Public Protection Guidelines: a Risk Informed Framework to Support Dam Safety Decision-Making

Dam Safety Office
Dam Safety and Infrastructure Directorate

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Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

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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Acronyms and Abbreviations

AFP	Annualized Failure Probability
ALARP	As Low As Reasonably Practicable
ALL	Annualized Life Loss
ANCOLD	Australian National Committee on Large Dams
AOP	Annualized Occurrence Probability
CAS	Corrective Action Study
CCDF	complementary cumulative distribution function
CR	Comprehensive Review
DSAT	Dam Safety Advisory Team
DSPR	Dam Safety Priority Rating
EAP	Emergency Action Plan
FEMA	Federal Emergency Management Agency
FEMA P-1025	2015 Federal Guidelines for Dam Safety Risk Management
IFM	Incomplete Failure Mode
IRRM	Interim Risk Reduction Measure
PFM	Potential Failure Mode
PPG	Public Protection Guidelines
RCEM	Reclamation Consequence Estimating Methodology
Reclamation	Bureau of Reclamation
RIDM	Risk Informed Decision-Making
SOD	Safety of Dams
SOP	Standing Operating Procedure

1. Introduction

1.1 Purpose and audience

The purpose of this document is to present the Bureau of Reclamation's (Reclamation) risk informed decision-making (RIDM) framework for evaluating high and significant hazard potential dams, determining the need for action, and prioritizing investigations and modifications to Reclamation dams. Reclamation is a Federal bureau with responsibility for 360 high and significant hazard storage dams and dikes that contribute to water resources infrastructure in the western United States. As the owner of these facilities, Reclamation is committed to protecting the public and the environment from the risks inherent in storing large volumes of water.

These updated Public Protection Guidelines (PPG) describe the application of the RIDM process of the Reclamation Dam Safety Program, whose primary purpose is to implement the Reclamation Safety of Dams Act of 1978, as amended. The mission of the Program is to ensure that Reclamation dams do not present unreasonable risk to people, property, and the environment.

These guidelines are intended to establish consistent levels of public protection when evaluating and modifying existing dams and appurtenant structures and to ensure thorough understanding of the risks when designing new dams or structures. This document is written to a level of detail intended to communicate the general concepts to an external audience.

1.2 Key changes to the Public Protection Guidelines

This document has been expanded and reorganized compared to the 2011 version [1]. In terms of how RIDM is applied at Reclamation, the following key changes are being made.

- Though the basic guideline values remain the same, the Reclamation risk portrayal chart (formerly referred to as the "fN chart") has been simplified to make the interpretation of the visual guidelines more straightforward.
- While the basic guideline values remain the same, an alternative explanation for the guidelines, which may be easier to understand for many readers, has been provided. This is not so much intended to replace the rationale given in the 2011 version as to supplement it.
- Use of the "as low as reasonably practicable" (ALARP) concept has been expanded, allowing it to be considered regardless of where on the risk portrayal chart a total risk estimate is plotting (as opposed to being applicable solely in the lower right corner of the chart).
- New guidance on several special RIDM topics, including interim risk reduction action, construction risk, and risk informed design, has been included.
- The need to consider non-failure incident threats has been acknowledged, and a definition of "dam safety incident" has been developed to provide a criterion for identifying threats that warrant evaluation through RIDM.

1.3 Consistency with the Federal Guidelines for Dam Safety Risk Management

Reclamation endeavors to continue to improve upon dam safety risk management through continued learning, application of practices, and adaptation. Review of other industry practices and coordination with other agencies invested in dam safety and risk management have been and will continue to be keys to success. The 2011 PPG [1] and supporting rationale document [2] were developed at a time in Reclamation's history when RIDM had been in practice for nearly two decades, and the documents provided a timely and well-established foundation for the overall practice. The guidance on risk analysis and risk assessment outlined in the 2004 Federal Guidelines for Dam Safety [3] is reflected in the 2011 PPG (as well as this document). The 2015 Federal Guidelines for Dam Safety Risk Management [4] and the associated approaches to risk management and dam safety programs and activities were developed with involvement from Reclamation and other Federal agencies with dam safety oversight responsibility, and the guidance provided therein is reflected in this document.

As outlined previously, updates to this document have been made based on experience gained since the development of the 2011 PPG in the interest of not only improving the guidance but providing a document that is consistent with the way Reclamation currently applies the RIDM process. These changes remain consistent with the 2015 Federal Guidelines in terms of both intent and overall accepted guidelines. As noted within the 2015 Federal Guidelines [4], "the guidance offered and specific procedures identified in these guidelines are not mandated. Individual agencies may vary in the way they apply these guidelines as necessary to accomplish their respective missions." Although Reclamation's updated approach may in some cases differ from that of the examples provided in the 2015 Federal Guidelines, the guidance provided does not differ in terms of its basic intent – to ensure a level of protection consistent with that of the other Federal agencies.

1.4 Interpretation as agency guidelines

The 2015 Federal Guidelines [4] provide the overall framework to implement RIDM in a dam safety program, but each agency must identify the specific factors used to inform decisions unique to that agency's mission. This document presents Reclamation's process and factors that guide the use of risk analysis and risk assessment in support of informed dam safety decisions. The guidelines presented herein, although they align with other Federal agencies' tolerable risk guidelines, are established specifically for Reclamation's dams and mission. As such, they do not make any broader claims about what failure threshold is tolerable, what level of risk society is or should be willing to accept in exchange for societal benefits, or what level of public disruption is permissible. Rather, the focus is on ensuring decision-making transparency and a consistent level of protection throughout the inventory.

Risk informed procedures are used to assess the safety of Reclamation structures, aid in making decisions to help protect the public from the potential consequences of dam failure, assist in prioritizing the allocation of resources, and build consensus for risk reduction actions where needed. Risk assessment for dam safety decision-making integrates the methods of both traditional engineering analysis and quantitative risk analysis, along with the sound professional judgement of engineers, review boards, economists, and decision-makers. In Reclamation's experience, the risk informed approach leads to better-supported decisions, clearer decision-making, and an allocation of resources consistent with the threat posed by each facility. While these objectives could potentially be achieved by other means, the approaches described in this document have proven to be well-suited for the needs of the bureau.

2. Overview of Reclamation's Risk Informed Decision-Making Process

2.1 Risk analysis

Risk analysis forms the quantitative component of Reclamation's RIDM process. The basic objectives of a risk analysis are to: 1) develop a working set of potential failure modes (PFMs) addressing the key vulnerabilities of the facility, as understood by the risk analysis team based on their review of design, construction, and analysis information as well as other relevant information; 2) assign an occurrence probability estimate, termed the annualized failure probability (AFP), to each of the credible PFMs or develop a convincing set of arguments that explain why the PFM is not considered credible; and 3) assign a consequence (life loss) estimate to each of the credible PFMs and estimate the annualized life loss (ALL) for each PFM. The information needed to calculate the ALL and AFP for each PFM is generally obtained using the expert elicitation process [5]. The basic probability calculations are outlined in the next section. Appendix A includes more detailed information on how the AFP and ALL are calculated for the facility as a whole and how subjective probability estimation is used by Reclamation.

2.1.1 Potential failure modes and probability calculations

As the primary means of documenting the various physical processes that could lead from a normal operating state to an uncontrolled reservoir release, PFMs form the basic units of meaning at the risk analysis level. In the evaluation of PFM risks, Reclamation uses quantitative risk analysis exclusively. However, before a risk estimate can be developed, a PFM must be fully conceptualized. Although the PFM is ultimately discretized into a series of events whose probabilities can be estimated, a well-written PFM description is more than just the sum of those parts. It represents the "story" or narrative that reflects the experience and common understanding of the risk analysis team. As such, considerable thought must go into the development of each PFM description.

The following is an example of a PFM description that: 1) logically bridges the gap between the normal and failed conditions, 2) includes site-specific factors and specific locations where various stages of the process may occur, 3) provides an explanation of how the dam could actually breach once the PFM has progressed, 4) is focused on events that are adverse (as opposed to a mix of "good" and "bad" events) in the sense that they can only lead to a worsening condition, 5) uses definitive statements (avoiding modal verbs such as "could" or "would") whose probabilities can be directly evaluated, and 6) provides the appropriate level of detail for subjective probability estimation (as opposed to, for example, detailed numerical modeling) to be tractable.

> As a result of the fractured nature of the granitic bedrock, near-surface foundation seepage is occurring through the left abutment (in areas where blanket grouting was not applied or was not effective). As the reservoir reaches a critical elevation, internal erosion initiates by scour along the dam-foundation contact, both upstream and downstream of the cutoff walls. Eroded materials are transported unfiltered through the bedrock and stored within the fracture network or in the abandoned downstream dewatering tunnel. The active erosion area is protected from collapse by the high Zone 1 fines content and further supported by the proximity of sub-vertical bedrock features. There is no source of crackstopper materials along the upstream seepage path, and enough high-velocity seepage continues to reach the active erosion area for the PFM to progress. As more and more foundation seepage is attracted toward the embankment contact, the upstream and downstream voids interconnect, and reservoir pressures are translated downstream, resulting in a seepage breakout along the left downstream groin. Intervention fails, the downstream shell begins to unravel, and progressive sloughing leads to the undermining of the crest, resulting in an uncontrolled release of the reservoir.

The basic mathematical premise of the Reclamation risk analysis approach is that, at the level of detail required to support a dam safety case, a failure process can be discretized into a sequence of n events E_i, and the probability of failure associated with the probability of their intersection:

$$P(E_1 E_2 \dots E_n) = P(E_1) \times P(E_2|E_1) \times \dots \times P(E_n|E_{n-1} \dots E_2 E_1) \quad (1)$$

Equation (1) is the multiplication rule of elementary probability theory, which gives the probability of the intersection in terms of the probability of a trigger or load event (E_1) and the conditional probabilities of the response events. Because the probability of the loading is often expressed in terms of annual exceedance probabilities, the intersection probability is termed the annualized failure probability (AFP). If the loading event is broken out into a series of load bins or branches, Equation (1) would be applied to each of the event sequences ("event tree branches") leading to breach, and the probabilities of the mutually exclusive load-bin specific intersection events summed across branches.

2.1.2 Evaluation of failure consequences

Another task completed as part of the risk analysis process is an evaluation of the life loss consequences that could result from failure. The magnitude of the potential life loss could vary between PFMs, and multiple life loss estimates are typically developed. Once the potential life loss has been estimated for each of the m PFMs (typically in the form of a range and best estimate), the ALL, a normalized measure of life loss risk, is calculated for the facility using the following formula:

$$ALL = \sum_{i=1}^{m} L_i \times AFP_i, \quad (2)$$

where AFP_i is the occurrence probability of the ith PFM and L_i the associated life loss estimate. Although the formula can be recognized as the expectation of a discrete random variable (in this case, life loss), distributional inputs can be passed through it in the context of a Monte Carlo simulation.

