Chapter 6

Dam-break risk management and hazard mitigation

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Abstract

Despite the increasing safety of dams due to improved engineering knowledge and better construction quality, a full non-risk guarantee is not possible and an accident can occur, triggered by natural hazards, human actions or loss of strength capacity of the dam due to its age. Some contemporary safety legislation and technical guidelines promote and support dam-break flood risk management, which is an important contribution to public safety along the downstream valleys as well as to the protection of economical and environmental resources.

There are two important phases in dam-break risk management: predicting the losses or damages and their likelihood, through risk assessment, and finding the appropriate mitigation measures, when residual risks are not acceptable.

Dam-break risk assessment defines the magnitude of the flood hazard that may occur due to a dam failure, estimates its main consequences and evaluates its significance. To assess this type of risk, it is generally necessary to undertake an integration between the dam reliability analysis, in order to evaluate the probability of dam failure and numerical dam-break flood simulations, in order to estimate the potential damages. Predicting the effects through flood simulation allows to identify the flood-prone areas, the flood path and magnitude and aims to assess valley vulnerabilities as well as losses and damages.

Hazard mitigation aims at organizing the prevention measures, namely safety control requirements, to be enforced at the dam site, and emergency preparedness measures, to be implemented in the downstream valley. Issues to be addressed are safety monitoring of dam, emergency planning and preparedness, early warning systems as well as rescue and relief measures for post-event actions.

Keywords: Risk, Risk Management, Risk Analysis, Risk Mitigation, Emergency Planning

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1 Introduction

Dam accidents, including the structure failure, are severe threats to life and property. Ageing of dams, changes in hydrologic conditions and increasing population in valleys justify increased attention to dam safety and valley management. Potential dam failures as well as the public pressure for a safer environment recommend in contemporary society the dam risk assessment and its reduction in downstream valleys.

In fact, as emphasized by Almeida and Viseu [1], the dam and the downstream valley must be considered as a combined system, in what concerns the risk induced by dam accidents, including both the dam-reservoir and downstream-valley systems.[1] An integrated risk management of both systems must be considered as a continuous and dynamic process during dam lifetime, namely in the dam design and construction phases.

Dam risk management is a consequence of two fundamental aspects: (i) a dam is always a potential hazard and (ii) there is a need to guarantee a reasonable and equitable safety to those involved, should an accident occur.

The process of dam risk management[2] can be considered as a consistent methodology based on a sequence of actions that need to be cyclically undertaken for downstream valley protection (fig. 1). Broadly speaking, the risk management process consists of two conceptually different parts (Plate [6]):

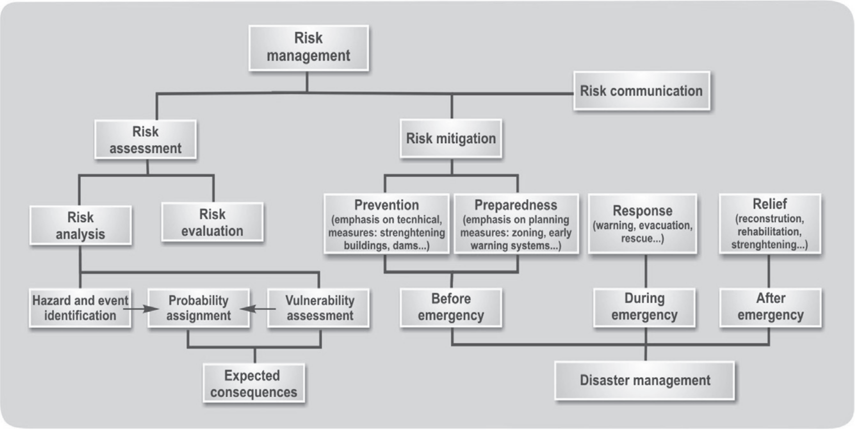

Figure 1: The dam risk management general process.

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[1] An integrated methodology was studied in a real Portuguese valley in the context of a NATO research program (Almeida *et al*. [2] and Almeida [3]).

[2] A complete overview of dam risk analysis, assessment and management can be found in Hartford and Beacher [4] and in the ICOLD Bulletin no. 130 [5].

the process of *risk assessment*, which is the process of updating the decisions regarding whether the existing risk is tolerable or not and the process of *risk mitigation*, which includes alternative risk control measures as the dam maintenance – *prevention* – and the land management and civil protection measures to be taken along the valley – *preparedness*.

The main purpose of a dam-break risk management and hazard mitigation is to reduce the expected human losses and the downstream damages related to dam accidents, through both structural and non-structural measures.

In *risk assessment*, the results of the risk analysis and risk evaluation processes are integrated and recommendations are made concerning the need to reduce the risk or to just control the residual risk.

Risk analysis provides an understanding of the nature and the extent of the uncertainty concerning the conditions under which the dam will be required to perform as well as the uncertainty in the response of the dam to those conditions. Risk analysis for dam safety is a structured process aimed at identifying both the extent and the likelihood of consequences associated with dam or dam component failures. A typical dam risk analysis incorporates different types of uncertainty:

the occurrence of some major event or hazard that may affect the dam safety and induce a dam break;

the prediction and characterization of the chain of events (scenarios) caused by a major event, including the physical response of the dam–valley system and the human response to the event;

the downstream valley vulnerability assessment through the prediction of the negative consequences (damages and losses) induced by a dam failure, including the number of lives lost, the economic damages and other possible adverse outcomes.

Risk evaluation is the process of understanding and judging the significance of the risk, including the comparison of the estimated level of risk with acceptance risk criteria. The main role of the risk evaluation phase is to generate decision guidance against which the results of the risk analysis can be compared. The process of supporting risk-based decisions requires a statement of the owner's safety management principles, values and preferences as well as those of the public, including consideration of the prevailing financial, legal and regulatory conditions.

Should the risk estimated by risk analysis be considered as not tolerable, resources are focused on the risk mitigation involving emergency planning: both internal, at the dam level (to reduce the probability of occurrence of an accident) and external, at the downstream valley (to reduce the loss of lives and the property damages). Therefore, methodologies and resources must be defined to enable the successful performance of the five general key aspects of an emergency plan: detection, decision, notification, warning and evacuation.

2 Dam-break risk assessment

2.1 Dam risk analysis

2.1.1 The general purpose of a risk analysis

The main purpose of risk analysis is the estimation of the value (or the level) of the risk induced by a dam (or a set of dams) to individuals or population, property or environmental assets. The quantitative risk analysis (QRA) makes possible a common metric for dam safety evaluation and ranking. Risk analysis is also the support for a risk-based management when the expected consequences due to management decisions are considered.

The estimated risk level will be the major variable for decision making related to dam and valley management actions or for the allocation of resources respecting a dam safety or a legal framework. However, dam risk analysis should not be the only element for decision. In fact, the dam safety and risk questions can be very important issues involving several political, ethical and economical constraints. The public perception can be a very crucial factor for the definitive decision concerning specific measures or a new dam investment.

The QRA pretends to quantify the possible losses due to a potential (future) and uncertain dam failure event. This implies different types of uncertainty in predicting the future performance of the dam(s), including the dam loading conditions due to different risk sources and factors, as natural hazards, man-made or induced hazards, dam structural weakness and the valley's physical vulnerability as well as the human actions and response.

The QRA process should be based on sound scientific and engineering knowledge and techniques. However, due to the uncertainties involved in the process, the risk estimation requires a reliable quantification of the likelihood of the estimated adverse consequences associated with the predicted dam-break scenarios.

