

RECLAMATION

Managing Water in the West

Interim

Dam Safety Public Protection Guidelines

A Risk Framework to Support Dam Safety Decision-Making



**U.S. Department of the Interior
Bureau of Reclamation
Dam Safety Office
Denver, Colorado**

August 2011

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Introduction

Purpose of the Guidelines

The Bureau of Reclamation (Reclamation) is responsible for about 370 high and significant hazard storage dams and dikes that form a significant part of the water resources infrastructure for the western United States. As the owner of these facilities, Reclamation is committed to providing the public and the environment with adequate protection from the risks which are inherent to collecting and storing large volumes of water for subsequent distribution and/or release. This document presents the basis and guidance for dam safety risk management including:

- Guidelines for a risk-informed approach to decision-making
- Guidelines for analyzing and portraying risks
- Guidelines for prioritizing actions and managing risk
- Guidelines for maintaining a focus on risk reduction when implementing agency actions

These Dam Safety Public Protection Guidelines are for use in evaluating high or significant hazard dams and are not applicable to the evaluation of risks for low hazard dams or other features, such as canal embankments or levees.

There are two companion documents to the Public Protection Guidelines:

- **Rationale Used to Develop Reclamation’s Dam Safety Public Protection Guidelines** outlines the basis for the terminology and structure of the guidelines.
- **Dam Safety Public Protection Guidelines - Examples of Use** gives examples of how the guidelines are intended to be used in practice.

The guidelines are intended to ensure consistent levels of public protection when evaluating and modifying existing dams and appurtenant structures and when designing new dams and/or structures.

Background

The mission of the Reclamation Dam Safety Program is:

“To ensure Reclamation dams do not present unreasonable risk to people, property, and the environment.”

Reclamation has the authority to modify its dams for safety purposes under the Reclamation Safety of Dams Act of 1978 [1]. This Act was passed in response to several dam failures in the 1960s and 1970s, including the failure of Teton Dam, a large Reclamation storage dam. The Act provides for the following:

“In order to preserve the structural safety of Bureau of Reclamation dams and related facilities, the Secretary of the Interior is authorized to perform such modifications as he determines to be reasonably required.”

Reclamation uses risk to make informed dam safety decisions. To estimate the risks associated with its structures, Reclamation has established procedures to analyze data and assess the condition of its structures. Prior to the failure of Teton Dam, dam safety issues were addressed through periodic examinations and project specific requests for Congressional funding to make necessary modifications to dams. The failure of Teton Dam demonstrated a need for a more comprehensive approach to evaluating and addressing dam safety issues.

In 1979, a committee of Federal agency representatives commissioned by the President developed the Federal Guidelines for Dam Safety [2] to promote prudent and reasonable dam safety practices among Federal agencies. While the Federal Guidelines recognized that risk-based analysis was a recent addition to the tools available for assessing dam safety, they encouraged agencies to conduct research to refine and improve the techniques necessary to apply risk-based analysis to dam safety issues:

“The agencies should individually and cooperatively support research and development of risk-based analysis and methodologies as related to the safety of dams. This research should be directed especially to the fields of hydrology, earthquake hazard, and potential for dam failure. Existing agency work in these fields should be continued and expanded more specifically into developing risk concepts useful in evaluating safety issues.”

Reclamation has established a risk-informed framework to meet the objectives of its program, the Safety of Dams Act, and the Federal Guidelines. Risk-informed procedures are used to assess the safety of Reclamation structures, to aid in making decisions to protect the public from the potential consequences of dam failure, to assist in prioritizing the allocation of resources, and to support justification for risk reduction actions where needed. Risk assessment for dam

safety decision-making integrates the analytical methods of traditional engineering analyses and risk-based analysis along with the sound professional judgment of engineers, review boards, and decision-makers in determining reasonable actions to reduce risk at Reclamation facilities.

Terminology

Key Risk Terms

Risk

Risk is the probability of adverse consequences. It can be measured in two ways – Annualized Failure Probability and Annualized Life Loss.

Annualized Failure Probability

Annualized failure probability is the probability of dam failure occurring in any given year. It is the product of the probability of the load and the probability of dam failure given the load. Annualized failure probability is sometimes equated with Individual Risk, which is further defined below.

Annualized Life Loss

Annualized life loss is the product of the annualized failure probability and the life loss that is expected to result from failure. A guideline for annualized life loss is commonly shown on the $f-N$ diagram as a line with a negative slope. That is, as the severity of the consequences increases, the probability of the event causing those consequences must decrease in order to meet the risk targets. The Reclamation guidelines use a slope of -1, as shown in Figure 2. Annualized life loss is sometimes equated with Societal Risk, which is further defined below.

Total Risk

Total risk is the sum of the annualized life loss for all potential failure modes associated with a structure.

Risk Analysis (and Risk Estimation)

As used in these guidelines, the term “Risk Analysis” refers to a qualitative or quantitative estimation of risk. The related term of “Risk Estimation” refers to the actual process used to assign categories or values to the probability and consequences of failure.

Risk Assessment

Risk assessment is the process of deciding whether or not additional risk reduction measures are justified and will be implemented. Risk assessment uses risk analysis results and risk guidelines, and considers other factors that could affect the decisions.

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Risk Management

Risk management encompasses the entire range of activities related to developing risk estimates, prioritizing risk reduction activities, and making risk-informed program decisions associated with managing a portfolio of facilities.

Other Terms

ALARP

The “As-Low-As-Reasonably-Practicable” (ALARP) considerations provide a way to address efficiency in reducing risks. The concept for the use of ALARP considerations is that risk reduction beyond a certain level may not be justified if further risk reduction is impracticable or if the cost is grossly disproportional to the risk reduction. ALARP only has meaning in evaluating the justification for, or comparison of, risk reduction measures: it cannot be applied to an existing risk without considering the options to reduce that risk.

Confidence

Confidence is a qualitative measure of belief that an engineering analysis, risk estimate, or recommended action is correct. Confidence is used to describe how sure the estimator(s) is about the general location of a risk estimate (or cloud of Monte Carlo simulation values) on an f-N chart. Similarly, the level of confidence influences recommended actions.

Consequences

Consequences of dam failure can include economic losses due to property damage, lost benefits, and ripple effects through the economy; environmental damages as a result of large downstream flows and release of reservoir sediment; damages to cultural resources; and socio-economic damages to the affected communities. Although these consequences can be considered in the decision making process, the primary consequences considered with respect to dam safety are human fatalities or life loss.

Comprehensive Reviews (CRs)

Comprehensive Reviews are in-depth routine examinations of facilities (structures forming an individual reservoir) carried out on a recurring basis. In addition to a comprehensive examination and records review, evaluations of potential failure modes and estimation of risks are typically completed by a senior engineer and peer reviewer.

Corrective Action Study (CAS)

A Corrective Action Study is a detailed investigation undertaken to evaluate potential alternatives and risk reduction options. A CAS is performed after a decision has been made that action is justified to reduce risks at a particular facility.

Cost-Effectiveness

In general terms, this is the amount of risk reduction achieved per monetary unit spent.

Dam Safety Case

The Dam Safety Case is a logical 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 at any given (current) time. It is sometimes referred to simply as “the case.”

Dam Safety Priority Rating (DSPR)

The DSPR is a categorization scheme that is intended to guide and prioritize appropriate actions at a structure or facility, particularly with regard to the urgency of actions, using risk as a component of the considerations.

