ENGINEERING GUIDELINES FOR THE EVALUATION OF HYDROPOWER PROJECTS

CHAPTER 18 – LEVEL 2 RISK ANALYSIS

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ABBREVIATIONS

ACE	annual chance exceedance
AEP	annual exceedance probability
APF	annual probability of failure
BOR	U.S. Department of the Interior, Bureau of Reclamation
D2SI	Division of Dam Safety and Inspections (FERC)
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
PAR	population at risk
PFM	potential failure mode
PFMA	potential failure mode analysis
RIDM	risk-informed decision making
SQRA	semi-quantitative risk analysis
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

18-1 INTRODUCTION

18-1.1 Purpose

This guideline describes the procedures used to conduct a Level 2 risk analysis in the Federal Energy Regulatory Commission (FERC) Part 12D dam safety program. As presented in currently interim Risk-Informed Decision Making (RIDM) Risk Guidelines (FERC, 2016), the primary purposes of a Level 2 risk analysis are:

- Evaluate the project potential failure modes and associated risks;
- Identify and prioritize the need for additional studies;
- Identify and prioritize any data collection and analyses;
- Identify operations and maintenance, monitoring, emergency action plan, training and other recurrent needs;
- Provide a better understanding of potential failure modes and a basis for future dam safety inspections and activities; and
- Provide support to inform dam safety decisions for taking action (or not) to better define risks through higher level studies, or reduce risks.

The risk analysis process described in this document is similar to the semi-quantitative risk analysis method documented in Chapter A-4, Semi-Quantitative Risk Analysis of the Best Practices in Dam and Levee Risk Analysis (BOR/USACE, 2019). However, there are some minor, but subtle and important differences between each process.

18-1.2 Need

Level 2 risk analyses have developed as a result of:

1. The need to maintain the current state-of-the-practice in dam safety. Many other federal agencies and international organizations are now using risk analyses in their dam safety programs. In the United States, this includes the Bureau of Reclamation (BOR), U.S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority. The risk methodologies and the state-of-the-practice has evolved to the point where risk analysis and assessment methods have become key tools and information in identifying, evaluating, and managing risk in dam safety.
2. The opportunity and ability to leverage an already significant investment in time and effort to review documents and project information needed to perform a PFMA and other Part 12D responsibilities, including inspection and evaluation of the project. The Federal Guidelines for Dam Safety require that all dams undergo an inspection and review that documents the condition of a dam at a point in time (FEMA, 1979). As implemented by FERC, this is the Part 12D inspection and review. Significant effort is required to prepare for these inspections and reviews.

This effort includes reviewing project information, studies, analyses, performance and monitoring information, and other key project data. Through the course of these efforts, much project knowledge is amassed and evaluated. The incremental addition of a risk analysis to this process enhances the value of the effort at a relatively low cost. Apart from developing estimates of loading frequency and consequences, typically only limited additional engineering analyses and studies are needed to perform a risk analysis since the risk analysis generally relies on existing information.

3. The need to provide better distinction and prioritization of potential failure mode actions than the former potential failure mode analysis (PFMA) categories, including an improved process of evaluating the likelihood/frequency of dam failure, frequency of loading, and estimated consequences for each potential failure mode.

In addition, in evaluating, reviewing, and prioritizing dam safety concerns, the FERC has found it extremely beneficial to also have a sense of the risks associated with each potential failure mode for each project. This information, combined with the information obtained through other dam safety submittals (inspection reports, dam safety surveillance and monitoring plans and reports, emergency action plans, owner's dam safety plans, and others), provides an overall basis to provide consistent and transparent dam safety decisions.

Finally, the dam owner and operator are legally responsible for the safety of their dam, its operation, and the consequences of a failure should one ever occur. All dam owners must fully understand and appreciate the legal, regulatory, moral, and social obligations of owning a dam. Without a deliberate effort to identify and understand the risks that a dam imposes on its surroundings—in both the magnitude and frequency of the hazards and magnitude of potential consequences, including impacts to life, health, and property—an owner cannot fulfill these obligations.

18-1.3 Approach

The traditional ongoing dam safety inspection, monitoring, and maintenance activities are of critical importance, but focusing them in a risk-informed manner should result in better management of dam safety programs and activities. While PFMA is the process for identifying potential failure modes, semi-quantitative risk analysis (SQRA) is a process to evaluate their significance from a risk perspective. A Level 2 risk analysis uses an SQRA approach and is a risk categorization system that assigns likelihood and consequence categories to potential failure modes based on existing data and available consequence estimates. A Level 2 risk analysis utilizes a risk matrix approach to assess individual potential failure modes as well as the total risk for a project. The SQRA method provides a relevant risk categorization system that is a useful and quick means to prioritize dam safety activities, especially to determine if higher level studies would be beneficial for specific potential failure modes (BOR/USACE, 2019).

