
- **Tolerable risk:** an annual risk of casualty between the values  $10^{-6}$  and  $10^{-4}$ .

The key component is risk to life safety. With respect to this, NSW Dam Safety Committee (2006) proposes two principles:

- With respect to individual risk, the increment of risk imposed on an individual by a dam should not exceed a small fraction of the average background risk that the population lives with on a daily basis.
- With respect to societal risk, the probability of an event that could result in multiple casualties should not exceed a value, which is a function of the number of possible casualties (*i.e.*, an expectation), and which is declining as the number of casualties increases.

How risk, especially individual risk, is defined may vary. CDA (2007) defines these two as follows:

- '*Individual risk*' relates to concerns of how individuals see the risk from a particular hazard affecting them and their property. It is usually defined as the risk to a hypothetical member of the public living in the zone that can be affected in the event that a hazard occurs. The criteria for individual risk depend on such factors as: whether or not the exposure is voluntary, whether the individual derives benefit from accepting the risk, whether the individual has some control over the risk, and whether the risk engenders particular dread.



- ‘*Societal risk*’ generally refers to hazards that, if realized, could impact society and thus cause socio-political response. Societal risk may be seen as a relationship between the frequency of a particular hazard and number of casualties if the hazard is realized. In applications dealing with hazards from engineered installations where the predominant issue is life safety, societal risk is characterized by graphs showing frequency of events that could cause multiple fatalities.

### 2.2.1 Explicit Individual Risk Criteria

Formulation of risk criteria can be guided by historical data on the activities being assessed, natural risks, and other sources of risk. Risk levels are then compared to those from natural sources, and a factor  $\gg 1$  is applied.

Many countries maintain databases on causes of death to their citizens. These data can be compiled to form a statement of what a particular community has historically accepted as reasonable risk. As an example, NSW Department of Planning has published an advisory paper (NSW Department of Planning, 1992) that outlines the criteria by which the acceptability of risks associated with potentially hazardous developments should be assessed. The criteria for individual fatality risk for the public exposed at new installations varies from  $5 \times 10^{-5}$  for industrial land use to  $5 \times 10^{-7}$  for hospitals, schools, child care facilities, old age housing.

Similarly, the Australian Geomechanics Society (2000) in their guidelines on landslide risk management suggests  $10^{-4}$  as tolerable risk for existing slopes and  $10^{-5}$  for the new slopes, and the NSW Dam Safety Committee (2006) imposes a limit of tolerability of the risk to an individual, after ANCOLD (2003), as  $10^{-4}$  for existing dams and  $10^{-5}$  for proposed dams or major modifications.

In Hong Kong, GEO (1998) recommends the maximum allowable individual risk level from natural terrain landslides and boulder falls to which any member of the public should be exposed is  $10^{-4}$  and should not exceed  $10^{-5}$  for new developments.

Vrouwenvelder et. al (2001) quotes that in developed countries the annual risk of a person under 60 years of age dying from natural causes is about  $10^{-3}$  per year. The probability of losing life in normal daily activities is in general one or two orders of magnitude lower than that. Other activities may entail much higher risk (e.g., rock climbing) and people do that voluntarily. He proposes to use  $10^{-4}$  as a reference number, leading to a formula:

$$P(\text{Loss of Life}) \leq \beta \times 10^{-4}$$

Where  $\beta$  depends on the degree of voluntariness and the benefits received. The lowest acceptance values (0.01 to 0.1) can be assumed for activities that are involuntary and of no benefit to the person at risk. Jonkman et al. (2002) indicate that the same formula as proposed by the Dutch Technical Advisory Committee on Water Defenses (TAW, 1985) and Bohnenblust (1998) was further developed by Vrijling et al. (1998) who proposed that the values for  $\beta$  can be selected from as low as 0.01 (involuntary risks for people having no benefits) to as high as 100 (entirely voluntary risk and direct benefits).

Goossens and van Gelder (2002) state that for complex societal systems as a whole, individual risk varies between  $10^{-4}$  and  $3 \times 10^{-3}$  (occupational, traffic, and consumer’s risks). In some cases of critical infrastructure (for example high speed train links), individual risk criteria are set in the Netherlands as  $4 \times 10^{-6}$  for passengers and  $10^{-6}$  for people living near the tracks or passing by.

In 1999, the Risk-Based Explosives Safety Criteria Team (RBESCT) on the request of US Department of Defense developed the Universal Risk Scales to assist in the task of selecting appropriate criteria for defining “how safe is safe enough?” In their report Pfitzer et al. (2007) summarize legal precedents and standards that contain criteria for risk acceptance. The report quotes the following regulatory standards for individual involuntary risk:

- Swiss Ammunition Storage (Swiss Technical Requirements for Storage of Ammunition, 1999) –  $10^{-5}$  fatality risk per year for non-participating third person
- Israeli MOD Launch Operations (RCC Standard 321-97, 1997) –  $10^{-5}$  as established by Israeli Ministry of Defense for the maximum annual individual fatality risk from launch operations for the non-participating, un-informed general public.
- Future nuclear power plants (HSE, 1992) –  $10^{-5}$ .
- Nuclear power plants (HSE, 1992) –  $10^{-6}$  stated as “broadly acceptable risk to an individual of dying from some particular cause” or in other words, “the level of risk below which, so long as precautions are maintained, it would not be reasonable to insist on expensive further improvements to standards”.
- Nuclear power plants and chemical industry facilities in the Netherlands (RCC Standard 321-97, 1997) –  $10^{-6}$  as acceptable risk standard used by Dutch industries for public individual fatality (for existing facilities) and  $10^{-8}$  as acceptable risk standard used by Dutch industries for public individual fatality (for future facilities).

Summarizing discussion of how tolerability criteria have developed in the past in different countries and in different hazardous industries can be found in (Hartford et. al., 2004).