Probability is a quantified statement of likelihood or level of confidence in the occurrence of a certain outcome. It is based on past experience or the expert degree of belief, and on personal experience and knowledge. Probability (P_r) is considered as a sound quantitative operator ($0 \leq P_r \leq 1$) to be applied to the estimated adverse consequences in order to obtain the expected consequences or risk value:

$$\text{Risk} = \left[\text{Probability } (P_r) \times \text{Consequences}\right] \text{ of potential failure} \tag{1}$$

By this definition, a risk value has the dimensions of the consequences related to the time interval associated with the probability of occurrence of the potential failure (e.g. euros/year).

2.1.2 Main contents of a dam risk analysis

It is assumed that the main goal to be considered is dam safety and failure. Consequently, the risk analysis is composed of three main parts:

system and hazard identification and definition;
dam-break scenario selection;
risk determination.

The first part consists of a clear identification of the dam reservoir and valley interacting components to be considered in the analysis, including the definition of their physical boundaries. The special definition of the system comprises the natural land topography and physical features as well as the constructed structures and the human, social and environmental sub-systems associated with the risk analysis.

The natural and non-natural hazards to be considered as risk sources need to be identified (e.g. floods, earthquakes, internal dam weakness or equipment malfunction) and defined, both in magnitude and in probability and by other specific characteristics considered relevant to the system response.

The building and selection of hazard scenarios is a fundamental part of the analysis. Each conceptual scenario comprises a selected combination of a hazard source and risk factors or system conditions that will frame the chain of outcomes (interlocked causes and effects) associated with the hazard pathway and impacts. The scenario analysis comprises:

hazard effects or loads acting on dams;
dam and reservoir response, including a partial or a total breach;
breach outflow and flood propagation or path along the downstream valley;
impact of the flood on the exposed components of the valley system;
valley system response to the flood impact (potential damages or consequences).

Each selected scenario is a possible hypothetical preview of 'how can a dam accident occur'. The likelihood of the successive events that are considered in each scenario will be quantified by their probabilities and will inform us 'how likely is it'. Finally, the estimated consequences of each dam-break scenario, namely those resulting from flood impacts, will inform us 'what damage would happen should such a scenario occur'.

Following a sound methodology of analysis applied to each dam-break scenario, *i*, it will be possible to obtain a quantitative determination or estimation of its risk, according to the general definition equation:

$$\begin{aligned}\text{Risk}_i = P_1(\text{load}_1) \times P_2(\text{response given the load } i) \\ \times (\text{consequences given the scenario } i)\end{aligned} \tag{2}$$

The load *i* is a simplified way to express the adverse conditions induced by a selected hazard or risk source combined with a set of selected factors associated with each dam-break scenario *i*. The research on the finding of response and structural failure modes and related probabilities in different types of dams (e.g. arch concrete or earth dams) is strongly recommended in what concerns the QRA framework.

The adverse consequences (damages) can be estimated in the following general way:

$$\text{Damages} = \text{Exposure} \times \text{Vulnerability} \times \lambda_{\text{r}} \tag{3}$$

where exposure (E) is a set of values under risk or exposed to the direct or indirect impact of the dam-break flood (human lives or property) and vulnerability (V) is the deterministic (or probabilistic) damage factor or damage level due to each specific hazard impact ($0 \le V \le 1$). A 'recovery factor' ($\lambda_{\text{r}} \ge 1$) can also be defined in order to consider the extra recovery costs that will surpass the replacement costs. For other types of damages (e.g. social trauma and cultural or environmental damages) similar concepts can also be considered.

2.1.3 Risk analysis methods and process

The principal methods available for conducting risk estimation are: (a) the failure modes and effects analysis (FMEA); (b) the event-tree analysis (ETA) and (c) the fault tree analysis (FTA). A detailed description of these methods can be found in Hartford and Beacher [4] and ICOLD [5].

2.1.3.1 FMEA FMEA is a method of analysis whereby the effects or consequences of individual components of failure modes are systematically identified and analysed. FMEA is based on the following main concepts:

failure, or when the component ceases to accomplish a required function;
failure mode, or the effect by which a failure is detected on a component of the system;
failure cause, or the events that lead to the failure modes;
failure mode effect, or the associated consequences related to the component failure.

FMEA is an introduction method that allows:

to identify the effects and the chain of events caused by each failure mode of the selected components of the system (dam);
to identify the importance of each failure mode on the dam operation and to evaluate the impact on the dam safety;
to rank the identified failure modes, according to their detection and treatment facility.

FMEA can be extended to include criticality (probability or frequency and severity) considerations (FMECA).

The method is very efficient for detecting simple component failures that can lead to the global dam failure. It is a very interesting tool to identify potential mode failures and evaluate their effects. FMEA can be completed with others methods of analysis.

2.1.3.2 ETA ETA is the most widely used method in dam risk analysis, according to Hartford and Baecher [4]. It is based on the event tree (fig. 2) that shows the possible logical sequences of causes and effects, induced by an initial hazard event or situation, towards a final event outcome (e.g. a dam breach or the final consequences or damages). 'The event tree can be considered as a determinant model of the binary functional states of the system where probabilities are assigned on a conventional way' (Hartford and Beacher [4], p. 47). By defining

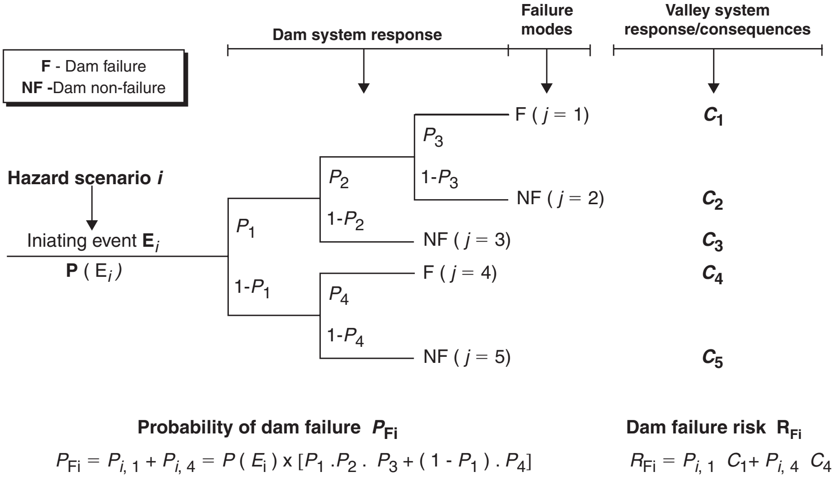

Figure 2: Simplified illustrative event tree.

probabilities for the initial events which start events of ($P(E_i)$) and conditional probabilities for each branch-off in the trees ($P(F_{jK}\,|E_i)$), it is possible to make an estimate of the compound probability $P_{i,j}$ for the sequence of events of each dam failure mode *j*, by multiplying together all the *k* conditional probabilities along that sequence *j* (fig. 2):

$$P_{i,j} = P(E_i)\,(\prod_k P(F_{kj}\,|E_i)) \tag{4}$$

ETA can easily show which sequences of events or modes are the major contributors to the dam breach probability. This constitutes an interesting tool for ranking prevention measures to reduce the dam failure probability and risk.

2.1.3.3 FTA FTA was one of the first methods to be developed for risk analysis. It is a logical diagram which graphically illustrates the combinations of faults which can lead to an undesirable event. It is a deductive analysis that is suited to quantify the probability of the undesirable event (e.g. a dam component failure) according to specific calculation rules.

2.1.4 The acceptance and difficulties of dam risk analysis

Risk- and standards-based approaches to dam safety procedures and decisions are often considered to be competing approaches, according to USBR [7]. In fact in some countries it is still very difficult to find an official acceptance of the practical importance of the dam risk analysis. This aspect is further clarified in USBR [7] (p. 6) by verifying that ‘risk-based approaches help decision makers to choose the appropriate course or action while standards-based approaches assure sound implementation of those actions’. In fact, applying standards to all dams ignores differences in the consequences, and their likelihoods, of dam failures at different sites or local conditions.

