Federal Guidelines for Dam Safety Risk Management

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On the cover.— Photograph of Glendo Dam, Wyoming, taken from right abutment showing main embankment and spillway.

ACRONYMS AND ABBREVIATIONS

ALARP	as low as reasonably practicable
ANCOLD	Australian National Committee on Large Dams
BCHydro	British Columbia Hydro
DSC	Dam Safety Committee
EMA	Emergency Management Agency
f-N plot	annualized failure probability vs. number of fatalities plot
F-N plot	probability per year of potential life loss ≥N vs. number of fatalities (N) plot
IRRMs	interim risk reduction measures
O&M	operations and maintenance
SBA	Standards Based Approach

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Appendix

A Guidelines on Risk Terminology

1.1 Background

Agencies, owners, and regulators have been using **risk**[1] for quite some time to inform decisions within various industries across the world. In particular, the United States, the United Kingdom, the Netherlands, and Hong Kong have integrated risk into safety decisions in various ways since the 1960s [1]. Those entities that analyze, evaluate, and manage risks have found that risk provides a rigorous, systematic, and thorough process that improves the quality of, and support for, safety decisions. In addition, several entities in the dam safety industry have been using risk to inform decisions since the late 1980s. Notably, the Australian National Committee on Large Dams (ANCOLD) [2], British Columbia Hydro (BCHydro) [3], and the Bureau of Reclamation [4] adopted **risk management**[2] strategies to assess and manage risks for their dams. For entities that own or regulate dams, various decisions are made regarding an individual structure or a portfolio of structures, including decisions about:

- The safety of a structure
- Necessary actions to reduce risks
- Prioritization of actions for a portfolio of structures

Using risk to inform decisions involves three distinct components. These components, each having their own purpose and function, are:

- Risk analysis
- Risk assessment
- Risk management

Figure 1 shows how **risk analysis**[3], **risk assessment**[4], and risk management relate to each other. Dam safety risk management includes routine and non-routine activities and is the umbrella under which risk is used to inform decisions by owners and regulators. Risk communication, although not specifically identified in figure 1, is a critical part of each component of risk management. While the main components of risk-informed decision making are risk analysis, risk assessment, and risk management, there are activities that dominate the

[1] Risk is the product of the likelihood of a structure being loaded, adverse structural performance, and the magnitude of the resulting consequences. In this document risk is in the context of dam safety and does not take into consideration physical security or cybersecurity risk.

[2] Risk management is action implemented to communicate the risks and either accept, avoid, transfer, or control the risks to an acceptable level considering associated costs and benefits of any action taken.

[3] Risk analysis and risk estimation are qualitative or quantitative procedures that identify potential modes of failure and the conditions and events that must take place for failure to occur.

[4] The process of considering the quantitative or qualitative estimate of risk, along with all related social, environmental, cost, temporal, and other factors to determine a recommended course of action to mitigate or accept the risk.

Note: The above definitions were developed for use in this document.

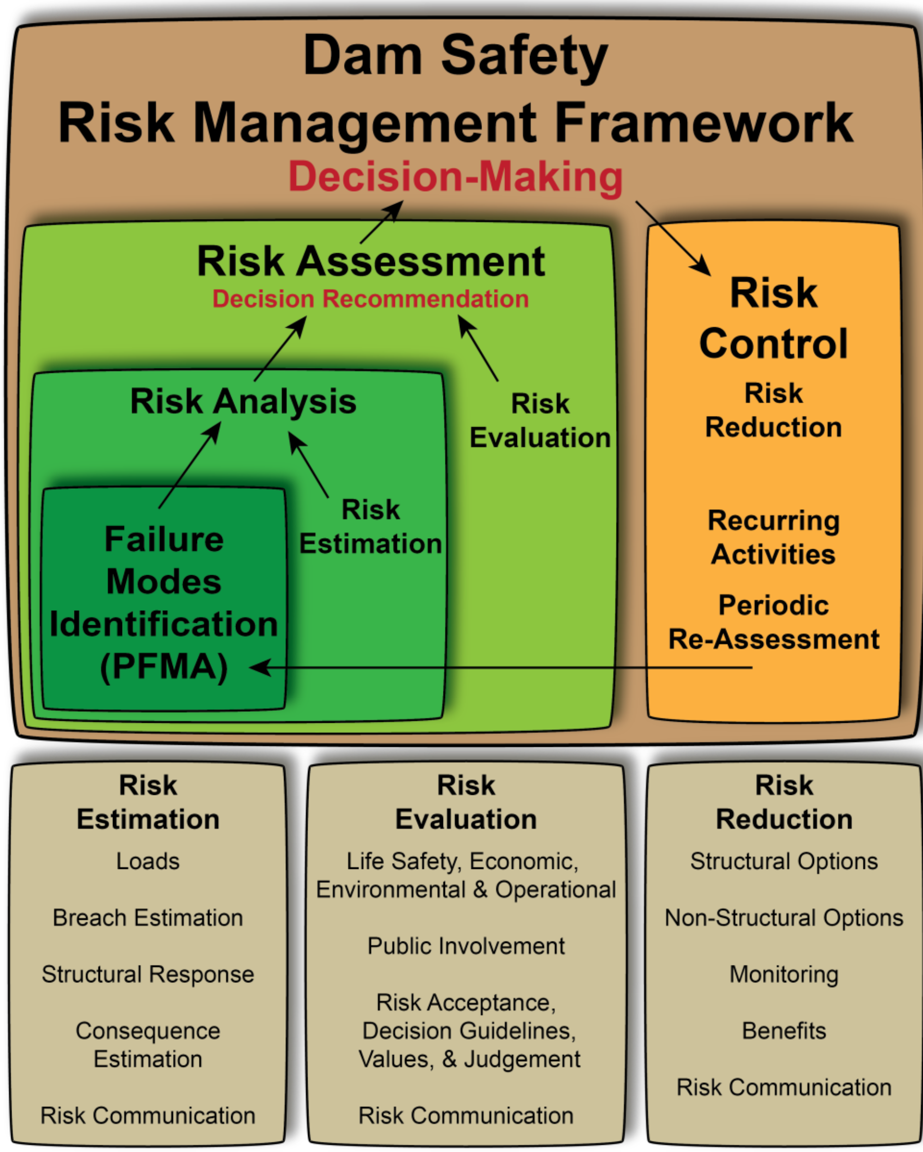

Figure 1.—Relationship between risk analysis, risk assessment, and risk management.

completion of each component. For risk analysis, the key activity is **risk estimation**. For risk assessment, the key activity is **risk evaluation**[5]. For risk management, the key activity for dams with high risk is risk reduction. These concepts are illustrated in figure 1.

[5] Risk evaluation is the qualitative or quantitative description of the nature, magnitude, and likelihood of the adverse effects associated with a hazard. A risk evaluation often includes one or more estimates of risk, a risk description, risk management options, economic and other evaluations, and estimates of changes in risk attributable to the management options.
Note: The above definition was developed for use in this document.

The term *risk*, when used in the context of dam safety, is comprised of three parts: (1) the likelihood of occurrence of a load (e.g., flood, earthquake, etc.), (2) the likelihood of an adverse structural response (e.g., **dam failure**[6], damaging spillway discharge, etc.), and (3) the magnitude of the consequences resulting from that adverse event (e.g., life loss, economic damages, environmental damages, etc.). Typically, the direct consequences of dam failure are estimated. Indirect consequences could also result, in which failure of the dam results in loss or failure of key facilities, which can ultimately lead to additional economic consequences or loss of life. If indirect consequences can be identified and estimated, they can be incorporated into the risk estimates. In some cases, it may not be possible to capture all of the indirect consequences. Figure 2 depicts the flow of recurring dam safety activities and how risk information is used to inform decisions on dam safety actions and setting priorities.

Risk estimates typically reflect the risk at a given dam at the snapshot in time when the risk analysis is performed. It is recognized that the conditions at the dam will likely change in the future and the consequences of dam failure may also change as development occurs within potential dam failure inundation boundaries. This potential future increase in consequences can be taken into account as part of a long-term consideration of risk.

This document provides guidelines for implementing risk-informed decision making in a dam safety program. The intended audience is Federal agencies that own or regulate dams. The guidelines could also be applied to non-federally owned or regulated dams that can impact federally owned or regulated facilities; however, this would require the cooperation and involvement of the non-Federal dam owner.

1.1.1 Risk Analysis

Risk analysis is the first component of risk management. It is the portion of the process in which the potential failure modes, structural performance, and adverse consequences are identified. It is also the process during which a quantitative or qualitative estimate of the likelihood of occurrence and magnitude of consequence of these potential events is made. A critical first step in a risk analysis is identifying the specific potential failure modes that are most likely at a given dam. The frequency of occurrence of the loadings (e.g., reservoir load levels, floods, earthquakes, ice loading, etc.) that could initiate potential failure and then cause adverse consequences is estimated and considered as part of a risk analysis.

[6] Failure characterized by the sudden rapid and uncontrolled release of impounded water or liquid-borne solids.