Consequence estimates represent an important risk analysis input and can be developed in a variety of ways. For most Reclamation dams, the Reclamation Consequence Estimating Methodology (RCEM) [6] is used for all levels of risk analysis. The basic assumption of the RCEM process is that the fatality rate applicable in a given portion of the inundation area is above all a function of flood severity and available warning time. The use of the RCEM process will typically result in a life loss best estimate and range for each of the breach scenarios considered. The basis for the RCEM fatality rate curves is a compilation of roughly 60 case histories (spanning 100 years) for which enough information was available to extract the warning time and flood severity parameters [7]. Since none of these case histories involved the rapid inundation of a very large city, simulation-based modeling [8] is sometimes used to help inform the process of life loss estimation.

It is interesting to note that outside of Reclamation, RCEM is sometimes considered a screening tool [9]. From Reclamation's perspective, there is a distinct difference between consequence estimates being developed for the purposes of emergency planning (where understanding the potential for evacuation difficulties could be crucial) and consequence estimates being used to support a dam safety decision on the need for long-term risk reduction. With regard to the latter, the precision of the consequence estimates is not as important as their overall magnitude. It should also be understood that all life loss estimates (regardless of how they are developed) have inherent uncertainty associated with them, and that the numbers should be questioned if they do not make sense. Rather than introduce conservative assumptions, it is appropriate to select reasonable best estimates along with appropriately broad uncertainty ranges.

2.2 Risk assessment and the dam safety case

Risk assessment forms the interpretive component of Reclamation's RIDM process. The basic objectives of risk assessment are to: 1) assign a total risk estimate (AFP and ALL) to the facility, 2) understand the key sources of uncertainty and their potential impact on confidence in the portrayal of risk, and 3) support a decision to reduce or better understand the risk or to not take any further action at a given decision point. The basic unit in risk assessment is the individual reservoir or facility (as defined in the project authorization) in the sense that risks are both tracked and managed at the level of the individual facility. In other words, the risks associated with the operation of a given project-defined facility are viewed as being attached to that facility (which could in some cases comprise multiple reservoir retention structures; e.g., main dam and dikes that retain the same lake or reservoir) rather than to broader groupings of facilities (e.g., all of the dams constructed along the two forks of a river) or some point downstream of them (e.g., a city located where the two forks meet).

The total AFP is defined as the probability of the union of the individual PFMs quantified at the facility (see Appendix A). In practice, it is often estimated as the sum of the individual PFM probabilities, although in some scenarios this could lead to overcounting [10] [11]. The total ALL is defined as the expected value of life loss over all life loss outcomes and PFMs. In practice, it is often estimated as the sum of the individual PFM ALL estimates, with the same caveats applying. Whereas individual PFMs have best estimate life loss values and ranges associated with them (corresponding to specific breach scenarios), an average or "conditional" life loss is not calculated for the facility as a whole. While the life loss coordinate of the total risk marker can be inferred from the total risk marker plotting position, this value is not particularly informative (since the dam cannot fail in an "average" manner) and is not used for risk assessment.

The terms "uncertainty" and "confidence" can have various meanings in science and engineering. For the purposes of the Reclamation RIDM process, uncertainty refers to the interval over which a probability best estimate could range as a result of knowledge limitations or inherent randomness, whereas confidence (or, more properly, confidence in the portrayal of risk) refers to the potential for an output best estimate (total AFP or total ALL) to change in a meaningful way given new information. The relationship between the two concepts is illustrated in Figure 2.1. High confidence is the idea that the portrayal of risk is essentially correct, whereas low confidence suggests that a different interpretation (with respect to the guidelines) may also be possible. Although significant uncertainty could result in low confidence, this is not always the case, and the concepts should not be treated as opposites. Furthermore, low confidence in the portrayal of risk should not be viewed as an undesirable outcome but rather as an opportunity to take action to better understand the risk.

A decision to reduce or better understand the risks at a facility must always be rationally supported. Because the numbers generated in a risk analysis (and the guidelines themselves) are inexact, it is not sufficient to argue that action is justified simply because the estimated risk plots above guidelines (or that action is not justified because the estimated risk plots below guidelines). The dam safety case is a written argument in support of a dam safety decision that reconciles the risk estimates with the design, construction, analysis, current performance, and current condition of the facility. It transcends the guidelines in the sense that a total risk estimate can be "allowed" to plot above guidelines if there is a well-founded case against further action at the present time (or, conversely, targeted for further action despite plotting below guidelines). A dam safety case can be thought of as consisting of three parts: one focused on deterministic factors, one on probabilistic factors, and one on confidence in the portrayal of risk (see [12] for an example).

It should be underscored that in Reclamation practice, the dam safety decision is proposed by the technical team and accepted by decision-makers. As such, the information presented must be definitive, rather than balanced (as would be the case, e.g., if the role of the technical team were simply to summarize the available information and that of the decision-makers to propose recommendations). For additional information on the dam safety case, refer to the 2015 Federal Guidelines [4].

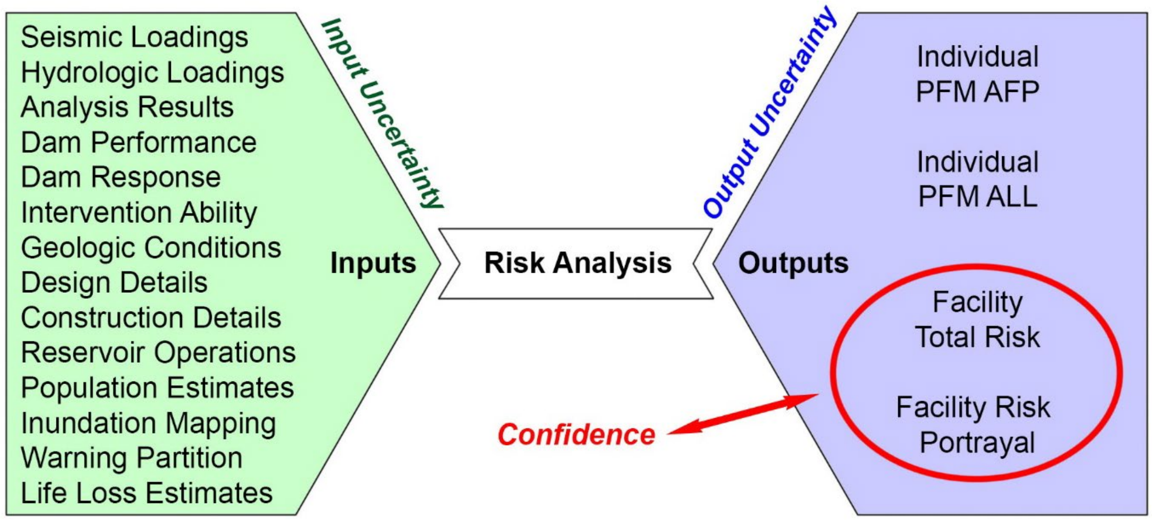

Figure 2.1. Input versus output uncertainty.

2.3 Prioritizing dam safety action

The ultimate objective of dam safety action is to reduce risk to the downstream public. In situations where confidence in the risk portrayal is low, potential actions should initially focus on increasing confidence. For situations where there is high confidence and estimated risks are high, potential actions should focus on reducing the risks. The guidelines and the portrayal of risk are used to help determine whether potential dam safety actions are justified. As a general rule, as the AFP and ALL increase above guideline values, the justification and urgency to act also increase. Similarly, as the AFP and ALL decrease below guideline values, the justification and urgency to act decrease. In theory, recommendations made for the highest risk dams will receive the highest funding priority. However, the way that funding and resources are allocated in practice is more complex. Since absolute consistency between risk estimates made for different facilities cannot be expected, quantified risk by itself is not used to establish the priority of action. Instead, a variety of factors (including qualitative ones) are taken into account.

To help prioritize and establish the urgency of risk management activities, a Dam Safety Priority Rating (DSPR) system has been developed by Reclamation. DSPRs apply to facilities as a whole and not to the individual retention structures or PFMs at a dam. The categorization of a dam is dynamic over time, changing as project characteristics are modified or as additional information becomes available that affects understanding of the loadings, AFP, or consequences of failure.

The descriptions and rationale for the DSPRs were revised as part of this PPG update, as shown in Table 1. The intent of the changes to the original DSPR table is to streamline the process of selecting a DSPR and improve the consistency of documenting and justifying priority ratings for dams across Reclamation's portfolio. Note that a DSPR would generally be assigned as the final step of a risk assessment once the case for or against action to better understand or reduce the risk had already been developed (i.e., it would not be used as a means of determining whether action is needed). For additional information on dam safety actions and Safety of Dams (SOD) recommendations, see Appendix B.

Table 1. Guidance for selecting a DSPR once the case for or against action to better understand or reduce the risks has been built.

<table>
<tr><td>DSPR 1 – IMMEDIATE PRIORITY
Immediate actions are necessary to reduce the risk of failure, including both interim actions and the implementation of long-term risk reduction alternatives.</td><td>Several of the following factors would typically apply at the DSPR 1 level:
• There is direct evidence of a condition that could lead to a failure if action is not taken.
• Risks are extremely high with respect to the applicable portion of the visual guideline.
• The high risk is driven by a PFM manifesting under normal operating conditions.
• The failure mechanism of concern has been observed in practice and/or the dam is in poor condition.
• Confidence in the portrayal of risk is high.</td></tr>
<tr><td>DSPR 2 – URGENT PRIORITY
Expedited actions are likely needed to reduce the risk of failure, including the implementation of long-term risk reduction alternatives and serious consideration of interim actions.</td><td>Several of the following factors would typically apply at the DSPR 2 level:
• Risks are very high with respect to the applicable portion of the visual guideline.
• While there may be evidence that a PFM has initiated, there is no direct evidence of advanced progression or a failure in progress.
• The high risk is driven by a PFM associated with a relatively frequent (per the interpretation of the team) loading condition.
• The risk is driven by a single PFM, but the residual risk (collective risk of the remaining PFMs) is also relatively high.
• Although the estimated risk is very high, the overall condition of the dam is good, the performance is relatively well understood (and not expected to deteriorate under loading conditions anticipated in the near future), and most of the DSPR 1 considerations above would not realistically apply.
• Confidence in the portrayal of risk is high.</td></tr>
<tr><td>DSPR 3 – HIGH PRIORITY
The identified dam safety deficiencies are a concern, and interim action may need to be considered while ways of addressing the long-term risks are being evaluated.</td><td>Several of the following factors would typically apply at the DSPR 3 level:
• The risks are relatively high with respect to the applicable portion of the visual guideline.
• The high risk is driven by a PFM (or PFMs) associated with a relatively remote loading condition.
• The high risk is driven by a PFM (or PFMs) associated with a normal operating condition or relatively frequent loading, but there is no clear or direct evidence of a PFM in progress.
• Confidence in the portrayal of risk is moderate to high.</td></tr>
<tr><td>DSPR 4 – MODERATE PRIORITY
The risks as portrayed indicate a potential concern, but interim action beyond routine monitoring may not be needed to effectively manage them.</td><td>Several of the following factors would typically apply at the DSPR 4 level:
• The plotting position of the total risk marker places it near the applicable portion of the visual guideline, but there are multiple PFMs contributing to the plotting position.
• The estimated risks are relatively high with respect to the applicable portion of the visual guideline but with low or low-to-moderate confidence in the portrayal of risk.
• The estimated risks are relatively low and confidence in the portrayal of risk is high or moderate-to-high, but most of the DSPR 5 considerations below would not realistically apply.
• The dam is in good condition and is performing well.
• The response of the dam to reservoir loading is predictable, and conditions do not appear to be changing.</td></tr>
<tr><td>DSPR 5 – LOW PRIORITY
The PFMs identified at the facility do not present a significant concern, and risks can be effectively managed via routine monitoring.</td><td>Several of the following factors would typically apply at the DSPR 5 level:
• The risks are relatively low with respect to the applicable portion of the visual guideline.
• The seismic and hydrologic loadings are reasonably up to date.
• The design of the dam is considered state-of-the-art, or the dam has been recently modified.
• Confidence in the portrayal of risk is high.</td></tr>
</table>

2.4 Use and interpretation of the ALARP concept

ALARP, or "as low as reasonably practicable," refers to the idea that even those risks that are nominally below guidelines should be further evaluated for action. The first step in applying the concept is establishing what is meant by "practicable." The dictionary definitions of this word include *capable of being accomplished*, *feasible*, *serving a useful function*, *available for use*, and *accessible*. For the purposes of this document, the definition may be extended to include *value added*, *impactful*, *having an intuitively high benefit to cost ratio*, and *low-hanging fruit*. Broadly speaking, a practicable action is one that adds value to Reclamation's risk management strategy.