A Level 2 risk analysis is performed in conjunction with a potential failure mode analysis (PFMA) as part of a Part 12D Comprehensive Assessment (CA), per 18 CFR 12.37(g). The risk analysis portion of a CA is built upon the PFMA and is based on existing data and limited development of seismic and hydrologic loading and estimated consequences.

Level 2 risk analyses will normally be conducted for all dams in FERC's Part 12D program as part of a CA (typically on a 10-year cycle), but more frequently as justified to accommodate unusual performance issues or other issues that need to be evaluated further to review or revise priorities. See Chapter 16 of the Engineering Guidelines for more information regarding the Part 12D program and Comprehensive Assessments.

The outcomes of a Level 2 risk analyses include a complete, yet concise and focused report that captures key information and provides the key information and rationale that "builds the case" for the path forward. Other outcomes include a better understanding of the project and the primary risk-drivers, better prioritization of studies, and more focused inspections and surveillance and monitoring. A Level 2 risk analysis focuses on credible potential failure modes (as defined in Engineering Guidelines Chapter 17) in order to determine which potential failure modes are considered significant at the dam.

Additional information on RIDM and how Level 2 risk analyses fit into the overall risk management framework in FERC's dam safety program is included in interim Risk-Informed Decision Making Risk Guidelines (FERC, 2016), available at:

https://www.ferc.gov/dam-safety-and-inspections/risk-informed-decision-making-ridm

18-1.4 Limitations

For all the benefits provided by a Level 2 risk analysis, typically the results will not be suitable for determining if the existing dam safety risks are tolerable. Higher level risk analyses (typically Level 3 and Level 4 risk analyses) will be required to demonstrate risk tolerability. More information on Level 3 and 4 risk analyses is provided in Chapter 2 of the interim FERC Risk-Informed Decision Making Risk Guidelines (FERC, 2016).

This document describes the process and procedures for performing a Level 2 risk analysis. Additional risk analysis methodology references are included in Best Practices for Dam and Levee Safety Risk Analysis (BOR/USACE, 2019).

18-2 BACKGROUND

There are generally three primary elements when considering dam safety risk:

1. Frequency/Probability of loading
2. Likelihood of dam failure (response) given the loading
3. Adverse consequences

The probability of failure is a function of both the frequency/probability of the loading condition (element 1 above) and the likelihood of failure given the loading condition (element 2 above). Failure has historically been defined as an uncontrolled, potentially life-threatening release of the reservoir due to breach. However, as discussed in Chapter 17 of the FERC Engineering Guidelines, failure can also include partial or operational failures that may not lead to an uncontrolled release of the reservoir, but can still result in major consequences (economic losses, operational restraints, etc.) to the dam owner, the public, other stakeholders, or the environment.

The third element of risk is the magnitude of consequences should failure occur. Failure consequences can take many forms, including loss of human life, destruction of downstream property, loss of service (project benefits, which may include power generation, recreation, etc.), environmental damage, and socio-economic impacts. For semi-quantitative evaluations, the focus is typically on the potential for life loss, with the idea that the broader socio-economic, environmental, and property damages would be generally commensurate. However, certain projects, because of their potential for large or extreme economic consequences, may require an explicit treatment of economic consequences which may include costs associated with disruption to water supply, flood damage to property, loss or disruption of services of regional or national significance, and others.

18-3 LEVEL 2 RISK MEASURES

Chapter 2 of the interim RIDM Risk Guidelines (FERC, 2016) provides a definition and discussion of typical risk measures. The primary risk measures included in a Level 2 risk analysis are societal incremental life safety risk and non-breach life safety risk. Annual probability of failure is also estimated in a Level 2 risk analysis. See Section 2.2.1.1 of Chapter 2 of the interim RIDM Risk Guidelines (FERC, 2016) for the definition of the term ‘incremental risk’.

For those projects where economic consequences and other consequences (environmental, cultural, etc.) may be significant or large (relative to a dam owner’s ability to fund or pay for damages as a result of a failure or incident), at a minimum, a qualitative assessment of those consequences must also be provided.

Although typically not estimated in a Level 2 risk analysis, individual incremental life safety risk estimates can be conservatively assumed to be equivalent to the annual probability of failure estimates.

18-4 OVERVIEW OF LEVEL 2 RISK ESTIMATING PROCESS

The basic steps for a Level 2 risk analysis are described below. The foundation of the Level 2 risk analysis are the results from the PFMA. This includes the review of the available project information. The review of the project information for the performance of the Level 2 risk analysis is generally completed with the project review conducted for the PFMA, as described in Chapter 17 of the FERC Engineering Guidelines. The review of information includes:

- basic statistics and key features of the dam (e.g., type of dam, height of dam, reservoir volume, etc.);
- available design reports/design memos, construction photographs, and engineering studies/ reports, site investigations, etc.;
- historical operating condition loadings (reservoir levels and freeboard);
- performance monitoring information from visual observations and instrumentation; and
- other information included in the Supporting Technical Information Document (STID) and other applicable sources.