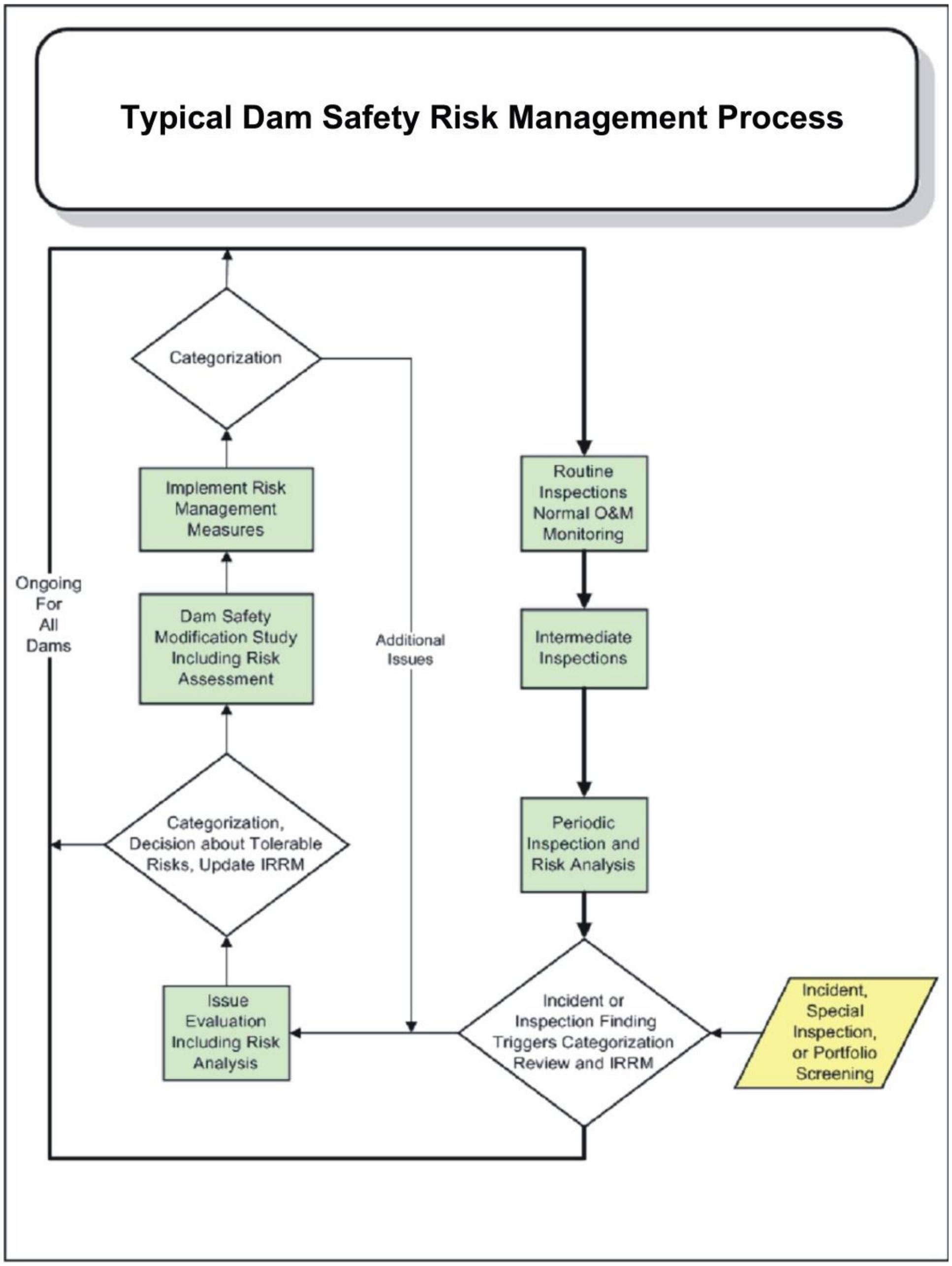

Figure 2.—Recurring dam safety activities.

1.1.2 Risk Assessment

Risk assessment is the process of examining the safety of a specific structure, making specific recommendations, and recommending decisions on a given dam or project using risk analysis, risk estimates, and other information that have the potential to influence the decision. The risks are assessed by the dam owner and, if applicable, the regulator, owner's engineer, or other stakeholders. The assessment considers all factors (e.g., likelihood, consequences, cost, environmental impacts, etc.) and may also use evaluation criteria established by the owner or regulator. Decisions may include additional or enhanced monitoring; additional investigations, evaluations or analyses; remedial actions; abandonment of the dam; or no additional actions.

1.1.3 Risk Management

Risk management is the overarching activity when risk is used to inform dam safety decision making and builds on risk analysis and risk assessment phases. It encompasses activities related to making risk-informed decisions, prioritizing evaluations of risk, prioritizing risk reduction activities, and making program decisions associated with managing a portfolio of facilities. Risk management includes evaluating the environmental, social, cultural, ethical, political, and legal considerations during all parts of the process. These activities include potential structural and nonstructural actions on a given dam or project, as well as activities such as routine and special inspections, instrumented monitoring and its evaluation, structural analyses, site investigations, development and testing of emergency action plans, and many other activities. All of the activities described above relate to risk control which involves dam safety actions to reduce risk and activities to identify issues early before potential failure modes can initiate.

1.1.4 Risk Communication

Risk communication is a critical component of an effective risk-informed decision process. It is not a separate component of the process; it must be integrated into all aspects of the process. Risk communication is essential within an owner/regulator organization and with other individuals/organizations that have a stake in the dam or would be impacted by its failure.

2.1 Objectives of the Guidelines

Federal agencies seek to ensure the structural integrity and operational safety of the dams in their charge and, in doing so, wisely allocate the use of monetary and human resources. In exercising their dam safety responsibilities, Federal agencies consider that:

- There are certain principles that should be held in common for consistency and correctness

- There should be a common understanding of risk management processes

- There are commonly recognized standards for safety and **tolerable risk**[7] (while there is a general consistency in these standards within the dam safety community, Federal agencies may establish their own standards to best accomplish their unique missions)

- There are technical tools and approaches related to risk analysis that can be mutually shared and jointly developed

Risk analysis and risk assessment provide fundamental input to risk-informed decisions. To the extent that is reasonable and practicable, the tools, procedures, and guidelines should be consistent among the agencies.

These guidelines will enable Federal agencies to use the general principles of risk management and make risk-informed decisions. The agencies will work to develop and maintain consistent application of risk analysis, risk assessment, risk management, and risk communication using equivalent procedures and tools.

The guidance offered and specific procedures identified in these guidelines are not mandated. Individual agencies may vary in the way they apply these guidelines as necessary to accomplish their respective missions. To foster consistency in using and implementing these guidelines, refer to appendix A, which defines selected terms related to the risk-informed decision process.

A number of principles apply to the overall objectives of these guidelines. Therefore, each major section of this document identifies principles for implementing risk-informed decision making, discusses these principles, and then summarizes them in a box at the end of the section.

Although dam failure can result in many different types of consequences (e.g., economic, environmental or cultural), life safety is of paramount importance. While a complete range of consequences can be considered in dam safety decision making, loss of human life is the primary factor to consider.

Risk-informed decision making provides a framework in which relative risks at a given dam and within an inventory of dams can be compared. When making dam safety decisions, it must be acknowledged that all risk estimates include **uncertainty**[8] and subjectivity. A risk analysis can provide valuable insight into the vulnerabilities at a given dam. Risk should inform the decision process and improve the state of safety related to dams.

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[7] Tolerable risk is a risk within a range that society can live with so as to secure the benefits provided by the dam.

[8] Uncertainty is the result of imperfect knowledge about the present or future state of a system, hazards, events, situations, or populations under consideration.

The primary purpose of a dam safety program is to identify the risk to life and property posed by dams. While dam safety risks cannot be eliminated, they should be reduced to a level that is as low as reasonably practicable.

Each agency has a unique authority, mission, and management practice. While the guidance in this document is intended to develop consistency within Federal agencies, the use of risk to inform decisions may vary.

Within a dam safety program, there will typically be limitations on the expediency of implementing dam safety recommendations. These limitations can be the result of funding or resource availability. The urgency of completing dam safety actions should be commensurate with the level of risk.

The following principles apply to the overall objectives of these guidelines:

1. Life safety is paramount.
2. Risk should inform the decision process and improve the status of safety related to dams.
3. Identify and reduce the risk to life and property posed by dams and reduce those risks to as low as reasonably practicable.
4. Each agency has a unique authority, mission, and management practice. Their use of risk to inform decisions may vary.
5. The urgency of completing dam safety actions should be commensurate with the level of risk.

3.1 Risk Analysis

3.1.1 Risk Analysis/Risk Estimation

Risk analysis is typically a quantitative process (i.e., the outputs and inputs to a risk assessment are numeric). However, risk may also be expressed qualitatively. Risk analyses can provide valuable input to decisions made at various stages of a project and serve other important purposes. Risk analysis can include decisions made for a single dam or within a portfolio of dams. Thus, several types of risk analyses can be used as described below. The first step common to all types of risk analyses is identifying the site-specific potential failure modes. Risks are typically quantitatively evaluated by failure mode. The failure modes are then rolled up within a decision framework at a particular structure. For a given dam or project, all of the relevant types of loadings that may be experienced should be considered when identifying potential failure modes.

Methods to calculate and estimate risks are constantly evolving. This document does not try to describe in detail how to analyze risks. It only describes the general practices used by those who analyze risks. The current state-of-the-practice for analyzing risks is the *Best Practices in Dam Safety Risk Analysis*, a document and accompanying training course developed by the Bureau of Reclamation and the U.S. Army Corps of Engineers [5].

3.1.2 Types of Risk Analysis

There are various types of risk analysis. The level of information and the uncertainty reflected in the risk estimates will vary. Generally, more detailed risk analyses (those associated with issue evaluations and risk reduction) have more detailed analyses available, and studies have been performed to try to reduce the amount of uncertainty. More detailed risk analyses will generally be led by an experienced facilitator and be performed by a qualified multi-disciplinary team.

3.1.2.1 Potential Failure Modes Analysis

Potential failure modes are mechanisms that can result in an uncontrolled release of the reservoir. A potential failure modes analysis is a critical first step in conducting a risk analysis. It requires a detailed records review and a review of dam performance (e.g., instrumentation, visual and operational). Information is also needed on flood and earthquake frequencies in order to consider hydrologic and seismic potential failure modes. The perspective of local office personnel, including dam operators, inspectors, and dam tenders, is invaluable. The goal of a potential failure modes analysis is to: (1) identify the site-specific **credible potential failure modes** for a given dam; (2) provide complete descriptions of the potential failure modes, including the initiating event and the progression of steps leading to an uncontrolled release of the reservoir; and (3) provide a general description of the magnitude of the breach, including identifying and recording the factors that make the potential failure more likely and less likely and the consequences more severe or less severe.

It is recognized that large controlled flood releases may result in significant downstream consequences, including loss of life, but these events have typically not been included as potential failure modes because they result from intended operation of the dam. Large controlled releases that may result in serious downstream consequences are typically made to prevent even greater consequences that would occur from dam failure. Agencies may elect to consider the risk from large controlled releases, and risk communications should occur when large releases are made.

3.1.2.2 Screening Level Risk Analysis

A screening level risk analysis is typically performed for a portfolio of dams. The goal is to: (1) identify potential failure modes and (2) develop relative risk estimates for each dam in a way that enables the relative risk among the dams to be evaluated and priorities for further study or remediation to be established.

Information on loadings, consequences, and analyses that relate to potential failure modes may be very basic and limited, typically consisting of data already available or prepared just in advance of the screening effort. Screening level risk analyses have typically had very mixed results in identifying key dam safety issues. A screening level risk analysis can be a valuable tool for identifying uncertainties related to potential failure modes and significant dam safety issues. It can be used to prioritize additional studies and initiate modification studies at dams. Screening level risk analyses can either be made quantitatively or qualitatively.