According to ICOLD [5] (p. 13), risk assessment is considered 'as an enhancement to traditional practice and not in any sense as a replacement'. In fact, their 'methods focus on relating performance levels to consequences and thus allowing the engineer to better demonstrate to decisions-makers the real human and economic risks associated with investment decisions'.

Risk-based approach can be very useful in what concerns the safety management of a portfolio of dams, because of the need to better allocate resources across multiple dams (Bowles [8]).

There are also other questions about the accuracy of a dam risk analysis such as those related to scenario choice and compound scenario criteria as well as to probability calculations and meaning: from a frequency approach, requiring a large number of similar trials (often hard to find), to probability as an expert's degree of belief (Hartford and Beacher [4]). For any computed value of risk or of probability, it will be important to characterize the uncertainties associated with those values: uncertainties due to natural variability of the input parameters or due to a lack of knowledge about the physical process as well as about the relevant hazard scenarios to be considered.

In practice, some types of uncertainty can be characterized by a sensitivity analysis, or by probability distributions of outputs (e.g. using Monte Carlo techniques).

In order to avoid some of the operational difficulties of risk analysis, some safety regulations are based on more 'soft' qualitative risk-assessment procedures (e.g. by considering 'risk indexes' or 'risk matrices'). However, it is crucial to understand that QRA is not the only way to assess dam-break risk: for non-specialists, stakeholders and members of the public, risk perception is always a natural framework for feeling and judging the risk situations. For this reason, *risk communication* is a crucial component of the overall risk-management process.

2.1.5 Downstream valley vulnerability assessment

Downstream valley vulnerability assessment is basically the definition of the potential flood-induced damages (losses) on exposed values existing along the dam-break flood path. To perform damage evaluation it is necessary to estimate the direct losses, which translate the expenses required to reinstate objects to the state they were in before the flood, and the indirect losses, which are typically the costs due to interruption and stoppage of human activities.

Among all the dam-break flood damages, the loss of human life (LOL) is a special item. In fact, due to ethical principles, the quantification of this type of loss in monetary terms is not acceptable, and therefore has an intangible cost. Other similar types of intangible damages are the ecological and heritage losses or the archaeological and environmental losses: both need to be considered as special items.

Other types of damages having a tangible cost can be converted by different specific methods to a monetary value: building and dam damages, cattle and agricultural losses, social equipment and lifeline losses among others.

Downstream valley vulnerability assessment is generally performed through a three-step approach, including:

the preparation of the inundation maps with the indication of the flood magnitude or characteristics resulting from the dam breach outflow and the flood propagation simulation;
the downstream valley characterization, using land-use maps of the potential inundation area, and estimating the number of persons and amount of valuables potentially affected – people and values at risk;
the loss of lives and damage evaluation, by intersecting the exposed people and values at risk with the magnitude of flood impact.

The preparation of inundation maps is based on hydrodynamic simulations and analysis. At present, the most widely used tools for predicting dam-break flood magnitude along the downstream valley are numerical computational models (*vide* Chapter 5). This assessment is based on a quantitative analysis estimating the hydrodynamic characteristics of the dam-break floods in the downstream valley, namely discharge flows, flow velocities, water depths, time of flood arrival, etc.

Downstream valley characterization is usually based on land-use maps; in many countries maps at the scale 1:25,000 are used to perform this analysis. Some key aspects of this characterization are the following:

the number of dwellings in the inundation area and an estimation of the exposed individuals or people at risk (PAR);
an inventory of the main infrastructures affected, especially roads, railways and bridges;
the land-use type in the flood-prone area, defining agricultural and industrial areas, urban and rural areas, forestry and natural resources, etc.

Even after real floods, the actual damage is difficult to assess. For buildings, inundation depth is, frequently, the main flood characteristic used to estimate expected flood damage by means of depth-damage curves (Smith and Ward [9]). While it is known that other variables such as velocity, turbulence, flood duration as well as debris load can have a significant impact on flood damages, these variables are usually assumed to be strongly correlated with inundation depth and are therefore ignored in a simplified analysis.

The most well-known instruments of flood damage estimation are the empirical depth-damage and the velocity-damage or vulnerability functions, which relate flood damage to the flood parameters obtained from flood computer simulations (e.g. maximum flow velocities, maximum water depths, and duration and time of flood arrival).

Compound flood characteristics to estimate damages can also be found in the literature. Clausen and Clark [10] obtained correlations between the $h \times v$ product (h being the water depth and v the flow velocity) and the damages suffered by buildings. The assessment was made according to three categories: (1) inundation damage (with no immediate structural damage; (2) partial damage and (3) total destruction or structural collapse. The following criteria were proposed by the authors:

boundary between inundation and partial damage: $h \times v = 3\ \text{m}^2/\text{s}$;
boundary between partial and total damage: $h \times v = 7\ \text{m}^2/\text{s}$;
inundation damage will occur if $v < 2$ m/s.

Different damages functions can be used depending on the type of the assets and the land-use patterns, namely buildings, infrastructures and economical values as agricultural or industrial areas. Figure 3 shows an example of a depth-damage function.

In what concerns the special aspect of the LOL along downstream valleys, different factors are usually identified for its evaluation, namely, among others:, the distance from the dam, the fact that the failure occurred during the day or night or during the weekend or normal week day, the season of the year, and the existence (or non-existence) of an operational evacuation plan and of a warning system. Graham [12] considered the difference between the number of PAR and the corresponding LOL, based on the variable warning time, the latter being related to the time of flood arrival. Therefore, three empirical equations are proposed for estimating the LOL when there is a warning system:

LOL = 0.5 (PAR) if the warning time is less than 15 min;
LOL = $\text{PAR}^{0.6}$ if the warning time lies between 15 and 20 min;
LOL = 0.0002 (PAR) if the warning time is more than 90 min.

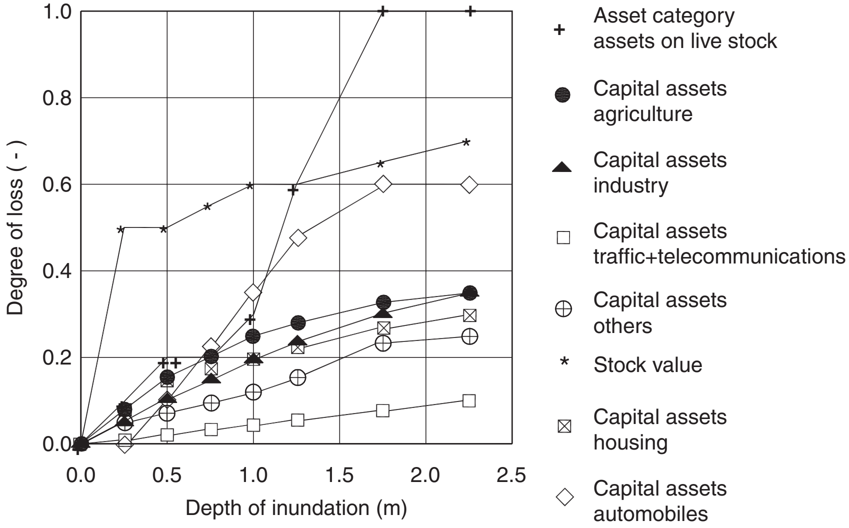

Figure 3: Example of depth damage or vulnerability functions for different asset categories (Elsner *et al.* [11]).