The following information and studies are performed prior to the risk analysis and the results are reviewed and used during the risk analysis session:

- Develop/Review/Update Loading Estimates. Loading estimates should be developed for:
    - Hydrologic loading (probabilistic hydrologic hazard curves). Of particular note are the frequencies of: the flood of record, the flood at the peak spillway capacity, the flood at the dam crest, and the projected frequency of the probable maximum flood (PMF). Development of the hydrologic loading curves is discussed in Section 18-6.2 of this chapter.
    - Seismic loading (probabilistic seismic hazard curves). Of particular note are the ground motions associated with the approximate return period of the maximum credible earthquake (MCE) and the ground motions used in any previously performed seismic analyses along with their approximate return period. Development of the seismic loading curves is discussed in Section 18-6.3 of this chapter.
- Develop/Review/Update Consequence Estimates. Consequence estimates, generally loss of human life, for the most critical potential failure mode scenarios and locations are needed. Interpolation/extrapolation of this information can be used to develop similar estimates for other potential failure modes and for other potential failure mode locations. A qualitative assessment of economic risk and

other significant risks should also be included. Development of consequence estimates are discussed in Section 18-9 of this chapter.

The following steps are performed as part of the Level 2 risk analysis session:

1. Perform a PFMA. The PFMA can be performed as a separate session prior to the Level 2 risk analysis or can be performed integral with the Level 2 risk analysis. The PFMA should be performed in accordance with guidance provided in Chapter 17 of the FERC Engineering Guidelines.
2. Perform Additional Screening of Potential Failure Modes. Additional screening of credible potential failure modes is performed to evaluate which potential failure modes are significant and should be carried forward into the Level 2 risk analysis and which potential failure modes do not have to be carried forward into the risk analysis. Additional screening guidance is provided in Section 18-7 of this chapter.
3. Develop Failure Likelihood and Consequence Estimates. For credible potential failure modes identified in the previous step, review, revise, and expand the factors from the PFMA that make the potential failure mode more likely and less likely to occur, including analysis results where applicable, and identify the key factors. Develop new factors, as needed. Determine the failure likelihood. A similar process is used to determine a consequence for each potential failure mode. Additional guidance is provided in Sections 18-8 and 18-9 of this chapter.
4. Develop Confidence Estimates. Develop estimates of confidence for the failure likelihood and consequence estimates for each potential failure mode. Additional guidance is provided in Section 18-10 of this chapter.
5. Develop Potential Risk Reduction Measures and Management Actions. Measures should include potential changes to type and frequency of dam safety inspections, improvements to the surveillance and monitoring, improvements to the emergency action plan (EAP), the need for follow up studies, and others. Potential permanent and interim risk reduction measures should be identified, when possible. Additional guidance is provided in Section 18-10 of this chapter and in Chapter 17 of the FERC Engineering Guidelines.
6. Portray Risk Estimates. The risk measures summarized in Section 18-3 of this chapter are determined for each potential failure mode and are plotted on established risk matrices. Additional guidance is provided in Section 18-11 of this chapter.

Finally, the results of the Level 2 risk analyses are documented in a report. The report documents the potential failure modes considered in the risk analysis; the failure likelihood, consequence estimates, and the rationale for their assignment; the confidence in the rating along with the rationale for its assignment and what additional information could be gathered to improve the confidence rating, if applicable; identified risk reduction measures and management actions; and the portrayal of the risk estimates. Additional risk analysis report documentation guidance is provided in Section 12.0 of this chapter.

A flowchart of the Level 2 risk analysis process is shown on Figure 1.