The ALARP concept was originally applied in the regulation of hazardous industries in the United Kingdom [13] and was extended into the dam safety arena by the Australian National Committee on Large Dams (ANCOLD) [14]. At the present time, some form of the concept is in use by each of the Federal agencies with dam safety oversight responsibility. Since the intersection of ALARP and tort law (which governs claims against the Federal government) is not well established in the United States, there is no universally agreed upon definition of what ALARP represents or how it should be applied. The following interpretation has been adopted for this document:

> ALARP represents an opportunity to expand the actions being taken to better understand or reduce the risk beyond those being justified under the initial dam safety case. It ensures that risk assessment teams have the ability to consider additional measures even if the risk posed by the facility (or by a given potential failure mode) is relatively low and may not otherwise support a dam safety case for action. ALARP-based actions can be recommended if their implementation is viewed as practicable and consistent with Reclamation's stewardship responsibility.

The first part of the definition expresses the view that ALARP should be applied as a second pass once the initial interpretation of the risk estimates has taken place. Applying ALARP after the dam safety case has been built is reasonable because it allows the dam safety case to focus on the key risk drivers rather than just any risks that could be reduced. The last part of the definition is obviously subjective, not only because different teams may have a different sense of what is practicable, but because the onus to recommend ALARP-based action effectively increases with increasing potential life loss (see Section 3). For this reason, ALARP-based recommendations should be discussed with the Dam Safety Office before they are formally made by a technical team. In general, actions for which the benefits are grossly disproportional to the costs (e.g., reconstruct an entire spillway in order to reduce the total AFP from 2E-7 to 1E-7) would be excluded from consideration.

In addition to its use in the management of long-term failure risks under normal operations, there are at least four other areas wherein the ALARP concept is considered to apply, including:

Dam safety modification design context.

- The basic purpose of a dam safety modification is to reduce the long-term risks of the controlling PFMs. In this context, ALARP is interpreted as the idea that if they are practicable, additional defensive features (targeting any PFM) should be considered for incorporation into the design, even if they do not result in a quantifiable reduction in the residual risk or if the risks of the associated PFMs are already below guidelines.

Evaluation of interim risk reduction measures (IRRMs) (Section 4.1).

- Since IRRMs are typically implemented in anticipation of more permanent risk reduction action, it is important that the cost of any such actions be carefully weighed against the short-term benefits. In this context, ALARP is interpreted as the idea that if they are practicable in the short-term risk management sense, IRRMs should be implemented even if their implementation does not result in quantifiable risk reduction.

Construction risk setting (Section 4.2).

- Since restrictions imposed on the timing or duration of the work could have operational implications, it is important that the cost of any such actions be carefully weighed against the short-term benefits. In this context, ALARP is interpreted as the idea that if they are practicable in the construction risk management sense, risk-control measures should be implemented regardless of whether construction risks are considered high or low.

Incident risk context (Section 5).

- There are currently no numerical criteria in place to help teams evaluate whether there is increasing justification to reduce a particular incident risk. In this context, ALARP is interpreted as the idea that if they meet the definition of a dam safety incident, incident threats may be targeted for practicable risk-reduction actions regardless of whether their annual probability of occurrence is high or low.

2.5 Broader dam safety risk management context

Reclamation uses a comprehensive approach to risk management, integrated into both the organizational structure and operations, to help control the risk associated with the continuing operation of Reclamation's dams. The dam safety decision process presented in this document is one component of Reclamation's overall risk management strategy. Risk analysis and risk assessment are major support tasks contributing to the safety efforts at Reclamation facilities and are integrated into many other activities, but they are by no means the only efforts performed to manage the risks associated with Reclamation dams.

The integrated approach also includes routine and recurring risk management activities to monitor and ensure the general condition and safe operation of Reclamation facilities. These activities consist of facility reviews and inspections, operations and maintenance activities, instrumentation and performance monitoring, emergency action planning and exercises, documentation and communication of dam safety issues, technical design and analysis, RIDM, and the programmatic oversight of these activities. This is all implemented within an environment that promotes open discussions, continuous learning, and improvement. The guidance and requirements for these activities are documented in the form of Directives and Standards posted in the Reclamation Manual [15] and in the Design Standards [16]. Appendix C includes a more detailed list of risk management references.

The integrated and comprehensive approach to risk management utilized by Reclamation is consistent with the concepts outlined in the 2015 Federal Guidelines [4] and in the dam safety risk management guidance documents of other Federal agencies. For example, the U.S. Army Corps of Engineers references four *tolerable risk guidelines* [17], the first two of which are analogous to Reclamation's visual guidelines (see below), and the second two of which cover the routine activities (discussed in this section) performed by Reclamation outside of the immediate RIDM context.

3. Risk portrayal chart

Figure 3.1 shows the updated version of the risk portrayal chart, which is used to compare risk estimates to the threshold values for increasing justification to reduce or better understand risks (also referred to as the "visual guidelines" in order to distinguish them from the PPG as a whole). The primary difference compared to the 2011 version is that the overlapping AFP and ALL segments have been dropped in favor of a single piecewise-linear guideline. In the decade since the 2011 PPG revision, the redundant segments have been a frequent source of confusion and have made it difficult for both internal and external audiences to differentiate between the operative guideline segments and the non-controlling segments. The intent of the update is to make it clear that there is only one meaningful threshold value of risk in any area of the chart. The chart is "tri-axial" in the sense that any point on the chart can be interpreted as having either an AFP and a life loss coordinate (as in the case of individual PFM risk estimates) or an AFP and an ALL coordinate (as in the case of the total risk estimates). Appendix D contains more detailed information on how risk estimates are plotted on the chart.

Another change from the 2011 version of the risk portrayal chart is that the vertical dashed line segment in the lower right corner has been eliminated. Previously, this line represented the left edge of the so-called "low probability high consequence box," wherein the ALARP concept was considered to specifically apply. The change is consistent with the current view that the applicability of the ALARP concept should not be limited to only one area of the risk portrayal chart, and that the concept should apply regardless of plotting position.

The updated Reclamation risk portrayal chart appears slightly different than the charts used by other Federal agencies with dam safety oversight responsibility. However, Reclamation continues to use the same basic visual guideline risk thresholds as the other Federal agencies and continues to strive for a level of protection consistent with that of the other agencies. As noted in the 2015 Federal Guidelines, "Federal agencies may establish their own standards to best accomplish their unique missions" [4], and the first step in updating the PPG was in fact evaluating whether the threshold visual guideline values were still consistent with Reclamation's mission and organizational objectives. In attempting to answer this question, Reclamation sought to develop an explanation that could convince a person without any background in decision science. The interpretation of the guidelines presented below is not intended to replace the 2011 rationale but to supplement it by providing a simple explanation of why the guideline values continue to be reasonable. For alternative explanations, refer to the 2011 PPG rationale document [2] or to the rationale used by other agencies [17].

Figure 3.2 shows the visual guidelines in terms of three segments, including a horizontal component plotted along an AFP contour of 1E-4 (Segment 1), a diagonal component plotted along an ALL contour of 1E-3 (Segment 2), and a second horizontal component plotted along an AFP contour of 1E-6 (Segment 3). Of these three components, Segment 1, analogous to the "individual risk" guidelines of other agencies [17], is significant in that it represents the basic level of protection provided to residents of the downstream area (regardless of how sparsely or densely populated the area is). In order for the 1E-4 value selected for Segment 1 to be viewed as reasonable, the continuing operation of a Reclamation facility whose total estimated risk plots close to the visual guideline would need to result in only a very small change in the risk exposure of the typical downstream resident. The idea that the use of a Segment 1 AFP threshold of 1E-4 is a step toward achieving this objective can be explained in terms of the average annual reference risk for U.S. residents.

The term "average annual reference risk" is defined as the average probability (prior probability) that a randomly selected individual will lose their life in a given year. It considers all possible causes of death and all demographic categories. Although the expression "background risk of death" is more common, it has become associated with a specific type of demographic breakout and is being avoided here to lessen the potential for confusion with respect to the rationale given in the 2011 document [2]. The average annual reference risk can be estimated as the number of deaths in a given year divided by the size of the population. As of this writing, the most recent published data is from 2019, when a total of 2,854,838 deaths were registered among U.S. residents [18]. In that same year, the U.S. population was reported as 328,329,523 [19], suggesting an average annual reference risk of about 0.009. This value is 90 times (nearly two orders of magnitude) greater than the 1E-4 Segment 1 threshold value, suggesting that for the average person, residing downstream of a Reclamation dam plotting near or below guidelines would result in a comparatively minor increase in risk exposure.

Segment 2 is analogous to the "societal risk" guidelines used by other agencies [17] and has previously been explained in terms of the idea that society may be willing to accept some level of risk in exchange for public benefits. However, it may be easier to explain in terms of individual risk. Whereas Segment 1 establishes the basic standard of care, Segment 2 reinforces it by requiring that the threshold AFP further decreases with increasing potential life loss. That the slope of this line is -1 (as opposed to some other value) or that it intersects Segment 1 at a life loss value of 10 (as opposed to some other number of fatalities) is less important than the idea that dams whose failure has the potential to result in mass casualties are generally being held to a higher standard. Thus, for example, when a failure has the potential to result in 100 fatalities, the threshold AFP value "at guidelines" becomes 1E-5, 10 times lower than the 1E-4 Segment 1 threshold value and approximately 3 orders of magnitude lower than the average annual reference risk.