Failure Mode

A failure mode is a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structure design, the construction, the operations and maintenance, or the aging process, which can lead to a capacity that is less than the applied loads, and an uncontrolled release of the reservoir.

***f*-*N* Chart**

An *f*-*N* ‘event’ chart is composed of individual *f*-*N* pairs, where each pair typically represents one potential failure mode (or in the case of total risk, the summation of all potential failure modes). On the *f*-*N* chart, *f* represents the annualized failure probability over all loading ranges. *N* represents the estimated life loss or number of fatalities associated with an individual failure mode, or the weighted equivalent number of fatalities associated with the summation of failure modes. A description of how the *f*-*N* chart is used to portray risks can be found in *Dam Safety Public Protection Guidelines - Examples of Use*.

***F*-*N* Chart**

Some organizations that quantitatively assess risk use complementary cumulative distribution functions to portray risk; they plot the number of fatalities (*N*) on the horizontal axis versus the annual exceedance probability for causing “*N*” lives or greater on the vertical axis. The *F*-*N* curves typically show the cumulative frequency of fatalities for all loading events and failure modes. This approach is seldom used to portray risks posed by Reclamation structures since the *f*-*N* chart provides a practical portrayal of results that is more easily utilized by both risk teams and decision-makers, and one that more clearly relates the risks of failure under various loading conditions.

Individual Risk

Although this term is not widely used in Reclamation, it is often considered equivalent to the annualized failure probability. In essence, this term is associated with the most exposed individual who is placed in a fixed relation to a hazard

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such as a dam. Individual risk is the sum of the risks from all 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 1 is equal to the failure probability).

Issue Evaluation (IE) Risk Analysis

Issue Evaluation level risk analyses are detailed team estimates of risks often focused on a small number of specific issues at a single facility, and facilitated by an experienced facilitator.

Residual Risk

The risk remaining after risk reduction measures have been implemented.

Risk-Neutral

In the context of Reclamation dam safety work, risk-neutral implies that there is no appreciable increase in risk due to changes in operation, or modifications to the dam or appurtenant structures. (Note: this is different than the definition typically used in the industry, where risk-neutral refers to an equal decrement in probability for a given increment in consequences.)

Risk Reduction Actions

These are actions taken to reduce risks, based on evaluation of a number of prudent alternative actions. The appropriate actions are based on the magnitude of the risk and the risk reduction, the degree of confidence in the estimated risk and/or the risk reduction, the likelihood of additional information providing a significantly different understanding of the risks, and the costs of taking the actions.

Societal Risk

As with “Individual Risk,” this term is not widely used in Reclamation documents. Societal risk is generally equivalent to Reclamation’s Annualized Life Loss. Societal risk is defined as the probability of adverse consequences from hazards that impact on society as a whole and create a social concern and potential political response because multiple fatalities occur in one event. Society is increasingly averse to hazards as the magnitude of the consequences increases.

Uncertainty

Uncertainty is a qualitative or quantitative measure of the range or spread of reasonable outcomes of a risk estimate. Uncertainty is used to portray variability or a range of values for loads, consequences, and risk estimates, rather than relying solely on single point estimates.

Unquantified Risk

Typically, risk is evaluated for a few potential failure modes and for loadings up to the maximum level to which the hazard studies were carried. Additional risk can be accumulated for loading levels higher than the maximum portrayed by the hazard curves, but analyses might not be available at these higher loading levels.

Typically, these unquantified risks are assumed to be small, but they may not actually be in all cases. Therefore, they should be evaluated when the potential consequences are large.

Risk Management

Risk management encompasses activities related to estimating risks, 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 of all parts of the decision process. Figure 1 illustrates the components of risk management. The risk management process emphasizes an ongoing and iterative process and the necessity of adapting to new information. Further information about how Reclamation approaches the decision-making process within risk management can be found in the Dam Safety Decision Process Guidelines [3].



Figure 1. Dam Safety Risk Management Components

Considering the Full Range of Loading Conditions

Historical design and analysis methods have generally focused on selecting a level of protection based on loadings from the (presumably) most severe

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combination of critical seismological, meteorological, and hydrologic conditions. In addition to ensuring public safety for extreme events, Reclamation is also committed to providing public safety for smaller events and loading conditions which occur more frequently. For example, an enlarged spillway designed for a probable maximum flood loading condition may increase the operational risks to the public for lesser events by causing larger releases than would have otherwise been experienced during these lesser events. In addition, it has been found that in some cases loading conditions that were thought to be “extreme” under a deterministic framework really weren’t that unlikely under a probabilistic framework. Assigning exceedance probabilities to the loadings that are considered in the dam safety evaluations helps to establish an understanding for just how likely they really are. This applies to reservoir levels for normal static loading as well as flood and earthquake loads. Conditional failure probabilities are estimated over continuous load ranges above a threshold load. Risk assessment provides a framework for identifying where the largest risks are likely to come from and addressing the most effective way to provide public protection over the full range of loading conditions.

Need for Probabilistic Methods

As a water resources management agency, Reclamation strives to provide decision-makers with the best available pertinent information on water resources management, hazard assessment, engineering, and public safety practices. Since the mid-1990s, there has been an increasing trend in water resources analysis toward using probabilistic design methods to evaluate the effectiveness of expending funds for enhancing public safety. There has also been greater recognition that even the most restrictive design standards result in structures that have some likelihood of failure for the conditions they cover, even though that likelihood may be very small. Standards-based approaches use established rules for events and loads, structural capacity, safety coefficients, and defensive measures that can result in uneven risk across failure modes and loading types.

Risk assessment also provides a means to examine potential failure modes that cannot be analyzed using traditional standards-based analysis methods such as operational failures (e.g. failure to open spillway gates during floods due to access problems, mechanical/electrical problems, or communications problems) or internal erosion failures of embankment or foundation soils.

Application

This document addresses the incorporation of risk-informed processes into Reclamation’s dam safety decision-making process to help assess public risks and allocate resources. While there are many issues that may be evaluated in a risk context, resulting in many types of consequences, this document focuses on the life loss, and the failure probability components of decision-making.

Approach to Decisions Using Risk

Risk analysis provides a means to quantify judgment and to identify the conditions and parameters that contribute to risk at a structure. The intent of a risk analysis is to review the potential failure modes for a dam and evaluate their likelihood and consequences. Valuable outcomes of the risk analysis include an improved understanding of the critical issues and potential vulnerabilities at a dam, a clearer identification of the issues that are the most significant contributors to risk, the uncertainties, and the level of confidence in the risk estimates. This knowledge can be used to focus attention on those issues, which, if mitigated, will provide substantial reduction of risk to the public.

Policy

Reclamation policy for dam safety decision-making delegates the decision-making responsibility to the Regional Directors in collaboration with the Chief, Dam Safety Office and the appropriate Area Manager [4]. In general, the Technical Service Center (TSC) provides significant technical advice that is critical to decision-making. The risk framework serves as a tool for aiding decision-makers in the determination of needs for risk reduction actions as well as the evaluation of different risk reduction actions that could be taken to address the identified issues.