### 2.2.2 Risk Criteria Derived from Standards

Often, explicit risk criteria are not available because the safety issues in a specific jurisdiction are governed thorough establishing standards. If standards are defined by Annual Exceedance Probabilities (AEP) the intended life safety risk criteria can be inferred from such standards. They may be inconsistent if the standards for different types of loadings are established using different criteria.

In Canada, for seismic induced failures of buildings, the National Building Code of Canada (2005) states that “the peak ground acceleration (PGA) and the 5% damped spectral response acceleration values  $S_a(T)$  are based on a 2% probability of exceedance in 50 years.” This value is equivalent to AEP values of  $4 \times 10^{-4}$  and if in the absence of additional analysis, conditional probabilities of failure providing the event occurred and conditional probability of fatality providing that failure occurred are conservatively assumed to be 1, then the individual risk inferred from the standard is also  $4 \times 10^{-4}$ .

In some countries standards defining requirements for Inflow Design Flood<sup>1</sup> are based on floods with a given return period. Using similar reasoning, acceptable risk can be derived from the AEP values by assuming that the IDF causes dam failure and the failure causes at least a single fatality. In general, a proper estimation of probability of loss of life can be obtained from the following formula (CDA, 2007):

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<sup>1</sup> In some countries the Inflow Design Flood is the flood whose exceedance results in dam overtopping. In other countries such flood is called Safety Check Flood (SCF). Considerations of this Section assume that the term IDF should be understood as a flood which if exceeded results in dam overtopping.

$$P_{LOL} = P_{IDF} \times P_{DamFailure/IDF} \times P_{Fatality/DamFailure}$$

Where:

$P_{LOL}$  is the probability of fatality for maximally exposed individual from a flood event equal to or exceeding the IDF;

$P_{IDF}$  is the unconditional probability that a flood equal to IDF or larger will occur;

$P_{Dam\ Failure/IDF}$  is the conditional probability that the dam will actually fail, given the flood;

$P_{Fatality/DamFailure}$  is the conditional probability of loss of life, given dam failure.

The assumption that both conditional probabilities are equal to 1 (which means that dam failure always results in fatality for the maximally exposed individual and that any case of dam overtopping always leads to dam failure) reduces the above formula to:

$$P_{LOL} = P_{IDF}$$

Clearly, this assumption may sometimes be a correct one but it also may be a very conservative one in other cases. In the first case the above equation holds; in the latter one the product of conditional probabilities is less than 1 and as a result  $P_{LOL} < P_{IDF}$ . Thus, if for example, IDF is a 10000 year flood, then

$$AEP = P_{IDF} = 10^{-4}$$

and finally,

$$P_{LOL} \leq 10^{-4}$$

### 2.2.3 Societal Risks Criteria

Societal risk is more elusive than individual risk. One of the most exhaustive reports on societal risk in hazardous industries (Ball and Floyd, 1998) states that,

*One of the problems with societal risk has been the term itself, which, as with the word risk means different things to different people at different times, leading to some misunderstanding and confusion. For instance, from an engineering perspective, societal risk is often regarded as no more than a relationship between the frequency and number of people suffering a specified level of harm from a particular hazard. Alternatively, other sees societal risk as a much broader concept incorporating many other dimensions of harm, in some cases even the socio-political response in the aftermath of major accidents, or even lesser accidents where these might give rise to a significant expression of public concern.*

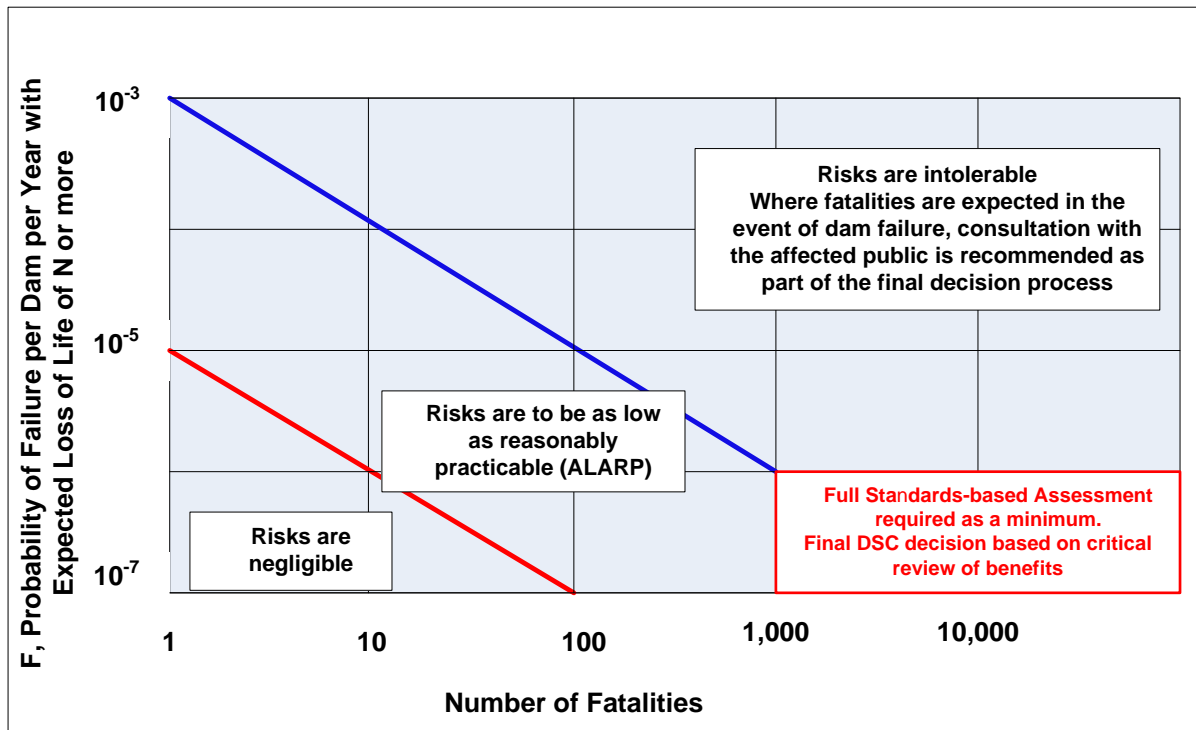
In general, societal risk refers to hazards that, if realized, could impact society beyond the individual and thus causes socio-political response. Some see societal risk as simply a relationship between the frequency of a particular hazard and number of casualties if the hazard is realized. Others understand the societal risk as “a much broader concept incorporating many other dimensions of harm, in some cases even the socio-politic response in the aftermath of major accidents, or even lesser accidents where these might give rise to a significant expression of public concern” (Ball and Floyd, 1998). ICE (1985) defines societal risk as “the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards”.

