United States Society on Dams

USSD

White Paper on Dam Safety Risk Assessment

What Is It? Who's Using It and Why? Where Should We Be Going With It?

February 2003

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Prepared by the USSD Committee on Dam Safety

USSD

The United States Society Dams (USSD), a Member of the International Commission on Large Dams, is a professional organization dedicated to:

advancing the technology of dam engineering, construction, operation, maintenance and safety;

fostering socially, environmentally and financially responsible water resources projects; and

promoting public awareness of the role of dams in the beneficial and sustainable development of the nation's water resources.

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United States Society on Dams

Emerging Issues White Paper

Dam Safety Risk Assessment:
What is it? Who's using it and why?
Where should we be going with it?

November 2002

Committee on Dam Safety
Working Group on Risk Assessment

SUMMARY

This Emerging Issues White Paper represents the consensus position of a diverse group of US Society on Dams (USSD) members and other dam safety professionals listed in Appendix A. It was prepared for the dam engineering profession in the US by a Working Group established by the USSD Committee on Dam Safety (CODS) in response to a request from the USSD Board. The request grew out of the growth of interest in and applications of dam safety risk assessment. The White Paper's overall purpose is "*To assess the state-of-the-practice in dam safety risk assessment, and to provide commentary on appropriate types of applications and ways to facilitate and strengthen its use.*"

The White Paper is neither a "how to" guide nor a standard of practice. The Working Group did not endorse any specific approaches. References made to applications are illustrative of what some owners and regulators have found to be useful. They should be understood in the context in which they were conducted and in which their outcomes were used. They should not be considered templates to be copied.

The Working Group held several half-day working sessions in addition to three-day workshop in March 2000 with sponsorship from FEMA through the Association of State Dam Safety Officials (ASDSO). The ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams provided the principal opportunity to develop the consensus position presented in the White Paper. The Working Group was assisted at the Workshop by some additional participants, including some from the States and some from Australia and Canada, who are listed in Appendix A.

The organization of the White Paper flows from the three questions posed in its title, "*Dam Safety Risk Assessment: What is it? Who's using it and why? Where should we be going with it?*" as follows:

- **What is it?** Section 2.0 summarizes some principles and fundamental concepts of dam safety risk assessment. Section 3.0 provides an assessment of the current state-of-the-practice for the four risk assessment application categories, which are listed below.
- **Who's using it and why?** Section 4.0 provides summaries and evaluations of applications in each of the four application categories by the owners or regulators who sponsored them.
- **Where should we be going with it?** Section 5.0 provides commentary on appropriate current practice of risk assessment, including cautions and limitations, which were identified by the Working Group. Section 6.0 summarizes technology transfer and training (T^3) needed to make the state-of-the-practice more broadly available to the profession. Section 7.0 summarizes research and development (R&D) needed to improve the breadth, depth and quality of applications.[1]

The Working Group's findings and commentary on appropriate current practice are summarized for each of the four risk assessment application categories as follows:

- **Failure Modes Identification (FMI),** which is an early step in performing a risk assessment, should also be standard practice for traditional standards-based approaches to

[1] Recommendations for T^3 and R&D are under consideration by the ICODS Research Subcommittee.

dam safety evaluation and design[2]. FMI provides a more comprehensive safety evaluation of a dam and a basis for strengthening many aspects of a dam safety program (e.g. instrumented and visual monitoring, emergency preparedness planning, O&M). Applications guidance is urgently needed for performing FMI. Users must recognize that FMI is a qualitative diagnostic approach and not a decision tool.

- **Index Prioritization (IP)** approaches are valuable and increasingly utilized for prioritizing dam safety issues and investigations, but should be calibrated and must incorporate a risk metric to be considered risk-based. They are generally less costly to use than PRA, but are more limited in the scope of their outcomes.
- **Portfolio Risk Assessment (PRA)** is a valuable and increasingly accepted approach for cost-effectively prioritizing dam safety remedial measures and further investigations for a group of dams. It provides insights that can better inform owners about the business and liability implications of dam ownership. PRA outcomes must be used with regard for the limitations of the approach and should be periodically updated.
- **Quantitative Risk Assessment (QRA)** approaches are valuable for providing insights and understanding of failure modes and associated stakeholder risks (probabilities and consequences). Uncertainties in inputs and outcomes must be taken into account. Improved approaches to the estimation of probabilities and consequences are needed. Acceptable/tolerable risk criteria need development and are yet to gain widespread acceptance. Stakeholders must decide on issues of appropriate use and defensibility.

By separating the category of QRA from the other application categories, the Working Group was able to recognize the applications potential of each category separately. For the case in which a QRA provides justification for a level of safety below that normally associated with the traditional approach, the Working Group considered that stakeholders must decide each case within its particular decision context, including legal and regulatory aspects. Differences in decision contexts and stakeholder information needs for dam safety decision making were given special consideration by the Working Group at the ASDSO/FEMA Workshop and provided the backdrop for the Working Group’s evaluation of application categories and other findings.

The Working Group’s recommendations for research and development and for technology transfer and training in dam safety risk assessment are many. The Working Group encourages the vigorous pursuit of these recommendations. This should include pilot studies and demonstration projects since, as with other new areas of engineering practice, while seminars and workshops are of value, it is only through hands-on experience that professionals can develop appropriate practice.

The application of risk assessment to dam safety continues to be a heavily discussed topic. Resistance and discomfort often accompany change in any field, especially when a significant paradigm shift is proposed. It is not that the traditional approach does not allow for risk and uncertainty, it does; but the risk-based approach seeks to consider them more explicitly and to empower the decision-maker with an understanding of their implications using the common currency of risk. The dam engineering profession must be confident that change will lead to improvements in dam safety and even more importantly in public safety. The Working Group’s commentary on the current practice of risk assessment is considered a cautious approach, which provides for flexibility in recognition of different decision contexts and information needs across the dams business. The commentary emphasizes that limitations must be fully considered and

[2] The FERC is developing a Performance Monitoring Program (PMP), which incorporates "failure mode thinking" in reviewing and evaluating the safety and performance of water retaining structures regulated by FERC in the context of the existing Part 12D program of Dam Safety Evaluation.

that risk assessment approaches should be used only as a supplement and not as a replacement for the traditional approach. This "risk-enhanced" approach provides a way for the benefits of improved understanding and management of dam safety risks to be realized, while maintaining a reference to established practice. As experience grows, and improved capabilities are developed, a future review of the risk assessment field may be bolder in its findings, but at this time, the Working Group considers that its findings and commentary on current practice are appropriate and justified.

TERMINOLOGY

Failure Modes Identification: A procedure by which potential failure modes in a technical system are recognized.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment. In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence. In the special case, average risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (that is, the product of the probability of occurrence and the consequence, combined over all scenarios) (ICOLD 2002)

Risk Analysis: The use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: scope definition, *risk (*hazard, *failure modes)* identification, and risk estimation (ICOLD 2002).

Risk Assessment: The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases (ICOLD 2002).

Risk Control: The implementation and enforcement of actions to control risk, and the periodic re-evaluation of the effectiveness of these actions (ICOLD 2002).

Risk Estimation: The process of quantifying the probability and consequences components of risk.

Risk Evaluation: The process of examining and judging the significance of risk (ICOLD 2002).

Risk Identification: The process of determining what can go wrong, why and how (ICOLD 2002).

Risk Management: The systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, treating and monitoring risk (ICOLD 2002).

Tolerable Risk: A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk that we do not regard as negligible or as something we might ignore, but rather as something we need to keep under review and reduce it still further if and as we can (ICOLD 2002). Tolerable risk can vary

	with different segments of society depending on the extent to which they are either participants in the benefits or exposed to the risks.
Traditional Approach or Traditional Standards-based Approach:	The traditional approach to dams engineering, in which risks are controlled by following established rules as to design events and loads, structural capacity, safety coefficients and defensive design measures (ICOLD 2002).

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1.0 INTRODUCTION

1.1 Background and Approach

Risk assessment in dam safety is a frequently discussed topic. In the past, some have denied the existence of risk associated with dams and some have suspected that the use of risk assessment is an attempt to avoid paying for costly dam safety improvements by changing the basis for judging safety. However, in recent years some organizations in the US and in other countries have found beneficial uses for risk-based approaches. As a result, interest in the topic has been aroused amongst dam safety professionals and owners, although the approaches used have varied, as has the degree to which their outcomes have influenced dam safety decisions.

In response to this growing interest in risk assessment, the Board of the United States Society on Dams (USSD) asked the USSD Committee on Dam Safety (CODS) to develop an Emerging Issues White Paper on the subject. The CODS established a Working Group comprised of approximately twenty members[3]. The group represented a broad cross-section of employment affiliations, with about half of its membership having experience with some aspect of risk assessment.

An important part of the preparation of this White Paper was the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams, held in March 2000 at Utah State University (USU) with sponsorship from the Federal Emergency Management Agency (FEMA) through the Association of State Dam Safety Officials (ASDSO). The Working Group was joined at the Workshop by some additional representatives, mainly from the US State Regulators and from Australia and Canada[1]. The workshop outcomes included the following:

1) A review of the state-of-the-practice[4] of dam safety risk assessment[5]
2) A prioritized list of research needs comprising research and development, and technology transfer and training needs.

The Workshop process and findings were documented in a report (ASDSO 2001) that was prepared by USU, reviewed by the Workshop participants, and submitted to FEMA by ASDSO. A summary paper was also prepared by Bowles and Johnson (2001).

The contents of this White Paper are built on the consensus that was established through the Workshop process and through other activities of the Working Group. In the summer of 2001, the Working Group reviewed a preliminary draft of the White Paper. The Working Group and the USSD Board reviewed a final draft in the summer of 2002.

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[3] Listed in Appendix A.