3.1.2.3 Periodic Risk Analysis

A periodic inspection of all dams is required under the *Federal Guidelines for Dam Safety* [6]. A comprehensive, periodic dam safety review that documents the condition of the dam at a point in time should incorporate a risk analysis to enhance the value of the effort. Additional analyses and studies are typically not performed specifically for a periodic risk analysis because the analysis relies on existing information. The risk analysis for a periodic dam safety review can be performed by an individual, but there are distinct advantages to engaging a small team. A periodic risk analysis focuses on all potential failure modes that are considered credible at the dam. Periodic dam safety reviews are performed on a recurring cycle, with the interval between assessments determined by the agency.

3.1.2.4 Issue Evaluation Risk Analysis

Issue evaluation risk analyses are focused on one specific (or more than one) potential failure mode that may require additional engineering analyses, studies, or investigations to support a quantitative risk analysis. These supporting activities are completed to reduce uncertainty and increase confidence in the resulting risk estimates. Typically, field explorations, material testing programs, detailed studies and analyses, or a combination of these will be performed to provide information for the risk analysis. Analyses and studies may focus on loadings, structural response, consequences, or a combination of these. Issue evaluation risk analyses are usually conducted with an experienced risk analysis facilitator and a team that have experience and backgrounds related to the potential failure mode or modes being evaluated.

3.1.2.5 Risk Reduction Analysis

A risk reduction analysis is used to estimate the anticipated risk for critical potential failure modes after potential dam modifications or non-structural measures are implemented. It typically involves reviewing risk estimates from an existing risk analysis, deciding which events will be impacted by the changes, and re-estimating the likelihood of those events. During the risk reduction analysis, risk reduction measures for the various alternatives are evaluated and a preferred alternative is selected (also considering other factors such as the cost to implement actions, construction risks and environmental and other factors). In addition, it is necessary to analyze the proposed alternative remediation measures to verify that they will successfully reduce the risks to the desired level.

3.1.3 Quantitative Versus Qualitative Risk Analyses

Each type of risk analysis can be accomplished using either a quantitative or qualitative approach. In either approach, a comprehensive identification, written description, discussion, and evaluation of factors that make events more or less likely to occur for each credible potential failure mode are documented. The magnitude of consequences related to a potential failure is also characterized (quantified), discussed, and documented.

3.1.4 Risk Analysis Results

Risk analysis results are typically portrayed with plots that graphically portray the risk estimates (i.e., likelihood of failure versus economic loss and potential life loss) and have an accompanying table that provides the input data used to generate the graphs. Two types of graphs are typically used: (1) the f-N plot and (2) the F-N plot.

An f-N plot shows individual failure modes that portray the potential for life loss as the estimated number of lives that would be lost (N) on the x axis and the annualized probability of the failure (f) associated with the life loss on the y axis. An f-N plot depicts both societal (impacting society as a whole) and **individual risk** (impacting the most exposed individual subjected to dam breach flows). In addition to displaying discrete risk estimates for individual **potential failure modes** (a way that dam failure can occur for a given loading condition), the total risk for the facility is plotted.

An F-N plot shows the cumulative risk posed by all failure modes and the associated potential life loss (discrete estimates for individual potential failure modes are not shown, but the plot does depict **societal risk**[9] in more detail). On the F-N plot, the end branch probabilities are accumulated by consequence level irrespective of failure mode. A cumulative curve is developed and plotted showing the probability of N or more lives lost. An F-N plot depicts societal risk. Both f-N and F-N plots require quantitative risk estimates. Figures 3–6 are examples of f-N and F-N plots. For qualitative risk estimates, the results can be plotted using a matrix. Figures 8 and 9 provide examples of an f-N and F-N plot with data added. Figure 9 depicts cumulative risk.

3.1.4.1 Preparing the Dam Safety Case

Numerical risk estimates are based on judgments, are typically subjective, and include varying degrees of uncertainty. These estimates should not be the sole basis to inform decisions. Understanding the basis of the risk estimates is as important as the risk numbers themselves. The dam safety case is a logical and objective set of arguments used to advocate a position that either additional safety-related action is justified, or that no additional safety-related action is justified. The dam safety case should cite the most compelling information that supports the risk estimates and the overall findings and also discuss the uncertainties that were identified in the risk analysis.

The arguments combine together key evidence regarding the three basic risk components (load probability, response likelihood, and consequences) in order to support decisions related to a dam's existing condition or ability to withstand future loading. The dam safety case should initially be developed in the risk analysis phase and completed as part of the risk assessment for a given dam. The risk analysis team will be in the best position to provide the supporting arguments for the risk analysis estimates. The risk analysis team should also identify a suite of options for additional actions to better define or reduce risk, if there is justification for taking actions. An independent group should review the risk analysis report and the dam safety case and then provide additional input and possibly revisions to any proposed dam safety actions. This independent group may identify additional factors to consider in the risk assessment or additional options for refining or reducing risk. Individuals who have the authority in the organization to make dam safety decisions will have the final input and determination on adopting recommended actions. The dam safety case is completed once the final actions (which may include a decision to take no action) have been determined within the organization. A number of principles apply to risk analysis. These principles are discussed below and summarized in the box at the end of this section.

[9] Societal risk is the probability of adverse consequences from hazards that impact society as a whole and that create a social concern and potential political response because multiple fatalities occur in one event.

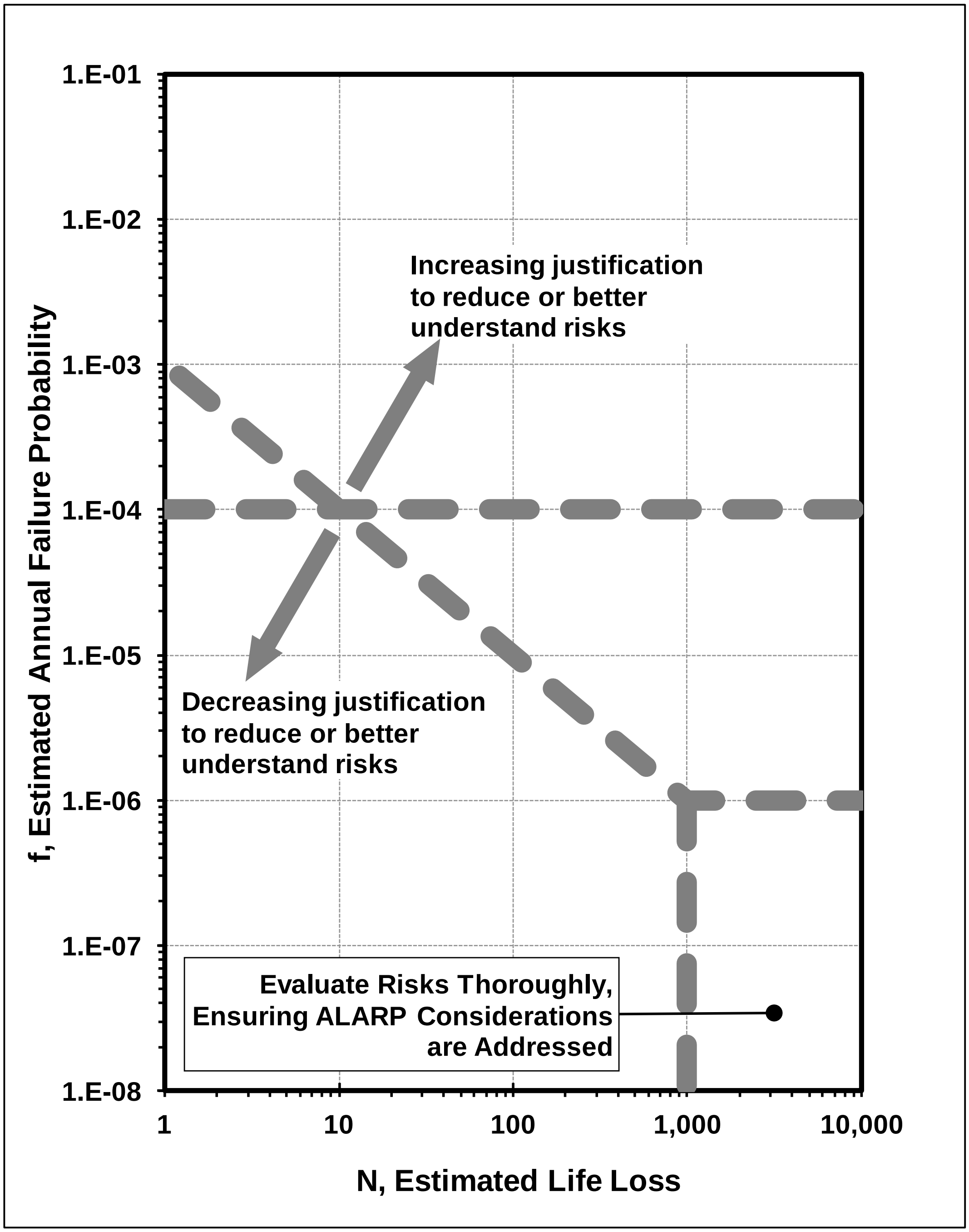

Figure 3.—Bureau of Reclamation [4] f-N plot.