For facilities with an elevated risk of failure (AFP), understanding the risks with reasonable levels of uncertainty or developing risk reduction alternatives can be fairly straightforward in terms of design options and impactful in terms of risk reduction. However, this is not necessarily the case when the baseline AFP is relatively low. Segment 3 can be explained in terms of the idea that there exists a point of diminishing returns beyond which expenditures to further understand or reduce the risk associated with a particular facility become economically unfeasible. For a dam whose total AFP estimate is close to the 1E-6 Segment 3 threshold value, the estimated risk of failure would be 2 orders of magnitude lower than the basic guideline value of 1E-4 and 9000 times (nearly 4 orders of magnitude) lower than the average annual reference risk. In contrast, there are numerous Reclamation facilities whose total AFP lies somewhere in the 1E-4 to 1E-6 range. Absent this "truncation" of the diagonal guideline segment, facilities with an estimated AFP lower than one in a million would be competing for funding against those with a much higher risk of failure (and more straightforward risk reduction options). As mentioned above, ALARP is now considered to apply anywhere on the risk portrayal chart (as in Figure 3.3), which provides an alternative means of addressing concerns associated with these scenarios. Any facility whose failure (e.g., by virtue of its geographical location) has the potential to result in extreme life loss still merits scrutiny beyond the basic risk considerations, and as shown in Figure 3.4, there is increasing justification to take practicable (ALARP-based) actions toward the right side of the chart.

In summary, the visual guidelines used by Reclamation continue to strike a reasonable balance between the objectives of not imposing excessive risks on the downstream public and minimizing the likelihood of a mass casualty event, and Reclamation's responsibility as a Federal bureau to exercise judiciousness in the expenditure of public monies while providing Congressionally mandated benefits. The approximately two order of magnitude difference between Segment 1 (the basic standard of care) and the average annual reference risk not only sets up the rationale for the remaining two segments but also ensures that the guidelines need not be interpreted rigidly to remain meaningful (e.g., a risk estimate plotting slightly above Segment 1 would still imply a relatively small increase in risk exposure). That said, it should be stressed that the numbers generated in a risk analysis are not exact, and risk estimates plotting slightly above guidelines are in many cases indistinguishable from those plotting slightly below. Taken outside of their proper context, the visual guidelines are merely lines on a drawing; it is only through the lens of the broader dam safety case that they become indispensable tools for supporting a decision.

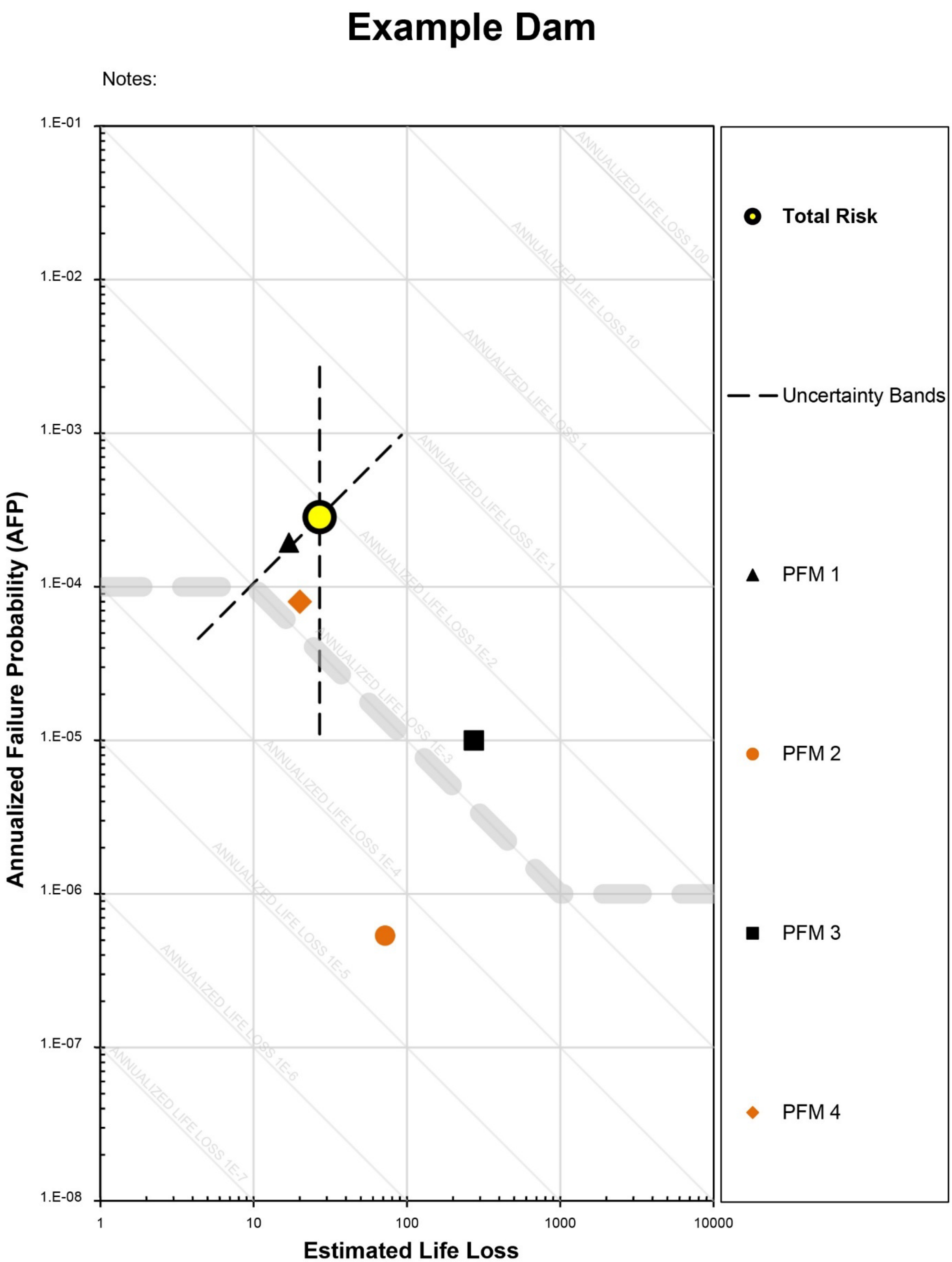

Figure 3.1. Updated Reclamation risk portrayal chart.

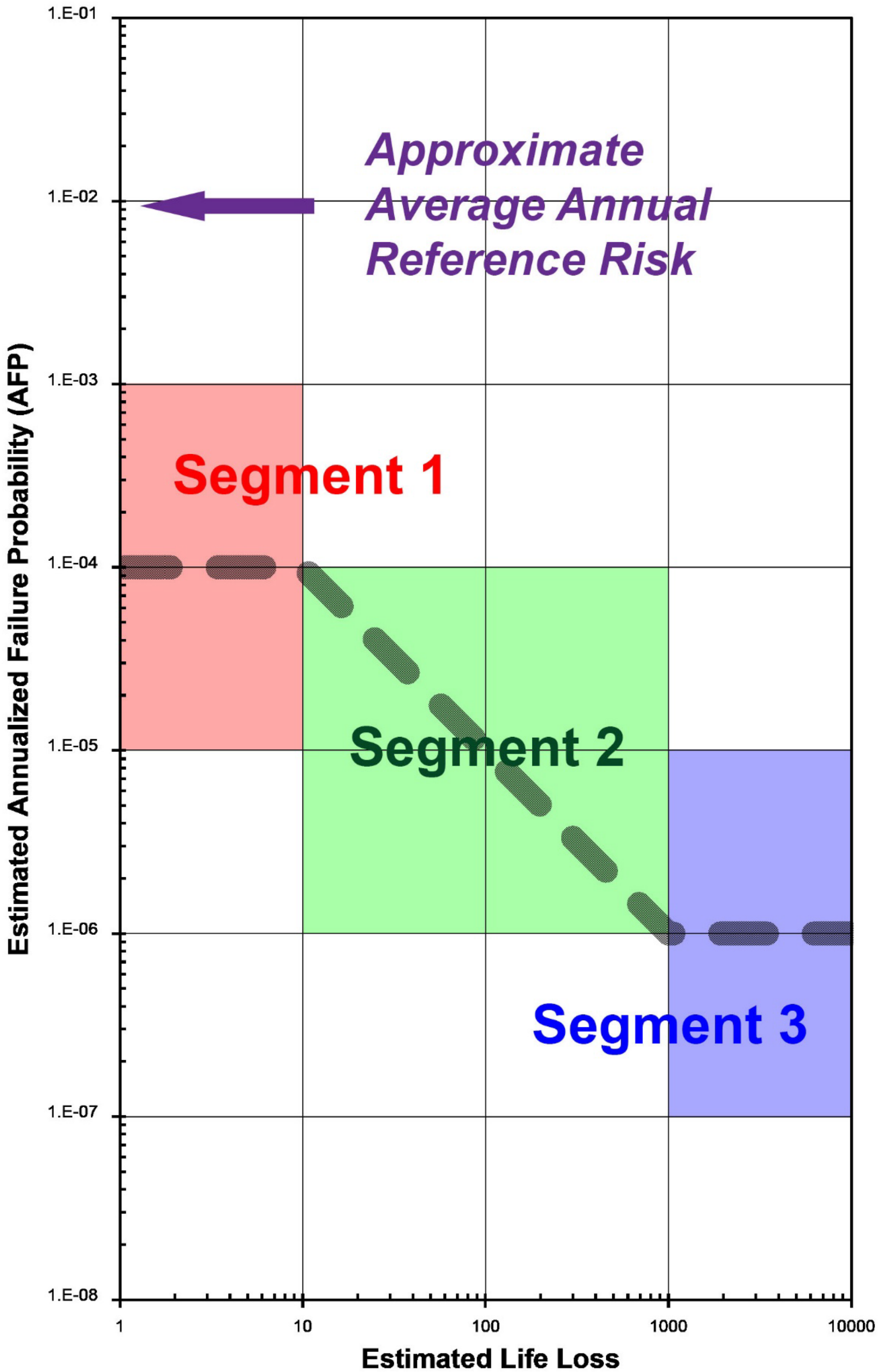

Figure 3.2. The visual guideline can be thought of as one feature consisting of three segments.