[4] For the purposes of the Workshop, and in this White Paper, we interpreted the term "state-of the-practice" to include only those approaches that are currently being used (i.e. in practice) by dam owners or regulators and their engineers to provide inputs to dam safety decisions. We did not limit the types of decisions to only the selection of a target level of safety for an existing dam or a proposed remedial measure. Instead, we included any type of decision that affects any aspect of dam safety, including monitoring, instrumentation, and surveillance, reservoir operating level, investigations, and emergency action planning.

[5] When we use the term "risk assessment" in this White Paper, it refers to a process that includes one or more of the components, such as failure modes identification, that make up the overall process of risk assessment (see Figure 2.1).

1.2 Purpose, Scope and Organization

The overall purpose of this White Paper is

> *To assess the state-of-the-practice in dam safety risk assessment, and to provide commentary on appropriate types of application and ways to facilitate and strengthen its use.*

The intended audience is members of the dam engineering profession, although non-technical owners and others may find it to be of value.

The organization of the White Paper flows from the three questions posed in its title, "*Dam Safety Risk Assessment: What is it? Who's using it and why? Where should we be going with it?*" Figure 1.1 is a schematic representation of the interrelationships among the sections of this White Paper.

What is it? Section 2.0 summarizes some principles and fundamental concepts of dam safety risk assessment and Section 3.0 provides an assessment of the current state-of-the-practice for the following four risk assessment application categories:

- Failure Modes Identification Approaches (FMI)
- Index Prioritization Approaches (IP)
- Portfolio Risk Assessment Approaches (PRA)
- Quantitative Risk Assessment Approaches (QRA)

The reasoning behind this categorization is discussed in Section 1.3.

Who's using it and why? Section 4.0 provides summaries and evaluations of applications of each of the four risk assessment application categories by the owners or regulators who sponsored them.

Where should we be going with it? Section 5.0 provides commentary on appropriate current practice of risk assessment, including cautions and limitations, which were identified by the Working Group. Section 6.0 summarizes technology transfer and training (T^3) needed to make the state-of-the-practice more broadly available to the profession. Section 7.0 summarizes research and development needed to improve the breadth, depth and quality of applications.

The Working Group discussed the extent to which it would be appropriate for this White Paper to provide commentary on which aspects of risk assessment were suitable for use by the profession. It was agreed that this was an appropriate role for the White Paper, if the commentary clearly stated current limitations and did not recommend any single approach; thus leaving flexibility for each user to adapt approaches to their unique context (see Section 4.1).

The Working Group also discussed whether this White Paper should present a vision for the future role of dam safety risk assessment. However, it was agreed to leave this task to a future group.

The Working Group caution readers that this White Paper is not a "how to" guide to dam safety risk assessment. Neither is it a standard of practice, and specific approaches or applications are not endorsed by the Working Group. References to applications are illustrative of what some owners and regulators have found to be useful. They should be understood in the context in which they were conducted and in which their outcomes were used. They should not be considered templates to be copied.

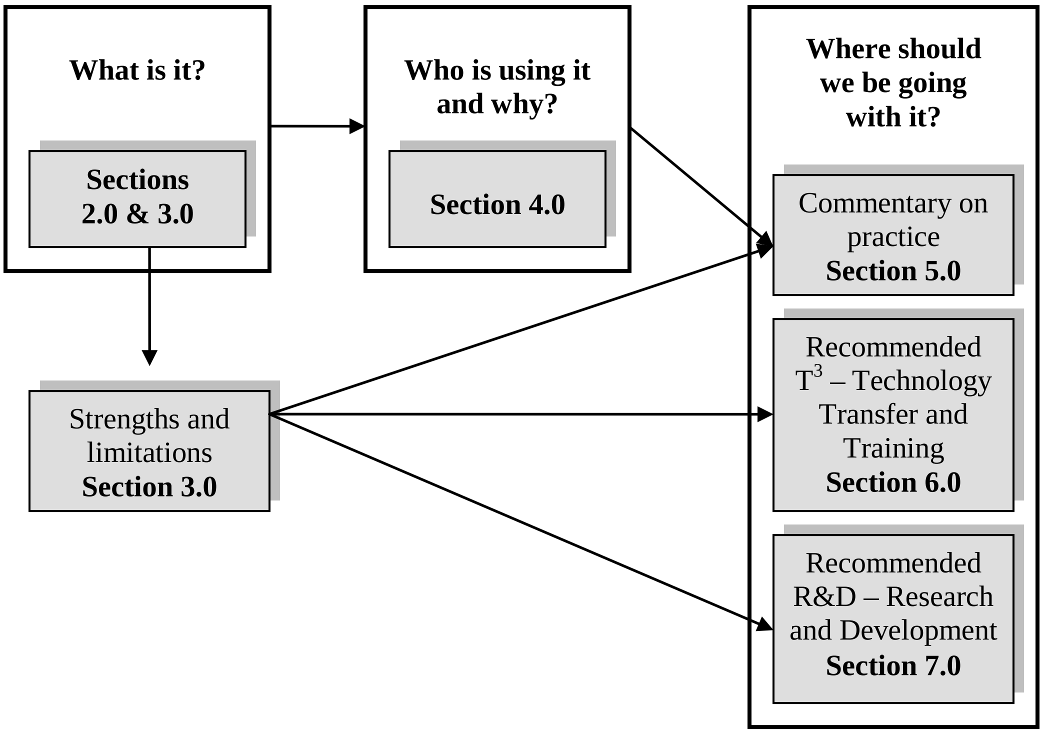

Figure 1.1. Relationship of White Paper sections to the questions posed in the White Paper title

1.3 Risk Assessment Application Categories: Selection and General Acceptability

The Working Group invested significant effort to achieve a broad consensus as a basis for preparation of this White Paper. A key aspect of achieving that consensus was to divide the applications of risk assessment in dam safety into the four categories listed in Section 1.2. These application categories were developed at the ASDSO/FEMA Specialty Workshop. They range from qualitative to quantitative approaches, and progress from more generalized approaches to approaches requiring more detailed analyses.

The degree of acceptance of each of the four categories by the dam engineering profession, based on the Working Group's assessment[6], is represented schematically in Figure 1.2. Acceptance is now relatively high for the first three categories (failure modes identification, index prioritization, and portfolio risk assessment), but lower for the fourth category (quantitative risk assessment). At present, no organization is known to be using QRA without traditional engineering analysis.

[6] See Section 3.0 for details of this assessment.

However, if QRA is used to supplement the traditional approach[7, 8] (TA) its acceptance is relatively high, unless it is used to justify a higher risk in the long-term than the traditional approach alone.

In Figure 1.2, check marks are used to indicate a general acceptance of the first three application categories. The fourth category, quantitative risk assessment, is divided into two subcategories, "QRA alone", and the risk-enhanced approach[9], or "QRA+TA". The Working Group does not consider that "QRA alone" is an appropriate application at this time (represented by an "X" symbol in Figure 1.2). The risk-enhanced approach is further divided depending on whether the decision outcome is i) stricter, or ii) less strict, than would be obtained using TA alone. Acceptance of the "QRA+TA" approach is relatively high in the first case (represented by a check mark in Figure 1.2). The second case, in which the decision outcome is less strict than TA alone, leads to the following important question (represented by a question mark in Figure 1.2):

How can we be confident that this decision is justified?

The Working Group has not provided an answer to this question. Instead, we recognize that the way that it is answered may vary from one dam owner to another, depending on their particular context (see Section 4.1). The answer should be based on input from the owner, the regulator, the community, the insurer, and other stakeholders. As with all dam safety decisions, it should be subject to periodic reassessment (see tolerable risk definition). The justification for this decision has been termed a "safety case" or a "business case" (Bowles 2000).

[7] The terms "Traditional Approach" or "Traditional Standards-based Approach" are used in this White Paper to refer to the approach to dams engineering, in which risks are controlled by following established rules as to design events and loads, structural capacity, safety coefficients and defensive design measures (ICOLD 2002). There was some concern that the term might be misinterpreted to have a negative connotation, or that it is difficult to define, because it is continuously evolving. On balance, however, the Working Group felt that the term would be clearly understood by the intended White Paper audience.

[8] The Working Group did not attempt to list the strengths and limitations of the traditional approach. Advantages of the traditional approach include that it is established by precedent, and that dam safety professionals are familiar with it. However, it shares many of the limitations of risk assessment approaches.

[9] The approach of supplementing the traditional approach with risk-based approach is referred to as a "risk-enhanced" or "risk-guided" approach.

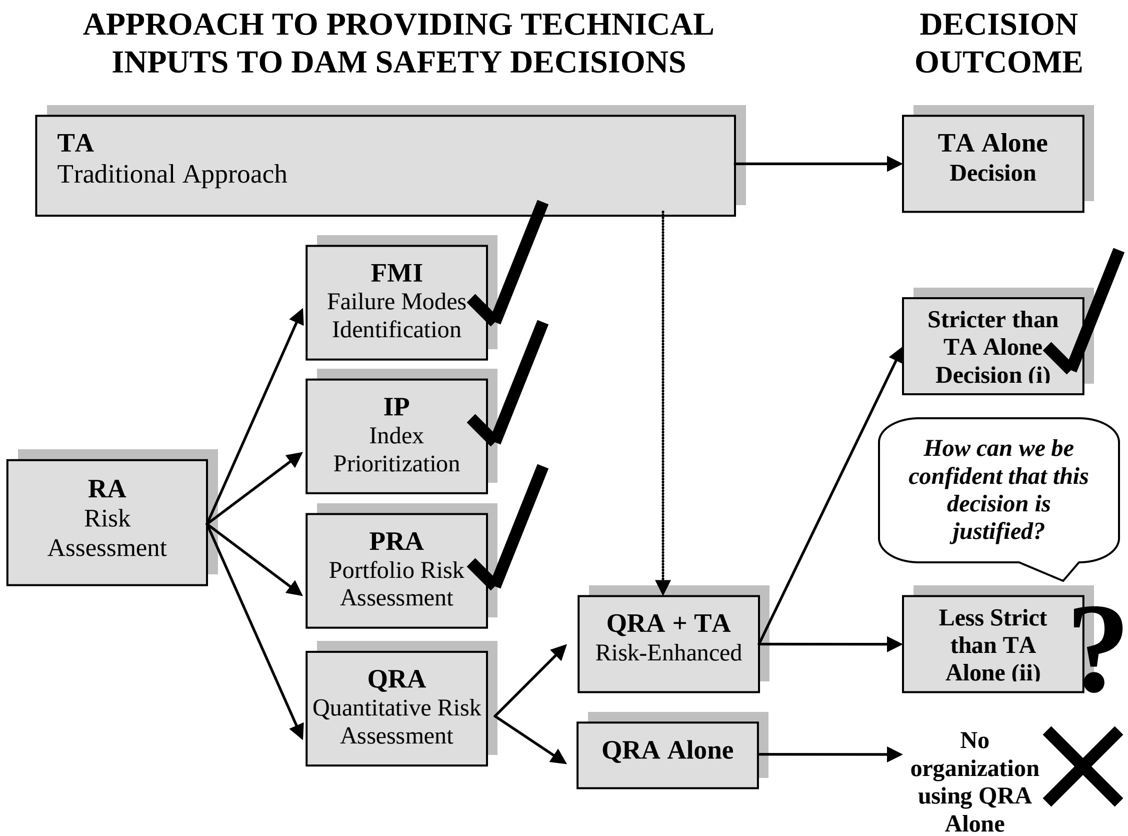

Figure 1.2. General acceptance of risk assessment approaches.