In applications dealing with hazards from engineered installations where the predominant issue is life safety, societal risk is often characterized by frequency-number (F/N) curves. These graphically display the potential for multiple fatalities by relating cumulative frequencies or probabilities (F) against number of casualties (N) on log-log plots. An example of the risk criteria for existing dams in the New South Wales is demonstrated on Figure 2.

Other measures are also used, depending of the nature of application. Piers (1998) defines the aggregated weighted risk (AWR) through integration of number of households and their individual risk measure over the affected area. Laheij et al. (2000) calculates the expected value of the number of fatalities by integrating the individual risk measures and the population density in the affected area. Carter (1995) defines a so-called Risk Integral, which accounts for characteristics of the affected areas and individual risks.

**Figure B2 - NSW DSC Societal Risk Requirements for Existing Dams**

(NSW Dam Safety Committee, 2010)



### 2.3 Demonstration of ALARP

The essence of the demonstration that risks have been reduced ALARP is to show that the costs of implementing of risk reduction measures would be grossly disproportionate to the benefits accrued. The term 'costs' is used here in a broad sense and does not preclude that non-monetary valuation can be applied in specific cases. It is also worthwhile to point out that the demonstration does not necessarily mean that a comprehensive risk analysis is required. It also does not mean that a quantitative argument based on

estimation of risks is always necessary. The objective is to design and perform an analysis which is fit for the purpose and is appropriate for a particular system or structure. Sometimes a qualitative analysis based on engineering principles and sound engineering judgment may be sufficient in demonstrating the case. It should however be noted that for the complex engineering structures or systems where there are significant hazards present, a comprehensive risk analysis and assessment study will need to be performed.

It has to be pointed out that HSE's position on ALARP demonstration is that the cost/benefit analysis of implementation of risk reduction measures alone is insufficient in demonstrating that ALARP principle is satisfied. The position of HSE on this issue as reflected in (HSE, 2001) is that full range of other considerations that include good practice and societal concerns need to be taken into account. Section 2.3.3 provides a brief characterization of societal concerns.

### **Cost Benefit Analysis (CBA)**

The most common analytical tool used for ALARP demonstration is Cost Benefit Analysis, which provides a quantitative evaluation of the benefits and costs of any decision by expressing these in monetary terms. There is no single CBA methodology but a family of methods sharing a common philosophical origin: namely, the value of a decision equals expected benefits minus expected costs, both expressed monetarily. Because all costs and benefits are expressed in a common currency, comparison can be made. Thus, the essence of CBA approach is the transformation of all benefits and costs into monetary values in order to determine what the maximum amount the society is willing to pay for accrual of benefits. The procedure is straightforward for the market goods but its application to non-market attributes is more difficult. Life safety valuation serves as an example since there is no clear market to determine the value of human life.

Treasury Board of Canada (TBCS, 1998) provides a guide on conducting cost-benefit analysis for the purpose of demonstrating the ALARP principle. It states that there is no universal or simple 'cookbook' for benefit-cost analysis and each analysis is different, demanding careful and innovative thought. However, it provides a standard sequence of steps that needs to be followed to ensure consistency. These steps are:

1. Examine needs and constraints; define the components of costs and benefits
2. Define the options to be considered
3. Analyze incremental effects; gather data about the costs and benefits
4. Express cost and benefit data in monetary units
5. Estimate the net present value
6. Conduct sensitivity analysis
7. Estimate expected net present value

The general principles of applying CBA are relatively straightforward assuming that all benefits and costs are deterministic. The net present value (NPV) of all costs and benefits can be found as the sum of discounted flows of costs and benefits over the presumed lifespan of the structure. If uncertainties are not included in the analysis, an NPV greater than zero indicates that the proposed alternative offers potential improved in terms of safety as the benefits exceed the costs.

The general formula can be expressed as:

$$NPV = \sum_{i=1}^N \frac{B_i - C_i}{(1+r)^i}$$

where:  $N$  is the length of the evaluation period (usually the structure's lifespan), in years;  $r$  is the discount rate;  $B$  and  $C$  are respectively benefits (for example, avoided loss of life) and costs related to the alternative being analyzed.

The above formula represents the Net Present Value which is often considered as the most straightforward form of cost-benefit analysis.

An alternative measure commonly used for example in both the United States and Canada is the Benefit-Cost Ratio:

$$BCR = \frac{\sum_{i=1}^N \frac{B_i}{(1+r)^i}}{\sum_{i=1}^N \frac{C_i}{(1+r)^i}}$$

Since in most applications  $r$ ,  $B$  and  $C$  are uncertain and require to be interpreted as random variables rather than deterministic constants, the equation for NPV should be modified to:

$$E[NPV] = E \left[ \sum_{i=1}^N \frac{B_i - C_i}{(1+r)^i} \right]$$

Or

$$E[NPV] = E \left[ \sum_{i=1}^N \frac{B_i}{(1+r)^i} \right] - E \left[ \sum_{i=1}^N \frac{C_i}{(1+r)^i} \right]$$

where  $E$  is the expectation operator.