Public Trust Responsibility

Decision-making to accomplish the Dam Safety Program is a complex process and must consider risk to the public as well as economic, environmental, social, and cultural impacts. Thus, it is difficult to be prescriptive when developing guidance for making decisions. While the technical analysis of risks associated with a dam cannot become the sole decision-making factor, it must be recognized that addressing these risks in a technically consistent and timely fashion is an important part of sustaining the public's trust in Reclamation to manage these facilities in the best interest of the nation. This public trust responsibility includes operating Reclamation facilities with reasonable assurance of the safety of persons in the vicinity of, and downstream of, the dams.

Consensus

A key part of the decision-making process is recognizing that it will generally involve building consensus regarding the appropriate actions to be taken. However, in the event of an emergency, the time for developing consensus may be severely shortened. Such a situation would require Reclamation to act quickly to avoid or minimize consequences.

Risk Assessment Guidelines

Reclamation uses two guidelines to assess dam safety risk. The first guideline addresses Annualized Failure Probability, which serves to fulfill the public trust responsibility associated with agency exposure as a result of dam failures (dams should not fail frequently even if the consequences are low). The second guideline addresses Annualized Life Loss, where multiple fatalities are possible as the result of dam failure. Protection of human life is of primary importance to public agencies constructing, maintaining, or regulating public works.

Annualized Failure Probability

A dam with zero chance of failure does not exist. However, in order to maintain public trust, the probability of dam failure must be very low. This ensures a minimum level of safety when the consequences are not high. **Reclamation terms this measure of risk Annualized Failure Probability, and uses a guideline of 1 in 10,000 per year for the accumulation of failure likelihoods from all potential failure modes that would result in life-threatening unintentional release of the reservoir. When the mean estimate is above this threshold level there is generally increasing justification to take action to reduce or better understand the risks. Below this threshold level there is generally decreasing justification to reduce or better understand the risks.** This guideline is shown as a horizontal line at 10^{-4} on the risk guidelines chart (Figure 2).

Annualized Life Loss

Society is increasingly averse to hazards as the scale of the consequences (lives lost) increases. **Reclamation defines this risk as Annualized Life Loss, and uses a guideline of 0.001 fatalities per year to address this measure of risk. When the mean estimate is above the guideline of 0.001 fatalities per year, there is generally increasing justification to take action to reduce or better understand the risks. There is generally decreasing justification to reduce or better understand the risks when they are below this guideline value.** The primary means to portray risks is the $f-N$ chart where risks associated with individual potential failure modes are plotted as well as the total risk. The guidelines are applied to individual potential failure modes when dominated by a single failure mode or the summation of failure mode risks when several plot near the guidelines. Figure 2 illustrates the risk guideline chart. The annualized failure probability multiplied by the estimated lives lost represents the annualized life loss. Therefore, the line with a slope of -1 represents a constant annualized life loss of 0.001. As the consequences increase by an order of magnitude, the annualized failure probability must decrease by an order of magnitude to maintain a constant value of annualized life loss. A description of how the $f-N$ chart is used to portray risk can be found in *Dam Safety Public Protection Guidelines - Examples of Use*.

Low Probability – High Consequence Events

Decisions related to failure of structures for remote loading conditions or failure probabilities, combined with high consequences, have been difficult for both decision-makers and risk estimators. Extrapolation of seismic and hydrologic hazards into remote areas is costly and results in loadings where the basis for the results becomes highly uncertain. Predicting events or failure probabilities that are expected to be less probable than 1 in 1,000,000 per year becomes less defensible and uncertainty becomes a major factor when considering potential decisions.

Structures that have the potential to cause more than 1,000 fatalities are generally large in size, highly visible, important to the local community, the region, and the economy. These high profile structures generally receive added attention during all parts of the risk management process by both decision-makers and technical staff. The existence of structures that have the potential to cause major catastrophes indicates that the trade-off between the hazards posed by the structure and the benefits secured by it should be demonstrated with a higher degree of defensibility. However, the profession's current ability to demonstrate failure probabilities to very low levels, less than 1 in 1,000,000 per year, is limited. This does not mean that these risks should be ignored or that an attempt should not be made to obtain the best information possible in these cases. The opposite is true, although the costs of obtaining the information should be carefully weighed against the potential to gain useful information that could be used to support a decision. As-low-as-reasonably-practicable (ALARP) principles should be considered and weighed against the residual risks posed by the structure.

The chart in Figure 2 includes an area bounded by 1×10^{-6} annualized failure probability on the top and 1,000 fatalities on the left. This 'box' is shown to indicate that ALARP principles should be considered and additional interaction should occur between the decision-makers and the risk estimators when the risks are thought to be in this region.

Often in this region, the decision strategy changes to considerations of the more qualitative aspects of the structure and the hazards it poses. Questions that may be asked include:

- Has everything reasonable been done to characterize the risk?
- Can the uncertainty be characterized and explained?
- Is the structure sensitive to a particular parameter or the performance of a particular feature?
- Does the structure contain robust and redundant defensive measures, or does it rely on a single feature to ensure structural integrity?

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- Would it be cost-effective to reduce risks further?
- Are there reasonable and prudent actions that should be taken?
- Can Reclamation responsibly operate a facility with the risks as they are understood and portrayed?

Consequence Considerations

For the purpose of evaluating risk, Reclamation considers the potential for life loss as the primary consequence of dam failure. Although economic consequences have not been incorporated into Reclamation’s dam safety risk assessment guidelines, they may be considered in the decision-making process. Economic losses include both the direct losses that result from the failure of a dam and other indirect economic impacts on the local, regional, or national economy [5]. Direct economic consequences include downstream property damage, lost benefits, and reconstruction costs. These direct economic losses can be compared to the costs of dam modification providing a measure of the proposed modification’s economic efficiency. Indirect economic consequences can be widespread, including loss of employment and business output. Reclamation economic analyses must comply with the guidelines provided by the publication commonly referred to as the “Principles and Guidelines (P&Gs)” [6], a publication from the U.S. Water Resources Council.

A dam failure has both direct and indirect consequences that cannot be directly measured in monetary terms. These stem from the impacts of the dam breach outflow and loss of the reservoir on environmental, cultural, and historic resources. In most cases, an assessment of the impacts of dam failure will include the area and type of habitat impacted, whether any threatened and endangered species are impacted, the number and type of historic sites impacted, and the number and type of culturally significant areas impacted. These types of consequences are not typically considered in dam safety evaluations, but may be important considerations in the decision-making process.

An additional indirect non-monetary consequence could be the exposure of people and the ecosystem to hazardous and toxic material released from landfills, warehouses, and other facilities that are inundated by the dam failure flood. An estimate of the locations and quantities that could be impacted by dam failure should be compiled, identifying where significant quantities are concentrated. A potential additional source of hazardous and toxic material is the sediment accumulated behind the dam. Identifying and enumerating these indirect hazards could be important enough to require additional risk assessments including estimating additional fatalities due to exposure to these hazards. These non-monetary consequences can provide additional risk information for decision-making. They can also be used to identify risks to be managed separately from dam modifications.

Intangible consequences are those that have no directly observable physical dimensions but can result in affected individuals feeling excessive levels of stress or grief in dealing with losses. Such consequences can also be considered in the decision-making process.

Guidelines Versus Criteria

The lines shown on Figure 2 do not represent hard prescriptive criteria, but rather represent broad advisory guidance. The guidance is intended to give site specific and case factors due importance and allow decision-makers latitude in choosing the course of action to be taken. The *Rationale Used to Develop Reclamation's Dam Safety Public Protection Guidelines* provides further discussion and rationale for this guidance. **Due to the approximate nature of the risk estimates, risks just below the lines are essentially the same as risks just above the lines. Therefore, risk estimates plotting just below the line have almost as strong justification for action as those plotting just above.** When risks are near the guideline values and confidence in the risk estimates is not high, a prudent course of action may be to gather additional data or conduct additional analyses to better define the risks.