2.0 WHAT IS DAM SAFETY RISK ASSESSMENT?

Scope: A summary of the principles and fundamental concepts of dam safety risk assessment.

2.1 Components of Risk Management for Dams

Dam safety risk management comprises various component processes, which are represented schematically in Figure 2.1. It begins with a scope definition followed by risk identification, which includes the process of recognizing the plausible failure modes for a dam. Risk estimation is the process of quantifying probabilities and consequences for the identified failure modes. The process of examining and judging the significance of risk is termed risk evaluation, which involves the consideration of tolerable risk criteria, the "as low as reasonably practicable" principle[10] (ALARP), and a range of other factors that are appropriate to the particular decision context. Risk control (treatment) includes structural measures and various recurrent dam safety management activities, such as monitoring and surveillance, emergency action planning, and staff training. It also includes periodic reassessments of dam safety, consistent with traditional dam safety practice, including updates of any earlier risk assessments.

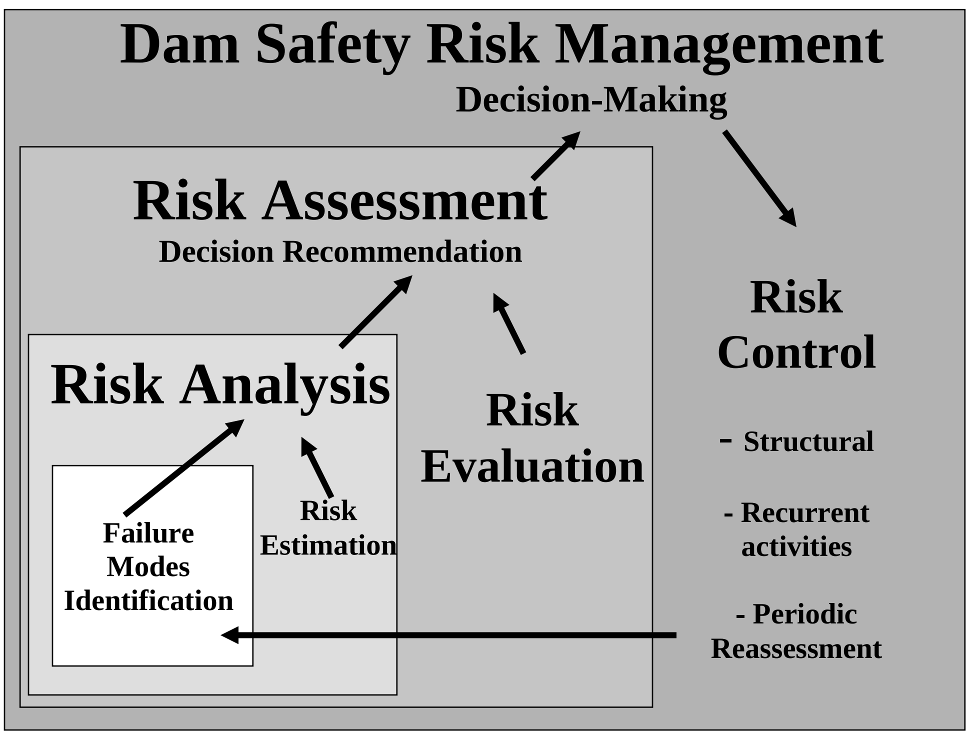

Figure 2.1. Interrelationship between components of risk assessment and risk management (adapted from Bowles et al 1999)

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[10] HSE (2001) refers to the implementation of the ALARP principle as requiring a "gross disproportion" test applied to individual risks and societal concerns, including societal risks. The gross proportion is between the cost of an additional risk reduction measure and the estimated amount of the risk reduction.

Dam safety risk management combines risk assessment, risk control, and decision-making on all aspects of dam safety. Risk assessment (RA) comprises risk analysis, risk evaluation, and formulation of decision recommendations. Risk analysis involves both risk identification and risk estimation.

The overall risk assessment framework is summarized in Section 2.2. The risk analysis, risk evaluation, and risk control components of dam safety risk management are summarized in Sections 2.3 – 2.5, respectively. These sections are adapted from Bowles et al. (1998).

2.2 Overall Risk Assessment Framework

An overall framework for dam safety risk assessment is presented in Figure 2.2. As shown by the "column" structure in this figure, the risk analysis process follows a five-step sequence from initiating events to system responses, outcomes, exposure factors, and consequences. Both external (e.g., floods, earthquakes, and upstream dam failures) and internal (e.g., the initiation of piping in an embankment dam under static loading) initiating events are considered. Each external initiating event is described by a number of loading ranges. Several sub steps may be necessary to describe adequately the system response to a given initiating event leading to an outcome of dam failure or no failure. Various types of consequences of dam failure may be considered, including the following: loss of life, economic damages, financial impacts on the owner, environmental damages, and societal effects.

There are four major components in a risk assessment, as illustrated by the "row" structure of Figure 2.2. These are as follows: 1) risk identification, 2) risk estimation, 3) risk evaluation, and 4) risk treatment. In Figure 2.2, the term "risk treatment" refers to the consideration of risk treatment (control or reduction) alternatives using risk analysis and risk assessment.

Various levels of effort have been proposed for performing risk assessments (McCann and Castro 1998); but underlying these is the concept that risk assessments should be staged (Bowles 1998), with additional detail being justified by the expected gains in understanding and capability to manage the risks. This is referred to as a "decision-driven" approach in a National Research Council (NRC 1996) report: "Risk characterization *(analysis)* should be a decision-driven activity, directed toward informing choices and solving problems."

2.3 Risk Analysis

Risk analysis involves both risk identification and risk estimation (first two rows in Figure 2.2). Risk identification is the process of recognizing the hazards (initiating events) to which the dam is exposed, potential dam failure modes, and the resulting adverse consequences. Typically, failure modes are represented in an event tree, which becomes the risk analysis model. Fault trees, logic trees and other forms of models may also be used.

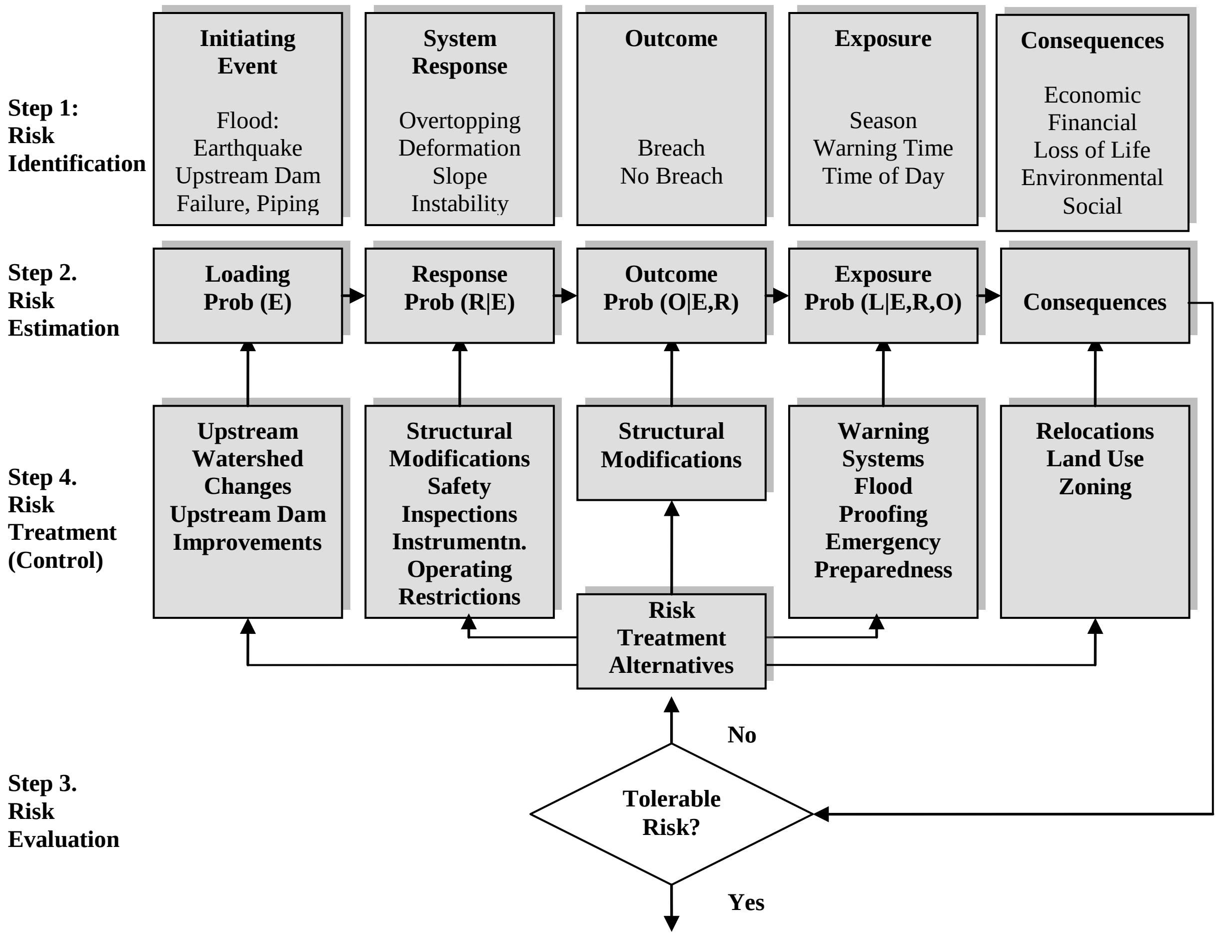

Figure 2.2. Framework for dam safety risk assessment (Bowles 1998)