Typically, LOL<PAR because historical experience sustains that the average conditional probability of the LOL occurring among the exposed individuals, once a dam-break flood had occurred, is less than one.

Nevertheless, the $h \times v$ product also seems to be a very important parameter to quantify LOL. Some dam safety guidelines include graphs published by the US Bureau of Reclamation ([13]), where the human risk level is classified according to the given parameters. Figure 4 presents an example of these vulnerability graphs.

In the context of the EU RESCDAM project, a people and building damage criteria review and new laboratory tests related to human stability in flowing water were presented (RESCDAM [14]); these developments constitute useful tools for the estimation of the LOL caused by floods.

Real cases of dam accidents and valley response can be an empirical basis for computer simulations, based on GIS and hydraulic modelling, combining flood severity with warning, people evacuation and shelter protection effects. Some of these computer simulations can provide human fatality-rate probability distributions to be included as vulnerability likelihood in the risk analysis (Aboelata and Bowles [15], Bowles and Aboedata [16] and Jonkman [17]). However, in most cases the estimated exposure and vulnerability values can be considered as the ‘expected’ (pseudo-deterministic) best values.

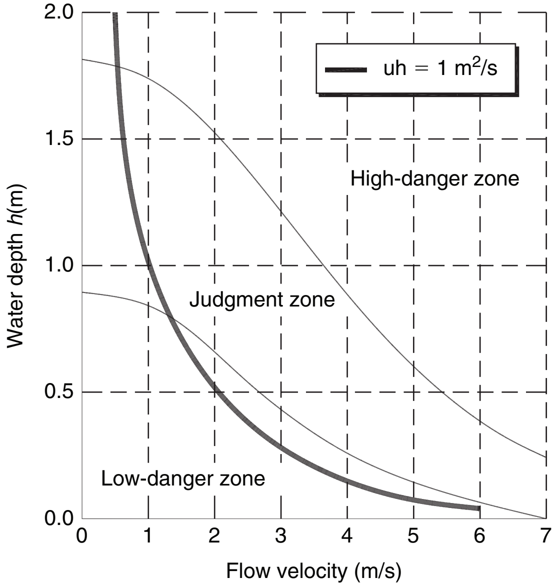

Figure 4: Example of vulnerability function for PAR (U.S. Bureau of Reclamation [13]).

2.2 Risk evaluation

Risk evaluation is the process of judging the significance of risk and of providing a framework for decision makers. The risk evaluation stage is the point at which social constraints (e.g. law system, societal risk aversion and policy of stakeholders) and judgements influence the decision process, explicitly or implicitly. The importance of the estimated risks and associated social, environmental and economic consequences will be judged in order to determine if action is required to reduce risks and identify a range of alternatives for managing the risks (Slunga [18]).

Experience and research have shown that the community can accept risks to life if they are low enough. Although there is currently no unique standard for determining what risks can be considered as acceptable or tolerable, some proposed risk criteria do exist. In fact, there is a large variation of opinions and cultural contexts and no definition of 'acceptable' will be acceptable to all stakeholders. Tolerable risk rather than acceptable risk is becoming recognized as a goal for risk management (ICOLD [5]). The existing proposed criteria need to be considered as just a reference framework.

According to McDonald [19] and most of the authors, the acceptable risk concept has two modes: the individual risk (IR) and the societal risk.

IR is the total annual probability of LOL imposed on an average individual or the person most at risk by a dam failure imposed by all specific conditions or scenarios considered in the analysis. Societal risk criteria reflect society's aversion to disasters or catastrophes. It has no relation to particular persons and limits the expected frequency of events that would be expected to kill more than a certain number of people. The societal risk acceptance criteria are generally depicted in so-called F–N diagrams, where F is the cumulative probability of events resulting in the loss of N or more lives.

To assess the IR it is necessary to evaluate the combined dam failure annual probability to exposed individuals based on all dam failure modes and compare it with a reference limit (e.g. 10^{-4} to 10^{-6}).

Vrijling *et al.* [20] presented a framework to judge the acceptability of individual and societal risks based on three general characteristics: (i) the decision to accept risk has a cost/benefit character; (ii) the risk acceptance depends on the degree of voluntariness and (iii) acceptance of societal risk takes place on a national level. The following general criteria were presented for dangerous activities:

IR criteria

$$\mathrm{IR} = P(N) \times P(N \mid \text{failure}) \leq \beta \times 10^{-4} \, (/\text{year}) \tag{5}$$

where β is the policy factor depending on the degree of voluntariness with which the risk exposure is undertaken $(0.01 \leq \beta \leq 100)$

Societal risk criteria

At the national level, the societal acceptable risk is judged by placing an upper limit on the expected number of victims per year (N) added to a confidence requirement σ (N) to represent risk aversion:

$$E(N) + k\ \sigma(N) < \beta \times 100 \tag{6}$$

where k is the risk aversion index. At the local level, the authors makes the national criteria compatible with the societal risk criteria proposed by the Dutch government or VROM type criteria:

$$F(N) \leq \frac{C}{N^n}\ (N \geq 10) \tag{7}$$

where C determines the position of the limit line (C may range between 0.001/year and 1/year) and n between 1 (risk neutral) and 2 (risk adverse).

Besides the LOL other types of social damages, such as the economic and environmental damages, play an important role in risk-based decision making. An economic approach of the acceptable risk should also be included: it is important to consider the social benefits of the dam as well as the investments needed for reducing the residual risks to a tolerable level. However, LOL will always be the critical social risk to be considered.

Two risk criteria levels can be specified. The first risk level will be an upper boundary: the annualized risks larger than this one are unacceptable. The other level is the bottom boundary: the annualized risks below this one are acceptable or tolerable. Risks between the two limits are tolerable only if the risk reduction is impracticable or are as low as reasonably practicable (ALARP principle). This ALARP principle can be interpreted as the condition when the costs of additional risk reduction are strongly disproportionate to the potential risk reduction benefits. In some countries, the legal system philosophy can be an obstacle to a case-by-case negotiation procedure in order to justify a final risk decision.

The Australian National Committee on Large Dams (ANCOLD) was one of the first agencies to introduce (1994) the ‘socially acceptable risk’ as a way to deal with the LOL in a dam risk assessment. Figure 5 shows the revised recommendation of this committee. The upper curve (limit) refers to existing dams. As originally conceived, the lower curve (objective) refers mainly to new dams (McDonald [19]). According to the ANCOLD criterion, a risk of 0.001 lives per dam per year is considered the maximum tolerable. Should 1000 life losses be estimated as a consequence of a dam failure, the criterion require the annual risk per dam to be 0.0001 lives or less or a probability of failure of 10^{-7} per year or less.

Others agencies, like FEMA and the US Bureau of Reclamation, and dam owners, like BC Hydro of Canada, are also using similar societal risk criteria (Salmon and Hartford [21], Bureau of Reclamation [7] and FEMA [22]).