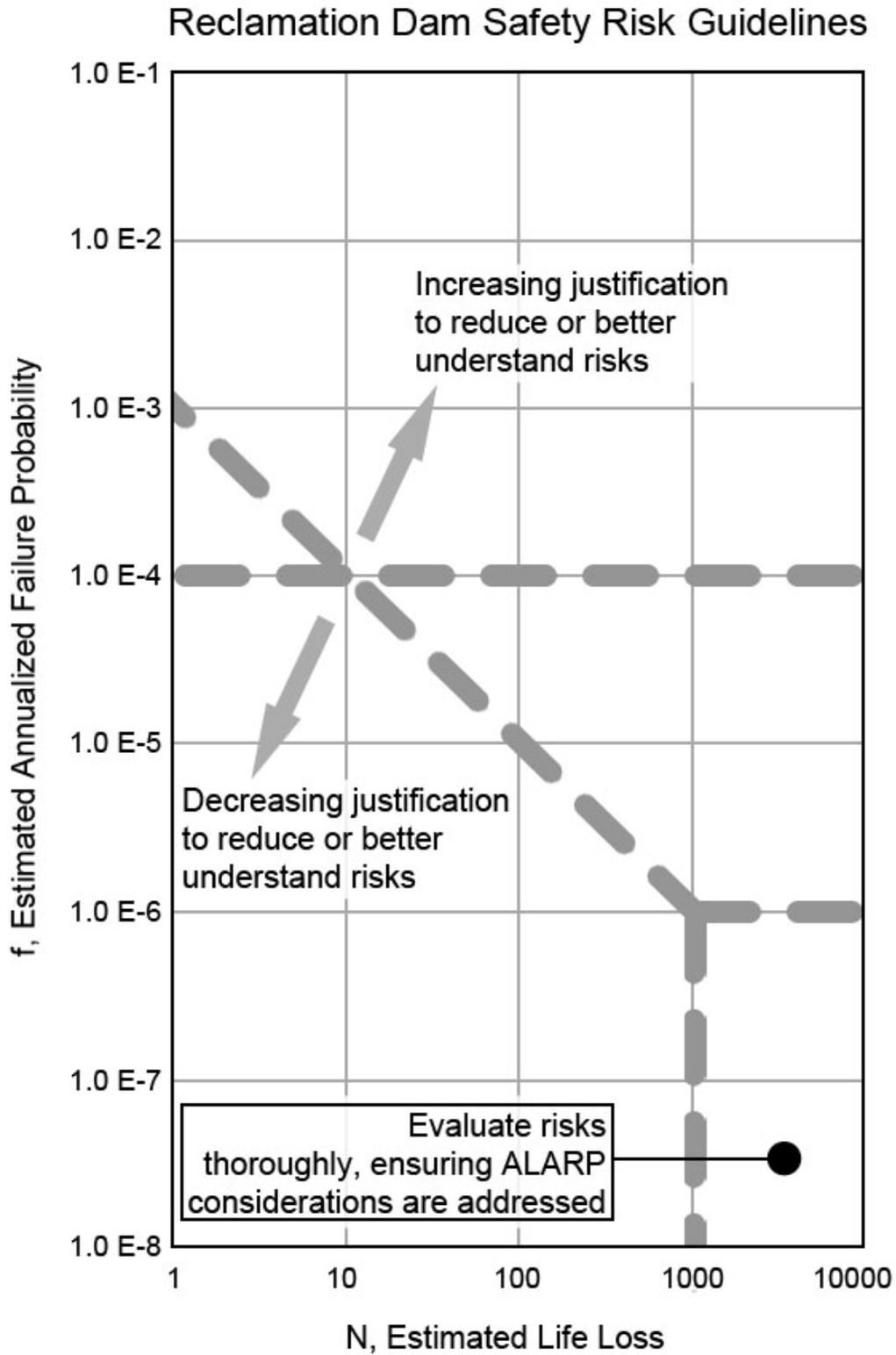


Figure 2. Reclamation Dam Safety Risk Guidelines Chart

Guidelines for Analyzing and Portraying Risk

Development and Portrayal of Risk Estimates

For high and significant hazard Reclamation facilities, estimates of risk should be developed and portrayed according to the framework described in the Dam Safety Risk Analysis Best Practices Training Manual [7]. At a minimum, each of these documents requires that the following information be provided to support potential decisions:

1. List and detailed description of the potential failure modes
2. Description of the potential consequences of each potential failure mode
3. Description of the annualized failure probability of a facility, which includes a discussion of the contributions from individual potential failure modes
4. Description of the annualized life loss risk posed by a facility, which includes a discussion of the contributions from individual potential failure modes
5. Estimates should be plotted for individual potential failure modes as well as for the total from all potential failure modes at a facility; the total estimate provides the fundamental basis for the Dam Safety Priority Rating (DSPR)
6. Description of how the dam was placed within the Dam Safety Priority Rating (DSPR) system (described below)
7. Recommended actions
8. Presentation of the case that has been built to support the risk numbers, classification, and recommendations

Qualitative Risk Categorization

In certain situations it may be appropriate to perform a qualitative screening of potential failure modes. Performing quantitative risk analyses can be time consuming and expensive. Often a potential failure mode analysis followed by assigning the risk of each failure mode to broad categories of likelihood and consequences (in matrix form) can identify those potential failure modes where the risk is likely to be low. This allows limited resources to be focused on performing quantitative estimates for the potential failure modes that are likely to

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dominate the risk. Additional details on these procedures can be found in the Best Practices manual [7].

Mean Estimate of Risk

Risk estimates for significant potential failure modes are generally portrayed to decision-makers in the form of the mean estimate of risk, whether it is individual potential failure mode estimates or total risk. This is one piece of information used to convey risks to decision-makers; the DSPR category and dam safety case are equally important pieces of information that should be used to support the recommended actions.

Uncertainty

The quantification of risk estimates is dependent on available data and analyses regarding the design, construction, performance and current condition of a dam. It also depends on the identified loads that the dam could be subjected to over its operating life and knowledge about how the downstream population would be affected by a dam breach flood. It is acknowledged that the quantification of risk estimates includes a degree of subjectivity regardless of how the estimates are made, and is a function of group dynamics, the experience and associated judgment of group members, models used in the analyses, and the available information for a dam. Thus, uncertainty in the risk estimates is expected. This uncertainty is typically captured by assigning ranges to probability and consequences estimates.

The role or contribution of uncertainty in proposed dam safety actions should be included in the dam safety case. It is not used explicitly in evaluating risks relative to the risk assessment guidelines. However, in prioritizing actions it is useful to consider how much of and how far the range in risk estimates extends into the area of increasing justification to reduce or better understand risks. It is also helpful to examine the “tightness” in the range of risk estimates. For example, if the mean and median of the risk estimates are significantly far apart, it could be an indication that there is significant spread in the estimates and that the high end of the estimates are driving the mean risk estimate. It would be important to understand these effects in the prioritization process.