It should be noted that the manipulation of the original equation in order to obtain the expected value of  $BCR$  is not simple because of the issues of statistical dependence between the random variables present in the numerator and the denominator of the original formula.

The annual benefit accruing from lowering the probability of a loss from  $p$  (the annualized probability of incurring the loss without implementing the alternative) to  $q$  (the annualized probability of incurring the loss with the alternative implemented) can be expressed as  $L(p-q)$ . For the case of  $r$ ,  $B$  and  $C$  assumed to be deterministic the expected benefits realized over the evaluation period can be expressed as:

$$E[B] = L(p-q) + \sum_{i=1}^N \frac{L(p-q)}{(1+r)^i} (1-p+q)^{i-1}$$

The calculations of  $E[B]$  become more complicated when  $r$  and  $B$  are non-deterministic and depending on the assumptions about probability distributions of random variables involved, analytic formulas may be not available. Monte Carlo simulation of expanded version of the above equations can provide adequate answers in such cases.

### 2.3.2 Cost Effectiveness Analysis (CEA)

Cost effectiveness analysis is an analysis where the terms reflecting expected cost per expected value of statistical life are calculated and used for decision making. This approach was first proposed by Rowe (1997)

and applied by Bowles (2003) to ALARP evaluation is dam safety. The evaluation of the effectiveness of proposed risk reduction measure is based on a cost effectiveness measure called the Cost to Save Statistical Life (CSSL). Two different measures of CSSL derived from the procedure developed in (Bowles, 2003) and recommended by Australian Guidelines on Risk Assessment (ANCOLD, 2003) are:

- Unadjusted  $CSSL_U$  calculated as:

$$CSSL_U = \frac{C}{E[LOL_I] - E[LOL_R]}$$

Where:  $C$  is the annualized cost of risk reduction option implementation; and operator  $E$  indicates expected values of annualized life loss before  $[LOL_I]$  and after option implementation  $[LOL_R]$ .

- Adjusted  $CSSL_A$  calculated as:

$$CSSL_A = \frac{C - (E[RC_I] - E[RC_R]) - (E[O_I] - E[O_R])}{E[LOL_I] - E[LOL_R]} \quad (\text{Or 0 if negative})$$

where: the expectation operator  $E$  is applied to annualized values of existing risk cost (product of the dam failure probability and owner's economic loss),  $RC_I$ , residual risk cost after implementing the option,  $RC_R$ , existing operating cost,  $O_I$ , and post-implementation operating cost,  $O_R$ .

$CSSL_A$  accounts for the extent to which the cost of risk reduction measures is offset by the expected value of the owner's financial loss and any reduction in annual operating costs. The Guidelines also indicate that the original procedure recommends using unadjusted  $CSSL_U$  only for initial prioritization of risk reduction measures and to use adjusted  $CSSL_A$  as a basis for judging compliance with the ALARP requirement.

### 2.3.3 Disproportionality

Although any considered risk reduction measure involves some costs to the Responsible Entity, its implementation is expected to reduce the risk from dam operation and bring benefits (for example, reduction in loss of life or improved life safety). The ratio of the costs to benefits is often defined as the disproportionality factor  $D$ . If the factor is greater than some pre-defined and broadly accepted value, then the costs can be understood as grossly disproportionate to the benefits and the risk reduction measure can be declared not to be reasonably practicable. (HID, 2004) provides the following framework on the disproportionality factor determination.

It assumes that within tolerable region (Zone 2 on Figure 1) the minimum value of  $D$  should be 1, otherwise the bias against safety could be argued. It also assumes that the value of  $D$  should increase as the risk increases. It can be interpreted that it would be reasonable to expect the dam, owner to spend more on risk reduction if the initial level of risk is close to intolerable level, and spend proportionally less if the initial risk is just above the broadly acceptable limit. In the region of intolerable risks (Zone 1) the owner is required to spend whatever is necessary to reduce the risk, regardless of cost, implying very high or even infinite  $D$ . The concept is explained on Figure 3.

HSE (1992) provided the following guidance on practical determination of  $D$ :

*The process of determining whether a benefit is sufficient to justify a cost depends on a judgment as to what constitutes 'gross disproportion'. This in turn depends on the prior level of*

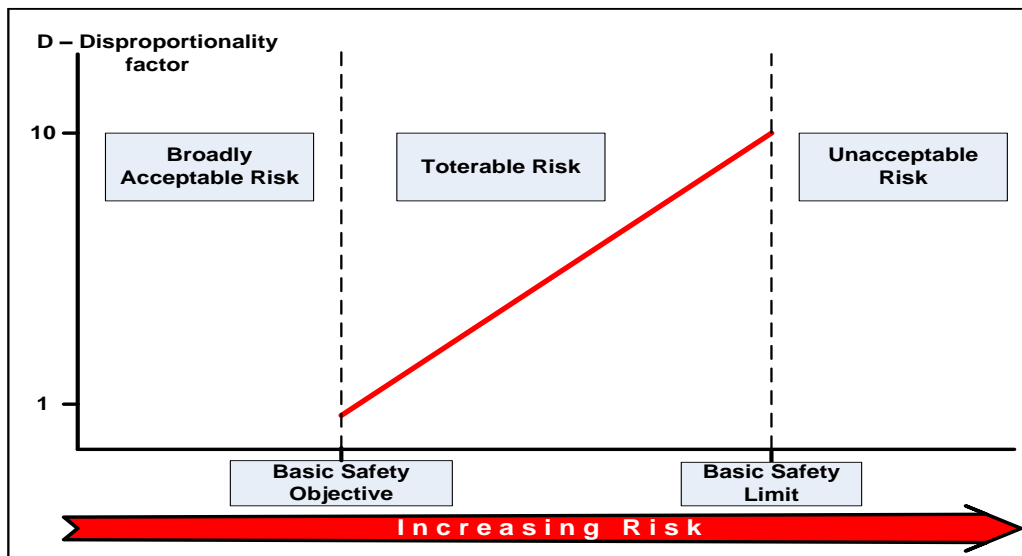
risk. Where this is above the 'broadly acceptable level', 'gross disproportion' essentially takes the form of a multiplier applied to the value of the health and safety benefits and increasing with the level of risk. Precise values for this multiplier have never been defined by the courts and neither the regulator nor the regulated have sought this; both recognize the drawbacks associated with trying to regulate by means of (arbitrary) numbers. Where there are smooth continuous safety cost functions this framework does not provide sufficient information to decide at what point the additional costs become 'grossly disproportionate' to the extra health and safety benefits. However, in most cases there will be discontinuities in the marginal safety cost function or points where rapidly diminishing marginal returns set in. At such points it will usually be fairly easy to decide, by comparing the marginal costs and benefits of further safety improvements, that any extra expenditure would be excessive relative to the increment in health and safety benefits.