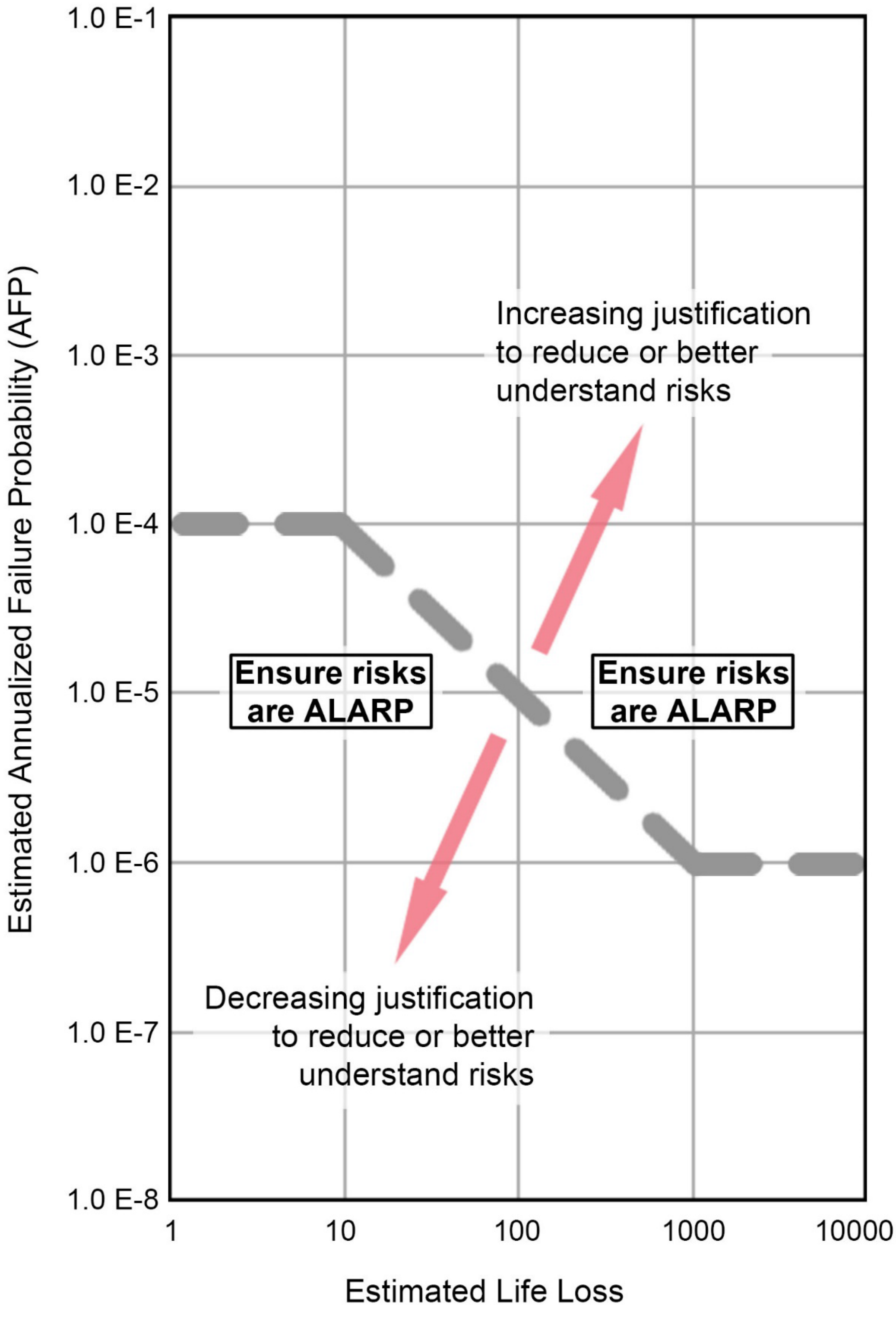

Figure 3.3. Annotated Reclamation risk portrayal chart. Justification to reduce or better understand risks would generally be considered to increase above the visual guideline and decrease below it. The ALARP concept is considered to apply everywhere on the chart.

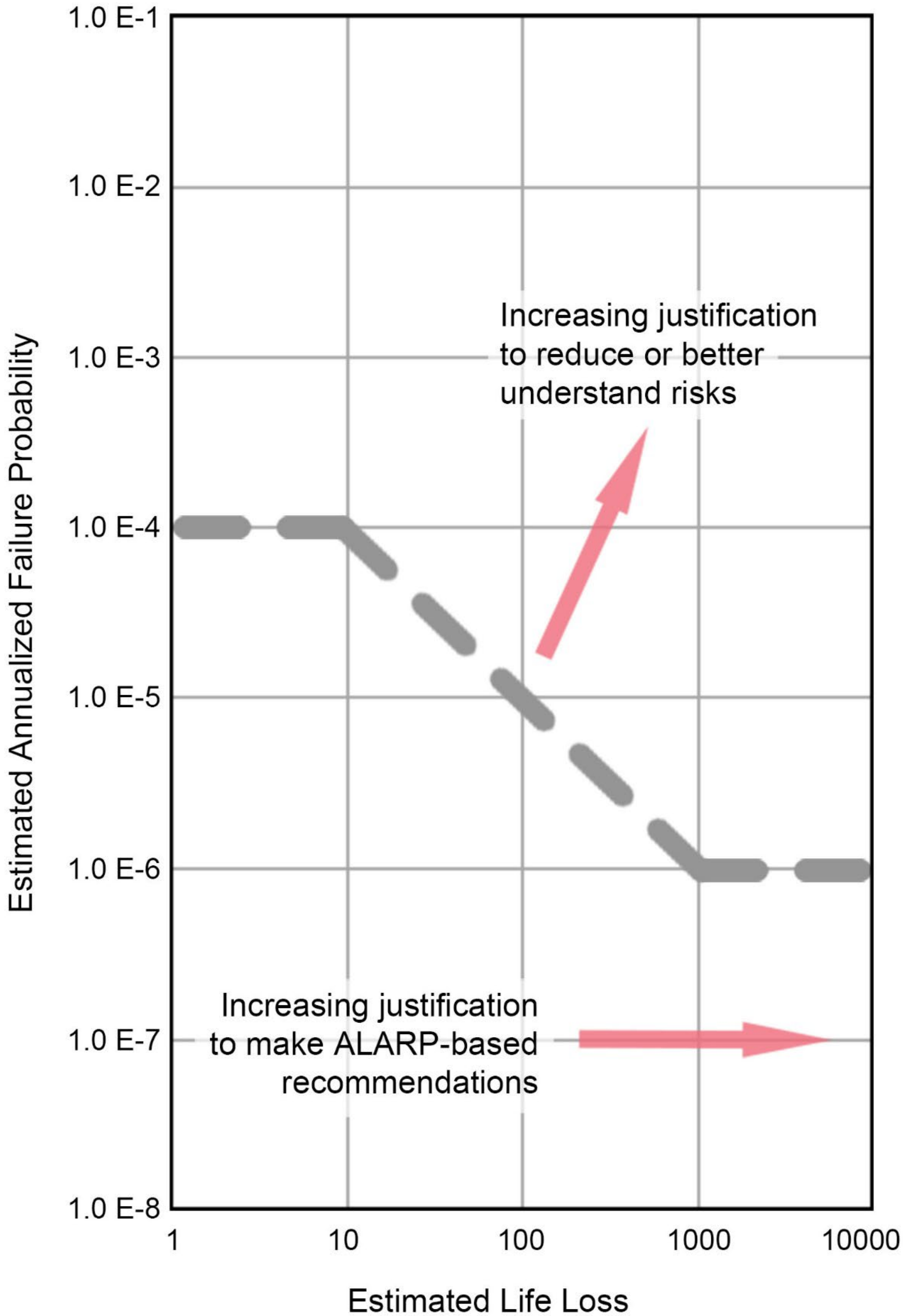

Figure 3.4. The expectation that ALARP-based actions be identified and recommended would effectively increase with increasing potential life loss.

4. Special topics

4.1 Interim risk reduction measures

Interim risk reduction measures (IRRMs) are actions to incrementally reduce risk at a facility until permanent risk reduction can be achieved (or in some cases, until a potential dam safety issue can be better understood). There is no requirement that the IRRMs being considered reduce the risk of the affected PFMs to below guideline values. Rather, the purpose is to reduce the risk associated with one or more risk-driving PFMs (if appropriate) to a level that is in principle lower than would exist if no interim measures were taken. Practicable IRRMs should be implemented if they add value to the process of managing short-term risks at the facility, even if their implementation does not result in a quantifiable reduction in the estimated risk.

The following are key considerations when assessing the potential need for IRRMs at any point in the dam safety evaluation process.

- Direct evidence of a failure in progress (or lack thereof) and the possibility that the dam could fail if action to reduce the risk is not taken quickly.
- Performance and condition of the dam (whether it is stable versus not predictable) and the likelihood that conditions will deteriorate over time.
- Confidence in the portrayal of risk relative to key uncertainty sources (with respect to guideline values) and the strength of the dam safety case for action.
- Relative frequency of loading events (earthquakes, floods, conditions associated with normal operations) contributing to dam failure potential with respect to the window for interim action and the estimated time to completion of permanent risk reduction measures.
- Relatively high failure probability versus relatively low failure probability with high consequences (i.e., if the controlling guideline is the ALL guideline, implementation of IRRMs – as opposed to long-term risk reduction actions – may not be as urgent).
- ALARP considerations with respect to the IRRM sub-definition in Section 2.4.

If implementation of IRRMs is considered appropriate, the following types of IRRMs can be options. In general, the options are listed in order of increasing cost and increasing potential risk reduction. This list is not comprehensive and consideration of other types of IRRMs may be appropriate.

- Conducting enhanced public outreach and education efforts.
- Updating the Emergency Action Plan (EAP) and conducting risk-driving PFM-related EAP exercises.
- Increased monitoring of the dam (including consideration of both in-person and remote monitoring).
- Stockpiling of emergency response materials at the dam (primarily associated with internal erosion-related PFMs).

- Early completion of repairs or modifications that could eventually be needed as part of the permanent modification.
- Temporary structural measures to reduce the probability of failure of a component feature (such as a radial gate or spillway chute) until permanent measures can be implemented.
- Various types of operational changes (e.g., taking a spillway gate out of service, adjusting the water delivery schedule, or requiring normal releases to be routed through an outlet works instead of a power penstock).
- Incremental reservoir operating restrictions.

The cost and benefit(s) of potential IRRMs can be evaluated qualitatively or quantitatively depending upon the level of information available.

As noted earlier in this document, dam safety recommendations are proposed by the technical team and are accepted by decision-makers; the same would be true of IRRM-related recommendations. The implementation of decisions to restrict the normal operating level of a reservoir or to perform significant and costly temporary modifications are the responsibility of senior level leadership. These decisions must carefully consider the confidence in the dam safety case for action and ensure the cost of any such actions is carefully weighed against the short-term benefits. Exceptions would be made in the case of a facility with direct evidence of rapidly worsening conditions, or when it is recognized that the dam could fail if direct action is not taken quickly. All decisions related to the need for and scope of IRRMs should be reviewed, and they must continue to be accepted by senior leadership at decision points throughout the dam safety process.

4.2 Dam safety construction risk

For a risk analysis focused on long-term conditions, the usual assumption would be that the dam has the basic ability to retain the reservoir (at least until the PFM being considered progresses) and is being operated in accordance with the Standing Operating Procedure (SOP). In other words, unless the purpose of a given PFM is specifically to question those assumptions, there is a certain set of expectations that gets built into the risk estimates: that if the crest is understood as having a particular elevation, the actual low point will not be ten feet lower; that if the SOP states the spillway gates shall be operated when the reservoir reaches a certain elevation, the operating entity will not wait until it is ten feet higher to begin releases; that if the performance monitoring schedule states the critical instruments shall be read daily, they will not be read only monthly. Construction conditions are different from long-term conditions in that these types of assumptions may no longer apply: the crest elevation could temporarily be 10 feet lower, the spillway could be obstructed by a cofferdam, and key instruments could be out of service. The purpose of a dam safety construction risk analysis is to identify the actions required to control the risk of a failure or incident under such unusual and temporary operating conditions.