Confidence

The “confidence” in the risk estimates and dam safety case is an important factor in assigning the DSPR category (as well as prioritizing within a category). The DSPR table and the “Examples of Use” document suggest how the confidence level can lead to a higher or lower DSPR category, as well as help prioritize the dam among others in the same DSPR category.

As confidence increases in the risk estimates, actions (if necessary) should concentrate more on reducing the risk than reducing the uncertainties.

Sensitivity

Sensitivity is a measure of how much risk estimates change when key input assumptions (i.e. nodal risk estimates) are varied. This is characterized by performing sensitivity analyses, varying the probability of variables that most affect the outcome of the risk analysis, and examining the resulting effects on the risk estimates.

Sensitivity studies can be used to assist in defining ranges of uncertainty of risk estimates. In addition, results from sensitivity studies can be used to judge the relative “confidence” in risk estimates and/or resulting conclusions. For example, if parametric studies indicate a relatively minor difference in estimated risks that leads to no change in whether the risks are providing increasing or decreasing justification for action, there would be confidence in the risk estimates and the case for action or no action. Conversely, if varying the parameter over a reasonable range results in a significant change in potential risks or conclusions, there would be less confidence.

Assessing Ability to Reduce Uncertainty and/or Increase Confidence

When making a decision regarding future actions, one should consider the risk estimates, the confidence in those estimates, the issues most influencing the risks, the sensitivity of the risks to particular critical inputs, the cost of additional actions, and the potential for reducing uncertainty. Uncertainty may be reduced and/or confidence may be increased by performing additional actions such as collecting more data, by performing more analysis, or by performing a more detailed analysis of the risks. However, there are occasions when additional efforts may not result in significant reduction in uncertainty or any change in the level of confidence. It is important to recognize when this is the case and consider the anticipated value of the additional efforts to reduce uncertainty and/or increase confidence as a factor in selecting a course of action. Sensitivity studies are often useful in evaluating key parameters that additional information would address. These studies could be used to address the following questions: If the additional information was collected, what would be the possible range of outcomes? How might the risk change over that potential range? Could the confidence in the risk estimates increase? Could the DSPR category change?

Communicating Risk

The key outcome of the risk analysis is to communicate the current understanding of risk (and its relation to the guidelines) to the decision-makers. Decisions will

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be facilitated by elaborating on the reasons the risk makes sense (or might be higher or lower), the confidence in the estimates, and the additional information that might better define the risk. For example, the mean estimate of risk and its uncertainty might not reasonably portray the risk if there is an important lack of information or if there are alternate interpretations of the available information about a structure. There could be one range of risk estimates that is high and another that is low with the difference being the assumption about the information that is lacking or the interpretation of the available information. This type of risk communication can be very useful to the decision-makers when proposals for gathering additional data or for more detailed technical analysis are considered.

Risk numbers may not adequately communicate risks to non-technical audiences and the focus on risk numbers may shift the emphasis away from the source of the risks and the potential hazards. Many policy- and decision-makers will not be familiar with portions of risk terminology or methods for estimating risk. Explaining these risks and hazards simply by stating the dam safety case is generally the goal of risk communication in non-technical settings.

Dam Safety Case

From the outset of implementing risk analysis, Reclamation recognized that procedures and data available for dam safety risk analysis, while quantitative, do not provide precise numerical results. Therefore, relying solely on the numeric estimates in comparison to hard line criteria (sometimes referred to as “risk-based” evaluation) would not be appropriate. Decisions are generally more complex than can be portrayed using only the results of a risk analysis. The agency has chosen to use a more “risk-informed” approach where additional information is included to support the case for proposed actions (or non-action). The intent is to use the entirety of the information available to build and support the case to take a particular action (or to take no action).

Though many efforts are made during a risk analysis to achieve high quality results, the risk estimates themselves are little more than index values. If arrived at in a consistent manner, they are useful in program management as they allow comparisons and rankings between different facilities, and promote a general sense of where the risks lie relative to the risk assessment guidelines.

Reclamation's risk assessment guidelines are not intended to be used as rigid decision-making criteria to declare a facility “safe” or “unsafe” based solely on a risk estimate. Since the numbers are only approximate measures of risk, and since the risk guidelines themselves are not rigid, additional reasoning is essential to justify the risk estimates and the recommended actions. The case is intended to present rationale in a formal and methodical manner to persuade decision-makers to take responsible action (or to justify no action).

The case is a logical set of arguments used to advocate either the position that additional safety-related action is justified, or that no additional safety-related

action is justified at any given (current) time. The arguments string together key evidence regarding the three basic risk components (i.e. load probability, response probability, and consequences) so as to convince decision-makers that the dam's existing condition and ability to withstand future loading, the risk estimates, and the recommended actions are all coherent. Since uncertainty is inherent in each claim, the arguments should also address whether confidence is high enough for the conclusions to stand on the basis of existing evidence.

The case and the identification of risk management options are recognized as essential elements in Reclamation's prioritization efforts to ensure public protection. They represent understanding of existing conditions and predicted future behavior stated as objectively as possible.

The risk estimates and the case to support them do not in themselves ensure the safety of a facility. The case becomes the basis for risk management in the effect it has on the activities and behaviors of the people who interact with the facility. The understanding given to all, from facility operators to design engineers to dam safety program managers to Reclamation directors, by a well constructed supporting case is intended to focus attention on behavioral and technical aspects essential to the facility's integrity so that the facility can be operated and maintained in as safe a manner as possible with the available information.

The case should be carefully crafted so that all descriptions and terms are easy to understand by the prime audience, all arguments are cogent and coherently developed, all references are easily accessible, and all conclusions are fully supported and follow logically from the arguments. A more thorough examination of making the case can be found in the Best Practices manual [7].

Guidelines for Prioritizing Actions

Dam Safety Priority Rating (DSPR)

The guidelines for analyzing and portraying risk are used to help guide whether actions are justified or not; they do not establish the priority or urgency of actions. As a general rule, as the annualized failure probability and annualized life loss increase, the justification and urgency to take action also increase. Similarly, as the annualized failure probability and annualized life loss decrease, the justification and urgency to take action also decrease. Reclamation strives to develop consistent risk estimates through established methodology and review. However, Reclamation recognizes that risk estimates are likely to come from a variety of sources. Complete consistency in the estimates cannot be expected. Therefore, the risk numbers by themselves may not be the best way to prioritize activities. To help prioritize and establish the urgency of risk management activities, a Dam Safety Priority Rating system has been adopted by Reclamation

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to assist with these decisions. DSPR ratings apply to dams and not to the individual potential failure modes at a dam. The categorization of a dam is dynamic over time, changing as project characteristics are modified or more refined information becomes available, affecting the loading, annualized failure probability, or consequences of failure.

DSPR System

The DSPR system (Table 1) presents different levels of urgency and commensurate actions. These actions range from immediate recognition of a critical situation, in which there is extreme confidence, requiring extraordinary and immediate action for high risk dams through normal operations and routine dam safety activities for dams with low perceived risks at a high confidence level.

DSPR Categories

The descriptions of the categories below, and on Table 1, include verbal descriptors related to level of risk and confidence to assist in assigning a DSPR. It may be acceptable to assign a DSPR to a dam with risk and confidence levels that differ from the guidance language below, if a case is built to support that rating.