HSE (2005) provides more detailed guidance on selecting **D**. Although it states that "...there is no precise legal factor or HSE algorithm for gross disproportion" it further recommends that **D** be determined on the basis of existing evidence in the following way:

*For risks to the public the factor would depend on the level of risk, and where the risks were low (consequence and likelihood) a factor of about 2 is suggested, whereas for higher risks the factor would be about 10 times... For our purposes, it is suggested that a factor of less than 10 in the vicinity of the intolerable region is unlikely to be acceptable and, for hazards that can cause large consequences, the factor may need to be larger still.*

The values of **D** suggested by HSE may be appropriate for some countries and jurisdictions but may also be totally inadequate for others. In general, the willingness to accept higher values of **D** at the upper end of the scale would be of interest to these jurisdictions where the overall wealth of the country provides political support for high levels of safety. In other countries, where the resources available are very limited, other societal and political goals may cause that the values suggested by HSE are not achievable.

**Figure B3 - Change of Disproportionality Factor with Risk (HSE, 2005).**





Zone 3 risk (broadly acceptable) does not require any guidance on establishing disproportionality factor and by implication its value can be assumed to be zero. However, the Responsible Entity may still decide to initiate some upgrades if any obvious and inexpensive measures are available.

### **Societal Concerns**

The term 'societal concerns' includes a broad range of disparate entities. HSE (2002) report which provides a detailed characterization of all issues related to societal concerns is briefly summarized below. It states that societal concerns are generated by many different groups within society and are motivated by numerous factors besides 'pure' risk (such as ethical and political beliefs, values, procedural issues, and political, commercial, social and professional self-interests and ways of working. HSE (2001) describes the term as follows:

*The risks or threats from hazards which impact on society and which, if realized, could have adverse repercussions for the institutions responsible for putting in place the provisions and arrangements for protecting people, e.g. Parliament or the Government of the day. This type of concern is often associated with hazards that give rise to risks which, were they to materialize, could provoke a socio-political response, e.g. risk of events causing widespread or large scale detriment or the occurrence of multiple fatalities in a single event. Societal concerns due to the occurrence of multiple fatalities in a single event are known as 'societal risk.' Societal risk is therefore a subset of societal concern.*

Societal concerns can be separated into the following 12 groups characterized by the underlying nature of a concern as follows:

#### Concerns associated with the hazard

1. The associated risk is genuinely high or believed or predicted to be high.
2. The hazard, or the way it is controlled, impinges adversely on some other aspect of life or the common good which is valued.

#### Concerns caused by differing value systems

3. The associated activity is inherently undesirable because it infringes the ethical considerations of one or more stakeholder groups.
4. The hazard is not being properly handled - failure to comply with legal requirements - does not accord with a specific group's beliefs about how hazards should be managed.
5. The activity is undesirable because some believe there are more important goals.

#### Concerns caused by the way the hazards are being managed

6. Consultation between risk managers (duty holders) and risk bearers is inadequate.
7. Confidence of stakeholders in one another is poor - lack of trust.
8. Risk amplification has occurred - activities of a particular group(s) give prominence to an issue.
9. Lack of concern about a risk (risk attenuation) - apathy; powerlessness (real or imagined).
10. The same ends can be achieved by alternative and better means.

11. Failure to consider risk transfers.

Stakeholder-derived concerns

12. A stakeholder group (not necessarily the public) has promoted an issue according to its own beliefs or needs.

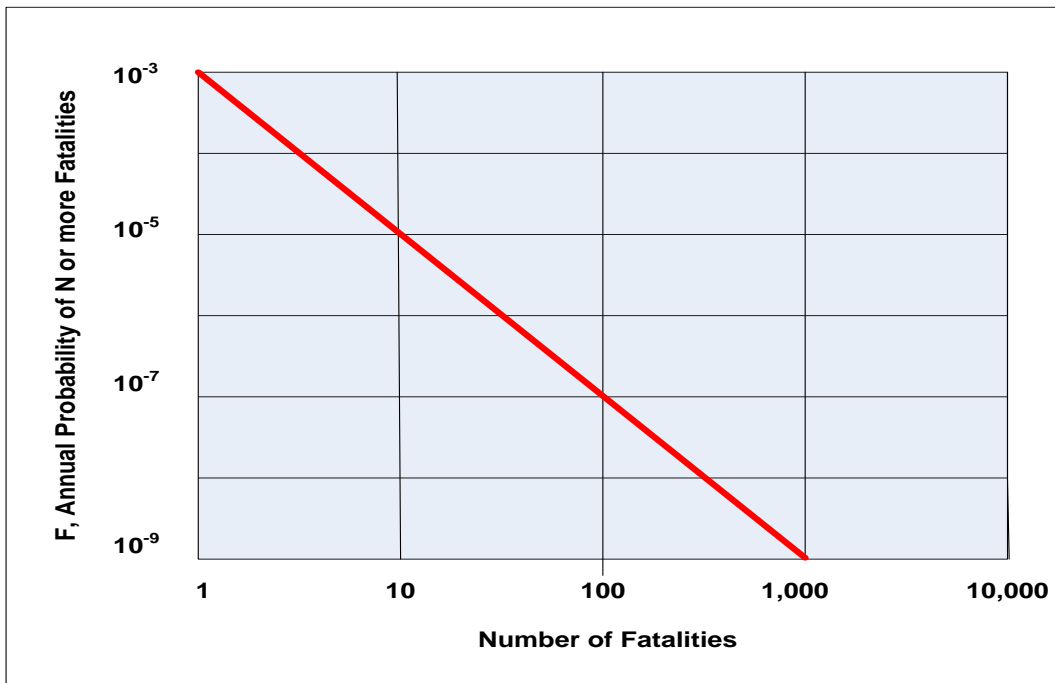
Societal risk can be quantified and considered in an explicit manner as explained in the previous section. Other societal concerns can be addressed qualitatively.