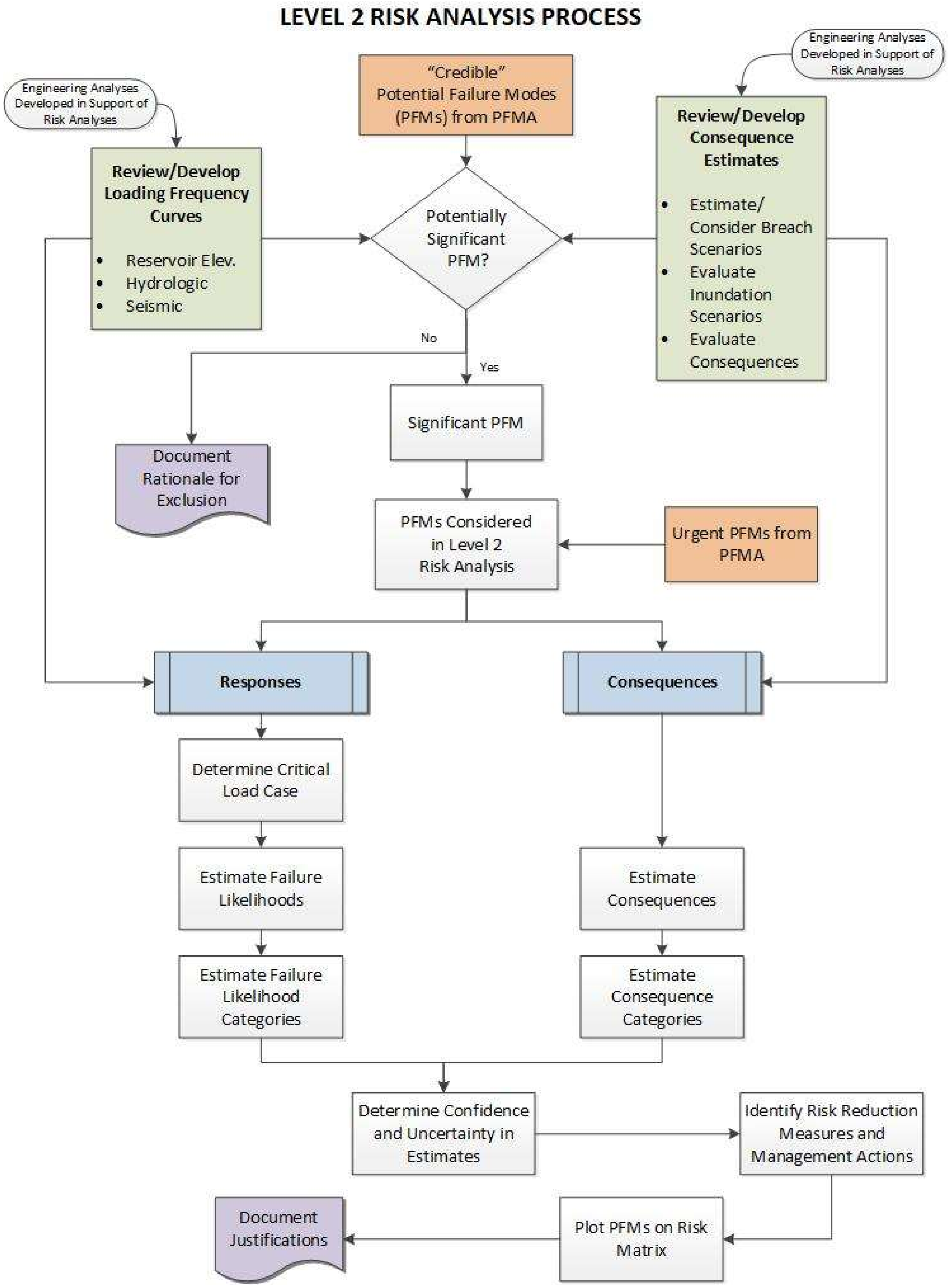

Figure 1: Level 2 Risk Analysis Process

18-5 LEVEL 2 RISK ANALYSIS TEAM

18-5.1 General

Ideally the Level 2 risk analysis session will be conducted concurrently or immediately following the PFMA session. This approach has the advantage that it efficiently uses the individuals already gathered for the PFMA session: similar or identical personnel are typically used for both the PFMA and risk analysis sessions, and project information is fresh and easily recalled because there has been no break or interruption in time between the different sessions.

Similar to the PFMA, advance planning is imperative to ensuring a successful Level 2 risk analysis. And like the PFMA, some questions should be addressed prior to conducting the risk analysis session, including:

1. What technical disciplines should be represented on the risk team?
2. How many people are expected to attend the risk session?
3. How many days is the session expected to last?
4. What are the meeting logistics? If held in person, what size of meeting room will be needed for the session? If held virtually, what type(s) of web-based audio and visual support/platforms will be needed?
5. Are there special considerations that should be accommodated in the session?

The Licensee should have preliminary discussions of these and other Level 2 risk analysis planning questions with FERC dam safety staff during the initial Part 12D coordination call as outlined in Chapter 16, Part 12D Program of the FERC Engineering Guidelines. Once the key members of the Level 2 risk analysis team have been identified and selected, these and any other questions should be revisited and plans adjusted accordingly and discussed with FERC dam safety staff during the second Part 12D coordination call as outlined in Chapter 16 of the FERC Engineering Guidelines.

18-5.2 Team Composition

The composition of the Level 2 risk analysis team is expected to be similar or nearly identical to that of the PFMA team with perhaps some exceptions. Like the PFMA team, the Level 2 risk analysis team generally comprises:

- Team Leader
- Facilitator(s)
- Core Team
    - Technical representatives from the owner’s staff
    - Subject matter experts

  - Independent Consultant(s)
- Note-taker(s)
- FERC Dam Safety Professionals
- O&M Staff
- Supplemental Resources

The roles of each are similar to the roles and responsibilities described in FERC Engineering Guidelines Chapter 17, Potential Failure Mode Analysis.