Risk estimation consists of determining loading, system response and outcome probabilities, and the consequences of various dam failure scenarios. No-failure scenarios are often considered so that incremental consequences can be estimated as the difference between the consequences estimated for failure and no failure scenarios. Probability and consequence estimates are then applied to the various branches of the event tree model. Consequences are a function of many factors including, the nature and extent of the breach, the extent and character of flooding, the season of the year, the warning time, and the effectiveness of evacuation and emergency action plans. Risk reduction alternatives are developed and analyzed in a similar manner to the existing dam. Various inputs, such as system response probabilities, are changed to represent the reduced risk for each alternative.

2.4 Risk Evaluation

Once risks have been identified and quantified for an existing dam and various risk reduction alternatives, they are evaluated against tolerable risk guidelines, including the ALARP (as low as reasonably practicable) principle. Quantitative criteria can serve a useful reference role in the development of a safety or business case for addressing dam safety issues. However, dam safety decisions should be made by those responsible for ensuring dam safety after all the relevant factors have been assessed and weighed; they should not be the automatic result of applying a guideline to the outcomes of a risk analysis (Bowles 1999). When tolerable risk guidelines are used, it should be recognized that guidelines that were developed by one organization might not be applicable to another organization. The appropriate use of risk assessment currently incorporates reference to traditional engineering standards. This is referred to as the risk-enhanced or risk-guided approach. It is consistent with the current U.S. Bureau of Reclamation practice, which considers risk assessment to be "an additional tool to improve decisions and risk management practices" (Achterberg 1998). It is also consistent with the widespread use of portfolio risk assessment in Australia, and with applications of risk assessment in other fields, such as the US nuclear industry.

2.5 Risk Control

From a business or management perspective, risk control (treatment) options can be grouped into the following categories (Figure 2.3), although these are "not necessarily mutually exclusive or appropriate in all circumstances" (AS/NZS 1995):

- "Avoid the risk" - this is a choice, which can be made before a dam is built, or through decommissioning an existing dam.

- "Reduce (prevent) the probability of occurrence" – typically through structural measures, or dam safety management activities such as monitoring and surveillance, and periodic inspections.

- "Reduce (mitigate) the consequences" – for example, by non-structural approaches such as effective early warning systems or by relocating exposed populations at risk.

- "Transfer the risk" – for example, by contractual arrangements or sale.

- "Retain (accept) the risk" - "after risks have been reduced or transferred, … residual risks … are retained and … may require risk financing (e.g. insurance)."

While the first three options reduce the risk to which third parties are exposed, the fourth and fifth options only affect the risk that the owner is responsible for and not the risk to which third parties are exposed.

Risk assessment does not prescribe dam safety decisions. These decisions need to be made by the dam owner in conjunction with the regulator, if applicable, and other stakeholders. However, each party can expect to be in a better position to make informed decisions and to prioritize dam safety work when they supplement traditional engineering approaches with insights obtained from an appropriately conducted risk assessment.

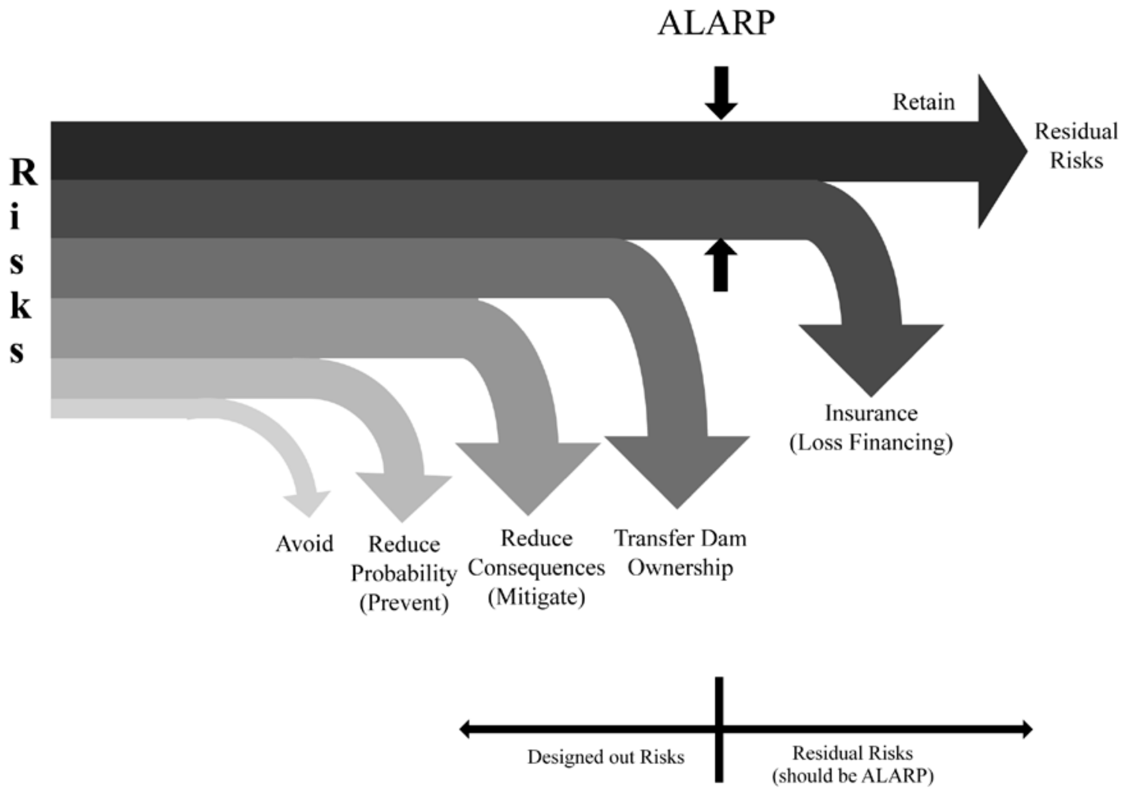

Figure 2.3. Risk control options (adapted from Bruce et al 1995)

3.0 ASSESSMENT OF THE CURRENT STATE-OF-THE-PRACTICE

Scope: Description, benefits and limitations.

3.1 Overview

The four risk assessment application categories listed in Section 1.2 are assessed in this section. These assessments are adapted from the ASDSO/FEMA Specialty Workshop Report (ASDSO 2001). They include tabular summaries of the strengths and limitations of each application category, listed in decreasing order of emphasis as determined by workshop participants. Another workshop held today with the same or different participants could potentially yield different results. The identified limitations were considered by the Working Group in developing the technology transfer and training (T^3) needs and the research and development (R&D) needs, which are summarized in Sections 6.0 and 7.0, respectively.

3.2 Failure Modes Identification Approaches

Failure Modes Identification (FMI) is a procedure by which potential failure modes of a specific dam are recognized and listed. A failure mode is a sequence of system response events, triggered by an initiating event, which could culminate in dam failure. Procedures for FMI vary, but in a typical approach, a small team of dam engineers would develop the list of failure modes. Team members must have a good knowledge of historical dam failure mechanisms and a good understanding of the subject dam. The form of the FMI outcome may vary from simply a list of failure modes, to a tabulation of the associated effects, consequences, compensating factors or possible interventions, and potential risk reduction alternatives. In some cases a root cause analysis, an event tree, or another graphical representation of the failure modes may be included. FMI does not include quantification of the risks. It is therefore, by itself, not a risk analysis or a risk assessment, although, it is a foundational step in performing a dam safety risk assessment. Failure modes and effects analysis (FMEA) is an example of an FMI approach.

3.3 Index Prioritization Approaches

An Index Prioritization (IP) approach is a means of quickly ranking dams, typically for the severity of dam safety issues. The ranking is based on an index, calculated from a combination of weights, which are assigned to capture various attributes of identified dam safety deficiencies. The attributes and ranking procedures are usually prescribed in order to form a common basis for ranking a group of dams. These approaches are best used as an initial screening of a portfolio of dams, or as a comparison to other forms of risk analysis. Failure modes, effects and criticality analysis (FMECA) is an example of an IP approach. Another example is the USBR's "Risk Based Profiling System" (USBR 2000). Not all IP approaches use a risk metric and some that use simplified risk metrics can distort risk severity rankings.