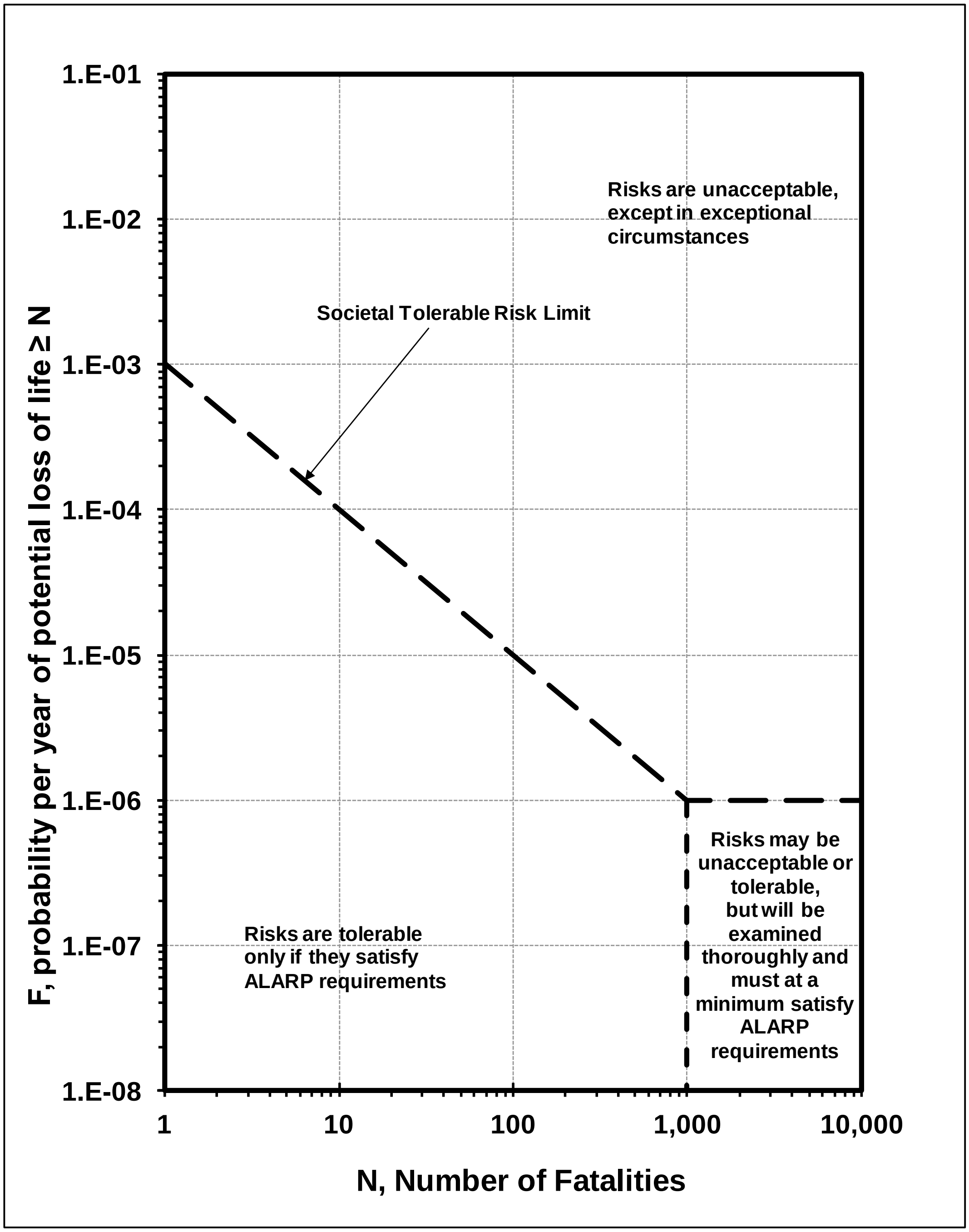

Figure 4.—U.S. Army Corps of Engineers [7] F-N (societal risk) plot.

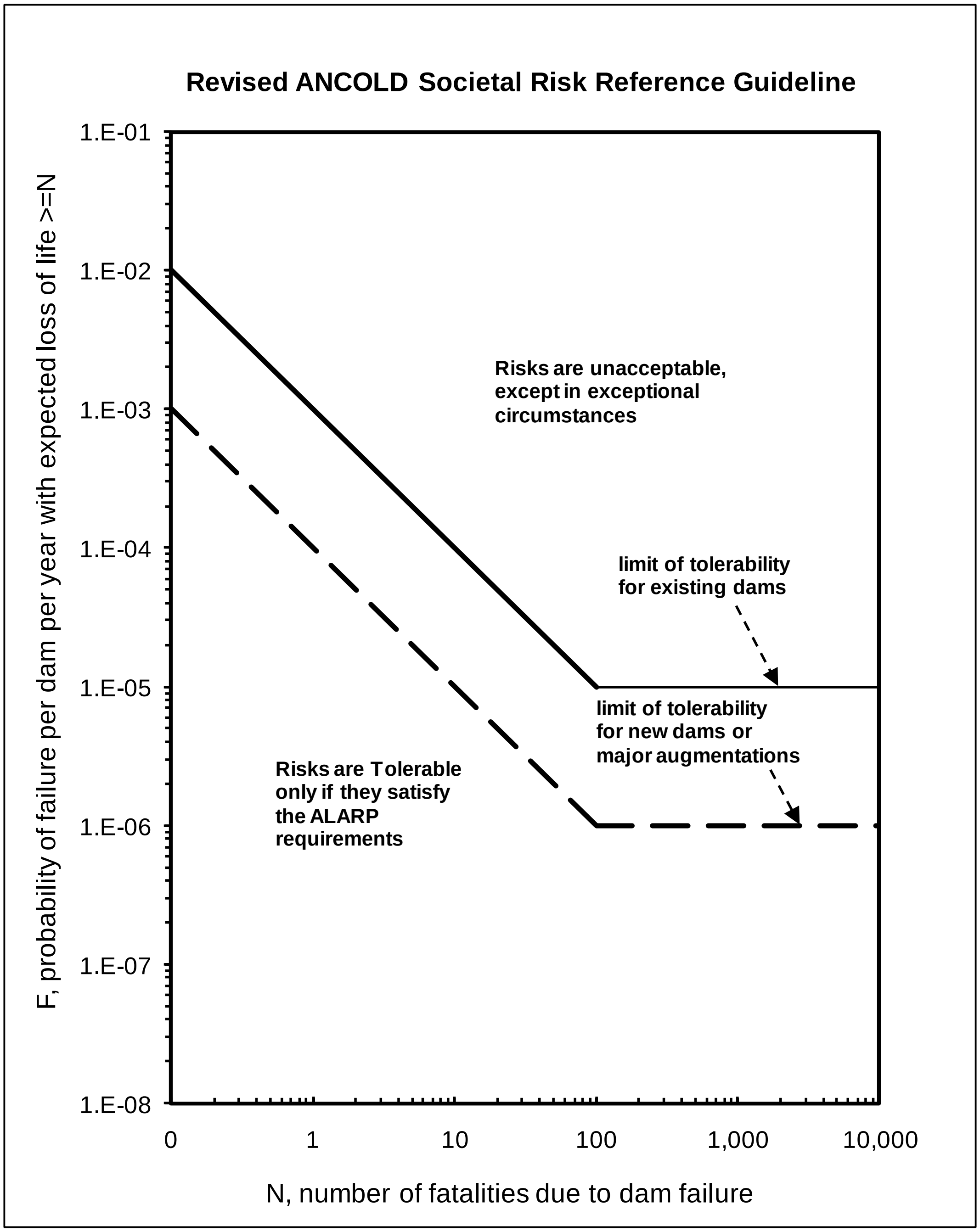

Figure 5.—Australian National Committee on Large Dams [2] F-N (societal risk) plot.

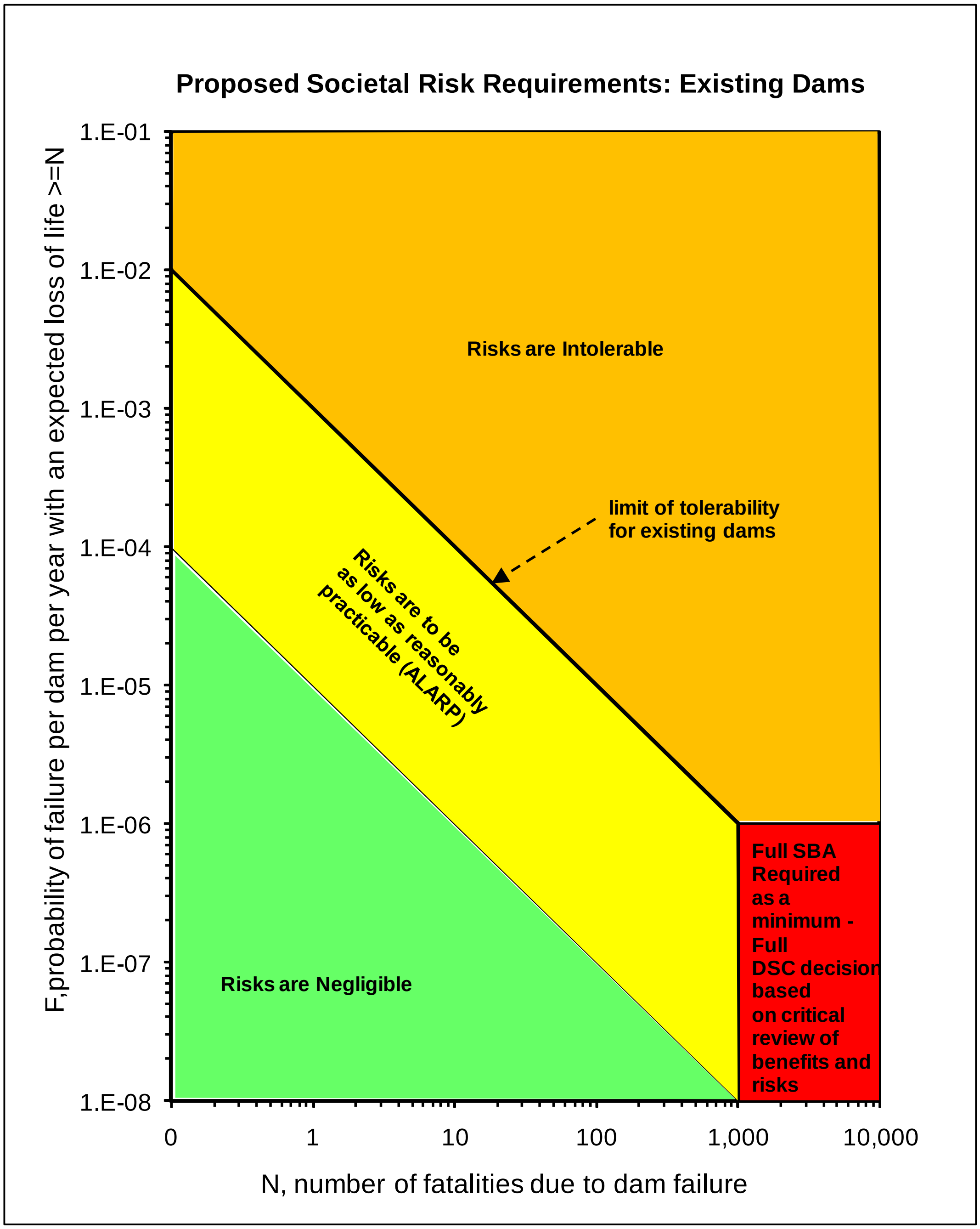

Figure 6.—New South Wales Dam Safety Committee [8] F-N (societal risk) plot.