The US Bureau of Reclamation criterion (1997) has a two-tier assessment process: the Tier 1 criterion relates the justification for remedial action to the

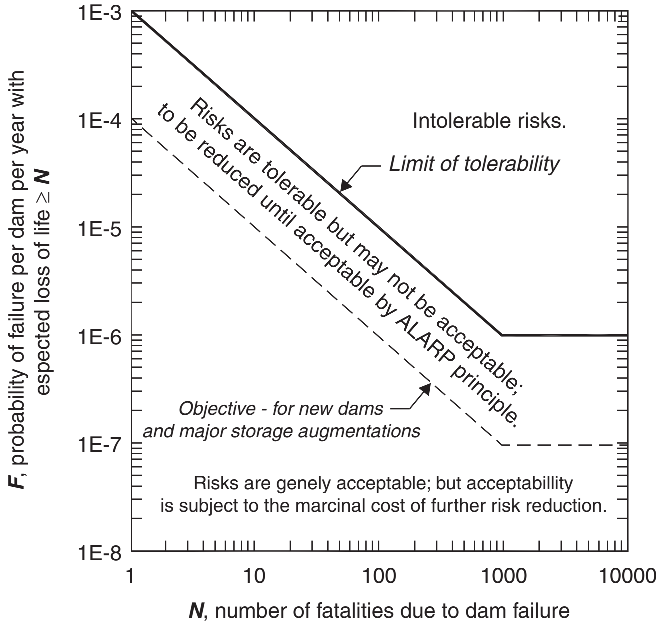

Figure 5: ANCOLD's Revised Societal Risk Criterion (Slunga [18]).

expected annual value of life loss. The Tier 2 criterion requires that no dam in the Bureau portfolio has a probability of failure greater that 10^{-4} per annum (McDolnald [23]).

There are a number of problems in using this kind of societal risk criteria approach (Fell [24]):

Are the acceptable risks reasonable?
How can the probability of a dam breaching from earthquake, flood and other causes be estimated with reasonable accuracy?
How can the probability of LOL, on average and for the individual most at risk, be estimated?

The upper limit in a societal risk criterion when applied to densely populated valleys gives very questionable results indeed. Typically, we can say that a loss of more than 500–1000 lives due to a large dam failure could be an expected value in a large number of valleys. ANCOLD criterion requires the probability of dam failure per year be less than or equal to 10^{-6} to 10^{-7} which can be beyond the limit of accuracy that can be guaranteed by engineering. So, for high-hazard dams, with very severe expected human losses, the best-available technology and engineering judgement are required. These accidents are viewed as 'national tragedies that are forever remembered by the public': efficient specific actions are then very difficult for these cases and 'multiple defences' should be implemented

(USBR [7]). This means that the societal risk approach cannot be powerful enough to support the risk management of very densely populated valleys. However, for valleys not so populated (e.g. with the number of lives lost less than 200) it can be the basis of an operational risk assessment methodology.

Risk-based decision making can be associated with the optimization of objective cost/risk-benefit functions or cost-benefit functions with the risk's expected penalties. For intangible damages, other methodologies should to be selected (e.g. multicriteria techniques Meyer *et al.* [25]).

3 Dam-break risk mitigation and response to hazard

3.1 Introduction

Should the valley residual risk be not acceptable, there are two key elements for the effective implementation of an integrated strategy to reduce risks associated with potential dam failures, improving safety in the downstream valley (fig. 6):

prevention at the dam site, in order to reduce the probability of occurrence of an accident, applying both structural measures, strengthening the dam for instance, and non-structural measures, which are traditionally associated with dam safety and monitoring control systems;

preparedness at the downstream valley, in order to reduce LOL and damage loss.

Long-term valley preparedness measures can be implemented in order to control the exposure to the hazard (e.g. valley risk zoning and land-use planning). Other types of mitigation measures will try to reduce the human vulnerability (e.g. emergency plans). Another way to deal with risk mitigation is just to minimize the economical damages by risk transfer (e.g. insurance policy).

The development of emergency plans to cope with the risk of living in downstream valleys is a non-structural risk mitigation measure and also a preparedness measure developed in the phase of pre-emergency in the disaster management cycle (fig. 1).

An emergency action plan (EAP) is a formal document that identifies potential emergency conditions at a dam and specifies pre-planned actions to be followed to minimize property damage and LOL. The EAP specifies the actions that the dam owners will perform in order to moderate or alleviate the problems at the dam. It contains procedures and information to assist the dam owner in issuing early warning and notification messages to responsible downstream emergency management authorities of the emergency situation. It also contains inundation maps to show the critical areas for action in case of an

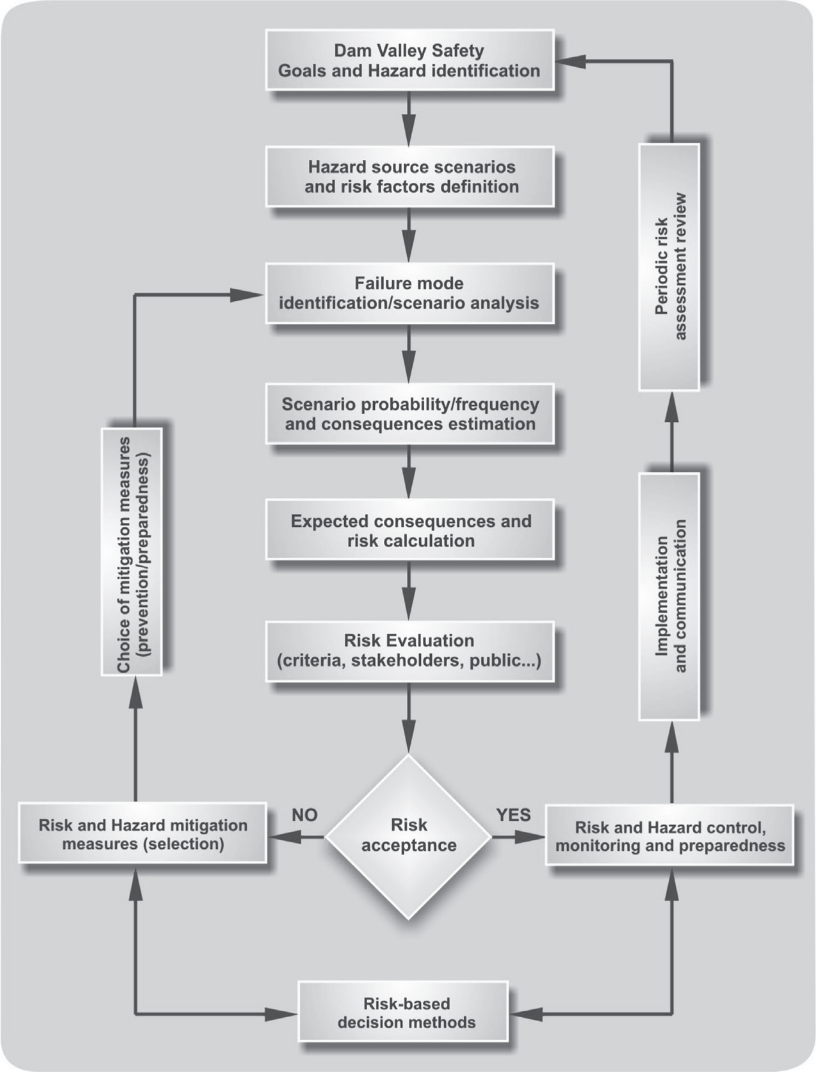

Figure 6: The dam risk management operational process.

emergency. It is a common practice to divide the EAP into five basic elements (USBR [26] and [27]):

detection of the occurrence of an extreme event or of a dam anomalous behaviour;
decision at the dam site, which is the establishment of procedures to respond to the event or to the dam anomalous behaviour;
notification system;

warning to the population at risk;
evacuation of the population at risk.

The first three components are generally a responsibility of the dam owner and must be considered in the emergency plan for the dam (internal emergency action plan – IEAP). The warning and evacuation components are actions generally of the responsibility of local emergency management authorities and must be considered in the external emergency action plan – EEAP.[3]

Field exercises and simulations are a way to test the level of efficiency of the valley response procedures, including public information which is a crucial component of a public risk-mitigation system.

The selection of specific risk mitigation measures should be based on efficacy and social equity criteria as well as on cost-efficiency criteria, among others.

3.2 Detection of the hazard or of the dam anomalous behaviour

Being capable of detecting that there is a real problem at a dam that can affect its safety is a mandatory first step during emergency events. The key aspect of this ability is the existence of a dam safety monitoring system with a 'fast' capability of analysis, integrating the results of installed instrumentation and the performance of dam visual inspections.