### 3. Alternative Safety Decision Making – Explicit Consideration of Risk

#### 3.1 Legal Framework Considerations

The general legal framework has a profound impact on decision-making mechanisms with the explicit consideration of risk. The decision-making scheme outlined in the previous section was developed under the common law legal system in the United Kingdom providing a consistent and logical framework for quantitative risk analysis and risk evaluation utilizing a set of quantitative risk criteria. The criteria precisely define in numerical terms what individual and societal risks can be considered as unacceptable and acceptable, leaving a spectrum of risk (ALARP region) where tolerability of risk can be established using judgmental approach.

**Figure B4 - Societal Risk Criteria in the Netherlands (Ale, 2005)**



In contrast to this approach, Dutch land-use regulations (established within the Roman/Napoleonic civil code framework) for hazardous industrial activities have legally binding end-points clearly separating the risks into two subsets of acceptable and unacceptable risks. Criteria for individual risk differ for vulnerable and less vulnerable objects. For vulnerable objects (residential areas, hospitals and schools) the legally binding limit is

$10^{-6}$ . For less vulnerable objects (office buildings, hotels, restaurants, shops, recreation facilities, etc.) the limit is  $10^{-5}$ .

Societal risk criteria (see Figure B4) which are not legally binding can be considered as guiding values for planning authorities which have to explain how the societal risk were accounted for in the planning process. Similarly to individual risk criteria, there are only two subsets of risks, acceptable (below the line) and unacceptable (above the line).

Thorough discussion of legal system implications on risk criteria and risk-informed decision making can be found in Hartford (2009) who also points out that

*One of the most striking differences between the two systems is that in terms of the common law system, what is not explicitly allowed is forbidden, unless it can be justified to the regulator or where necessary in court after the fact; whereas, in terms of the Roman/Napoleonic system, everything that is not explicitly forbidden is allowed. This important distinction leads to completely different interpretations of the meaning of “As Low As Reasonably Practicable” under the different legal systems, where the notion of ALARP would merely be a token statement under the Roman/Napoleonic system. These differences of legal definition mean that “seemingly different” or “seemingly similar” measures or metrics can lead to completely different conclusions*

Ale (2005) and Ale and Piers (2000) succinctly state that the concept of tolerable risk and ALARP is moot in the Dutch risk regulations and if the regulators desire higher levels of safety, they have to establish stricter limits. From a practical point of view, there is no requirement and no justification for application of ALARP and gross disproportionality principles (which lead to continual improvement of safety).

### **3.2 Disproportionality and ALARP Justification**

Munger et al. (2009) provides another modification to the approach proposed by HSE in setting interim tolerable risk guidelines for USACE dam safety risk management framework. Individual and societal risk guidelines as well as annual probability of failure guidelines are presented on Figures 5, 6 and 7.

Figure B5 - Individual and Societal Risk Guidelines for Existing Dams (Munger, 2009)

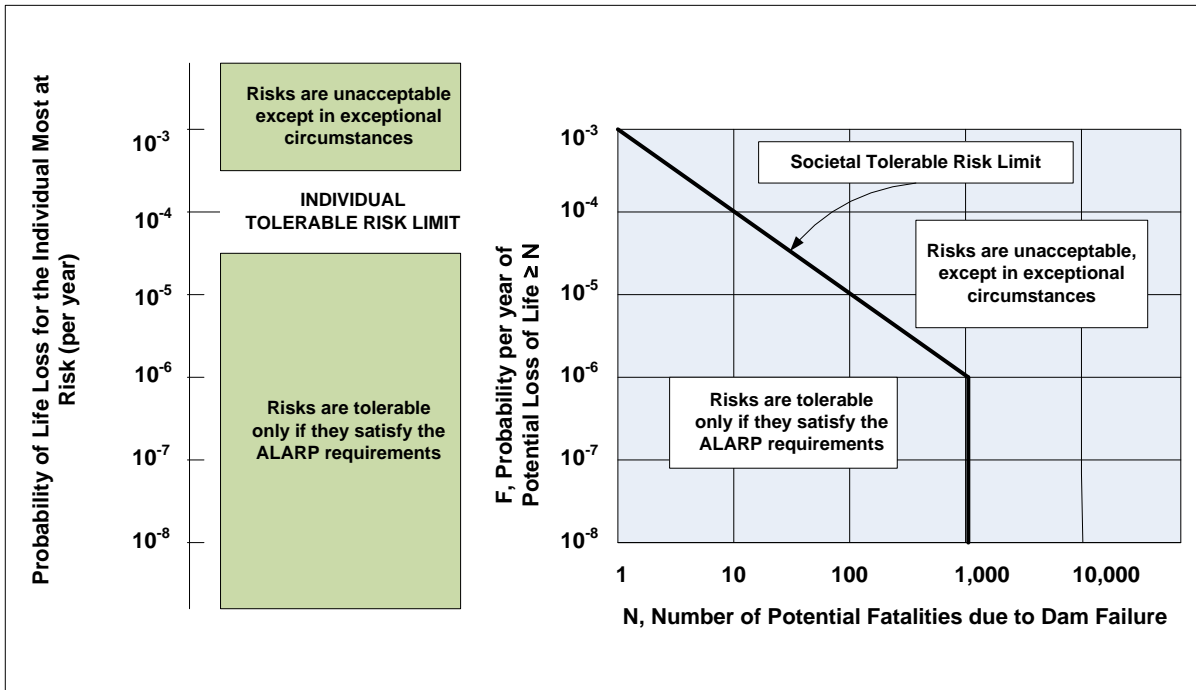


Figure B6 - Individual and Societal Risk Guidelines for New Dams (Munger, 2009)