DSPR 1 – Immediate Priority. This category is reserved for cases where extremely high annualized life loss or annualized failure probability is combined with high confidence. The assignment of a DSPR 1 category would be appropriate for facilities where an active failure mode is in progress or when the likelihood of failure is judged to be extremely high. Immediate interim risk reduction measures followed by long term risk reduction measures would be appropriate. The following items can be used to determine whether this category is appropriate. For dams that are a DSPR 1 category, prioritization is not particularly relevant as all dams in this category will typically require immediate attention.

- Direct evidence that failure is in progress and the dam is almost certain to fail if action is not taken quickly.
- A case where both the annualized failure probability and the annualized life loss are extremely high would generally be more critical than a case where only one or the other is extremely high. Equal weight would be given to cases where one or the other (annualized life loss or failure probability) are in this category.
- A case where the extremely high annualized life loss or failure probability is driven by a single potential failure mode would generally be more critical than a case where risk estimates from several potential failure modes must be accumulated to arrive at extremely high total risk.

- A case where the risk is driven by potential failure modes manifesting during normal operating conditions would be more critical than cases where the risks stem primarily from flood or earthquake loadings.

DSPR 2 – Urgent Priority. This category is reserved for cases where the annualized life loss or annualized failure probability is judged to be very high with high confidence or is suspected of being very high to extremely high, but with low to moderate confidence. In the former case, implementing interim and long term risk reduction measures would be appropriate. In the latter case, timely confirmation of the risk would be appropriate, and implementing interim risk reduction measures may be appropriate. The primary difference between a DSPR 1 and a DSPR 2 category is that DSPR 1 will typically indicate an “emergency” situation that calls for immediate action due to the possibility of an impending failure. DSPR 2 facilities have very high risks or likelihoods of failure, but are not in “imminent” danger. The following items can be used to determine whether this category is appropriate. In addition, these factors can help establish the relative priority ranking of all dams within the category.

- A case where both the annualized failure probability and the annualized life loss are very high with high confidence or very high to extremely high with low confidence would generally be more critical than a case where only one or the other falls into these categories. Equal weight would be given to cases where one or the other (annualized life loss or failure probability) are very high with high confidence or very high to extremely high with low confidence.
- A case where the annualized life loss or failure probability is driven by a single potential failure mode would generally be more critical than a case where risk estimates from several potential failure modes must be accumulated to arrive at the total risk.
- A case where the risk is driven by potential failure modes manifesting during normal operating conditions would take priority over cases where the risks stem primarily from flood or earthquake loadings.
- A case where the uncertainty band is relatively tight and the mean and median estimates are close to each other would take priority over a case where there is significant scatter in the data and the mean and median are far apart. (Note: this factor is only applicable for higher level risk analyses where there has been a detailed uncertainty analysis)
- A case where it is relatively easy and inexpensive to mitigate or confirm the risk may take priority over a case that is difficult and expensive to mitigate or confirm. For risk confirmation, programs that require extensive field investigations and significant study would be considered difficult and expensive cases.

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DSPR 3 – Moderate to High Priority. This category is reserved for annualized life loss risks or failure probabilities estimated to be moderate to high (near, and generally above, the guideline values), with generally moderate to high confidence. For cases with high confidence, long term risk reduction action would be appropriate. For cases with moderate confidence, confirmation of the risks would be appropriate as soon as they can be scheduled within the other priorities. Interim actions that are reasonable and prudent would be appropriate. DSPR 3 categorizations indicate that the facility has potential dam safety deficiencies with significant risks or probabilities of failure to justify actions to better define or reduce the risk. The following items can be used to determine whether this category is appropriate. In addition, these factors can help establish the relative priority ranking of all dams within the category.

- A case where both the annualized failure probability and the annualized life loss are moderate to high would generally be more critical than a case where only one or the other meets these descriptions. Equal weight would be given to cases where one or the other (annualized failure probability or annualized life loss) are moderate to high.
- A case where the annualized life loss or failure probability is driven by a single potential failure mode would generally be more critical than a case where risk estimates from several potential failure modes must be accumulated to arrive at the total risk.
- A case where the risk is driven by potential failure modes manifesting during normal operating conditions would take priority over cases where the risks stem primarily from flood or earthquake loadings.
- A case where the uncertainty band is relatively tight and the mean and median estimates are close to each other would take priority over a case where there is significant scatter in the data and the mean and median are far apart. (Note: this factor is only applicable for higher level risk analyses where there has been a detailed uncertainty analysis)
- A case where it is relatively easy and inexpensive to mitigate or confirm the risk may take priority over a case that is difficult and expensive to mitigate or confirm. For risk confirmation, programs that require extensive field investigations and significant study would be considered difficult and expensive cases.

DSPR 4 – Low to Moderate Priority. This category includes those cases where the annualized life loss risks and failure probabilities are estimated to be low (typically, but not always, below the guideline values), but with low confidence such that collection of additional information has the realistic potential to move the estimates into the area of increasing justification to reduce risk. In addition, this category also includes facilities where estimated risks and failure probabilities are moderate to high, but with low confidence such that additional information

may lower the estimated risks. DSPR 4 facilities may have “potential” concerns, but the issues typically will not reflect a pressing need for action. Additional studies to better define the risks should be scheduled as time and budget permit. It is anticipated that in most cases these can wait until after the next comprehensive review of the dam.

DSPR 5 – Low Priority. This category includes those dams for which the annualized life loss and failure probability are estimated to be low to very low with high confidence such that the estimates are unlikely to change with additional investigation or study. Normal dam safety risk management activities (including monitoring), operations, and maintenance would continue.

DSPR System Usage

Because Reclamation has finite financial resources available to address dam safety issues, it is critical to not only identify future actions but also to identify the priority or the time frame associated with these actions. The priority for initiating actions to address risks depends in part on available resources and on the risks throughout Reclamation’s dam inventory. The intent is to make the greatest reduction in risk throughout the inventory of Reclamation dams within the resource limitations of the program, while at the same time assuring that no dam presents an unreasonably high risk in the short term.

The DSPR system (and associated subcategories) forms the initial basis for prioritization after which priorities may be adjusted for other reasons. No specific numerical criteria are provided for what constitutes Extremely High, Very High, High, Moderate, or Low annualized life loss or failure probability, although they may be thought of as broad “order of magnitude” ranges within the continuum of risk with Moderate to High risks occurring near the guideline values. The range in risk estimates, and how much and how far the range in risk estimates extend into the area of increasing justification to reduce or better understand risks, should also be considered when assigning a DSPR category. ***Ultimately, the case must be made as to which DSPR category represents each dam as part of the risk analysis and risk assessment activities.*** Within each DSPR category, annualized failure probability and annualized life loss risks are assumed to have equal weight when prioritization is considered. Within each DSPR category and subcategory, everything else being equal, the actual numerical values may be used to set priorities. However, risk is not the sole piece of information used to set priorities, as other information and unique opportunities can affect the prioritization queue. Other factors may include (but are not limited to) the confidence in the risk estimates, the number of potential failure modes driving the risk, the type of loading condition(s) driving the risk, and the costs of additional actions to reduce or better define the risks.