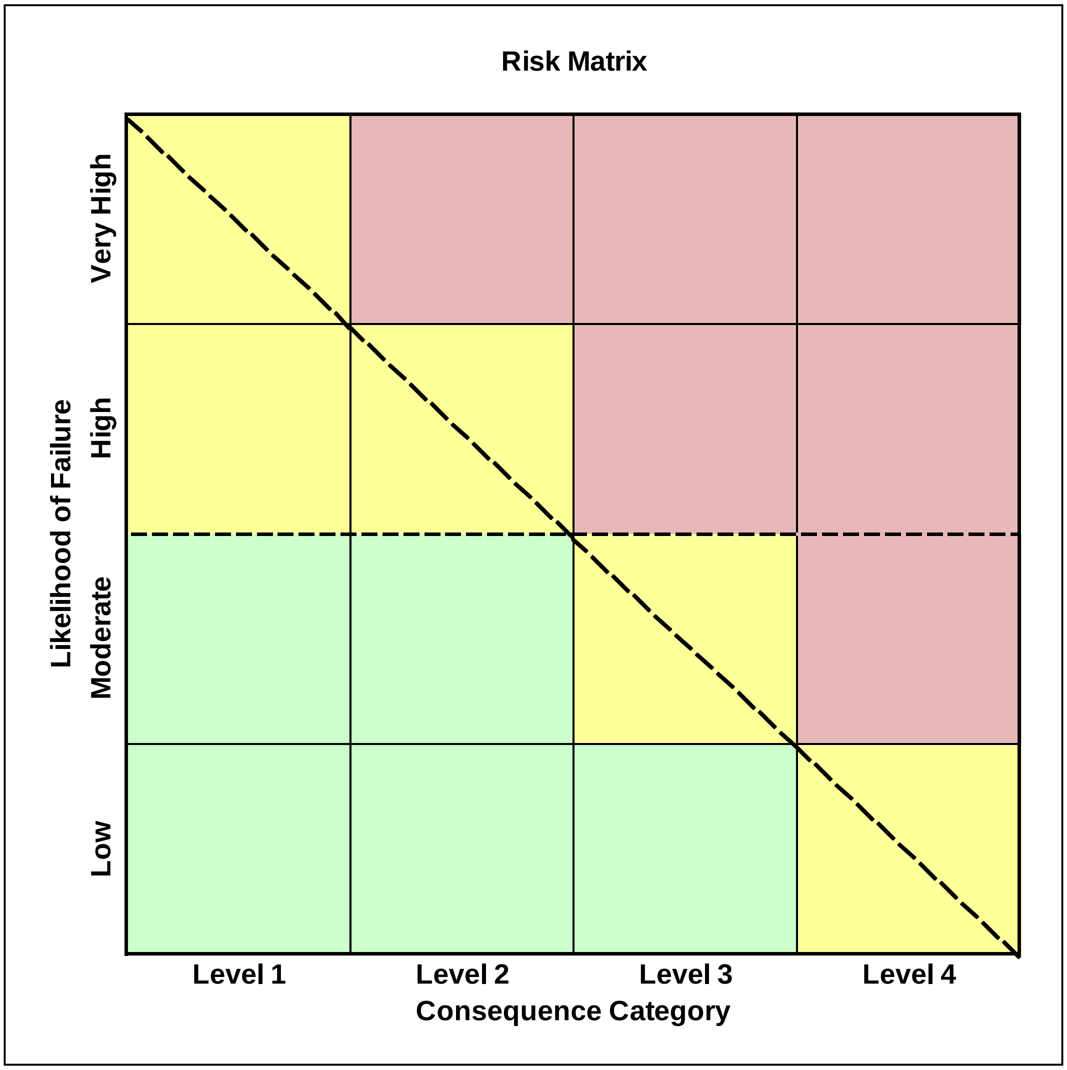

Figure 7.—Qualitative risk matrix.

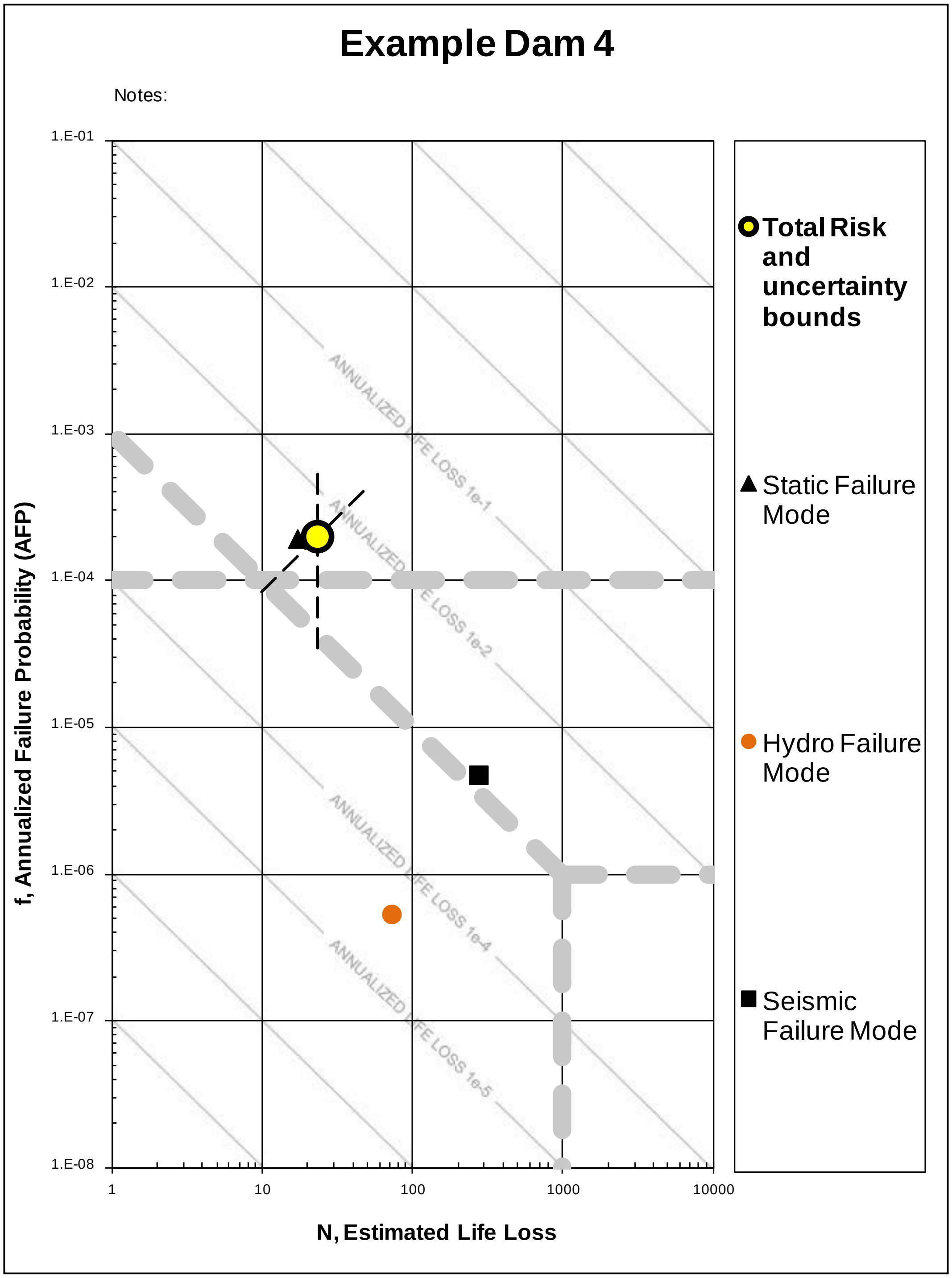

Figure 8.—An f-N plot showing individual potential failure modes and total risk [4].

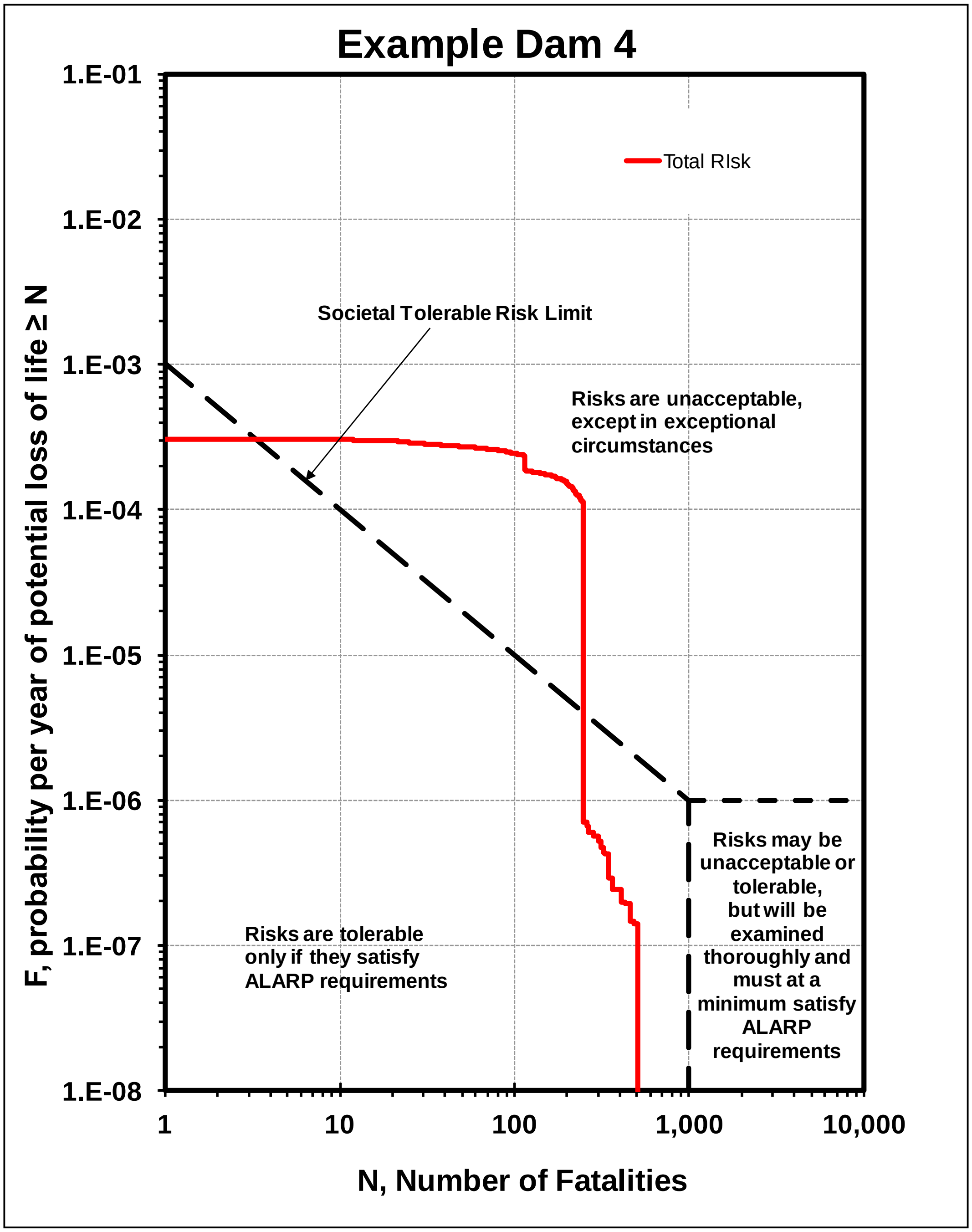

Figure 9.—An F-N plot showing cumulative risk [7].