In most cases it is likely that the facilitator(s) will be the same for the PFMA and risk analyses; however, there may be occasions that a different facilitator or facilitators are used from the one(s) used to facilitate the PFMA. For example:

1. The PFMA facilitator may not be comfortable or may lack the requisite training and experience to facilitate the Level 2 risk analysis.
2. Because of the complexity of certain project features requiring specialized technical expertise, a separate facilitator may be used to facilitate certain parts of the Level 2 risk analysis (e.g., highly complex mechanical systems with large incremental consequences).
3. Because of the complexity and size of the project, different facilitators than those used for the PFMA may be used for different components of the project.

Unless otherwise approved by the facilitator, **the core team members are the only SQRA team members that provide risk estimates of the individual potential failure modes.** In order to maintain their independence and not bias the group, **facilitators do not provide risk estimates of the individual potential failure modes**.

FERC personnel will provide comments regarding the estimation of risks when, in the opinion of the FERC personnel, the core team has not adequately justified the rationale for the risk estimate. The lack of comments by FERC personnel during the risk analysis workshop does not indicate acceptance or approval of the team's findings.

18-5.3 Qualifications

In general, the qualifications of the facilitator and core team members are similar to those for the PFMA, as described in Chapter 17 of the FERC Engineering Guidelines, with the notable exceptions described in this section. In addition, the approach to selecting the core team members (technical disciplines, etc.) should be similar to that described for selecting the PFMA core team in Chapter 17 of the FERC Engineering Guidelines.

In addition to the qualifications of a PFMA facilitator described in Chapter 17 of the FERC Engineering Guidelines, the qualifications of a Level 2 risk analysis facilitator include:

- Have training and experience in semi-quantitative risk analysis or quantitative risk analysis methods. This includes having:
    - Attended a FERC-sponsored semi-quantitative risk analysis training workshop (or equivalent SQRA training).
    - Participated as a subject matter expert for at least two previous risks analyses (semi-quantitative or quantitative).
    - Assimilated the information and written the report for at least one SQRA or quantitative risk analysis.

- It is also strongly recommended that the facilitator have training and experience in risk analysis methods, including having:
    - Attended training in quantitative risk analysis methods, similar to those described in Best Practices for Risk Analysis in Dam and Levee Safety (BOR/USACE, 2019).
    - Observed or participated in at least five SQRA or quantitative risk analysis sessions.

- Have training and experience related to facilitating a semi-quantitative risk analysis or quantitative risk analysis. This includes having:
    - Attended a FERC-sponsored semi-quantitative risk analysis facilitator training workshop (or equivalent SQRA facilitator training).

- It is also recommended that the facilitator have experience in risk analysis facilitation, including having:
    - Served as a co-facilitator for at least one SQRA under the supervision and training of an experienced facilitator.

Additional knowledge, skills, and abilities a risk analysis facilitator should possess are included in Chapter 17 of the FERC Engineering Guidelines. The risk analysis facilitator must fully understand the objective and requirements of a Level 2 risk analysis. This ensures that the person leading the Level 2 risk analysis process knows not only how the process is carried out, but also is aware of what can be accomplished. This is especially critical if the Core Team members have not previously been through a Level 2 risk analysis.

Group dynamics can become even more important in the risk analysis session than in the PFMA session. There is a greater opportunity for heuristics and bias to enter the process through the estimation of risks. These concepts are discussed in Chapter 17 of the FERC Engineering Guidelines. The facilitator should have the ability to recognize and understand these concepts and the ability to lead the risk team to mitigate these occurrences when they occur.

Limitations of risk analysis facilitators are similar to those of a PFMA facilitator and include:

- Ideally, the facilitator will have limited prior project experience with respect to examining the dam's operation and history. This is considered an advantageous situation, but not a requirement, with respect to providing a fresh and vigorous look at the structure.
- A person is not eligible to serve as a Level 2 risk analysis facilitator for projects if they were the engineer-of-record for, or contributed substantially to, a significant analysis, design, or construction effort. However, the facilitator may be from the same organization provided they did not have a significant role in the analysis, design, or construction effort and can demonstrate their independence to serve as a facilitator.
- Licensees and their staff are not eligible to facilitate a Level 2 risk analysis on their own structures.
- Individuals serving as a contracted Chief Dam Safety Engineer (CDSE) or other members from their organization may not serve as a facilitator for projects in which they provide such services.
- Individuals serving as a contracted Chief Dam Safety Coordinator (CDSC) or other members from their organization may not serve as a facilitator for projects in which they provide such services.

In general, only those individuals that believe they have sufficient knowledge and understanding of the technical aspects of the potential failure mode should provide risk estimates. It is expected that not all core team members will provide risk estimates for every potential failure mode. Depending on the personalities and self-awareness of the core team members, the facilitator may need to take a more active role in limiting participation of risk estimators for certain types of failure modes.