The aim of a dam safety monitoring system is to provide indicators for detecting the occurrence of an extreme event or of an anomalous structural behaviour. These indicators are used to take necessary countermeasures in due time and without any reduction in safety. A successful dam safety monitoring system consists of the following four components: (a) visual inspections, (b) instrumentation, (c) data collection and (d) data evaluation and management.

3.2.1 Visual inspections

Visual inspections are a key factor in a dam safety monitoring system. In fact, there are a lot of situations, like the evolution of an important crack, which can only be evaluated through visual inspections. Problems can also occur far from instrumented spots, namely in long earth-fill dams. In concrete dams, with a more continuous behaviour, the visual inspections are a major determinant, but continue to play a very important role.

3.2.2 Instrumentation

The instrumentation component includes sensors for the measurement of key parameters that can be used to monitor the ongoing performance of the dam. These parameters are usually the seepage flow, the ground water levels, the deformations or other physical measurements on the dam.

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[3] The two main components of a EAP, the internal (related to the dam and the near valley) and the external (related to the far downstream valley) are similar to EAP related to other hazards (e.g. in the chemical industry).

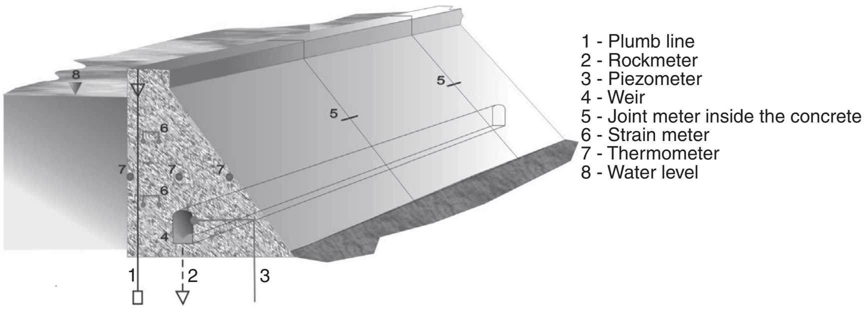

Figure 7: Typical dam safety monitoring system.

The instrumentation can also include sensors to monitor loading conditions and background information such as reservoir level, seismic shaking and weather conditions (i.e. rainfall, temperature and barometric pressure). Sensors must be installed in order to undertake the following recommended measurements (Tavares de Castro [28]):

temperature;
seepage and flow and uplift pressure;
displacements;
strains and stresses;
accelerations.

A typical example for the configuration of the instrumentation is shown in fig. 7.

3.2.3 Data collection

How the data is collected from the instrumentation defines another component of the monitoring system. Data collection can vary from manually read instruments to fully automated data acquisition systems. Intermediate systems include the use of hand-held computers and pre-programmed data loggers. The most appropriate data collection system depends upon the dam safety monitoring objectives.

A fully automated data acquisition system rests on extensive electronic measuring equipment. This equipment consists of two essential components: sensors–transmitters and data recorders (data loggers). The sensors are installed at specified positions inside the structure and are controlled by electronic equipment sending electronic impulses. After having received an impulse, the sensors return a signal which can be a measurement of voltage, resistance or frequency.

The electronic equipment scales the signal into a value, and either stores it in an internal memory or transfers it to a local database. An automatic monitoring system is customarily completed with a local computer, usually placed in a control room near the dam. As redundant data storage is essential in dam monitoring, measured data can be stored in a local database and additionally transferred to a central database.

A typical dam safety monitoring system consists of a small number of measurements with fully automated data acquisition, sufficient for allowing a fast and efficient evaluation of the dam safety conditions, complemented by a large number of instruments read by hand-held computers, thus allowing a better and complete knowledge of the dam behaviour.

3.2.4 Data evaluation and management

This last critical component is also the most important component of a dam safety monitoring system. The ongoing data evaluation, data management and presentation of results require forethought expertise and planning. Its main purpose is the detection of problems through the comparison between data provided by the dam safety monitoring system and the results of models that represent the dam structural behaviour.

Numerical models can be used to represent the dam behaviour. These models are calibrated by the past observed behaviour of the dam and by statistical models that relate each monitoring data with the evolution of main loads. For some key variables, like the displacement or the seepage flow, it is possible to establish limits, defined by the analysis of the past behaviour, corresponding to automatic alarms if an anomalous value is detected.

Those automatic alarms must, in most cases, be furthermore analysed by dam engineering experts due to the complexity of the dam behaviour characterization. In fact, not only it is very difficult to have an overview of the global structural behaviour taking into account only one variable but also one measurement out of the established limits can be non-representative. Most commonly, this situation can be associated with local effects and therefore has no real importance for the global safety of the dam.

In recent years, there have been developments in the area of artificial intelligence, namely in the field of expert systems, trying to implement automated systems that can perform an integrated analysis for all the monitoring data and, in accordance with the rules pre-defined by experts, they can also perform alarms and recommendations concerning anomalous monitoring data (Portela [29]).

3.3 Decision at the dam site

After an unusual situation or emergency event is detected or reported, the responsible for the IEAP must classify the event into a scale of emergency levels. According to most of the existing IEAP, three or four emergency levels are usually defined, corresponding to a growing level of emergency seriousness. For each level, the typical set of situations can be as follows:

Emergency level 0 – non-emergency, minor incidents occurring in the dam which do not compromise its structural safety (for instance, the occurrence of high-intensity precipitation); the situation needs to be monitored or repaired;

Emergency level 1 – unusual event, slowly developing, leading to possible discharges (effects in the downstream valley);
Emergency level 2 – rapidly developing accident that may compromise the structural safety of the dam; this situation may eventually lead to dam failure and the occurrence of flash floods downstream;
Emergency level 3 – dam failure appears imminent or is in progress and cannot be prevented; flash floods will occur downstream of the dam.

For each of these emergency levels the IEAP must provide specific information for decision making regarding the condition of the dam and the appropriate level of response, namely the following:

define clear descriptions of trigger situations to adopt for each emergency level, in particular those concerning the population warning and evacuation actions;
provide the specific actions and procedures that must be performed to respond to each emergency level;
identify the human, material and technical resources as well as allocate the emergency equipment;
define the decision chain and identify all persons who act in case of an exceptional or an accident occurrence.

The decision chain must be clearly defined by a flow chart. In fact, a crucial factor in dam safety is that the distribution of functions, tasks and responsibilities is well-known and acceptable to all parties. It is important to define who is in charge at each of the emergency levels. Another important issue is the consideration of a special crisis group for real-time emergency action (integrating members of the dam safety authority and civil protection services authorities).

3.4 Notification system

The notification system is the communication system to be implemented between the dam owner and the agencies responsible for the dam safety (e.g. the dam safety authority), also including the downstream civil protection services. There are two key elements for the effective notification: the identification of the individuals to alert in the agencies and the design of the notification devices.

The notification flow chart is the detailed call-out list of the persons appointed by each of the agencies involved in the IEAP, namely:

the dam operators and the person responsible by the dam;
the dam owner (usually the reservoir operation agency);
the dam safety authority;
the downstream civil protection services.