A critical first step in a risk analysis is an evaluation of the design, construction, analysis, and performance of a dam and an identification of the specific potential failure modes that apply to that dam. If critical potential failure modes are overlooked, the risk analysis results will be incomplete and misleading.

It should be recognized that each dam is unique in terms of purpose, geologic and demographic setting, design, structure, operations and consequences. While certain dams may be similar to other dams in type, design and size, there are unique factors that need to be considered when identifying potential failure modes and when estimating risk.

Numerical risk estimates by themselves provide an incomplete basis for dam safety decision making. There are a number of factors that should also be considered, including the uncertainty and confidence in the risk estimates. The dam safety case provides supporting justification for the numerical risk estimates. A well-constructed dam safety case should include a discussion that supports and supplements the numerical risk estimates.

The following principles apply to risk analysis:

1. The basis for a coherent risk analysis should be a thorough examination and description of potential failure modes analysis.
2. It should be recognized that each dam is unique in terms of purpose, geologic and demographic setting, design, structure, operations, and consequences.
3. A well-constructed dam safety case should include a discussion that supports and supplements the numerical risk estimates.

4.1 Risk Assessment

4.1.1 Risk Assessment/Risk Evaluation Process

Risk assessment is the process of considering the quantitative or qualitative estimated risk of the existing dam or project, along with all other factors related to a safety decision. These factors can include the dam safety case, social/economic impacts, environmental impacts, constructability, and potential to do harm. The risk assessment is conducted to determine a recommended course of action (which may involve considering a range of options) for mitigating or accepting the risks related to a specific dam or project or with regard to a specific dam safety issue or operational concern on that project.

Typically the risk assessment and proposed recommendations are initially developed by the risk analysis team and then reviewed, and possibly revised, by a technically qualified and experienced team, rather than a single individual. This specialized team can discern the relative criticality, the measure of concern, and the type and degree of remedial action needed to address the issue. When there is justification to take dam safety actions, a suite of options should be identified, and the costs and potential benefits of each option should be developed and presented. The final decision to adopt any recommended dam safety actions is made by the authorized decision makers within the organization. The most obvious and direct factors that enter into the assessment are the results of a risk analysis. These results may come in the form of quantitative/numeric results or qualitative statements that indicate the measure of concern relative to public safety. Quantitative results provide three measures related to risk. They are:

- Likelihood of occurrence of a failure or adverse consequence in terms of annual probability

- Estimated population at risk and/or life loss given failure or adverse consequence presented as the total estimated loss for a given annual probability of failure (often plotted or graphed), or the product of those two values which is called the "annualized life loss"

- The economic damages (e.g., downstream damages, cost to rebuild facilities, loss of operational revenue, regional social/economic damages, environmental damages, etc.). Again, these can be given or plotted as the lost economic value versus the annual probability of occurrence or as an annualized cost

However, there are many factors that may be included in a dam safety case and can be considered in the decision recommendation. They include:

- The risk analysis input for the dam safety case

- The design and construction of the dam, including defensive design features

- The past and future performance monitoring of the dam

- Environmental considerations

- Public perception and public input

- Regional, social, and economic considerations

- Ease, difficulty, and practicality of remediation
- Potential to do harm as a result of carrying out remediation

- Uncertainty about the results and the success of the remediation

This document focuses on a risk-informed approach to make decisions. This method has the advantage of providing a more consistent basis for decision making. Also, since it is risk-informed, rather than risk-based, it allows for other important factors (such as those listed above) to be considered in the decision, beyond a sole reliance on numerical risk estimates. The factors that are considered in making dam safety decisions will be at the discretion of each Federal agency.

4.1.2 The Dam Safety Case

The risk estimates and the recommended actions need to be coherent. Since uncertainty is inherent in each assertion, the arguments should also address whether confidence is high enough for the assertions to stand on the basis of existing evidence.

The dam safety case and the identification of risk management options are recognized as essential elements to ensure public protection. They represent the understanding of existing conditions and predicted future behavior stated as objectively as possible.

4.1.3 Approach to Making Risk-Informed Decisions

The concept and practice of the use of risk to inform dam safety risk assessment decisions evolved primarily from the recognition of, and the desire to address, the great deviation in the magnitude of potential life loss and, to a lesser degree, great variation in economic impact of potential failure of dams classified as high hazard. When dam safety became prominent in the late 1970s, decisions were primarily based on the standard hazard classification of the dam (e.g., high, significant, or low). Thus, a dam with an estimated potential life loss of more than one person in the event of dam failure was classified and treated in the same way as a dam with a potential life loss of several thousand people. This lack of discrimination between the levels of consequences among high hazard dams led to proposals of criteria that would take the magnitude of loss into consideration. Among others, ANCOLD [2], BCHydro [3], the Netherlands [9], and the Bureau of Reclamation [4] proposed or developed evaluation criteria or guidelines.

The above discussion presumes that a quantitative risk analysis will be carried out. However, evaluation criteria could also be readily established, converted, or mapped for a qualitative risk analysis.

4.1.4 Tolerable Risk

Inherent in the use of risk analysis and risk-informed criteria or guidelines and, specifically, in risk assessment is the recognition and understanding of tolerable risk.

Risk assessment teams, which include the organization's decision makers, can make a variety of decisions such as:

- Remediation for a project or dam will not be required, but monitoring of the concern will continue.
- A nonstructural alternative will be implemented.
- An alternative that addresses the major portion of the concern, but does not deal with all aspects, will be the course of action.

The risk remaining after decisions are implemented, related to a specific dam safety issue, is considered a tolerable risk. It can also be thought of, considered, or called the **residual risk**. It is the risk that remains after prudent actions to address the risk have been taken, or the remote risk associated with a condition that was judged to not be a credible dam safety issue.

Threshold values are typically established to help guide decisions on tolerable risk. While the threshold guideline values are generally consistent within the dam safety community (see figures 3, 4, 5, and 6), agencies may elect to use different values to address their unique mission.

Another way of describing or thinking about tolerable risk is that, after hearing all the facts and information related to an issue or issues on a dam or project, an organization decides that further action is not reasonably practicable. When a judgment is made that risks are as low as reasonably practicable, this is often determined by comparing the effectiveness of reducing risk further (evaluated by considering the cost to further reduce risk and the amount of risk reduction achieved, and then comparing it to other risk reduction actions implemented by the agency). If the costs to achieve an additional level of risk reduction are disproportional to achieving the same magnitude of risk reduction at other dams, the current risk may be as low as reasonably practicable. There are many factors besides the numerical estimate of risk that can contribute to the decision that no further action is justified, including:

- The cost to reduce risks further
- The level of certainty or uncertainty on various aspects of the problem
- A precedent of comparable decisions on other projects

- The possibility that the concern is not reasonable to address in a practical manner

- The chance of success of an action

- Time to perform the remediation

- Other considerations

It should also be recognized that regardless of what actions are taken or not taken, there will always be a certain level of residual risk. Therefore, rather than ignoring or supposing that the risk is zero, it is appropriate that tolerable risk levels for various aspects of the dam be discussed and identified.

A number of principles apply to risk assessments. These principles are discussed below and summarized in the box at the end of this section.

Remedial actions should do no harm. The goal of remedial dam safety actions is to reduce risk. Some remedial actions may have unintended consequences, however. In order to implement some remedial actions, construction risks may be excessive during certain phases of the work. A remedial action to address a specific potential failure mode can increase the probability of another potential failure mode. Decisions should be **risk-informed**[10], not **risk-based**[11]. Decisions should be based on consideration of the results of a risk analysis as a key input, but other factors, such as the uncertainty and confidence in the risk estimates, should also be considered. Decisions should not be based solely on where risk estimates plot on an f-N or F-N chart. The decisions made should consider the risk estimates, including the uncertainty and confidence in the risk estimates, the

The following principles apply to risk assessment:

1. Remedial actions should do no harm.

2. Decisions should be risk-informed, not risk-based.

3. Interim risk reduction measures (IRRMs) should be considered and implemented where needed.

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[10] Risk-informed dam safety decision making implies that decisions are made considering risk estimates and many other contributing factors that might include confidence in the risk estimates, risk uncertainty, deterministic analyses, and the overall dam safety case in addition to other local or regional considerations.

[11] Risk-based dam safety decision making implies that a comparison of a risk estimate to risk criteria is the basis for decision-making.

likely outcomes if dam safety actions are completed, and other factors important to an agency's mission.

Interim risk reduction measures should be considered and implemented where needed. While the ultimate goal may be to reduce risks to certain levels at a given dam, IRRMs can achieve timely incremental risk reduction, often at a reasonable cost.

5.1 Risk Management

Risk management encompasses activities related to making risk-informed decisions, prioritizing evaluations of risk, prioritizing risk reduction activities, and making program decisions associated with managing a portfolio of facilities. Risk management processes vary with respect to an organization's dam safety governance. Risk management is greatly facilitated and enhanced by having the knowledge base supplied by the risk analyses and risk assessment inputs for the dams as described above. Such knowledge allows a logical and consistent basis for substantiating and prioritizing risk reduction activities and/or making program decisions associated with managing a portfolio of facilities. Risk management, because it uses the findings from a risk assessment/risk evaluation process, includes considering the environmental, social, cultural, ethical, political, and legal factors. Risk management should be regarded as an ongoing and iterative process that needs to adapt to new information.