It is **strongly suggested** that individuals that provide risk estimates have the following training (in addition to the qualifications of a core team member for a PFMA described in Chapter 17 of the FERC Engineering Guidelines):

- Attended a FERC-sponsored semi-quantitative risk analysis training workshop (or equivalent SQRA training).
- Have understanding, experience, and training in quantitative risk analysis methods, similar to those described in Best Practices for Risk Analysis in Dam and Levee Safety (BOR/USACE, 2019).

Documentation for proposed Level 2 risk analysis facilitators should be submitted in accordance with the provisions of Chapter 16 of the FERC Engineering Guidelines. Level 2 risk analysis sessions should not be conducted until the risk analysis facilitator(s) has been approved. Submittal of the names and qualifications of Level 2 risk analysis core team members is not required.

18-6 LOADING

18-6.1 General

For most dams the likelihood (frequency) of the reservoir loading under normal (static) conditions is typically high. For static or normal loading potential failure modes, the likelihood of reservoir loading can be developed from past reservoir operation records**. If the reservoir is full or nearly full for the majority of the year, a value of one (1) can be conservatively used**. Additional guidance on developing estimates of reservoir loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis, Chapter B-1 Hydrologic Hazard Analysis (BOR/USACE, 2019).

For floods or earthquakes, the likelihood (frequency) of the loading could be small. Therefore, the likelihood of the loading needs to be considered in the risk assessment.

To obtain a credible risk estimate, the hydrologic and seismic loading curves need to encompass the entire range of annual exceedance probabilities that includes capturing the critical loads for all potential failure modes, capturing the risk for all potential failure modes that might be urgent or potentially significant, and when needed, and where possible, capturing the assumed physical upper limit of the hazard. This last point becomes more important for high consequence potential failure modes. For example, seismic hazard curves extended to arbitrary annual exceedance probabilities from 1/10,000 to 1/50,000 may or may not be adequate depending on the criteria above.

18-6.2 Hydrologic Hazard

Hydrologic hazard curves for Level 2 risk analyses are usually developed from simplified screening processes and typically take the form of annual exceedance probability (AEP) (commonly referred to by hydrologists as annual chance exceedance (ACE)) for increasing reservoir levels or flood inflows. An example is shown on Figure 2. In some cases, AEP as a function of release flows, such as for spillway erosion potential failure modes, is also developed. Hydrologic hazard curves should extend far enough out to a frequency that captures the full range of response and project risk. This may require portrayal of the hydrologic hazard curve to frequencies less than what is represented by the Probable Maximum Flood (PMF) – in other words, events more remote than the PMF. More often it is sufficient to truncate the hydrologic hazard curves at a flood representing the threshold of overtopping or to a flood approaching the PMF if the dam does not overtop under such an event, provided the estimated consequences are low; however, this takes experience and judgment to determine when this would be appropriate.

There are various ways in which such curves can be developed. They typically rely on statistical evaluation of historical information and some method to estimate loading levels for more extreme flood events, possibly performing some limited flood routing using reservoir operating rule curves. **The estimated AEP of a flood that is likely to cause failure indicates the approximate likelihood of hydrologic failure**; however, for reservoirs where there is the potential for large increases in reservoir elevation (i.e., flood risk management dams), it may be necessary to subdivide the entire range of reservoir loading to identify the critical load level (see Section 18-8.3 for further discussion on critical load level). For qualitative assessments, flood loading is typically limited to existing information or information that can be easily obtained from sources such as the US Geological Survey websites (although data from the USGS websites will be limited to a flood with an AEP of about 1/500).

Guidance on developing hydrologic hazard curves for a Level 2 risk analyses is beyond the scope of this document. Supplemental information on hydrologic hazard loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter B-1 Hydrologic Hazard Analysis (BOR/USACE, 2019).