The visual guidelines of the risk portrayal chart are not particularly informative in the construction risk context. For starters, the visual guidelines are tied to the average annual reference risk, whereas the trigger events in a construction setting (e.g., an excavation at the toe of the dam reaching its lowest point, or the occurrence of a flood at precisely the time that the residual crest elevation is lowest) may not be practical to annualize. Furthermore, many of the risks that could apply in a construction setting are "voluntary" (in the sense that there is a broad range of control, construction, and operational approaches that can be considered), and imposing a temporary loss of reservoir benefits (while never desirable) is always an option. As such, the idea that a quantified construction risk estimate plots "below guidelines" would not be taken as evidence that a given risk control measure will be effective and sufficient, or that alternative (and potentially more expensive) actions do not need to be further evaluated. In general, construction risks should be ALARP with respect to the sub-definition provided in Section 2.4.

A team preparing to evaluate the long-term risk posed by a facility will generally be aware, before any probabilities are estimated, of what the key susceptibilities may be. In contrast, this may not be obvious in the construction setting, and a key objective of construction risk analysis is to identify the biggest threats to the dam. As with the normal RIDM process, the identified threats should be conceptualized in the form of PFMs. However, once this has been accomplished, risk estimation should be performed only to the extent needed to articulate the threat and help support the idea that action to address or mitigate it is warranted. In other words, the purpose of generating risk estimates would not be to discover the "true" probability of the adverse event but to provide a means of communicating the idea that one set of construction techniques, operational restrictions, or risk control strategies may be preferable to another. For example, one approach that has worked well when the threat of overtopping is being evaluated has been to plot the "instantaneous" (not properly annualized) failure probability as a function of time in order to highlight the months of the year when the spillway must be available for flood releases and construction must not occur.

A construction risk analysis should be performed regardless of whether the modification is for the benefit of Reclamation (e.g., a dam safety modification intended to reduce the long-term risk) or the benefit of a third party (e.g., construction of a powerplant under a national hydropower license). It should be performed early enough to allow for meaningful changes to the specifications, but not so early as to exclude vital information (such as design details that could be important to fully understanding the construction risks). In some cases, it may be appropriate to plan for multiple reviews at different points in the design process. If the overtopping of the dam or work area is a potential concern, sufficient lead time may need to be provided for a flood loadings specialist to develop a suite of seasonal hydrographs. With regard to the latter, risk analysis teams should give proper consideration to the upper bound loadings (rather than automatically using the best estimate loadings), and there is little value in merely acknowledging uncertainty in the voluntary risk setting. For instance, a risk control strategy focused on the 99 percentile 100-year flood may in some cases be more appropriate than one focused on the mean 1000-year flood.

4.3 Risk informed design

Risk informed design is simply the idea that the risk posed by a facility should be considered when designing or modifying a dam, as opposed to assuming that following accepted design practice will automatically lead to a safe structure. In other words, when the design of a new feature or modification has been developed to the point where its details can be sufficiently understood, a risk analysis must be performed. All Reclamation designs (as well as contractor designs prepared on behalf of Reclamation) use the Reclamation design standards [16] as the basic starting point. The prototypical design called for by the standards is then further strengthened or expanded to ensure that it does not pose an unreasonable risk to the public. Risk informed design should apply the ALARP concept (as defined in Section 2.4) to achieve a product that meets or exceeds the design standards while also satisfying the goals of the Dam Safety Program (including any risk neutrality objectives that may apply, as discussed in Section 4.4).

Risk-based design optimization is a misuse of risk analysis. Risk estimates cannot be used to justify removal of standard design features or elements for the sake of cost savings alone, even if doing so would apparently result in a total risk estimate below the visual risk guidelines. The Reclamation risk portrayal chart is not intended as a design tool. If any deviations from the design standards are proposed, they must be rationalized based on practical considerations rather than risk. While it is recognized that the design standards do not and cannot cover all possible aspects of dam design, and that the designer's experience may be the primary means of assessing whether a particular "optional" design feature should be included where guidance is incomplete or lacking, the visual guidelines should never be used as the sole criterion of acceptability. Rather, they should form the starting point for further discussions on whether the design is appropriate.

The 1976 failure of Teton Dam, which ultimately led to the establishment of the Dam Safety Program, provides an example of why risk informed design is important. Before the start of construction, a test-grouting program had indicated that grout takes would be high. To reduce the amount of foundation grouting needed, a design change was made fairly late in the process whereby significant portions of the rock foundation would be excavated and replaced with compacted fill. While this approach placed the grout cap on sounder rock and eliminated the need to grout the more broken near-surface layers, it also placed erodible backfill in direct contact with open fractures, within a steep-sided excavation whose walls would have tended to produce an arching effect [20]. The use of these "key trenches" at Teton was novel, but because of their superficial similarity to cutoff trenches (with which Reclamation had extensive experience), it was not immediately seen as a danger. If this type of design change were being proposed today, a PFM would be screened for, the risk implications considered, and the design adjusted as appropriate.

4.4 Risk neutrality

Inventory decisions that could increase Reclamation's risk exposure must be fully understood and carefully weighed. 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, the risk impacts of the proposed designs or changes must be evaluated. This guidance applies to:

- Significant changes to reservoir operations (including any changes from the existing SOPs for the facility).
- Modifications and construction at Reclamation dams for purposes other than dam safety.
- New dams and development of supplemental water supplies.
- New or existing dams being accepted into Reclamation's inventory or into Reclamation's Dam Safety Program.

It is desirable that such changes be risk-neutral – that is, that there be no appreciable increase in the total risk posed by the facility (or the portfolio risk). A typical requirement of risk neutrality consideration (and the basic premise in the case of a new or existing dam being accepted into the program) is that the baseline risks are below guidelines with reasonable confidence (e.g., preserving or accepting a baseline risk estimate that is already above guidelines would not necessarily meet the intent of risk neutrality). Ultimately, Reclamation decision-makers must decide if any increases in the total risk (of the dam or portfolio) are acceptable. Often this will involve weighing the benefits of the proposed changes against the potential increase in the total estimated risk.

Some of the other considerations that may apply include:

- The potential to add design features to the concept or modify the concept to offset or eliminate the risk with respect to specific PFMs.
- Consideration of any deviations from design standards for components of the proposed modifications or new structures. Any deviations from design standards must follow the waiver process and not simply be rationalized by the idea that the proposed deviation would have a minimal impact on the estimated risk (see Section 4.3).
- Changes to proposed construction timing, methods, or the addition of risk mitigation elements to the construction project (see Section 4.2).
- The design of a new dam should be robust enough to ensure that the long-term risk of the structure under a variety of loading conditions will be comfortably below the risk portrayal chart visual guidelines (as opposed to the design being risk-optimized or reverse-engineered from a target plotting position on the risk portrayal chart).
- In some cases, when accepting an existing dam into the inventory, the concept of risk neutrality would not be held to strictly apply. An example of this would be a scenario where a decision by Reclamation to not accept title would result in greater risks to the public (e.g., because the transferring entity was incapable of maintaining the dam), or where the dam is accepted into the inventory with plans to expeditiously reduce the risk. However, risk analysis and risk assessment should still be completed for these facilities prior to formal acceptance into Reclamation's inventory. This will ensure that decision-makers are apprised of potential dam safety issues in advance of accepting oversight responsibility.

Generally, if significant increased risk is anticipated for a proposed (non-dam safety-driven) change at one of Reclamation's dams, and the increased risk cannot be effectively mitigated, the proposed change will not be considered acceptable to Reclamation. For more information on risk reduction objectives for dam safety modifications, see Appendix E.

5. Incident risk

The objective of Reclamation's Dam Safety Program is to ensure that Reclamation dams do not present an unreasonable risk to people, property, and the environment. Traditionally, the focus of the Program has been on controlling the threat of breach-type events, with the understanding that a reduction in the risk of failure would not only reduce the risk of life loss but also the potential for non-life loss consequences. With respect to the latter, the sufficiency of the traditional approach has been called into question as a result of the February 2017 spillway incident at Oroville Dam, California [21]. This non-breach incident resulted in the evacuation of over 180,000 downstream residents, environmental impacts to the Feather River, and over $1 billion of reconstruction costs to the facility. The recognition that the public and organizational impacts of some types of incidents could rival or eclipse those of a traditionally defined failure is a key reason that the scope of Reclamation's RIDM process is being expanded. Moving forward, the process will include direct consideration of adverse event chains that do not result in a large-scale uncontrolled release of the reservoir and are unlikely to lead to direct life loss.

To prevent overwhelming risk analysis teams with a potentially limitless set of scenarios, and in order to avoid taxing an inherently limited pool of financial resources, a definition of "dam safety incident" that provides some initial level of screening (beyond any additional screening performed by the risk analysis team) is needed. This idea was explored in several incident risk pilot studies performed by Reclamation in the wake of the Oroville incident [22]. The following definition was found to provide an intuitive and practical means of broadly differentiating between events with the potential to trigger a societal response and those that would not necessarily rise above the level of an internal alert:

> A dam safety incident is defined as an adverse occurrence associated with the basic purpose or function of a dam that does not have the significant potential to result in direct life loss, but is both visible enough and unusual enough to result in public concern or disruption, significant economic or environmental consequences, or an adverse impact on Reclamation's ability to independently perform its mission.

The manner in which a dam safety incident is defined is consequential in terms of how the incident risk evaluation process is applied and how actions to reduce or better understand the risks are recommended and implemented. One of the obvious implications is that agreement on what might reasonably qualify as "visible" or "unusual," and what level of economic or environmental consequences could be considered "significant," may vary from team to team. In other words, for a particular facility, different risk evaluation teams may end up identifying a different set of incident threats or interpreting the same set of threats differently. This type of autonomy is actually desirable and consistent with the objectives of the periodic review process, wherein risk analysis teams are instructed to take a fresh look at each facility and not simply agree with what has been done before. The use of a flexible definition ensures that over time a broader spectrum of incident threats will be considered.

In a traditional dam safety risk analysis, the most plausible ways that a dam could fail are captured in the form of PFMs. While many different types of PFMs are considered, each of them must involve a breach of the reservoir retention system. A narrative describing a process that leads to severe damage but not breach would be excluded from consideration under the traditional process but would be of interest in the evaluation of threats that could result in a dam safety incident. Such processes may be termed incomplete failure modes (IFMs) and form the basic units of meaning in an incident risk analysis. Like PFMs, IFMs must be fully conceptualized before they can be discretized into sequences of events, and some level of screening is required at the front end of the process (e.g., discussions about whether an IFM is likely to be a credible incident risk contributor, whether its occurrence would satisfy the definition of a dam safety incident, etc.). For the quantification of incident risks, essentially the same methodology would apply as for PFMs, with the following points noted:

- Since an incident is not required to result in an uncontrolled release, the number of events that an IFM can practically be decomposed into will generally be smaller than for a PFM.
- Since fewer things need to happen for an adverse non-breach condition to be realized, the quantified occurrence probabilities will generally be higher than for a PFM.
- Since the partial or incomplete occurrence of a previously quantified PFM could potentially result in an incident, some low-probability PFMs or highly unlikely PFMs could potentially resurface as credible IFMs (though an IFM need not be associated with an existing PFM).