All individuals in the notification flow chart must be fully identified by the following information: (a) name, address and official post, (b) agency fax and

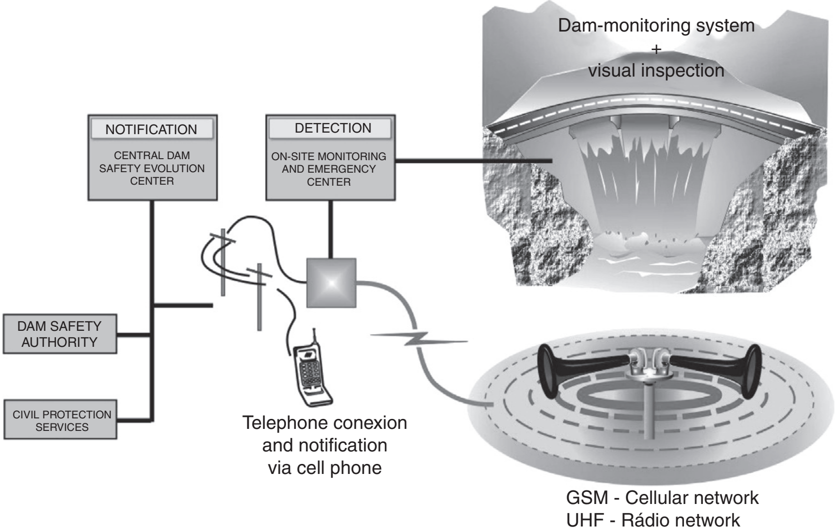

Figure 8: Typical flow diagram of a fully automated data acquisition, notification and warning system (Viseu *et al*. [30]).

phone number, (c) personal telephone number and (d) cellular phone number and e-mail address.

The usual notification devices are telephones, mobiles phones, faxes and radios. There must be redundancy of resources (either in the type or in the number of channels).

In recent years, the processes of detection, notification and even warning the population are commonly assured by automated systems, with more or less human assistance. Therefore, automated data acquisition systems continuously monitor the dam, transferring information to a central dam safety and emergency operation centre which supervises the global behaviour of the dam having the capability to issue notification messages to a pre-defined list of maintenance personnel and experts calling for correction measures and, when the emergency level obliges, warning the downstream population by an early warning system (fig. 8).

Very important issues to consider in this part of the IEAP are the accuracy of the notification flow chart, which must always be up-to-date and the regular testing of the notification system.

3.5 Warning the population at risk

3.5.1 Introduction

The warning system, at the IEAP level, is commonly implemented between the dam and the population in the most dangerous zone of the downstream valley.

Early warning systems are non-structural instruments intended to minimize flood impacts on populations and welfare, which can also play an important role in crisis management and be a competitive alternative to structural modification projects in order to reduce risk in dam-break flood-prone areas. Warning systems can be generally divided into the following types (Viseu [31]):

public warning using audible systems as well as adopting visible systems (strobe lights and billboards);
personal direct notification via telephone or cell phones, also including the door-to-door warning and, nowadays, the use of short message service (SMS) in mobile phones via cellular diffusion;
television or radio station news broadcasts.

The choice of the solution to warn the downstream valley must consider the geographic dispersion of the population (small rural areas, densely urbanized urban areas, dispersed dwellings, etc.) and must also lay on the distance from the dam location as well as on the proximity of the civil protection services resources (fig. 9). In the most dangerous zone, due to the small delay in the flood arrival time, an early warning system based on sirens can be envisaged, namely in most densely occupied zones. In zones with scarce population and more distant from the dam, personal warning and the use of loudspeakers by civil protection personnel can be envisaged. Television and broadcast notification can be used in the zones less affected by the dam-break flood and are very efficient ways of public information during an emergency, especially if the anomalous event has a gradual evolution pattern.

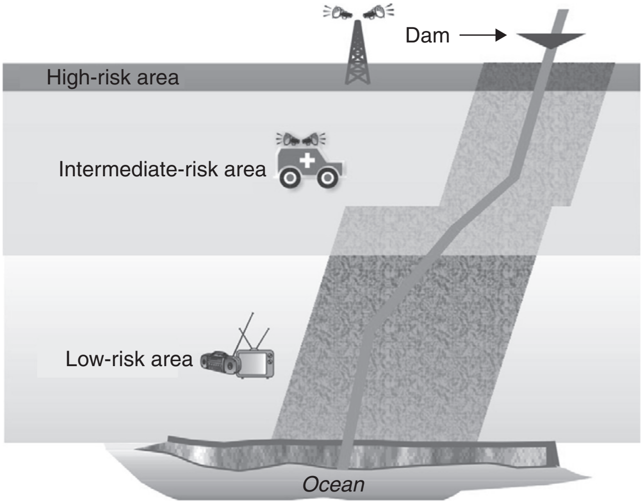

Figure 9: Example of a joint early warning system solution for a valley downstream a dam.

Typically, there is no single warning system that can meet all the desired notification requirements. Each system has its advantages and disadvantages.[4] However, very important aspects to consider are to be sure that the message is easily understood by the public and to guarantee that the system is reliable: false alarm must be avoided and maintenance needs to be efficient.

3.5.2 Public warnings

Audible sirens is the most commonly used warning system, providing immediate notification by broadcasting a tone consisting of a siren wail or a voice message and can include options to broadcast pre-recorded voice messages.

According to Duston and Myers [32], the strengths of this warning alternative are that they allow an instant communication to all PAR, namely enabling fast alerting to highly populated areas, guarantee a good coverage (including in isolated areas) and have a high degree of credibility to audience. Furthermore, this warning solution can have a low maintenance cost, is flexible and expandable for future and can be, for units provided with electric accumulators, available during both phone and electric outages.

The main disadvantages of this warning alternative are mainly its high cost of implementation and the fact that warning units may suffer degradation due to environment or vandalism. Special attention has to be given to the public education and training in order to assure that PAR will recognize the meaning of the siren signals.

Loudspeakers can be installed in vehicles typically driven by civil protection personnel through the affected area, broadcasting to the public either live or by a recorded message. This method of notification is only effective for small areas. The main strengths of this warning alternative are its low cost and high degree of credibility to audience.

The disadvantages of this warning alternative are the facts that only limited information can be delivered and only a limited area can be notified quickly. Furthermore, the messages can be hard to decipher if people are indoor (Duston and Myers [32]). Certainly, the main weakness of this way of warning is that it exposes the personnel delivering the message to risk and uses resources that could be more essential in other tasks such as those corresponding to emergency rescue responses (evacuation and rescue).

Visible warnings are essentially strobe lights often present on the top of sirens to alert people in the vicinity and are of limited utility except for PAR with direct views to the warning units. Nevertheless, this solution is sometimes used linked to reservoir operations for power generation causing hazardous conditions in rivers near residential and recreational areas. In those situations, visible warning devices are activated automatically prior to water-level changes, for instance during night, when audible warning is considered undesirable.

Visible warning also includes bulletins issued by authorities, generally affixed in the downstream civil protection buildings (community councils, police and firemen

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[4] A general overview of the strengths and weaknesses of warning systems types can be found in Duston and Myers [32].

headquarters, for example) and nowadays largely using the Internet and the World Wide Web pages of those organizations in order to expand coverage. Billboards also constitute a simple and inexpensive way of warning but are a solution limited in coverage. The traditional board solution does not allow keeping people up to date and is often a victim of vandalism. Electronic billboards are nowadays largely used to issue warning messages to those travelling on highways.

3.5.3 Personal notification

Automated telephone services generally use a computer to phone PAR, delivering a warning. To initiate this type of warning, a phone call is made from those responsible for the IEAP of the dam to the telephone service provider. Once a security authentication is completed, the service provider starts a call-out operation to notify the targeted population.

The main strength of this warning alternative is that it guarantees a good coverage and has an efficient audio component. This solution also has a relatively low cost[5] and the notification is fast and targeted to only those on the phone call list.

The main disadvantages of this warning alternative are that proximity to the instrument is necessary and it is only effective if people have a telephone which is turned on and not in use as well as if the call is answered (Duston and Myers [32]). Furthermore, congestion problems can occur in serving large populations.