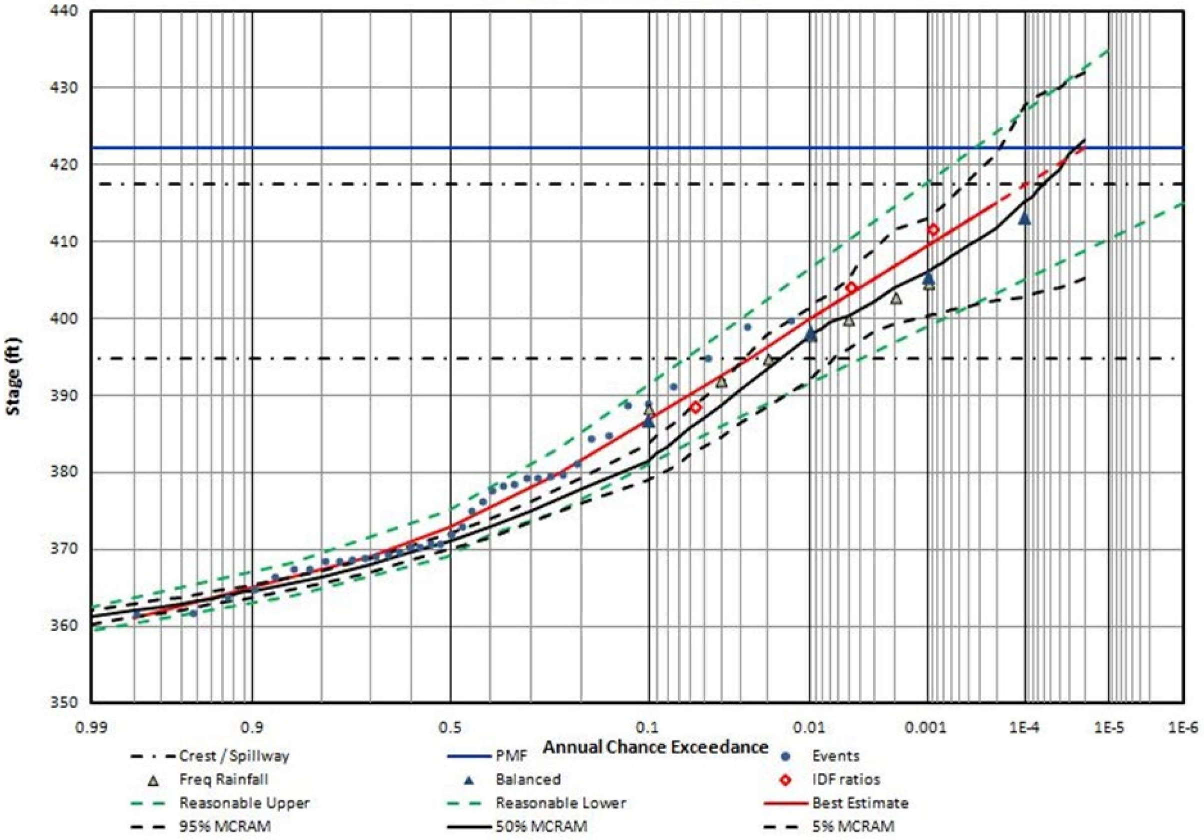

Figure 2: Example of a Stage-Frequency Hydrologic Hazard Curve

The influence of discharge reduction due to partial or full blockage of discharge facilities due to debris loading and gate reliability impacts should also be evaluated, when appropriate, in developing hydrologic hazard curves.

18-6.3 Seismic Hazard

An estimate of the seismic hazard at a dam site is needed to assess the probability of ground shaking caused by earthquakes that could lead to an adverse response of the dam, appurtenances, and components. If a detailed probabilistic seismic hazard study is available for a site, it would be used in the assessment. However, if such a study is not available, simplified seismic hazard curves such as those available from the USGS website are used. Typically, seismic hazard curves with AEP out to 1/10,000 to 1/50,000 are needed, with the more remote values needed for higher consequence projects. An example probabilistic seismic hazard curve is shown on Figure 3. Seismic hazard curves representing peak horizontal ground acceleration are typically considered. For some concrete and steel structures, seismic hazard curves corresponding to the spectral acceleration at the natural period of the structure may be more useful. **The estimated AEP of an earthquake that is likely to cause failure indicates the approximate likelihood of seismic failure**.