The quantified risks of the IFMs at a particular facility can be compared to each other using a risk portrayal matrix that captures both their approximate occurrence probabilities and very roughly estimated economic consequences (including repair costs, property damage, environmental remediation costs, and potential lost benefits). The purpose of the four-by-four matrix adopted by Reclamation (Figure 5.1) is not to identify or indicate the need for action but rather to highlight the highest risk contributing IFMs. The color bands used in the matrix are not intended to serve as proxy guidelines but simply emphasize that IFMs with markers plotting toward the upper right corner may be associated with an increasing magnitude of incident threat.

The basic elements of the workflow developed during the incident risk pilot studies [22] include:

- Developing a working set of IFMs based on past performance issues, identified vulnerabilities, and a review of both the quantified and highly unlikely PFMs at the facility.
- Removing from consideration those IFMs that would not reasonably satisfy the definition of a dam safety incident.
- Discretizing the remaining IFMs into event sequences, estimating their annualized occurrence probabilities (AOPs), and, using Figure 5.1, selecting an annual likelihood bin (or bins) for each IFM.
- Evaluating the potential range of damages and lost benefits for each IFM and, using Figure 5.1, selecting an economic consequences bin (or bins).
- For IFMs plotting in the upper-right halfspace of Figure 5.1, determining whether action to reduce or better understand the incident threat is justified and building the dam safety case for any recommended actions.

In building the case for action, the controlling incident threats and the actions being recommended would need to be placed within the broader context of the facility setting (how it is operated, overall condition, design and construction history), similar to what is done for PFM-related recommendations under the traditional process. As part of the dam safety case, the ALARP concept, as defined for incident risks in Section 2.4, should be considered. Although a variety of incident threats may be targeted for action, there would generally be greater justification to reduce or better understand incident risks that are relatively high *and* relatively practicable to address (i.e., costs are not grossly disproportionate to benefits) than there would be to address those that are relatively low *or* relatively difficult to address. While this approach could result in some credible incident threats not being addressed at a given decision point, it should be emphasized that the processes under consideration do not (by definition) have the significant potential to result in direct life loss. In some cases, it may be appropriate for Reclamation to acknowledge that if an incident occurs, the cost of any repairs or economic consequences will need to be dealt with at that time.

Annual Likelihood	Economic Consequences			
	Low < $1 Million	Moderate $1 - 10 Million	High $10 - 100 Million	Very High > $100 Million
Very High > 1/10				
High 1/100 - 1/10				
Moderate 1/1000 - 1/100				
Low < 1/1000				

Figure 5.1. Incident risk portrayal matrix. The plotting style is similar to that of the "qualitative risk matrix" [4] used for semi-quantitative risk analysis by other agencies.

References

[1] "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, CO, August 2011.

[2] "Rationale Used to Develop Reclamation's Dam Safety Public Protection Guidelines (Interim)," U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office, Denver, CO, August 2011.

[3] "Federal Guidelines for Dam Safety," Interagency Committee on Dam Safety. U.S. Department of Homeland Security, Federal Emergency Management Agency, Reprinted January 2004.

[4] "Federal Guidelines for Dam Safety Risk Management. FEMA P-1025," U.S. Department of Homeland Security, Federal Emergency Management Agency, January 2015.

[5] S. Vick, "Degrees of Belief: Subjective Probability and Engineering Judgment," ASCE Publication, Reston, 2002.

[6] "RCEM – Reclamation consequence estimating methodology. Guidelines for estimating life loss for dam safety risk analysis," Department of the Interior, Bureau of Reclamation, Denver, CO, July 2015.

[7] "RCEM – Reclamation consequence estimating methodology. Dam failure and flood event case history compilation," Department of the Interior, Bureau of Reclamation, Denver, CO, June 2015.

[8] "HEC-LifeSim life loss estimation. Technical reference manual, version 2.0," U.S. Army Corps of Engineers, Institute for Water Resources, Risk Management Center, July 2020.

[9] "Guidelines on Risk Assessment," Australian National Committee on Large Dams, Inc., 227 Collins Street, Hobart, Tasmania, Australia, 7000, July 2022.

[10] D. Galic, "The common cause adjustment in dam safety risk analysis: Scope, Purpose, and Applicability," in *Proceedings of the 2017 Annual USSD Conference*, Anaheim, CA., April 3-7, 2017.

[11] D. Galic and W. Heyder, "Beyond Pascal's Triangle: combining the risks of positively dependent potential failure modes," in *Proceedings of the 2022 Annual USSD Conference*, San Diego, CA, April 11-14, 2022.

[12] D. Galic and J. Major, "The Bureau of Reclamation approach to risk analysis and risk informed decision making – past successes, current challenges, and future direction," in *Proceedings of the 2022 ANCOLD/NZSOLD Conference*, Sydney, Australia, October 26-28, 2022.

[13] "Reducing Risks, Protecting People: HSE's Decision Making Process," UK Health and Safety Executive. Her Majesty's Stationary Office, Norwich, England, 2001.

[14] "Guidelines on Risk Assessment," Australian National Committee on Large Dams, Inc., 227 Collins Street, Hobart, Tasmania, Australia, 7000, October 2003.

[15] Reclamation Manual, U.S. Department of the Interior, Bureau of Reclamation, Policy and Programs Directorate.

[16] Reclamation Design Standards, Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center.

[17] N. J. Snorteland, "Rationale behind the U.S. Army Corps of Engineers tolerable risk guidelines," in *Proceedings of the 2019 ANCOLD/NZSOLD Conference*, Auckland, New Zealand, October 10-11, 2019.

[18] "Deaths: Final Data for 2019. National Vital Statistics Reports," vol. 70, no. 8, July 26, 2021.

[19] "2019 U.S. Population Estimates Continue to Show the Nation's Growth is Slowing," Census.gov, October 8, 2021.

[20] W. Engemoen, "A look at the failure of Teton Dam 40 years later," *ASDSO Journal of Dam Safety,* vol. 14, no. 3, 2016.

[21] "Independent Forensic Team Report on Oroville Dam Spillway Incident," Association of State Dam Safety Officials, January 2018.

[22] D. Galic and M. Rocha, "Pilot Study for Dam Safety Considerations Related to Low Failure Probability High Consequence Facilities," in *Proceedings of the 2019 USSD Conference*, Chicago, IL, April 8-11, 2019.

[23] W. Engemoen, "Latest Compilation of Internal Erosion Incidents at Bureau of Reclamation Dams," in *Proceedings of the 2017 Annual USSD Conference*, Anaheim, CA, April 3-7, 2017.

[24] M. Morgan, "Use and abuse of expert elicitation in support of decision making for public policy," *Proceedings of the National Academy of Sciences,* vol. 111, no. 20, pp. 7176-7184, May 20, 2014.

[25] "Safety of Dams Project Management Guidelines," U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO, January 2018.

[26] "Safety of Dams – Policy and Procedures. ER-1110-2-1156," Department of the Army, U.S. Army Corps of Engineers, Washington, DC, March 2014.

[27] "Guidelines on Safety Assessments for Referable Dams," Department of Regional Development, Manufacturing and Water, Queensland Government, Australia, November 2021.

[28] "Risk Informed Decision Making (RIDM): Risk Guidelines for Dam Safety, Version 4.1," U.S. Department of Energy, Federal Energy Regulatory Commission, Office of Energy Projects, Division of Dam Safety and Inspections, March 2016.

[29] D. Galic, "The big F-N plotting style: Right for every organization?" in *Proceedings of the 2018 USSD Conference*, Miami, FL, April 30-May 4, 2018.

Appendix A. Probability calculations and probability estimates

For the facility as a whole, the total AFP is defined as the probability of the union of the *m* individual PFMs whose risks have been quantified:

$$AFP_{Total} = P(PFM_1 \cup PFM_2 \cup \ldots \cup PFM_m) \quad \text{(A1)}$$

In practice, this formula is often simplified as:

$$AFP_{Total} = AFP_1 + AFP_2 + \cdots + AFP_m \quad \text{(A2)}$$

where AFP_m is the estimated probability of the *m*th PFM. Because this second formula would be exact only if the quantified PFMs were mutually exclusive (which is rarely the case), applying it will usually result in some overcounting of the intersection. In most situations, this will have little impact from the decision perspective, but in some cases [10] the exact formula in Equation A1 should be used. There are also scenarios where positive dependence can be accounted for in other ways [11].

With some exceptions, the input probability estimates required for a quantitative risk analysis are not directly adapted from frequency type data but are instead developed by subject matter experts. The methodologies used for obtaining load probability and response probability estimates differ significantly, and the estimates are developed independently by separate groups of staff. For example, flood and seismic loadings are developed before the risk analysis on the basis of published procedures currently accepted in those disciplines. In contrast, response probability estimates are usually developed in real time by adjusting the neutral (0.5) estimate or a reference frequency [23] up or down based on the more/less likely factors documented by the team. The elicitation of more/less likely factors allows the design and construction history of the dam, the results of prior analyses, recent observations of performance, and deterministic measures such as safety factors to be incorporated into the risk analysis. In this regard, risk analysis can be viewed as a means of organizing available information and improving understanding of key susceptibilities.

The concept of subjective probability estimation is central to Reclamation risk analysis practice. While some commentators have embraced the process [5], others have argued that it relies too heavily on "inherently fallible" engineering judgment [21], or that it operates within a rhetorical minefield where any number of cognitive biases can potentially skew the results [24]. However, in the context of dam safety risk analysis, the subjective probability estimates do not have to be precise for the results to be useful. Furthermore, it should be understood that Reclamation risk estimators are not being asked to evaluate statistical parameters whose accuracy could have a significant impact on the predictive value of a statistical model (as is often the case in expert elicitation settings); rather, they are providing their best estimates of occurrence probability for simply defined and physically tangible events. In a RIDM process whose ultimate goal is to inform the allocation of resources, and in which the numbers make up only one component of the dam safety case, the numbers being "off" by a factor of two or three should have little practical impact on the decisions being made.

The expert elicitation model used by Reclamation could be described as a strong facilitator model, in that the facilitator is ultimately responsible for the coherence of the quantitative risk estimates being documented. In a large team setting, it is the role of the facilitator to ensure that the estimators are qualified (i.e., have a basic understanding of the risk analysis process and their place in it), that they comprehend what they are being asked to estimate, and that their subjective probability estimates are consistent with the available information. Although the facilitator is not typically a risk estimator, they can and should push back on any obviously unreasonable risk estimates. Probability distributions should generally be selected so as to align the mean of the distribution with the majority of the individual estimates. While it is important that a variety of perspectives be captured, outlier estimates should generally not be given equal weight. If the facilitator, based on their extensive RIDM experience, believes that a team is consistently misinterpreting the available evidence or developing internally inconsistent estimates, the risk analysis should be stopped until the issue can be addressed.

Appendix B. Types of SOD recommendations

In many cases, a risk analysis and risk assessment will end up leading to recommendations intended to reduce or better understand the risk at a facility. Within Reclamation, SOD recommendations are the programmatic vehicles whereby such actions can be taken and tracked. SOD recommendations are developed by technical teams, reviewed by a Dam Safety Advisory Team (DSAT), and accepted by decision-makers. Since the first shot at framing the scope and substance of any SOD recommendations falls within its purview, a technical team can exert significant influence over how the subsequent actions will be sequenced and implemented. However, a technical team must be capable of building a compelling case for the recommended actions, and decision-makers must fully endorse the recommendations before they become active. Traditionally, the motivation for a SOD recommendation has tended to fall into one of three classes:

Motivation Class 1. Increasing justification to better understand the risk.