Table 3.1. Summary of Strengths and Limitations of Failure Modes Identification

Strengths	Limitations
Relatively low effort	Incurs an additional cost
Identifies failure modes	Lack of available guidance leads to concerns about repeatability, consistency, and influence of individual team members
Interdisciplinary team approach	Limited case histories of dam failures exist for which failure mechanisms have been analyzed in detail
Enhances understanding	Not a process that can readily involve the general public
Has wide acceptability	
Strengthens traditional approach – can provide some quality assurance that significant failure modes have been considered in a design or a dam safety evaluation	
Can be used as an input to a prioritization of dam safety issues	
Meets some important information needs for dam safety decision-making	
Provides useful inputs for explaining failure modes	

Table 3.2. Summary of Strengths and Limitations of Index Prioritization

Strengths	Limitations
Provides a means of prioritizing dam safety issues	Danger of misusing results
An efficient process	Perfunctory rather than substantive – may miss important failure modes
A readily defensible process[11]	Lack of published guidance
Provides justification for dam safety program priorities	Only provides a relative measure of risk severity
Can be readily explained	May not be highly defensible[11]
A systematic process	Often is not based on a risk metric
Includes some identification of dam safety issues	

[11] There may appear to be an inconsistency between the third strength and the fifth limitation in this table. However, it should be borne in mind that the group, which developed the list of strengths and limitations, included individuals who felt that the degree of defensibility of IP approaches was a strength and others who felt that it was a limitation. We have faithfully presented both of these perspectives. This disparity of opinion should be addressed in future work.

3.4 Portfolio Risk Assessment Approaches

Portfolio Risk Assessment (PRA) typically involves the reconnaissance level application of the identification, estimation, and evaluation steps of dam safety risk assessment to a group of existing dams and representative risk reduction measures. The outcomes include an engineering standards assessment and a risk profile for the existing dams. They also include a basis for identifying and cost-effectively prioritizing risk reduction measures and supporting investigations. Various bases can be used for prioritization or ranking, but, if the cost effectiveness of risk reduction is used, the rate of risk reduction will be maximized for the funds that are to be expended. Other outcomes can be used to strengthen various aspects of the owner's dam safety management program (e.g. monitoring and surveillance), and to provide inputs to various business processes (e.g. capital budgeting, legal evaluations, loss financing, and contingency planning). Bowles et al (1999a) present a PRA application and Bowles (2000) presents a perspective on the current state of the practice of PRA. PRA involves more effort than IP approaches, but its range of outcomes is broader. In addition, PRA can identify a more rapid rate of risk reduction than IP approaches, which do not consider the cost effectiveness of risk reduction. At present, there are few experienced PRA practitioners and many of those are in Australia. In addition, there is no written guidance for implementing PRA. However, the Corps of Engineers is currently conducting a research and development program with a focus on developing practical tools, field expertise, and guidance for PRA applications within Corps.

3.5 Quantitative Risk Assessment Approaches

A Quantitative Risk Assessment (QRA) comprises the steps of risk identification, estimation, and evaluation leading to a decision recommendation. The purpose of performing a QRA is typically to provide insights into the adequacy of an existing dam, or to provide justification for risk reduction measures. Different owners vary in the level of detail that they require but to our knowledge, none relies on risk assessment alone for making dam safety decisions. Some examples of QRA include McDonald and Wan (1998), Bowles et al (1999b) and Dise and Vick (2000).

Table 3.3. Summary of Strengths and Limitations of Portfolio Risk Assessment

Strengths	Limitations
Provides a means of prioritization of dam safety risk reduction measures	Uncertainty in PRA inputs and danger of misusing PRA results
By using the cost effectiveness of risk reduction as the basis for prioritization it leads to the most rapid rate of risk reduction for a given expenditure	Typically does not involve in-depth risk analyses
	Cost
Provides justification for the prioritization and for risk reduction	Lack of published guidance and experienced practitioners
Can readily communicate outcomes of PRA	
Generally considered to be a defensible process	
Uses a risk metric	
An efficient process	
Provides for an identification of dam safety issues	
Provides a basis for integration of dam ownership and dam safety considerations into the owner's overall business	
A systematic process	

Table 3.4. Summary of Strengths and Limitations of Quantitative Risk Assessment

Strengths	Limitations
Valuable as an input to, and justification for, dam safety decisions, including prioritization of dam safety issues	Lack of standardized procedure and experienced practitioners
Provides for a quantification of dam safety issues by using systematic process based on a risk metric	Guidelines for determination of tolerable risk need development and are yet to gain widespread acceptance
Can lead to a better identification, understanding, and communication of dam safety issues; and assurance that significant issues have been considered and addressed	Uncertainty in estimating probabilities and life loss
Can include consideration of estimated uncertainties	Communicating uncertainties to decision makers and others
Generally includes more in-depth supporting analyses	Cost
Based on an interdisciplinary team process and relates dam safety considerations to owner's overall business	New and complex terminology

4.0 WHO IS USING DAM SAFETY RISK ASSESSMENT AND WHY?

Scope: To provide summaries and evaluations of applications by the owners or regulators.

4.1 Introduction

This section contains summaries of applications of each of the four risk assessment application categories. Dam owners and regulators in the U.S.A., Canada and Australia contributed these summaries. Each summary generally follows the following outline:

1) Context, background, and purpose for the study
2) A summary of what was done
3) A brief evaluation of the benefits derived and limitations, and how the results have been used
4) Contact information

McGrath (2001) contains a summary of risk assessment applications in several countries.

4.2 Differences in Decision Context and Information Needs

In reading the application summaries in this section, it should be kept in mind that the decision contexts can vary widely from one dam owner to another. Differences can exist in external factors, such as regulatory requirements, public perception, tolerable risk guidelines, environmental issues, and the role of stakeholders, including a regulator, the community, and special interest groups. Differences in internal considerations can include the capital projects approval process, the corporate risk management strategy and position, the dam safety decision-making process, and the relationship of a dam and its safety position to corporate loss financing and insurance, business criticality, competition for funds, contractual obligations, and organizational mission, goals, and values.

It should also be recognized that different stakeholders for any given dam safety decision might have different information needs. For example, information that is required for an owner's in-house decision-making process may not be needed by the regulator who oversees the owner's decision outcomes and performance. Since information needs vary widely, the Working Group recognized that it would be unrealistic to expect that any single approach to risk assessment would meet the needs of all organizations. The ASDSO/FEMA Specialty Workshop report (ASDSO 2001) documents an introductory session, "Information needs for dam safety evaluation and management", which covered the following types of organizations: the government owner, the large private owner, the small private owner, the federal regulator, the state regulator, and the consulting engineer. The diverse outcomes of this session formed a basis for evaluating the strengths and limitations of a range of risk assessment approaches in Section 3.0 and for identifying research needs in Sections 6.0 and 7.0.

4.3 Failure Modes Identification – Ontario Power Generation Incorporated – Private Owner

Ontario Power Generation Incorporated (OPGI) operates and maintains 69 hydroelectric generating stations and some 250 dam structures on 27 river systems across Ontario, Canada. The smallest station has a generating capacity of just one megawatt (MW), the largest more than 1,300 MW. The dams vary in age from 100 years to three years. Total installed hydroelectric capacity is more than 7,300 MW. While hydroelectric constitutes only 25% of OPGI's capacity and energy production, it is a key component of its generation mix due to its renewable nature, its low production cost, reliability, and flexibility to meet base load as well as peak demands.

OPGI's Dam Safety Program was created in the mid 1980's. A corporate Dam Safety Policy commits to maintaining and operating the Corporation's dams in a manner that meets or exceeds the Canadian Dam Association (CDA) Dam Safety Guidelines. These guidelines are primarily traditional standards–based, typically analyzing a dam for normal and extreme loading conditions. OPGI has now completed a first-time assessment of all its dams, and in 1998, began the first periodic reviews.

At the same time, OPGI began exploring the usefulness of incorporating Failure Modes and Effects Analysis (FMEA) as an enhancement and a supplement to the traditional standards-based assessment approach. A draft guideline was developed in 1999 and a pilot project was undertaken to evaluate the process and the benefits it can help to achieve (Dupak and Smith 2000).

The process developed was based on a team approach incorporating the various disciplines involved in the dam safety assessments, with coaching from a facilitator experienced in the FMEA processes. Initial staff training was provided; but the pilot applications were also considered a learning experience with the intent to apply "lessons learned" upon completion of the work to modify and improve the approach and process.

Recognizing that risk assessment methodologies and their application to dam safety are developing, OPGI Dam Safety Program Management requested an external validation of the process and its pilot application from two independent external reviewers, and recognized experts in the field. The results of the reviews were generally positive, but some items were identified for improvement, both in the process and its application. OPGI is now revising its guidelines and plans to use its revised process for other assessments.

From an owner's perspective, OPGI feels that the primary benefit of conducting an FMEA is to enhance the traditional standards-based assessment by allowing an improved understanding of the dam system and its response to an initiating event. Other benefits realized are an improved assessment of the dam system reliability and an identification of key site-specific issues including operational, mechanical, and debris–related. In addition, the results of the FMEA can be readily applied to improve the detection and intervention measures at a site, including improvement to the monitoring and surveillance system, and emergency action plans.

For more information contact: Tony Bennett, Ontario Power Generation, 700 University Ave., Toronto, Ontario M5G 1X6, Canada. tony.bennett@opg.com

4.4 Index Prioritization: U.S. Bureau of Reclamation – Federal Government Owner

Reclamation has been using risk analysis to varying degrees for more than fifteen years to help in its dam safety decision-making process. Different levels of risk analyses are used at various points in dam safety studies. The highest level, the Risk Based Profiling System (RBPS) (USBR 2000), is summarized in this section and two levels of QRA are described in Section 4.9.

The RBPS is essentially a "portfolio ranking" tool that utilizes a standardized set of questions to calculate a quantitative point total for each dam in a given inventory. By applying this profiling system to all dams, an agency has a system that can compare and rate relative risks among their dams. Reclamation uses this system as one input for prioritizing dam safety issues for evaluation and for establishing target completion dates for the evaluations. Nearly all of Reclamation's 350 high and significant hazard dams have been ranked using the system.

The RBPS can be used to characterize the risk associated with individual loading conditions, such as flood (hydrologic/hydraulic), earthquake (seismic), or normal operating (static) loads, or it can be used to sum the total risk imposed by a given structure.