The primary goal of risk management is to implement actions to either: accept, further monitor or evaluate, control, or reduce risk, while considering the cost and benefits of any actions taken. When reducing risk either at a single dam or within a portfolio of dams, actions should be taken as quickly and as efficiently as possible, recognizing that there will likely be limits on available funding. Consideration should be given to how much risks are reduced compared with the costs necessary to achieve risk reduction. Generally, the priorities will be to address the dams with the highest perceived risk first, assuming there is confidence in the risk estimates; however, if the cost of reducing risk at the highest risk dam is disproportional to the risk reduction achieved, it may be appropriate to consider risk reduction activities at other dams first.

The agencies recognize that the methods used to calculate risk do not provide precise numerical results. Therefore, it would not be appropriate to rely solely on the numeric estimates in comparison to definite established criteria (i.e., risk-based evaluation criteria). Decisions are usually more complex than can be portrayed using only the numerical results of a risk analysis. The strength of the dam safety case should also be considered in the risk management phase.

In order to effectively prioritize dam safety actions, information on the cost and duration of the actions and the risk reduction potential is needed. This type of information is necessary to evaluate the efficiency of risk reduction actions and can be used to fine-tune dam safety actions. A record of the baseline risks, the dam safety case and rating, and updates that resulted from risk reduction activities should be maintained for each dam in an agency's inventory.

For Federal dam owners with large dam inventories, or for private dam owners with large dam inventories, it will be important to prioritize dam safety actions because funding will limit how quickly actions can be completed. If an owner is dealing with a large dam inventory, a risk categorization scheme may be helpful in making an initial cut at prioritizing dam safety actions. Table 1 shows a method of categorizing dams by risk that will provide an initial sorting of dam safety actions.

Table 1.—Joint Federal risk categories

Urgency of action	Characteristics and considerations	Potential actions
I – VERY HIGH URGENCY	CRITICALLY NEAR FAILURE: There is direct evidence that failure is in progress, and the dam is almost certain to fail during normal operations if action is not taken quickly. OR EXTREMELY HIGH RISK: Combination of life or economic consequences and likelihood of failure is very high with high confidence.	• Take immediate action to avoid failure. Communicate findings to potentially affected parties. • Implement IRRMs. • Ensure that the emergency action plan is current and functionally tested. • Conduct heightened monitoring and evaluation. Expedite investigations and actions to support long-term risk reduction. • Initiate intensive management and situation reports.
II - HIGH URGENCY	RISK IS HIGH WITH HIGH CONFIDENCE, OR IT IS VERY HIGH WITH LOW TO MODERATE CONFIDENCE: The likelihood of failure from one of these occurrences, prior to taking some action, is too high to delay action.	• Implement IRRMs. • Ensure that the emergency action plan is current and functionally tested. • Give high priority to heightened monitoring and evaluation. Expedite investigations and actions to support long-term risk reduction. • Expedite confirmation of classification.
III - MODERATE URGENCY	MODERATE TO HIGH RISK: Confidence in the risk estimates is generally at least moderate, but can include facilities with low confidence if there is a reasonable chance that risk estimates will be confirmed or potentially increase with further study.	• Implement IRRMs. • Ensure that the emergency action plan is current and functionally tested. • Conduct heightened monitoring and evaluation. Prioritize investigations and actions to support long-term risk reduction. • Prioritize confirmation of classification as appropriate.
IV – LOW TO MODERATE URGENCY	LOW TO MODERATE RISK: The risks are low to moderate with at least moderate confidence, or the risks are low with low confidence, and there is a potential for the risks to increase with further study.	• Ensure that routine risk management measures are in place. • Determine whether action can wait until after the next periodic review. • Before the next periodic review, take appropriate interim measures and schedule other actions as appropriate. • Give normal priority to investigations to validate classification, but do not plan for risk reduction measures at this time.
V – NO URGENCY	LOW RISK: The risks are low and are unlikely to change with additional investigations or studies.	• Continue routine dam safety risk management activities and normal operations and maintenance.

To prioritize actions within a category, consider each of the following factors, which will contribute to increasing the priority of actions at a given dam:

- Both the failure probability and the annualized life loss exceed the threshold guideline values
- The failure probability or the annualized life loss is driven by a single potential failure mode
- The failure probability or the annualized life loss is driven by a potential failure mode manifesting itself during normal operating conditions
- The range of risk estimates is tightly clustered and the mean and median are similar (for detailed uncertainty analyses only) and/or sensitivity studies instill confidence
- Risk reduction or confirmation is relatively easy and inexpensive

The above factors can also be considered if a dam appears to border two categories. If a dam owner has a small inventory of dams, the above factors alone can be used as the basis for establishing priorities. The initial effort to place the actions in one of the five risk categories would have limited value for small dam inventories.

Prioritization of dam safety actions can be done on a facility basis (where total risk is the focal point, and the goal is to reduce total risk to tolerable levels) or on an individual potential failure mode basis (where single potential failure modes are addressed).

A number of principles apply to risk management. These principles are discussed below and summarized in the box at the end of this section.

Reducing risk at a given dam or within a portfolio of dams will typically require setting priorities. Factors to consider will be the magnitude of risk at a given dam and the confidence in the risk estimates, the costs of implementing risk reduction actions, and the timeframe required to achieve the risk reduction. All of these factors should be considered when establishing priorities. The objective of an organization should be to reduce dam safety risk as effectively and as efficiently as possible.

Each organization should have a transparent process for establishing priorities and the urgency of completing dam safety actions. Within an organization, the responsibility for the inventory of dams will often be divided among a number of offices. Having a transparent process will develop confidence within the organization that decisions are made objectively and fairly.

Prioritizing work within a portfolio of dams will typically be a dynamic process. While priorities can be established annually, new dam safety issues that have a high priority may develop in between annual prioritization activities. This requires flexibility in prioritizing work within a portfolio, allowing for adjustments in planned work as new, high priority issues are identified.

Use a dedicated, established group to review and prioritize proposed dam safety actions within a portfolio of dams or when establishing urgency for action at a specific dam. This will help ensure consistency in establishing priorities and will improve efficiency because a consistent group will maintain knowledge of the overall inventory.

Independent review is critical to the credibility of risk management. This will help ensure that biases and individual preferences do not dominate the decision making process.

The urgency of completing dam safety actions should be commensurate with risk. In general, dams with the highest estimated risk should receive the highest priority because they are the dams most likely to fail in the inventory.

The following principles apply to risk management:

1. The objective of an organization should be to reduce dam safety risk as effectively and as efficiently as possible.
2. Each organization should have a transparent process for establishing priorities and the urgency of completing dam safety actions.
3. Incorporate flexibility in prioritizing work within a portfolio, allowing for adjustments in planned work as new, high priority issues are identified.
4. Use a dedicated, established group to review and prioritize proposed dam safety actions within a portfolio or when establishing urgency for action at a specific dam.
5. Independent review is critical to the credibility of this process.
6. The urgency of completing dam safety actions should be commensurate with risk.

6.1 Risk Communication/Public Awareness

Communication is important in all aspects of dam safety within an organization, with the public, and with the specific owners or stakeholders of a project. However, communication about the work associated with risk is particularly important because of the fears, sentiments, perceptions, and emotions surrounding the word *risk* and the use of *risk analysis* in engineering. Thus, it is important to understand and have a good plan for communicating risk, including:

- What information is available at a given dam related to potential failure modes and how the information is considered in a risk analysis

- How risk will be considered by an organization

- What the results of the risk analyses are

- What decisions were reached and what risk remains

This communication can help create an awareness of potential dam safety issues and help all parties gain a greater understanding. Creating an understanding of risk and dam safety issues is important for those who have varying degrees of connections to the dam and the associated potential impacts. These diverse groups have a variety of backgrounds, experience, and sophistication. Communication plans and strategies should be developed for the following:

- Internal to a dam safety organization
- Owners and stakeholders
- Dam site and project personnel
- Local organizations
- Technical organizations or consultants
- Decision makers
- The public

6.1.1 Internal Communication within a Dam Safety Organization

There are at least four levels at which communication garnered from risk studies and resulting decisions needs to take place within an organization. These include:

- Communication with employees at the dam or project site

- Communication at the local level of the organization, where the responsibility for managing the operation and maintenance, as well as the routine visual surveillance and instrumental monitoring for the suite of dams associated with one or more projects typically resides

- Communication at the technical level, where traditional engineering and geologic studies and investigations are performed, where risk analyses and risk assessments are carried out, and where independent staff check and review studies, analyses, and risk analysis results

- Communication at the decision making level, where funding is secured and decisions are made regarding dam safety actions and risk management decisions on program priorities

6.1.1.1 Dam Site and Project Site Personnel

The dam tenders, inspectors, staff performing visual inspections and taking readings of seepage and instruments, and plant operators responsible for gate operations provide a valuable source of information relative to risk analyses and need to be included. Dam operators often have detailed information and understanding of the dam history, past performance issues, and a good perspective on perceived changes at the dam. It is important to include them in risk analysis activities to benefit from their knowledge of the dam. In addition, it is very important for them to gain an understanding of potential failure modes at the dam, specific locations at the dam where potential failure modes might develop, and the initiating mechanisms for the potential failure modes. This will allow them to more effectively monitor the dam. Likewise, the results of risk analyses and the decisions and rationale used in risk assessment and risk management need to be provided to these personnel so that they have a full understanding of the outcome of the risk process.

6.1.1.2 Local Level of an Organization

Supervision and management of the operation of a number of projects and dams are usually the responsibility of a local office within a dam safety organization. These offices have the responsibility to staff for routine operation and maintenance of the projects and dams under their purview, as well as for inspection and monitoring of the dams. In addition, they are often responsible for implementing structural and nonstructural actions which may be specified as the outcome of the risk-informed decision analyses. Often, these local offices cover a number of facilities and manage a staff that must distribute its time between several sites. Local office personnel, as appropriate, also need to be consulted and included in risk analyses relative to failure modes and dam performance, either because they have previously been assigned to dams under their purview and have an intimate historic knowledge and/or they have a broader perspective by virtue of being associated with all the projects and dams under their responsibility. With respect to communicating the findings from the risk analyses, and the decisions from risk assessment and risk management, the local office is typically the key intermediary between the desired objectives of the organization's dam safety office and the field site that will be affected by the outcomes.