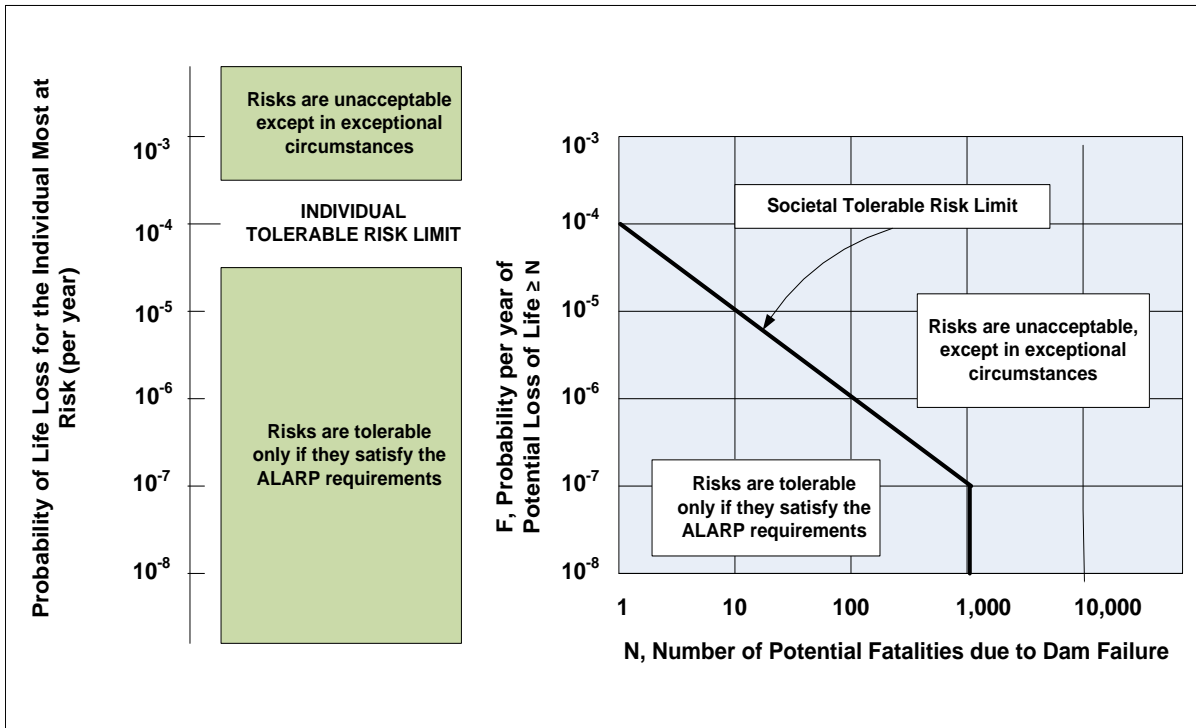
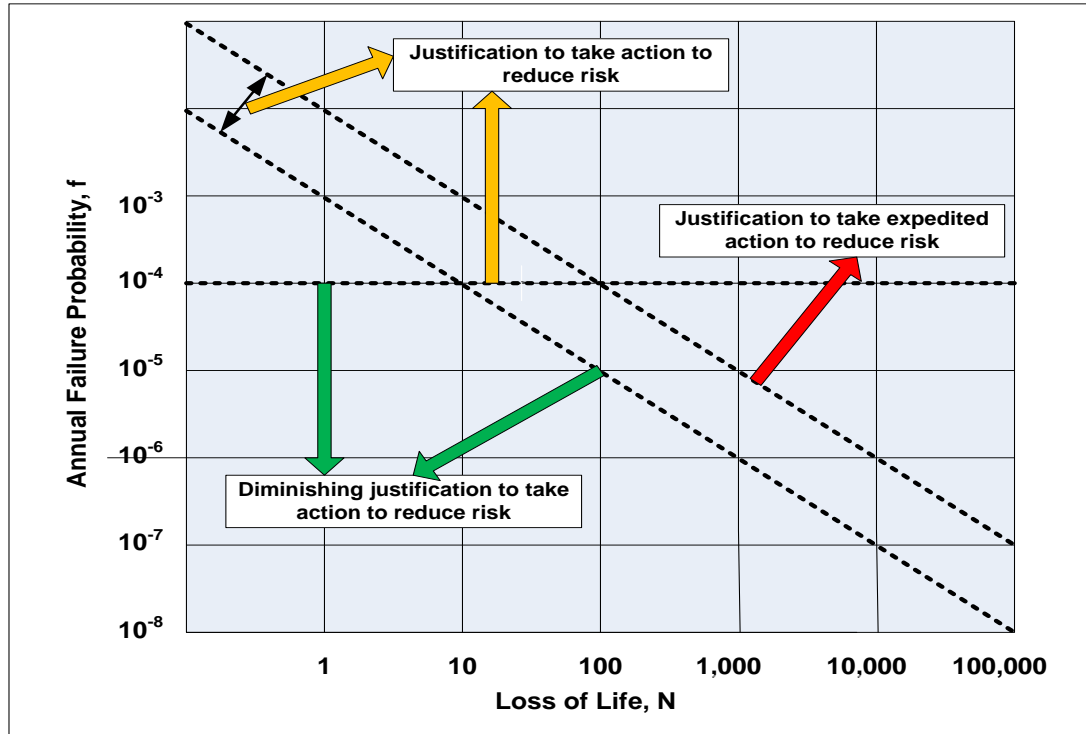


Figure B7 - Annual Probability of Failure and Annualized Life Loss (Munger, 2009)



There are two distinctive features of this approach which differ significantly from the model presented in the previous section. Firstly, broadly acceptable risk zone (equivalent to negligible risk zone on Figure 2) is absent from the criteria. Justification provided states that because of the nature of the hazards dams pose to the public the risks cannot be regarded as insignificant or trivial.