The system develops a "Failure Index" (Load x Response) for the flood, earthquake, and normal operating cases. These three cases are viewed as being the primary categories of how dams can fail. Operations, maintenance, and occupational and public safety issues are included as a fourth case. By using readily available data and information, and engineering and scientific judgment, estimates of points are made for a dam using these four cases. The Failure Index serves as an indication of probability of failure.

An additional step to further prioritize and compare dams on a common risk-based level is to multiply the Failure Index by a Loss of Life Factor, which characterizes the consequences associated with a failure, as is done when determining the annualized loss of life in a QRA. This product is called the "Risk Index." The Loss of Life Factor is determined by consideration of several factors, including the total population at risk, the location of this population below the dam, the severity of the flooding expected should the dam fail, and the severity of the failure mode in question. This Risk Index is calculated separately for each of the four cases of the Failure Index and these are summed to obtain the Total Risk Index.

The final scoring for any particular dam is calculated by comparing its score to the highest score found for all of the dams in Reclamation's inventory, expressed as a percentage. This ranking is calculated for all the Failure Indexes and Risk Indexes. This provides for consideration of risk in a variety of ways.

For more information contact: Bruce Muller, US Bureau of Reclamation, PO Box 25007, D-6600, Denver, CO 80225. bmuller@do.usbr.gov.

4.5 Index Prioritization: Washington State – State Regulator

In 1972, Public Law 92-367 directed the Corps of Engineers to conduct inspections of all non-federal, high hazard dams in the US. This program included the inspection of over 100 dams impounding 70 reservoirs in Washington State. The inspection reports concluded that the majority of these dams did not meet present standards for spillway capacity or static and seismic stability. In 1982, the responsibility for addressing these deficiencies was transferred to the states.

The management approach of the Washington State Dam Safety Office through the remainder of the 1980s began with providing dam owners with a copy of their inspection reports for review and comment. This was followed by a directive to resolve the safety concerns by a specified date. In many cases, two and sometimes three follow-up letters were sent when deadlines expired. However, formal enforcement action was rarely utilized. The approach had limited success with some 34 fixes in eight years, although nine of those fixes were to a system of small dikes on a single reservoir project. Several other fixes consisted of relatively simple, non-structural measures, such as permanently opening the low-level outlet works to remove the impoundment from service. Unfortunately, the vast majority of the dams with significant structural safety concerns defied resolution under this approach.

In 1990, the Dam Safety Office's management approach changed to one that melded risk concepts with an engineering standards-based approach. The first step was the development of risk-based design standards (Schaefer 1992) that varied in accordance with the downstream consequences[12] setting. This moved spillway and seismic design away from the standard "one size fits all" deterministic approach. The second step was the development of a risk-based prioritization scheme (Johnson 2000), which served to focus regulatory efforts on those dams posing the greatest risk to public safety. Engineering analyses were performed to estimate the adequacy of the dams under risk-based design loads. The results of these assessments, the respective downstream consequences[7] classifications, the age of the dam, and other factors served as the input to a numerical ranking scheme, which ordered the projects by the aggregate public safety threat. At any point in time, the Dam Safety Office then invested its limited compliance and enforcement resources in resolving safety concerns for the top ten ranked projects. This approach secured safety improvements at over 80 dams in the 1990s. In contrast to the earlier approach, these fixes included the higher risk dams in the state's inventory.

The paradigm shift to a risk-based approach has transformed Washington State's dam safety program. For the evaluation of existing dams, the Dam Safety Office has utilized this approach to determine if a dam has an adequate level of protection against failure. If a dam does not meet state standards, the relative level of risk is estimated, and compliance efforts are prioritized based on those projects with the greatest risk. This approach has been used to inform dam owners, not only that their dams are "unsafe", but also, as to what level of risk their unsafe project poses to the downstream public. It has doubled, and in some years tripled, the number of dams repaired from the previous management approach. The backlog of deficient dams has dropped from over 65 in the late 1980's to under 30 today. Furthermore, completed fixes targeted the dams posing the greatest public safety concern. In conclusion, the risk-based approach of Washington State has guided the expenditure of the Dam Safety Office's limited resources in a manner that best managed the resolution of public safety concerns with dams.

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4.6 Portfolio Risk Assessment: Portland Water Bureau – Local Government Owner

The Portland Water Bureau in Oregon operates eight high hazard dams. One dam increases the storage in the natural Bull Run Lake. Two hydropower dams form impoundments on rivers. Five dams form large reservoirs at city parks. One of these is located approximately 150 feet horizontally and 30 feet vertically from the nearest residence. Another is located immediately above the portal of a light rail tunnel.

The Portland Water Bureau always undertakes the maintenance, repair and modification of its facilities that is needed to meet the standards of regulatory agencies (FERC, EPA, Oregon Health Division, Oregon Water Resources, National Marine Fisheries, etc.). However, once this mandated work is accomplished, there remain other system needs, such as system reliability during catastrophic events and maintenance issues, which must be addressed. Modified portfolio risk assessment techniques were incorporated in a three-year effort to recommend and prioritize these other projects to enhance the reliability of the water system.

[12] Referred to as "hazard" in the Washington State approach. This traditional use of the term "hazard" in the dam safety field conflicts with its common dictionary definition and its accepted use in the risk management literature.

Working with EQE International (Ballantyne 2000), the Portland Water Bureau undertook the System Vulnerability Assessment (SVA) to determine the vulnerabilities to the system and the components impacted by the vulnerabilities, and to develop a prioritized list of what it should do to mitigate these vulnerabilities. The study used techniques similar to those associated with the risk assessment of dams to do a risk assessment of its supply, transmission, and distribution facilities. A list of 38 natural and human-caused potential hazards (initiating events) was developed. The system responses for various systems and individual components of the water delivery system from each of the potential hazards were estimated for various annual exceedance probabilities. The outcomes of impairment of various systems and components to deliver water were also estimated. The exposures were based on the historic and projected consumption of customers based primarily on season of year when the initiating event took place. The consequences on the delivery of water to the customer, if any, were based on the availability of system redundancy to mitigate for system or component impairment following the initiating event.

Customer expectations about water service following initiating events with various annual exceedance probabilities (1 in 10, 1 in 50, 1 in 100, 1 in 500 and 1 in 1,000 per year) were determined using focus groups of civic leaders, emergency responders (fire and medical), industrial customers, residential customers, wholesale customers, etc.

The study determined that, as is often the case for dams, two events dominated the risk to the water system: earthquake and heavy rains/runoff. Keeping in mind that all regulatory work is always completed ahead of everything else, the study identified 37 non-regulatory driven mitigation projects, which it placed in five priority classifications, as follows: High (four projects costing $32 million), Moderate High (eight projects costing $73 million), Moderate (five projects costing $18 million), Quick Fix (14 projects costing $6 million) and Long Term (five projects costing $152 million).

The SVA helped Portland determine the priority for mitigation of its exposure to outage caused by various initiating events. Portfolio risk assessment has proven to be a powerful tool for setting the priorities (rank order) among projects beyond those required by regulators and in determining how many projects need to be undertaken within a given interval (speed).

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4.7 Portfolio Risk Assessment: South Australia Water Corporation – Private Owner

The South Australian Water Corporation (SA Water) provides water and wastewater services to a population of more than 1 million people throughout South Australia. It operates 17 large dams, many of which do not meet modern engineering standards. SA Water needed to make some important choices on how much dam safety improvement is justifiable at each of its dams, how to prioritize these improvements, and at what rate to proceed. In 1997, to provide inputs to these important decisions, SA Water commissioned RAC Engineers & Economists to conduct an initial portfolio risk assessment (PRA). The PRA was designed to provide a baseline assessment of the existing dams and an initial prioritization of investigations and possible risk reduction measures. The PRA included both reconnaissance-level engineering assessments and risk assessments for flood and earthquake loading, and normal operating conditions. Twenty-three structural risk reduction measures were formulated at a reconnaissance level as separable construction upgrade projects, with the intent of meeting an engineering standards level of risk.

A Dam Safety Improvement Program (DSIP) was developed based on PRA outcomes. It comprises prioritized lists of further engineering evaluations and structural and non-structural risk reduction measures. First priority was given to reducing life safety risks to a point of diminishing returns. Second priority was given to reducing direct SA Water and third party losses. Work is proceeding on the first priority projects.

SA Water summarized the benefits of the PRA process in Bowles et al (1999) as follows: "Many useful insights into dam safety issues, which might not otherwise have been obtained, were provided by the PRA process. SA Water now has an overall picture of the current dam safety status of its large dams from both a standards-based perspective and a risk-based perspective[13]. The proposed phased implementation of structural measures and further evaluations is proving useful for prioritizing and managing dam safety evaluation and improvement efforts, and importantly, is regarded as a defensible strategy for reduction of risk.

Another significant benefit of conducting the PRA is that it identified a more rapid approach to risk reduction than the existing dam safety program prioritization, which was based on traditional approaches. By taking a risk-based approach to prioritizing dam safety evaluations and improvements, SA Water has obtained information that is useful for integrating dam safety issues into overall business planning. The close partnership between the consultant and SA Water technical staff and the periodic involvement of SA Water executives and the Board of Directors contributed to the effective conduct of the PRA. This level of interaction is clearly an essential ingredient for maximizing the value of a PRA process to the owner and achieving rapid acceptance of PRA outcomes."

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andy.parsons@sawater.sa.gov.au.

4.8 Portfolio Risk Assessment: State of Victoria – State Regulator with Dams Owned by Corporatized Authorities

A reconnaissance study of water industry dams in the State of Victoria, Australia conducted in 1995 recommended, among other things, the adoption of risk-based methods for managing the State's dams (SMEC/RAC 1995, Watson et al 1997). In recognition of this recommendation, the State Government provided a significant dam safety improvement-funding package to the Victorian water industry in 1997 as part of an extensive water industry reform program. A condition of the receipt of this funding was that all significant and high hazard dams be subjected to a Business Risk Assessment (BRA) of their portfolio of dams (Watson 1998; Watson and Adem 1998). The BRA process is similar to what is referred to as Portfolio Risk Assessment in this White Paper.