Dam Safety Actions and their Priorities

The ultimate objective of dam safety actions is to reduce risk to the downstream public. In situations where the confidence in the risk estimates is low, potential actions (if any) should be focused on increasing the confidence. For situations where there is high confidence in high risk estimates, actions should be focused on reducing those risks. Figure 3 illustrates the general process of how potential actions can lead to gaining confidence in the risk estimates.

| | | Confidence | |
|------|--------------------------|--|---|
| | | Low | High |
| Risk | Increasing Justification | <p>Second Priority</p> <p>Potential Actions:</p> <ul style="list-style-type: none"> Take action to increase confidence Collect data and/or perform studies Re-evaluate risk <p>Likely Outcomes:</p> <ul style="list-style-type: none"> Stay in area of increasing justification, but with greater confidence Moves to area of decreasing justification, but with greater confidence | <p>First Priority</p> <p>Potential Actions:</p> <ul style="list-style-type: none"> Initial Corrective Action Studies Take Interim Risk Reduction <p>Likely Outcomes:</p> <ul style="list-style-type: none"> Reservoir restrictions (temp or perm) Modify dam |
| | Decreasing Justification | <p>Third Priority</p> <p>Potential Actions:</p> <ul style="list-style-type: none"> No action may be justified Take action to increase confidence Collect data and/or perform studies Re-evaluate risks <p>Likely Outcomes:</p> <ul style="list-style-type: none"> Move to area of increasing justification, but with greater confidence Stay in area of decreasing justification, but with greater confidence. If this outcome is likely, actions will be considered low priority | <p>Fourth Priority</p> <p>Potential Actions:</p> <ul style="list-style-type: none"> No Action Reasonable and prudent, low cost actions |

Figure 3. Risk, Confidence, and Actions

Once the risks have been estimated and the level of risk has been considered, technical teams recommend appropriate actions, given the portrayal of risks. There are six potential actions that can be supported with risk results.

1. The estimated risk is in the area of decreasing justification to reduce or better understand the risk, and confidence is high so that no further actions or studies are deemed necessary at the present time.
2. The estimated risk is in the area of decreasing justification to reduce or better understand the risk, but the confidence is low and there is the potential that additional information could increase the confidence and estimated risk to the extent that risk reduction actions may be justified.
3. The estimated risk is in the area of increasing justification to reduce or better understand the risk, but the confidence is low and there is the potential that additional information could increase confidence. Ideally,

this would lead to better defined risk estimates that may increase, decrease or remain the same.

4. The estimated risk is in the area of decreasing justification to reduce or better understand the risk and confidence is high, but relatively low cost, reasonable and prudent actions are recommended nonetheless.
5. The estimated risk is in an area of increasing justification to reduce or better understand the risk and confidence is high so that no further studies are necessary before moving to a Corrective Action Study and possibly implementing interim risk reduction measures.
6. The estimated risk is in an area of very low probability and very high consequences such that consideration of ALARP principles thorough study of the risks and possible risk mitigation alternatives is appropriate.

Each of these potential actions requires that the case be established with respect to two main issues: First, the technical team must persuade decision-makers that risks are such that actions are justified (or not). Second, a case must be made for the confidence in the risk estimates and whether additional exploration, investigation, or analysis has the potential to change the perceived risk such that it falls in a different category. It is the rationale and structure of the case that helps convince decision-makers whether the risk numbers generated and the actions recommended are reasonable.

The level of risk analysis, including data, technical studies, and related analyses, needs to be factored into building the case. For example, some risk analyses are completed by individuals rather than teams, and may rely on screening-level data, or preliminary analyses. There may be a staged approach where recommendations are first made, for example, in improvements to monitoring, collection of additional data, or performance of additional analyses to reduce uncertainty or improve confidence in risk estimates.

Monitoring and Other Risk Management Activities

The above discussion relates to taking actions to better define or reduce risks. However, it is recognized that there may never be enough information to have complete confidence in the risk estimates. Therefore, additional risk management activities are warranted even when the risks are in the area of decreasing justification to take action, but are of practical concern for the dam. Prudent activities to ensure the general health of the structure and risk management activities would also fall into this category. These activities are the safety net that helps catch things that might have been missed in the evaluations. Such activities may include visual inspections, instrumentation monitoring, inundation mapping, exercising of Emergency Action Plans, periodic examinations and evaluations, and similar measures considered to be “good practice.”

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Table 1. Bureau of Reclamation Dam Safety Priority Rating (DSPR)

| Dam Safety Priority Rating | Characteristics and Prioritization Considerations | Potential Actions |
|--|--|--|
| <p>1 – IMMEDIATE PRIORITY An active failure mode is in process or the likelihood of a failure is judged to be extremely high, such that immediate actions are necessary to reduce risk.</p> | <p>TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY IS EXTREMELY HIGH WITH HIGH CONFIDENCE To assign this category consider if:</p> <ol style="list-style-type: none"> 1. There is direct evidence that failure is in progress and the dam is almost certain to fail if action is not taken quickly. 2. Both the failure probability and the annualized life loss are extremely high. 3. The annualized life loss or failure probability is driven by a single failure mode. 4. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions. | <p>Take immediate action to avoid failure. Implement interim risk reduction measures including operational restrictions, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation. Expedite investigations and designs to support long-term risk reduction. Initiate intensive management and situation reports.</p> |
| <p>2 – URGENT PRIORITY Potential failure mode(s) are judged to present very serious risks, either due to a very high probability of failure or due to very high annualized life loss, which justify an urgency in actions to reduce risk.</p> | <p>TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY IS VERY HIGH WITH HIGH CONFIDENCE OR SUSPECTED OF BEING VERY HIGH TO EXTREMELY HIGH WITH LOW TO MODERATE CONFIDENCE To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> 5. Both the failure probability and the annualized life loss are very high to extreme. 6. The annualized life loss or failure probability is driven by a single failure mode. 7. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions. 8. The range in risk estimates is tightly clustered and the mean and median are similar (for detailed uncertainty analysis only) and/or sensitivity studies instill confidence. 9. Risk reduction or confirmation is relatively easy and inexpensive. | <p>Consider implementing interim risk reduction measures, including operational restrictions as justified, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation if appropriate. Expedite confirmation of rating, as required. Give very high priority for investigations and designs to support remediation, as required.</p> |
| <p>3 – MODERATE TO HIGH PRIORITY Potential failure mode(s) appear to be dam safety deficiencies that pose a significant risk of failure, and actions are needed to better define risks or to reduce risks.</p> | <p>MODERATE TO HIGH TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY WITH AT LEAST MODERATE CONFIDENCE To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> 10. Both the failure probability and the annualized life loss are moderate to high. 11. The annualized life loss or failure probability is driven by a single failure mode. 12. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions. 13. The range in risk estimates is tightly clustered and the mean and median are similar (for detailed uncertainty analysis only) and/or sensitivity studies instill confidence. 14. Risk reduction or confirmation is relatively easy and inexpensive. | <p>Consider whether implementation of interim risk reduction measures is appropriate, which may include ensuring that emergency action plan is current and functionally tested for initiating event; conducting heightened monitoring and evaluation; and in some cases even operational restriction. Prioritize investigations to support justification for remediation and remediation design, as appropriate.</p> |
| <p>4 – LOW TO MODERATE PRIORITY Potential failure mode(s) appear to indicate a potential concern, but do not indicate a pressing need for action.</p> | <p>LOW TO MODERATE TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH LOW CONFIDENCE AND THE REALISTIC POTENTIAL TO MOVE THE ESTIMATE INTO “HIGH”; OR MODERATE TO HIGH TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH LOW CONFIDENCE AND THE REALISTIC POTENTIAL TO MOVE THE ESTIMATE INTO “LOW” To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> 15. The failure probability and annualized life loss are near guidelines 16. The likelihood that refinement of risk may change to a different category (a 3 could fall to a 4, or a 4 could rise to a 3) | <p>Ensure routine risk management activities are in place. For those actions for which the case has been built to proceed before the next comprehensive review, take appropriate interim measures and schedule other actions as appropriate. Determine whether action can wait until after the next comprehensive review of the dam and appurtenant structures.</p> |
| <p>5 – LOW PRIORITY Potential failure mode(s) at the facility do not appear to present significant risks, and there are no apparent dam safety deficiencies.</p> | <p>LOW TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH MODERATE TO HIGH CONFIDENCE The annualized life loss and failure probability are estimated to be low and are unlikely to change with additional investigations or study.</p> | <p>Continue routine dam safety risk management activities, normal operation, and maintenance.</p> |