SMS in mobile phones is another more general and promising solution allowing overcoming some of the disadvantages of the personal notification via automated telephone service or public warning via sirens. In this solution, warnings are issued to all individuals remaining in the flood-prone area during emergency. Considering the existing extensive mobile global penetration a very large number of citizens can actually be reached through this solution (Santos *et al.* [33]).

The main strengths of this solution are its low cost and the fact that it is addressed to the risk area and not to the user; it is therefore able to assure efficient distribution of information not only to residents but also to all people remaining in the risk area during emergency. Nevertheless, the use of SMS can be affected by coverage (namely in isolated areas) and also by congestion issues (eventually causing a large number of users to start calling). Another very important disadvantage is the vulnerability to hoax warnings.

Door-to-door notification allows warning each citizen personally in the affected area. Within this method, civil protection personnel spread out in the entire inundation area delivering the evacuation notice personally to all occupants.

The main strengths of this warning alternative are the performance of a targeted notification to only those affected and its high degree of credibility to audience. Furthermore, this solution can reach those with disabilities. The main disadvantage of this warning alternative is the fact that it is extremely

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[5] Typically, the telephone service provider charges an initial fee, an annual fee and a per call charge for each number dialled during the emergency.

time-consuming, exposing to risk the personnel who delivers the message, and is therefore effective only for the notification of small areas.

3.5.4 Television or radio broadcast notification

This type of notification uses television or radio station broadcasts to warn the public during an emergency and is typically used for areas that do not require immediate emergency response action. The strengths of this warning alternative are its wide coverage, low cost and availability as most people have televisions. This solution allows an instant communication to all affected, gives detailed information and can keep people up to date.[6]

The disadvantages of this warning alternative are the following (Dutson and Myers [32]): (i) risk of an uncertain delay until emission effectively begins; (ii) limited message control by authorities; (iii) limited usefulness when televisions or radios are turned off or if only a few people are watching/listening; (iv) limited usefulness for people who are outside their houses at the time of emergency; (v) not a selective broadcast audience, emergency message being carried to all people receiving TV or radio signal and (vi) not available during power outages.

3.6 Evacuation of the population at risk

It is possible to divide the factors that influence the possibilities of survival into three groups (Funnemark [35]):

characteristics of the dam-break flow: water depth, flow velocity, debris carried by the flow, water temperature, etc.;
warning time: decision of starting evacuation either prior to the dam break or not; celerity of the dam-break wave, distance to the dam, reliability of the warning system;
evacuation efficiency: population knowledge on how to act in case of a dam break;
quality and training of the civil protection teams, availability of escape possibilities, fraction of more vulnerable persons (children, elderly and disabled persons).

The purpose of an evacuation plan is to relocate people to safe areas whenever they are threatened, regardless of the hazard. This action implementation is generally the responsibility of the local authorities. The dam owner must incorporate in the EAP an inundation map, indicating the areas below the dam that would be flooded if the dam were to fail. The local community will use this map for plan and define the evacuation routes for people and access roads for providing resources. The key aspects of the evacuation phase are the following (fig. 10):

delimitation of the inundation map, defining areas to be evacuated;

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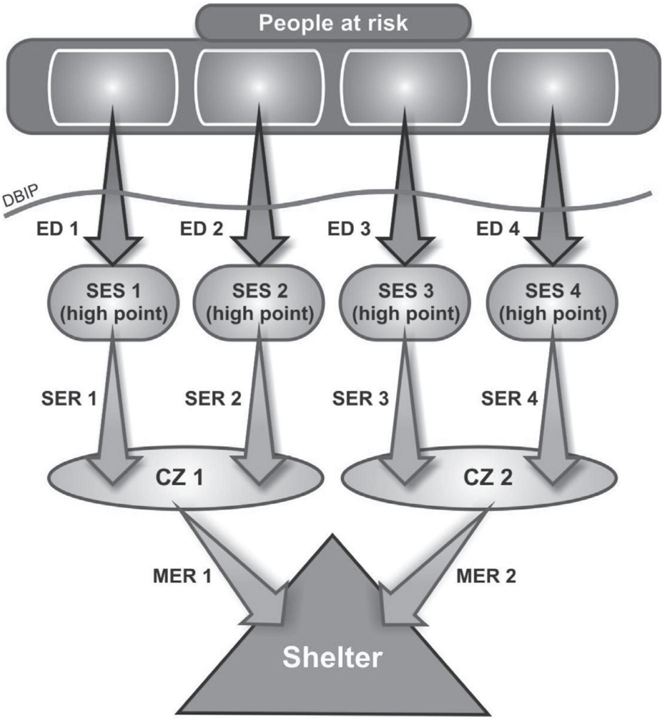
[6] In addition to this technique, all the important information (as road closings and shelters localization) that is being given orally, can be also visually delivered, namely running closed captions or visual displays. These types of resources can play a very important role for message understanding, namely for people with special needs (NAD [34]).



DBIP - Dam-break innundation perimeter
ED - Escape direction
SES - Safe evacuation spots
SER - Secondary evacuation route
CZ - Concentration zone
MER - Main evacuation route

Figure 10: Typical flow diagram for population evacuation (Viseu [31]).

identification of safe evacuation spots nearby the inundation area but out of water path;

designation of emergency transportation of evacuees from safe evacuation spots to shelters.

Evacuation procedures typically include:

delineation of general traffic routes and definition of traffic control measures;

definition of special procedures for evacuation and care of disable persons and of people who may be physically challenged from institutions such as hospitals, nursing homes and prisons;

identification of procedures for the security of the perimeter and the interior of the affected area during and after evacuation;

identification of the procedures for allowing evacuees to return to their homes into affected areas;
assignment of specific functions and responsibilities to state and local emergency response agencies and other organizations;
details defining how specific materials, equipment and personnel resources will be provided.

The success of a PAR evacuation will strongly depend on a good organization, preparation and testing as well as efficient public information in a crisis context: risk communication strategies need to be selected, tested and efficiently implemented.

4 Final remarks

Potential effects or damages at downstream valleys should a dam break occur are now taken into consideration in most of the dam safety guidelines, regardless of their probability of occurrence. These procedures introduce several challenges to all organizations involved in dam exploitation as well as in dam and valley safety and civil protection.

Private dam owners face a responsibility towards society in what concerns the internal dam procedures that will avoid a dam failure or diminish the probability of a dam-break flood should an abnormal event or action occur. Insurance premium related to dam failure consequences will also be a serious factor to be considered by dam owners in the future.

Civil protection authorities on downstream valleys face a responsibility to diminish the probability of human and economic losses should a dam-break event occur. To mitigate the risk along the valley, defence passive procedures should be implemented as land-use control according to flood risk zoning. These procedures can generate local political resistance.

Emergency planning and effective warning systems are now mandatory issues in modern dam safety and civil protection regulations. However, these procedures need to be implemented with the support of local authorities and with an adequate public information and participation according to the risk perception level of the population at risk.

Evacuation planning needs to be well prepared and with trained staff, and in almost all real cases, the alarm needs to be switched on as soon as a failure is predicted, in order to evacuate a large number of inhabitants. This condition implies:

advanced monitoring systems with real-time capability to predict a dam accident with more accuracy;
good coordination between dam owners, dam safety authorities and civil protection authorities in order to be sure that emergency and evacuation plans are effective;
good public information in order to guarantee a good response to flood crisis.

Risk analysis and assessment is a way to select risk mitigation measures and efficiently increase dam safety. What will be the impact of these new safety and risk management procedures on the population living for a long time downstream dams and on the reaction to new dams is a challenge for those involved in risk management.

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