As a result, some 145 dams belonging to twenty water authorities have been assessed using portfolio risk assessment, or in some cases using detailed individual dam risk assessments (QRA). The levels to which risks need to be reduced, or further detailed assessments undertaken, were determined by the owners, based on appropriate protection levels, such as the Australian National Committee on Large Dams (ANCOLD 1994) interim risk guidelines, and business performance criteria, which included maximizing the cost effectiveness of risk reduction. Where concepts are still being developed, or the level of uncertainty is unacceptable, conservative upper-bound risk

[13] However, SA Water plans to fix its dams to at least a traditional standards-based level.

levels were normally assumed. In these situations, further investigation and assessment would normally be required unless shown to be cost-ineffective compared with implementing an acceptable solution.

The BRA's were undertaken based on a broad set of guidelines and specified outputs provided by the Department of Natural Resources & Environment, the State of Victoria's dam safety administrator (DNRE 1997). BRA is seen as an integral part of the business and asset management planning process for dam owners and aims to achieve an acceptable level of dam management performance and safety through progressive improvement. This requires that risks are continually reassessed as enhanced information and improved techniques become available. Safety improvements identified in the BRA's are now being implemented over a five-year period, and in some cases over a ten-year period, where higher funding levels than originally assumed have been identified.

Overall, risk assessment is seen as an important enhancement and not an alternative to a traditional standards-based approach. Some key benefits of the BRA process, set out in more detail in Watson and Perera (2000), are as follows:

- The principle of risk assessment for dams is utilized as a fundamental business-planning tool including reference to the various guidelines developed or being developed by ANCOLD.
- Dam owners use financial resources efficiently against priority dam improvement areas.
- BRA promotes involvement and commitment of managers, operators and other appropriate contributors.
- Confidence in targeting key dam improvement risk areas.
- The risk assessment process can be undertaken only down to a level where adequate confidence in acceptable risk outcomes and cost-effective improvements are achieved.
- A basis for measuring risk reduction is available, including assessment against key performance criteria such as potential life loss and economic impacts.
- BRA outputs have provided an excellent basis for presenting and justifying options to decision-makers.
- The BRA process has enabled owners, operators, and the regulator to get to know their dams better.

The BRA process has shown a number of areas that need to be addressed, including shifting the basis for allocating state government funding assistance on an overall statewide basis instead of an authority-by-authority basis. A pitfalls paper developed out of the BRA process identifies areas of misconceptions and where care should be exercised (Bowles/DNRE 2000).

It is recognized that risk assessment is an evolving process. Much investigation, research and development, peer review, discussion and consultation needs to continue to achieve a wider level of confidence in the value of risk assessment for dam safety decision-making. These actions are continuing to take place in ICOLD and different parts of the world, with Australia being one of the leading players.

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4.9 Quantitative Risk Assessment: U.S. Bureau of Reclamation – Federal Government Owner

In addition to the Risk Based Profiling System, which is described in Section 4.4, Reclamation performs risk analysis at the Comprehensive Facility Review (CFR) and Issue Evaluation levels. Both are examples of QRA, but at different levels of detail.

CFR Risk Analysis: A Comprehensive Facility Review is conducted for each Reclamation dam every six years. As part of the CFR, the Senior Dam Engineer is expected to use existing information, judgment, and considerable experience to quantitatively estimate the risks posed by various failure modes for a given dam. This level of risk analysis is much less detailed and less complicated than the team approach described below for the Issue Evaluation level, and is therefore considered more of a screening-level risk analysis.

The CFR risk analysis includes a definition of loading conditions, failure modes, and consequences for all load classes (normal operating, flood and earthquake). Structural failure modes are identified to improve understanding of dam behavior, however, system response probabilities and associated uncertainties are typically only considered in a global sense and detailed event trees are usually not prepared. Flood and earthquake hazard studies are also prepared for the review and are used by the Senior Engineer when performing the risk analysis for the structure.

The results of this level of risk analysis are used by program managers to validate dam safety recommendations and to prioritize future dam safety work.

Issue Evaluation Risk Analysis: This level of risk analysis is generally the most comprehensive type utilized by Reclamation. It is performed by two experienced facilitators and a team, which usually includes subject experts, design engineers and geologists most familiar with the dam, and field personnel responsible for inspection and maintenance of the structure. This type of analysis involves preparatory time, usually about a week of team meeting time, and then a significant effort to document the processes followed and conclusions developed from the risk analysis.

Typically, event trees are developed to describe failure modes. System response probabilities, load probabilities, and consequences are estimated. The appropriate technical staff is involved in the process by sharing their knowledge of the dam and how it will respond to various loads as well as participating in estimating response probabilities. Areas of uncertainty may be identified and portrayed in the results for consideration by decision makers during their assessment of the risk. The team may identify data needs where data collection would be expected to significantly improve risk estimates at an economical cost in terms of time and money.

Over time, there may be multiple team risk analyses commissioned to continue to refine the baseline risk estimate as data are collected, different site information is obtained, other expertise is brought in, or as structural modifications are proposed. The goal is to progress to a level of understanding of the baseline risk that is adequate for the decision makers to select the appropriate response to the risk.

A very important point associated with the use of any of the three types of risk analyses used by Reclamation[14] is that they only serve as a tool to promote a more thorough understanding of the

[14] I.e. RBPS, which is described in Section 4.4, and CFR and Issue Evaluation Risk Analyses, which are described in this section.

technical issues for a dam and to help decision makers with determining a prudent course of action. A risk analysis is not, by itself, intended to serve as the definitive "answer" to whether a dam safety issue requires remediation. Rather, the risk analysis results incorporate other technical analyses and judgments in a risk framework that is very useful in deciding future actions to reduce the risk.

An example of an Issue Evaluation Risk Analysis is the study performed on Como Dam near Hamilton, Montana. The risk analysis was performed to address, primarily, the formation of reservoir sinkholes and changing piezometer readings at the site. A team analysis was conducted that resulted in the conclusion that further modification of the dam was not required at this time. Areas of further study and investigation were identified, however, and are being actively pursued.

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5.0 SUMMARY OF FINDINGS

Scope: To provide commentary on present appropriate use of risk assessment, including appropriate cautions and limitations.

5.1 Introduction

The Working Group weighed carefully the appropriateness of this White Paper providing commentary on which aspects of risk assessment should become part of present practice. It was agreed that this was an appropriate role for the White Paper, but that such commentary must also clearly state current limitations. The following summary was developed in the consolidation session at the end of the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams. It was revised by USSD Working Group at its July 2000 working session.

While it can be argued that some points listed below would apply to more than one application area, the intent of this summary was to capture some of the most important findings in each application area. More detailed lists of strengths and limitations are contained in Section 3.0.

5.2 Failure Modes Identification (FMI) Approaches

1) FMI, which is an early step in performing a risk assessment, should also be standard practice for traditional standards-based approaches to dam safety evaluation and design.
2) FMI provides a more comprehensive safety evaluation of a dam and a basis for strengthening many aspects of a dam safety program (e.g. instrumented and visual monitoring, emergency preparedness planning, O&M, etc.).
3) Applications guidance is urgently needed for performing FMI.
4) Users must recognize that FMI is a qualitative diagnostic approach and not a decision tool.

5.3 Index Prioritization (IP) Approaches

1) IP approaches are a valuable and increasingly utilized approach for prioritizing dam safety issues and investigations. However, to be considered risk-based, they should be calibrated against risk assessments for groups of dams and must incorporate a risk metric.
2) They are generally less costly to use than PRA, but are more limited in the scope of their outcomes.

5.4 Portfolio Risk Assessment (PRA) Approaches

1) PRA is a valuable and increasingly accepted approach for cost-effectively prioritizing dam safety remedial measures and further investigations for a group of dams.
2) It provides insights that can better inform owners about the business and liability implications of dam ownership.
3) PRA outcomes must be used with regard for the limitations of the approach and should be periodically updated.

5.5 Quantitative Risk Assessment (QRA) Approaches

1) QRA approaches are valuable for providing insights and understanding of failure modes and associated risks (probability and consequences) for stakeholders.
2) Uncertainties in inputs and outcomes must be taken into account.
3) Improved approaches to estimation of probabilities and consequences are needed.
4) Acceptable/tolerable risk criteria need development and are yet to gain widespread acceptance.
5) Stakeholders must decide on issues of appropriate use and defensibility.

6.0 TECHNOLOGY TRANSFER AND TRAINING (T^3) NEEDS: WAYS TO FACILITATE APPLICATIONS

Scope: Helping others do what some are already doing – identifying ways to make the state-of-the-practice available more broadly to the profession.

Table 6.1 lists the prioritized technology transfer and training (T^3) needs that resulted from the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams (ASDSO 2001). The target risk assessment application areas for each need are indicated along with some suggested modes of technology transfer and training suited to each need. The number of votes cast for each T^3 need is presented as an indication of the relative importance assigned to each need by Workshop participants.