Secondly, the interpretation of the ALARP principle based on cost-effectiveness philosophy leads to a very different outcome in risk reduction justification. Consider the following example. A risk reduction option has a cost (TC) of \$160 million and if implemented can result in saving of (n) 8 lives. If the VSL value is \$5 million, then the disproportionality factor is:

$$D = \frac{TC}{n \times VSL} = \frac{160}{8 \times 5} = 4$$

If the current risk is close to the unacceptable zone, the approach states that there is only moderate justification for proceeding with the risk reduction option (see Table B - 1).

**Table B.1 - ALARP Justification for Risk Just Below Tolerable Risk Limit (Munger, 2009)**

ALARP Justification Rating	Range of Disproportionality Ratios	
	Greater than or equal to	Less than
Very Strong	0	1
Strong	1	4
Moderate	4	20
Poor	20	

HSE (1992) guidance on practical determination of  $D$  would produce a different outcome. Since the risk is close to the tolerability limit only the values of  $D$  close to 10 would be considered as grossly disproportionate.

## 4. Programmatic Decision Making

This type of decision making has mostly to do with various prioritization tasks in support of safety decisions. By prioritization we usually understand rank ordering of a set of items (alternatives, options) according to an assumed metric which reflects priority. Depending on the way the risk is approached within the decision-making framework, the programmatic decision-making approach will differ substantially.

The term 'priority' is often understood intuitively but the exact interpretation of the term depends on the context within which it is defined. It may be defined in a number of ways, for example 'precedence', 'rank', 'urgency', 'consequence', 'importance' or even some combinations of these terms. 'Setting priorities' is another term which without the context may mean different things. For example, resources prioritization would establish the order in which available resources (which may include financial or manpower resources or both) are spent on issues under consideration. Temporal prioritization would establish the order among the issues being considered by defining which ones take precedence over the others.

The need to establish priorities arises at many levels of decision making and in different areas of dam operation. The consideration of this section is restricted to these activities which affect dam safety management.

### 4.1 Implicit Consideration of Risk

Traditional dam safety management approach that does not attempt to quantify the risk has relatively simple ways of addressing dam safety deficiencies.

For a single dam with a single deficiency (for example, performance not meeting standards) a programmatic decision is quite straightforward: the deficiency has to be corrected and the cost of achieving the compliance with the standard is driving the process of selecting the most appropriate alternative.

A single dam with multiple deficiencies presents a slightly more complicated process. In the absence of the common metric characterizing the magnitudes of individual deficiencies, it is difficult if not impossible to precisely establish the rankings within the set of deficiencies. For these of the deficiencies which have to do with non-compliance with the standards, the metric can be established based on the relative magnitude of the gap between the standard and the performance. However, for these non-performances that are not related to standards the available option for the decision makers is to establish the rankings on the basis of judgment, experience and other appropriate subjective criteria. Prioritization will have to address both temporal and financial issues. Some of the identified deficiencies may be more urgent to deal with than others and the extent of fixing may depend on available resources and funds.

Multiple dams or so-called portfolios of dams present additional complications to the decision-making process by the fact that the temporal and financial prioritization may need to be extended to a number of dams, each one with very different safety issues. The lack of a common metric in measuring the magnitudes of deficiencies and the necessity to resort to more subjective and judgmental assessment adds to the complication.

## **4.2 Explicit Consideration of Risk**

Making programmatic decisions when the safety decisions are made on the basis of explicit consideration of risk is easier, more consistent and transparent. A single performance metric, that is the total or absolute risk as determined for each dam, provides a complete characterization of the safety status and also the guidance with regard to necessity of risk reduction actions.

If a dam presents an unacceptable risk (whether individual or societal), risk reduction measures have to be implemented in order to bring the residual risk to at least a tolerable level. If a number of dams in the portfolio have the associated risks at the unacceptable level, all these risks have to be reduced to at least a tolerable level. Prioritization scheme of risk reduction activities for this sub-set of dams can be developed by:

1. Ranking the dams by the magnitude of risk 'unacceptability' ("worst-first" list) which can be measured by the distance to tolerability threshold. If the owners' resources are insufficient to address all dams at once, the ranking will provide the order in which improvements will be made.
2. Ranking the dams by cost-effectiveness of risk reduction which provides the owner with maximization of benefits (risk reduction) for the resources available.
3. Ranking the dams by probability of failure which provides the owner with the 'urgency ranking' if the avoidance of dam failure is of the highest priority.

In principle, there is nothing which prevents the Responsible Entity from considering multi-attribute decision-making framework which takes into account all three prioritizing schemes with appropriately assigned weights. In practical situations some of the schemes will be preferable to others since the numerical value of risk is only one of many attributes in risk management. However since the dams in question present unacceptable risk it seems that schemes 1 and 2 would be preferable.

For a portfolio of dams with all structures below the limit of tolerability prioritization the scheme 3 would offer the best effectiveness of the risk reduction program, providing that the structures form a relatively tight cluster. However, if the disproportionality factors for the dams in the portfolio vary significantly, the prioritization scheme based on

4. Ranking the dams by disproportionality factor reduction.  
should be considered first.



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