6.1.1.3 Technical Elements of an Organization

Detailed communications are required among the technical staff (including consultants and contractors) performing the basic analytical studies and evaluations, the persons performing the risk analyses, and the staff performing the risk studies who will be reviewing studies, analysis reports, and risk analysis reports and making their assessments on specific dams and dam safety issue evaluations. The reports prepared by each previous study level will need to include sufficient detail so that the primary reviewers (as well as analysts in future years) can understand assumptions made, detailed results of studies, analyses and risk analyses, and the technical basis for overall findings. Further, these results may be called for at any future stage in the process (e.g., risk management, stakeholder review, etc.); thus, good documentation is essential. Briefings are typically performed for technical staff on the results of studies, risk analyses, the overall findings, and the dam safety case for proposed actions. Briefings may also be performed for consultant review boards, which provide an independent review of studies and findings. At this level, the communication will be the most technically demanding.

6.1.1.4 Decision Making Level of an Organization

Decision makers need to have a general understanding of the potential failure modes at a dam, the results of studies and analyses performed, the risk analysis results, and the dam safety case. Decision makers have the responsibility for formally accepting dam safety actions and must be convinced that the proposed actions are warranted and appropriate. Summary technical information is typically presented in briefings for decision makers, and the detail needs to be sufficient to support the key findings and dam safety case. Individuals who have the responsibility for setting priorities within an organization will also need to understand the basis and urgency of dam safety actions at a given dam. This is needed to prioritize actions across an entire inventory.

6.1.2 Communications with Stakeholders

Risk communication with stakeholders and owners is important in order to be successful. Risk communication and stakeholder participation should ensure that (1) responsible and affected stakeholders will be partners and be afforded the opportunity to participate in decisions that affect them and (2) communications regarding potential inundation hazard, consequences, and shared solutions will be open, transparent, and understandable.

It may be helpful to include individuals from stakeholder organizations as observers in the risk analysis, especially in the risk assessment meetings. This will allow those individuals to gain a better understanding of the basis of the risk analysis estimates, the subsequent findings, and the rationale on which a decision is made. They will typically be interested in the rationale behind proposed dam safety and will want to ensure that the chosen actions are appropriate and efficient. It will also be helpful to explain the overall dam safety process used and explain the risk guidelines that were used in the risk assessment. Funding partners may enlist consultants to review reports, attend briefings, and interact with technical staff. Detailed technical reports and briefings may need to be provided for consultants.

There may be multiple levels of stakeholders that will be impacted by risks at a given dam or that could be impacted by the risk at another dam upstream or downstream of the given dam. Impacts may be related to new or updated risk estimates at a given dam or may be related to a change in operations (or expected releases for a given magnitude flood). These potential impacts may need to be shared with dam or facility operators, owners, or the regulators who oversee the facilities.

Local emergency management authorities are key stakeholders in dam risk management. Effective communication of dam risks with emergency management authorities responsible for responses and evacuation actions is essential. Effective risk communication should provide timely and best available information to facilitate the development of response plans and risk mitigation strategies.

6.1.3 Communications with the Organizations and the Public Impacted by the Dam

Communications should also be provided proactively for organizations and the public that will be, could be, or consider themselves impacted by a dam failure or by dam safety actions that will restrict or modify the operations at the dam. These communications should be initiated at the planning or investigation stage to prevent erroneous information and rumors from developing. Such presentations need to be appropriately technical, conveying the technical information in a manner that conveys the key issues and concerns at the dam, the potential impacts of a dam failure, the proposed actions to address the issues/concerns, and the impacts of these actions on organizations and the public. In addition, the presentation needs to convey the costs and schedule for the dam safety actions.

The diverse audience that attends the public and stakeholder meetings may include persons who can fully comprehend the technical content being presented. Therefore, a definite way to alienate the audience is to presume they are incapable of understanding the work that is planned or has been done. Information should be presented in a manner that is easy to understand but not condescending to the audience. While recognizing this, the presentation should avoid the use of technical jargon and unnecessary detail. Technical staff should be available to answer detailed technical questions from individuals with technical backgrounds that may attend the briefing.

Organizations may have security concerns related to information that is presented in these general briefings or public meetings, and the presentations may have to be adjusted to take this into account. Security concerns will vary with individual dams, and security protocols will vary within each agency. Each agency will need to establish their own guidelines on the type of information and the level of detail that are appropriate for public briefings. Decisions on the level of information to share should balance legitimate security concerns with the benefits of creating a public awareness of potential dam safety issues.

A number of principles apply to risk communication. These principles are discussed below and summarized in the box at the end of this section.

Enhance communication with the public, internally within dam owning and regulating organizations, and Emergency Management Agencies (EMAs). Risk communication provides many benefits, including improving the chances that dam safety decisions will be supported within and outside of the organization, better preparing the organization and the public for taking action in the event of an emergency, and instilling confidence in the dam safety office of an organization.

Emergency Action Plans identify emergency situations that may develop at a given dam and establish protocols for reacting to the emergency. The advance planning inherent in these plans, and the familiarity of local officials and the public with the plans, will save valuable time during an emergency. Emergency Action Plans and communication with the public are important and integral aspects of reducing risk to life.

Communications should be open and transparent. This will help instill confidence in the organization and better prepare the organization and the public for responding to an emergency.

Dams present both a benefit and a risk to the public. When dam safety risks are presented, the public may focus on the negative aspects of the dam and not realize the offsetting benefits that the dam provides. When describing dam safety issues at a given dam, the presenter should focus on the benefits as well as the risks posed by the infrastructure.

Integrate risk communications early in the process of responding to dam safety issues. This is beneficial because by including individuals in the process and giving them the opportunity to provide input and, possibly, influence decisions, they are more likely to accept the decisions being made. Provide context for risk communications (i.e., compare with other risks). This is especially important for the public who may have trouble identifying the significance of dam safety risks. Focus communications on actions that individuals/organizations need to take. This is important because an effective dam safety program and effective risk reduction actions involve a number of organizations and individuals: those that monitor and maintain dams, those that evaluate and make decisions regarding the safety of dams, and those that react and respond to emergencies at dams. Risk estimates are inherently uncertain, with the nature and the amount of uncertainty varying from dam to dam. It is important to acknowledge the uncertainty and put it into the proper context. The following aspects of uncertainty in risk estimates and the dam safety case should be discussed:

- What is certain
- What is likely, but not certain
- What is possible, but not likely

The following principles apply to risk communication:

1. Enhance communication with the public, internally within dam owning and regulating organizations, and Emergency Management Agencies.

2. Emergency Action Plans and communication with the public are important and integral aspects of reducing risk to life.

3. Communications should be open and transparent.

4. When presenting dam safety issues at a given dam, focus on the benefits and the risks posed by the infrastructure.

5. Integrate risk communications early in the process of responding to dam safety issues.

6. Provide context for risk communications (compare with other risks).

7. Focus communications on actions that individuals/organizations need to take.

8. Discuss uncertainty in risk estimates and the dam safety case:

    - What is certain
    - What is likely, but not certain

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APPENDIX A

Guidelines on Risk Terminology

Appendix A – Guidelines on Risk Terminology

To facilitate the cooperative agreement for all elements of risk-based decision analysis, it is extremely valuable to use common terminology and have a common understanding of that terminology. It is recognized that this is not a simple task because words related to dam safety risk have been used in different ways by the member agencies over the years since their initial application over 35 years ago. However, to establish consistency in terminology, this guideline provides definitions for the terms given below that are used in risk management, risk assessment, risk analysis, and risk evaluation. These definitions have been developed for use in this document.

Dam failure: Failure characterized by the sudden rapid and uncontrolled release of impounded water or liquid-borne solids. It is recognized that there are lesser degrees of failure and that any malfunction or abnormality outside the design assumptions and parameters that adversely affect a dam's primary function of impounding water could be considered a failure.

Credible potential failure mode: A potential failure mode that is considered to affect the total risk at a given dam and for which action could potentially be taken to reduce risk. A non-credible potential failure mode is a potential failure mode which is judged to have very low risks and for which a strong case can be made to that affect. Non-credible potential failure modes are often judged to represent a risk that is well below tolerable risk guidelines and orders of magnitude less than that of the more dominant potential failure modes at a given dam.

Individual risk: This term is associated with the most exposed individual who is placed in a fixed relation to a hazard, such as a dam. Individual risk is the sum of the risks from all potential failure modes associated with the hazards that affect that person. The similarity to annualized failure probability is apparent when life loss of that individual is virtually certain (because the failure probability multiplied by a life loss of one person is equal to the failure probability).

Potential failure mode: A way that dam failure can occur (i.e., the full sequence of events from initiation to failure) for a given loading condition. A condition of a potential failure mode is that it results in an uncontrolled release of the reservoir.

Risk: The product of the likelihood of a structure being loaded, adverse structural performance, (e.g., dam failure), and the magnitude of the resulting consequences.

Risk analysis/risk estimation: A qualitative or quantitative procedure that identifies potential modes of failure and the conditions and events that must take place for failure to occur. A quantitative risk analysis yields a numerical estimate of the risk of adverse consequence, multiplying the probability of load times the probability of dam failure given the load times the magnitude of adverse consequence given dam failure.

Risk assessment: The process of considering the quantitative or qualitative estimate of risk, along with all related social, environmental, cost, temporal, and other factors to determine a recommended course of action to mitigate or accept the risk.

Risk based: This term implies that a comparison of a risk estimate to risk criteria is the basis for decision-making.

Risk evaluation: The qualitative or quantitative description of the nature, magnitude, and likelihood of the adverse effects associated with a hazard. A risk evaluation often includes one or more estimates of risk, a risk description, risk management options, economic and other evaluations, and estimates of changes in risk attributable to the management options.

Risk governance: The process of risk-informed decision making and the process by which risk-informed decisions are implemented.

Risk informed: This term implies that decisions are made considering risk estimates and many other contributing factors that might include confidence in the risk estimates, risk uncertainty, deterministic analyses, and the overall dam safety case in addition to other local or regional considerations.

Risk management: Actions implemented to communicate the risks and either accept, avoid, transfer, or control the risks to an acceptable level considering associated costs and benefits of any action taken.

Residual risk: Risk remaining at any time.

Tolerable risk: A risk within a range that society can live with so as to secure the benefits provided by the dam. It is a risk that is not to be regarded as negligible or ignored, but needs to be kept under review and reduced further if possible.

Societal risk: The probability of adverse consequences from hazards that impact society as a whole and that create a social concern and potential political response because multiple fatalities occur in one event. Society is increasingly adverse to hazards as the magnitude of the consequences increases.

Uncertainty: The result of imperfect knowledge about the present or future state of a system, event, situation, or population under consideration.

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