Table 6.1. Prioritized Technology Transfer and Training Needs

Priority	Description	Number of Votes	Suggested Modes of T^3	Risk Assessment Application Category: Failure Modes Identification (FMI)	Index Prioritization (IP)	Portfolio Risk Assessment (PRA)	Quantitative Risk Assessment (QRA)
1	Wider use of Failure Modes Identification thinking and current expertise in this area	30	Document process. Document case histories, Training seminars, Hands-on workshops, Train facilitators, NPDP collect and disseminate (journal or web-based) case histories	X			
2	Guidelines for what constitutes a Portfolio Risk Assessment and how it may be done	25	Guidelines			X	
3	Training in understanding probability and skills such as expert elicitation	23	Training seminars (e.g., FEMA) and web-based training for practicing engineers. Include risk and uncertainty in BS curriculum and make sure that they are part of accreditation requirements			X	X
4	Build FMI into standards-based reviews	18	Similar modes of T^3 to Priority 1	X			
5	Sharing experience on PRA with others, how well the process worked, and what should be changed	14	Publish completed Portfolio Risk Assessments with evaluations of their strengths and weaknesses and ways to improve			X	
6	Tools for owners with limited resources	12	Hire an engineer. Do dams in groups with same experts	X	X	X	
7	Risk indexing and prioritization approaches for state regulators and owners with limited resources	10	Compilation and summary of existing approaches and development of an appropriate approach for the States, including equipping the States to evaluate risk assessment submittals		X	X	
8	Demonstration projects	8	Hands-on experience – not just observers at USBR RA. Owners could cooperate to sponsor	X	X	X	X
9	More experience by more people	7	Demonstration projects. Train more facilitators. Sponsor seminars aimed at education non-technical staff among owners.	X	X	X	X
10	Regular program for operator training	5	Dam owner's responsibility – need for material from professional bodies, etc. for small dam owners	X			
11	Documentation of state-of-the practice and training workshops	5	Documentation and training workshops				X
12	Compilation of case histories	5	Case histories	X		X	X
13	Produce a life safety tolerable risk criteria discussion paper, exhibit publicly, and invite submissions	5	Discussion paper				X
14	Dam safety community should interact with DOE, NRC on QRA	3	Interaction				X

7.0 RESEARCH AND DEVELOPMENT NEEDS: WAYS TO IMPROVE BREADTH, DEPTH AND QUALITY OF APPLICATIONS

Scope: Improved procedures and tools needed to strengthen the current state-of-the-practice.

Research is needed to improve the "breadth" (types of applications), "depth" (level of effort and sophistication), and "quality" (rigor, credibility and defensibility, including acceptability to regulators) of risk assessment applications. Table 7.1 lists the prioritized research and development needs that resulted from the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams (ASDSO 2001). The target risk assessment application areas for each need are indicated. Table 7.1 also shows which of four importance-difficulty categories each need was classified into through Workshop participant voting using a Strategic Planning Process, based on the IBM "MetaPlan" approach. The four importance-difficulty categories are as follows:

- Low Hanging Fruit - Easy and important
- Strategic Items - Hard and important
- Do later - Easy but less important
- Consider - Hard and less important

Both identification and prioritization of research needs should be reassessed as more knowledge and experience are gained in this field.

Table 7.1. Prioritized Research and Development Categories

Priority	Description	Difficulty-Importance Category and Interpretation	Risk Assessment Application Category: Failure Modes Identification (FMI)	Index Prioritization (IP)	Portfolio Risk Assessment (PRA)	Quantitative Risk Assessment (QRA)
1	Prioritization and Portfolio tools	Low Hanging Fruit – Easy and Important		X	X	
2	Data Base of Failure Case Histories		X		X	X
3	Tolerable Risk Criteria	Strategic Items – Hard and Important			X	X
4	Flood Loading				X	X
5	Earthquake Response				X	X
6	Improve Loss of Life Estimates				X	X
7	Risk Communication				X	X
8	Subjective Probability				X	X
9	Uncertainty	Do Later – Easy but Less Important			X	X
10	Risk Process				X	X
11	Skills to Identify Failure Modes		X		X	X
12	Standards					X
13	Static Response				X	X
14	Earthquake Loading	Consider – Hard and Less Important			X	X

REFERENCES

Achterberg, D., C. Hennig, and C. Redlinger. 1998. Implementation of Risk Analysis Principles into the Bureau of Reclamation's Dam Safety Program Actions. Eighteenth Annual USCOLD Lecture Series, Buffalo, NY.

ASDSO. 2001. Report on the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams. Submitted to FEMA by ASDSO.

Australian National Committee on Large Dams (ANCOLD) 1994. Guidelines on Risk Assessment.

AS/NZS. 1995. Risk Management. Australian/New Zealand Standard, AS/NZS 4360, Stathfield, New South Wales, Australia, and Wellington, New Zealand.

Ballantyne, D. 2000. System Vulnerability Assessment Portland Bureau of Water Works, EQE International, September.

Bowles, D.S., L.R. Anderson, and T.F. Glover. 1998. The Practice of Dam Safety Risk Assessment and Management: Its Roots, Its Branches, and Its Fruit. Eighteenth Annual USCOLD Lecture Series, Buffalo, NY.

Bowles, D.S. 1999. Alamo Dam Demonstration Risk Assessment: Results. Presentation to the U.S. Army Corps of Engineers, Los Angeles, CA, January.

Bowles, D.S., A.M. Parsons, L.R. Anderson and T.F. Glover. 1999a. Portfolio Risk Assessment of SA Water's Large Dams. ANCOLD (Australian Committee on Large Dams) Bulletin 112:27-39. August.

Bowles, D.S., L.R. Anderson, J.B. Evelyn, T.F. Glover and D.M. Van Dorpe. 1999b. Alamo Dam Demonstration Risk Assessment. Presentation at the 1999 ASDSO 16th Annual Conference, St. Louis, Missouri. October.

Bowles, D.S. 2000. "Advances in the Practice and Use of Portfolio Risk Assessment." Proceedings of the Australian Committee on Large Dams Annual Meeting, Cairns, Queensland, Australia.

Bowles, D.S./DNRE. 2000. Some Common Pitfalls in Dam Safety Risk Assessment, Department of Natural Resources & Environment, Melbourne, Victoria, Australia. March.

Bowles, D. S. and D.L. Johnson. 2001. ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams. Proceedings of the 2001 ASDSO 21st Annual Conference, Snowbird, Utah. September.

Bruce, R.L., A. Minty, C.A.J. Gregory. 1995. Holistic Risk Management. In Integrated Risk Assessment, Melchers and Stewart (Eds.). Balkema, Rotterdam.

Department of Natural Resources & Environment (DNRE). 1997. Proposal for Business Risk Assessment Requirements. Department of Natural Resources & Environment, Victoria, Australia.

Dise, K.M., and S.G. Vick. 2000. Dam Safety Risk Analysis for Navajo Dam. Proceedings of the 20th International Commission on Large Dams (ICOLD) Congress, Beijing, China. September.

Dupak D.D. and G.F. Smith. 2000. An owner's perspective with FMEA. Canadian Dam Association, Third Annual Conference, Regina, Saskatchewan, September.

HSE. 2001. Reducing Risks, Protecting People: HSE's decision-making process. Risk Assessment Policy Unit, Health and Safety Executive. HSE Books, Her Majesty's Stationery Office, London, UK.

ICOLD. 2002. Risk Assessment in Dam Safety Management: A reconnaissance of Benefits, Methods and Current Applications. ICOLD Bulletin, Draft Version 2.2, International Commission on Large Dams, August.

Johnson, D.L. 2000. Risk is not a Four Letter Word: Ten Years of Success Using a Risk-Based Dam Safety Approach in Washington. 2000 Annual Conference Proceedings, Association of State Dam Safety Officials, Lexington, KY.

McCann, M.W., and G. Castro. 1998. A framework for applying and conducting risk-based analysis for dams. Eighteenth Annual USCOLD Lecture Series, Buffalo, New York. August.

McDonald, L.A. and C.F. Wan. 1998. Risk Assessment for Hume Dam – Lessons from Estimating the Chance of failure. Proceedings of the 1998 Australian Committee on Large Dams (ANCOLD) Annual Meeting, Sydney, N.S.W., Australia. September.

McGrath, S. G., 2001. International Practice and Use of Risk Assessment in Dam Management, Year 2000 Churchill Fellowship Report, The Winston Churchill Memorial Trust of Australia.

National Research Council (NRC). 1983. A Framework for Characterizing Extreme Floods for Dam Safety Risk Assessment.

National Research Council (NRC). 1996. Understanding Risk.

Schaefer, M.G. 1992. Dam Safety Guidelines, Technical Note 2: Selection of Design/Performance Goals for Critical Project Elements, Dept. of Ecology, Water Resources Program, No. 92-55F, Olympia, WA.

Snowy Mountains Engineering Corporation Ltd. and RAC Engineers & Economists (SMEC/RAC). 1995 Review of Headworks. Volumes 1-3. Prepared for the Office of Water Reform, DNRE, Victoria, Australia.

USBR. 2000. Risk Based Profiling System. U.S. Bureau of Reclamation, Technical Services Center, Denver, Colorado. February.

Watson, D. J., C. Gratwick, D.S. Bowles, L.R. Anderson, T.F. Glover, P.H. Jacob, G.S. Tarbox. 1997 Statewide Review of Headworks dams: Status, Risks, Future Business Focus and Approach to Regulation. ICOLD Congress, Florence, Italy.

Watson, D. J. 1998. Business Risk Assessment of Dams – An Australian (Victorian) Experience. Proceedings of USCOLD Annual Lecture, Buffalo, New York, 1998.

Watson, D., and J. Adem. 1998. Risk Assessment of Dams – Future Directions for Victoria, ANCOLD, 1998.

Watson, D. J. and S. Perera. 2000. Risk Assessment Issues for Dam Safety Management. Proceedings of the ICOLD Congress, Beijing, China.

APPENDIX A

Membership of the USSD CODS Working Group on Risk Assessment

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Charlie Ahlgren	Pacific Gas & Electric Company
Mike Akridge	Southern Services, Alabama Power
Mike Baleda	Electric Power Research Institute and American Society of Civil Engineers Task Committee on Risk Assessment
Mona Bechai	Ontario Power Generation Incorporated and Canadian Dam Association
David Bowles (Chair)	Utah State University, RAC Engineers & Economists and International Commission on Large Dams Bulletin on Risk Assessment
Al Davis	Consultant/Factory Mutual Insurance Company
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Jerry Foster	U.S. Army Corps of Engineers
Terry Hampton	Gannett Fleming (formerly Mead and Hunt)
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Dan Mahoney	Federal Energy Regulatory Commission and American Society of Civil Engineers Task Committee on Risk Assessment
Kevin Marshall	Portland General Electric
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Glenn Tarbox	Harza Engineering
Constantine Tjoumas	Federal Energy Regulatory Commission
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