Risk Reduction

A key to formulating risk reduction alternatives is using the risk analysis information to assure that proposed alternatives will result in effective risk reduction. When developing the alternatives, the event trees should be reviewed to evaluate which events or conditions are the most significant contributors to the annualized failure probability or annualized life loss risks. In some cases, very significant risk reductions can be accomplished by focusing on a specific event or condition. In other cases, with multiple sources of risk, several issues may have to be addressed simultaneously in order to reduce risk to appropriate levels. Detailed explanations of how to manage risk reduction activities can be found in Reclamation's Safety of Dams Project Management Guidelines [8].

Risk Creep and Aging

Risks may increase over time due to population growth in the flood plain without any condition changes occurring at the dam. Also, as structures age, they may become more likely to fail despite reasonable operations and maintenance activities.

Construction Risks

During dam safety modification construction activities, it may be necessary to excavate at the toe of a water retention structure or take the spillway out of service. This could result in incurring a much higher probability of dam failure during the period of time that the dam is being modified. These construction risks need to be carefully examined, as it may not be appropriate to modify a dam under these conditions if it raises the accumulated risk during the life of the dam to a level higher than would be incurred by not pursuing risk reduction action at all. This factor may influence the choice of modification alternatives, special requirements to be followed during construction, or reservoir operations during construction. It should not in general be used to support a "do-nothing" alternative.

Cost Effectiveness and ALARP Principles

Cost effectiveness, or the level of risk reduction achieved per monetary unit spent, is considered for all risk reduction alternatives regardless of the location of the risk in relation to the guidelines. To ensure program effectiveness, cost effectiveness measures are used to compare risk reduction alternatives for a single project and across multiple projects, with the goal of allocating resources to reduce risks in the most efficient manner for the entire portfolio.

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Determining that ALARP is satisfied is ultimately a matter of judgment. In making a judgment on whether risks are ALARP, the following factors should be taken into account (adapted from New South Wales Dam Safety Committee [9]):

- The level of risk in relation to the risk guidelines;
- The cost-effectiveness of the risk reduction measures;
- The disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved;
- Any relevant recognized good practice; and
- Societal concerns as revealed by consultation with the community and other stakeholders.

When considering ALARP principles, an evaluation must be made in which risks are balanced against a sacrifice of money, time, or trouble involved implementing the measures necessary to reduce or avoid the risk. In many cases, these computations need not be complex or overly detailed (see *Dam Safety Public Protection Guidelines - Examples of Use*). Regardless of the magnitude of risk reduction, cost effectiveness is a critical component of evaluating ALARP.

Design Requirements for New Structures and Dam Safety Modifications

When new structures are proposed to be added to Reclamation's inventory of dams or when existing structures are proposed to be modified or the operations changed in a way that would potentially change the risks, the proposed designs or operations must be evaluated relative to the dam safety public protection guidelines. This applies to:

- Significant changes to reservoir operations;
- Increases in the maximum water surface elevation for existing structures;
- Modifications to Reclamation dams for the purposes of dam safety;
- Modifications to Reclamation dams for purposes other than dam safety, and;
- New dams and appurtenant structures.

It is desirable that changes at Reclamation dams are risk-neutral; that is that there is no appreciable increase in risk. Ultimately Reclamation decision-makers must

decide if any increases in risk are acceptable. Often this will involve considering the benefits of the proposed changes versus an increase in dam safety risk. Considerations in evaluating increases in risk for individual potential failure modes should include:

- The magnitude of the baseline risk (an increase for a potential failure mode that has a low baseline risk may be more acceptable than an increase in risk for a potential failure mode where the baseline risk is near Reclamation's guideline values).
- The potential to add design features or modifications to offset or eliminate risk for specific potential failure modes.
- The total risk and the potential to offset an increase in risk for one potential failure mode by reducing the risk for a different potential failure mode.

Generally if significant increased risk is estimated for a proposed change at one of Reclamation's dams, and the increased risk cannot be mitigated, the proposed change will not be acceptable to Reclamation.

Reclamation Design Standards

Once decisions have been made to take action to reduce risk at Reclamation facilities, corrective action alternatives are developed to accomplish the desired amount of risk reduction. Although the magnitude of risk reduction varies from project to project, the design methods used to develop these alternatives must consider the agency's appropriate design standards and state-of-the-art methods used by the dam engineering industry. While these design standards invariably apply to new structures, in the case of dam safety modifications it may not be possible to completely incorporate them without essentially tearing down the structure and starting over. There may be other cost effective methods to reduce risk that follow sound engineering principles which can be considered in such cases.

Risk Reduction Guidelines

Although Reclamation's design standards and standard industry methods include many characteristics that have been proven successful and prudent for individual aspects of design and construction, Reclamation recognizes that these standards do not evaluate the effectiveness of engineering systems. Furthermore, lessons learned from incidents and failures of dams have shown that robustness should be an important consideration when designing and constructing dams and appurtenant structures to perform well over time. Reclamation uses a risk-informed process to evaluate the system effectiveness and robustness of designs.

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When Reclamation evaluates existing structures it uses risk and the dam safety case to evaluate them with respect to the risk assessment guidelines. Methods to evaluate risks have inherent uncertainty and the tools themselves change over time. In order to ensure that risks satisfy agency guidelines well into the future, it is important to ensure that the risks have been reduced or designed to be as low as reasonably practicable (and with prudent consideration of project economics). New designs and dam safety modifications should be comfortably below Reclamation's risk assessment guidelines when construction is complete. Design loadings must be selected so as to be remote enough to ensure an adequate level of risk reduction is achieved. Future growth in the downstream flood plain, increases in the loading estimates, and changes in the state-of-the-art may result in increases (or perhaps decreases) in risk estimates. The more risk reduction achieved, the less likely it becomes that future studies will conclude that risks no longer meet Reclamation's guidelines for dams that have been recently modified.

Although there are many approaches that could be used to determine whether or not a design is comfortably below the guidelines, a rule of thumb that has been used in the past is for the mean risks of new designs and major modifications to be at least one order of magnitude below the guidelines. This is consistent with other risk-informed dam regulatory agencies, which mandate that risks for new dams or major augmentations be at least one order of magnitude below their risk assessment guidelines. However, in the case of reducing risk for existing dams, cost effectiveness must be an important consideration in making the final decision. For example, if risks can be taken into the area of decreasing justification to reduce risks, but to get an additional order of magnitude in risk reduction requires more than an order of magnitude increase in expenditures, it may be appropriate to opt for the alternative with less risk reduction so that the additional resources can be applied to other projects. However, this increases the chances that additional modifications will be needed in the not too distant future.

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