- These types of SOD recommendations are made to collect field data (geophysical investigations, geotechnical investigations, concrete samples, etc.), update loadings (hydrologic, seismic), perform analyses (liquefaction triggering, post-liquefaction stability, nonlinear finite element, etc.), and update the consequence estimates (perform inundation mapping, perform a population at risk study, estimate life loss using simulation-based modeling, etc.). The dam safety case for these recommendations is usually built around the idea that the portrayal of risk could change with new information (in a way that is meaningful with respect to the visual guidelines), i.e., that there is low confidence in the portrayal of risk. The majority of SOD recommendations made at the Comprehensive Review (CR) level fall within this motivation class. The acceptance of a Motivation Class 1 recommendation will typically result in a higher-level study (e.g., an Issue Evaluation) being initiated.

Motivation Class 2. Increasing justification to reduce the risk.

- These types of SOD recommendations are made to perform a modification (install a seepage filter, remove liquefiable materials, replace a spillway intake structure, reconstruct a spillway chute, etc.), impose operational restrictions (e.g., a limitation on the maximum permissible non-flood reservoir elevation), or initiate further studies that are expected to lead to an eventual modification or operational change (Issue Evaluation or Corrective Action Study). The dam safety case for these types of recommendations is usually built around the idea that the risks of continuing operation are relatively high, are likely to remain high (high confidence in the portrayal of risk), and that this interpretation is consistent with the design of the structure (i.e., there is a design deficiency with respect to static, hydrologic, or seismic loading conditions) or the performance of the structure (excessive seepage, material transport, foundation displacement, concrete cracking, etc.). A significant number of SOD recommendations made at the Issue Evaluation level and the majority of SOD recommendations made at the Corrective Action Study (CAS) level fall within this motivation class. The acceptance of a Motivation Class 2 recommendation will typically result in a CAS being initiated or in the project moving into the final design stage [25].

Motivation Class 3. Monitoring enhancement.

- These types of SOD recommendations are made to replace damaged instruments (whose replacement would fall outside the scope of routine maintenance), abandon instrumentation that is no longer being used (e.g., internal vertical movement devices, hydraulic piezometer terminal wells), or improve the existing monitoring capability (e.g., install new piezometers, install new seepage measurement points). These types of SOD recommendations do not require a dam safety case, and it would not be inconsistent to argue, for example, that there is decreasing justification to reduce or better understand the risk but that additional instruments should be installed. However, if the installation of new instrumentation is recommended, the instruments 1) must be capable of providing information relevant to one of the quantified PFMs, and 2) the cost must not be excessive (in the interpretation of the decision-makers). For example, a monitoring enhancement-based SOD recommendation to install 100 new piezometers would likely be viewed as inconsistent with the intent of this motivation class and would likely be rejected. These types of SOD recommendations are made almost exclusively at the CR level. A monitoring enhancement-based SOD recommendation would generally not trigger a formal Issue Evaluation.

In addition to the above, there is a new motivation class associated specifically with ALARP-based actions. As of this writing, a final decision on whether ALARP recommendations will be SOD recommendations has not been made, but the guidance below remains valid.

Motivation Class 4. Increasing justification to take ALARP-based action.

- Once the dam safety case for or against action has been built, the ALARP concept is used as a second pass to ensure that any other reasonable actions that could be taken to better understand or reduce the risk are identified and considered. This could include a variety of options, including those normally considered under motivation classes 1 and 2, but for which there is no broader dam safety case (e.g., because the risk of the associated PFM is relatively low). Although ALARP-based recommendations fall outside the scope of the dam safety case, it must be demonstrated that the recommended actions are worthwhile (they will provide value-added information or benefits), and that the cost of implementing them (in a very approximate sense) is not clearly and grossly disproportionate to the benefits. It is expected that the majority of these types of recommendations will be made at the CR level. The scope of an ALARP-based recommendation will generally determine whether it results in further studies being initiated. For example, a recommendation to pursue limited field investigations for the benefit of a future CR team would not result in an Issue Evaluation since no further action would be needed once the data had been transmitted.

Appendix C. Risk management references

Reclamation design standards [16] are a key part of managing risks at Reclamation dams. The design standards establish technical requirements and processes to enable preparation of designs, reports, and analyses of Reclamation structures. Material deviations from Reclamation design standards must be formally approved in writing. The design standards are available at https://www.usbr.gov/tsc/techreferences/designstandards-datacollectionguides/designstandards.html.

Other dam related risk management practices and programs are documented in the Reclamation Manual [15]. The Reclamation Manual consists of a series of Policies and Directives and Standards. Policy documents establish leadership's philosophy and principles and define the general framework for the accomplishment of Reclamation's mission. Directives and Standards provide the level of detail necessary to ensure consistent application of policy and consistent program execution Reclamation-wide. Relevant Policies and Directives and Standards are referenced below and are available on the Reclamation Manual website, https://www.usbr.gov/recman.

Policies

FAC P02, *Decisions Related to Dam Safety Issues*

FAC P03, *Performing Design and Construction Activities*

SLE P08, *Emergency Management*

CMP P01, *Floodplain Management*

Directives and Standards

CMP 01-01, *Floodplain Management*

FAC 01-01, *Emergency Management for Water Impoundment Structures*

FAC 01-07, *Review/Examination Program for High and Significant Hazard Dams*

FAC 01-08, *Dam Safety Performance Monitoring for High and Significant Hazard Dams*

FAC 02-01, *Operating Practices and Procedures for High and Significant Hazard Potential Dams (and other facilities, as applicable)*

FAC 03-02, *Construction Activities*

FAC 03-03, *Design Activities*

FAC 04-11, *Operations Configuration Management*

FAC 06-01, *Dam Safety Program*

Appendix D. Plotting risk estimates and uncertainty bands

Once an AFP and an ALL have been estimated for each of the quantified PFMs, the Reclamation risk portrayal chart (Figure 3.1) can be used to plot the risk estimates. For each of the individual PFMs, the plotting marker is defined in terms of its best estimate AFP coordinate (vertical axis) and its best estimate life loss coordinate (horizontal axis). For the total risk estimate, the plotting marker is defined in terms of its best estimate AFP coordinate (vertical axis) and best estimate ALL coordinate (parametrized in terms of the diagonal contours shown in the background of the chart). Uncertainty bands are plotted through the total risk marker showing the reasonable range of the best estimate in the AFP (vertical) and ALL (diagonal up-right) directions. There is no uncertainty band plotted in the horizontal direction since the total risk marker is not considered to have a life loss coordinate.

Plotting risk estimates on the risk portrayal chart requires a standardized template file that includes a data entry table for information relating to the individual PFMs. The template file calculates the best estimate total AFP (and ALL) as the simple sum of the individual-PFM AFP (and ALL) best estimates (as noted in Section 2.2, simple summation may not be appropriate in all cases). Previous versions of the template file repeated this calculation for the lower and upper bound estimates to generate the uncertainty bands in Figure 3.1. However, this is being discontinued for several reasons:

- The summation of percentile values does not always give the corresponding percentile of the distribution of the sum.
- The information conveyed by the uncertainty bands is only useful to the extent that it can be used by the team to support a decision.
- Once calculated in the template, the uncertainty bands tended to be viewed as objective scientific information (they are not), and there was hesitation on the part of some users to alter them (even if they were not consistent with the actual state of uncertainty).

Moving forward, it will be the responsibility of the user to select a reasonable set of total risk bounds consistent with the team's understanding of uncertainty and the broader dam safety case.

According to the 2015 Federal Guidelines [4], for the purposes of risk portrayal, "two types of graphs are typically used: 1) the f-N plot and 2) the F-N plot." The first of these plotting styles is functionally equivalent to the one used by Reclamation (Figure 3.1), whereas the second treats risk as a complementary cumulative distribution function (CCDF) of life loss. Although the F-N format is currently used by the U.S. Army Corps of Engineers [26] and others [9] [27] [28], it has not been used by Reclamation because it is not seen as conveying unique information [29]. Furthermore, any epistemological questions surrounding these two plotting styles (or the use of specific symbols or nomenclature) have little bearing on their practical use. Comparing a set of risk estimates to the threshold values for increasing justification to reduce or better understand risks could just as easily be done in writing without using a plot. As such, it is asserted that the Reclamation risk portrayal chart provides a convenient visual aid, without any deeper mathematical meaning.

Appendix E. Risk reduction objectives for dam safety modifications

Once a decision is made to modify a structure due to a relatively high level of risk, risk reduction alternatives are developed. A key to formulating risk reduction alternatives is using the risk analysis information to ensure that the proposed alternatives will result in effective risk reduction. This underscores a subtle but important difference with respect to the approach used for non-dam safety modifications, where consistency with any applicable design standards would be the foremost consideration (with risk not necessarily being invoked until a working design had been developed). When developing alternatives for a dam safety modification, the PFMs should be reviewed to evaluate which events or conditions are the most significant contributors to the overall AFP or ALL. The crucial attributes of the modification design can often be identified on the basis of this type of sensitivity analysis.

Dam safety modifications should be designed such that the risk of the modified structure is comfortably below the applicable portion of the risk portrayal chart visual guideline when construction is complete. A general rule of thumb used in the past is for the mean estimated risk of the as-built modification to be at least one order of magnitude below guidelines (though this may not be necessary or achievable in all situations). When developing designs and risk reduction estimates, future growth in the downstream inundation area, possible increases in the hydrologic and/or seismic loading estimates, and potential changes in the state of the art should be considered, as these factors may result in subsequent changes in the estimated risks. The loadings used in design should be reasonably up to date (or fully consistent with the state of the practice if critical to the design or residual risk portrayal) to ensure an adequate level of risk reduction can be achieved. The greater the risk reduction initially planned, the less likely it becomes that future studies will conclude risks are high enough to justify additional action.

When evaluating risk reduction alternatives, cost effectiveness is an important consideration in selecting the preferred alternative. The level of risk reduction achieved per monetary unit spent is sometimes considered for risk reduction alternatives regardless of the location of the baseline risk in relation to the visual guidelines. To ensure program effectiveness, cost-effectiveness measures are sometimes used to compare risk reduction alternatives both 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. For example, if the preliminary level of risk reduction considered will result in the total risk plotting close to guidelines, but an additional order of magnitude of risk reduction would require more than doubling expenditures, it may be appropriate to opt for the alternative with lower projected risk reduction so that the additional resources can be applied to other projects.

As part of the development of risk reduction alternatives for dam safety projects, it is prudent to consider whether the risks as evaluated will be ALARP with respect to project economics. When considering ALARP principles, an evaluation must be made whereby the estimated risks are weighed against the sacrifice of money, time, or effort involved in implementing actions to further reduce or avoid the risks. If additional protective features can be included at a reasonable cost, incorporating them into the design should be considered even if the PFMs benefitted are not the risk controlling PFMs. Section 2.4 of this document includes a definition of ALARP that is specific to the dam safety modification design context.