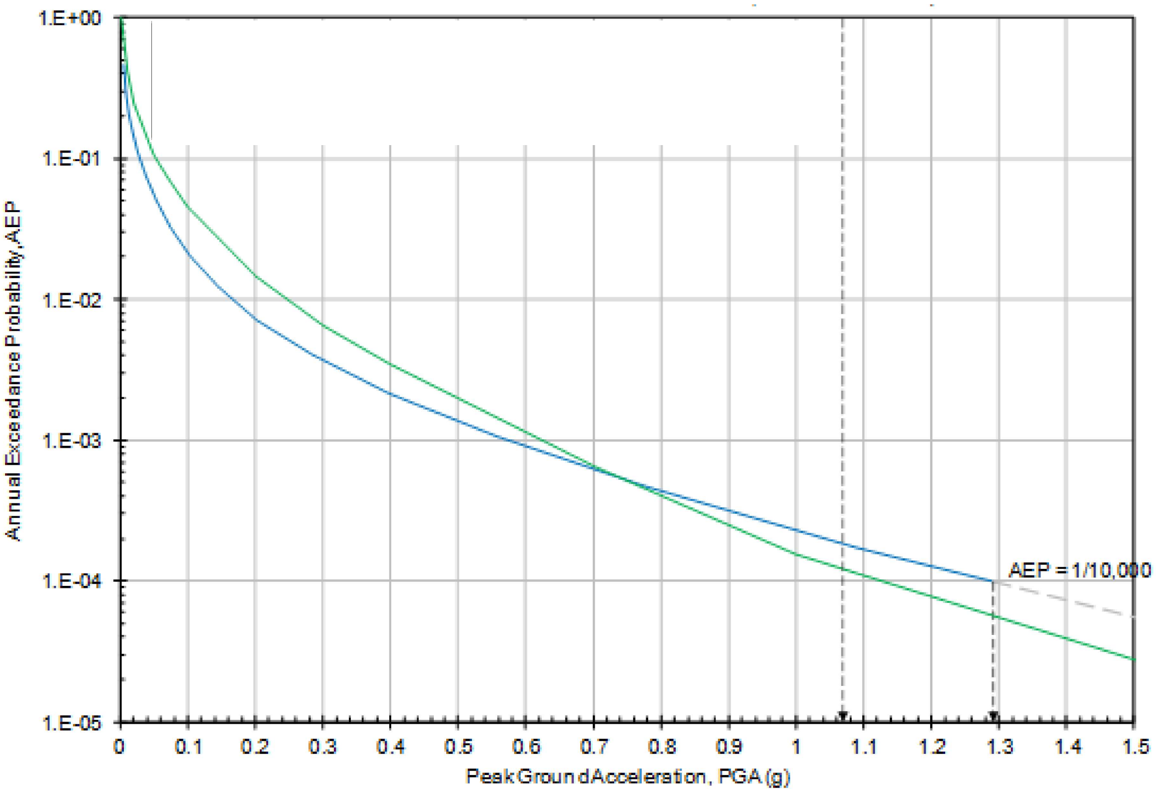

Figure 3: Example of a Probabilistic Seismic Hazard Curve

For some flood risk management projects, water supply projects, irrigation projects, and other facilities where the reservoir level can vary significantly throughout the year, the probability of the initial reservoir level at the time of the earthquake must also be considered. This information should be obtained from a reservoir stage-duration relationship; for these projects, the approximate likelihood of seismic failure is a function of the joint probability of exceeding a particular reservoir elevation and seismic acceleration.

A general description of probabilistic seismic hazard analyses can be found in Chapter 13 – Evaluation of Earthquake Ground Motions of the FERC Engineering Guidelines. Additional guidance on developing estimates of seismic hazard loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter B-2 Seismic Hazard Analysis (BOR/USACE, 2019).

18-6.4 Other Loading Conditions

The magnitude and frequency of other loads may also be required. These might include environmental conditions such as ice loads, the use of dewatering bulkheads or caissons, and other operational conditions such as changes to reservoir or flood loading due to extended duration maintenance activities or other special circumstances. Some examples might include:

- Multi-year maintenance or refurbishment of water discharge features (gates, turbines, etc.) that may change project discharge capacity. This may require re-evaluation of hydrologic hazard frequency for the project.
- Temporary and recurring changes to tailwater elevation that could impact project discharge capacity. This may require re-evaluation of hydrologic hazard frequency for the project.

18-7 POTENTIAL FAILURE MODES

18-7.1 Identification and Evaluation of Potential Failure Modes

The foundation of the Level 2 risk analysis is the identification and development of a clear and comprehensive list of all the project's potential failure modes based on the project's vulnerabilities. If this first step is not diligent and thorough, it can have a significant adverse impact on the results of the risk analysis and may lead to inappropriate or incorrect conclusions and subsequent actions. Missing potential failure modes, particularly those potential failure modes that are critical to the estimation of risk, and potential failure modes that are unclear or are ambiguous have the potential to jeopardize or nullify the results of the risk analysis.

The process of identifying, developing, and evaluating potential failure modes is documented in Chapter 17 of the FERC Engineering Guidelines.

Candidate potential failure modes that are developed in a PFMA that are considered credible, including those considered "credible" and "urgent," and financial/damage state potential failure modes are the potential failure modes that initially are carried forward into a Level 2 risk analysis. Other potential failure modes, including ruled out, clearly negligible, and asset management potential failure modes are not included in a Level 2 risk analysis.

Insufficient information potential failure modes should also be carried forward into a Level 2 risk analysis. The risk analysis team should endeavor to screen and provide likelihood estimates, when and where possible, similar to credible potential failure modes. While these potential failure modes may not have sufficient information to estimate a single likelihood and consequence, there may be sufficient information to establish a range of likelihoods or consequences that could be important in prioritizing future investigations or studies, as well as the need for interim measures. It is recognized that it might not be possible to further screen and provide likelihood estimates for every insufficient information potential failure mode; however, the team should do their best in attempting to do so as these discussions can greatly aide in identifying the investigations or studies that are needed to effectively reduce uncertainty.

This potential failure mode screening process described in Chapter 17 is shown on Figure 4.

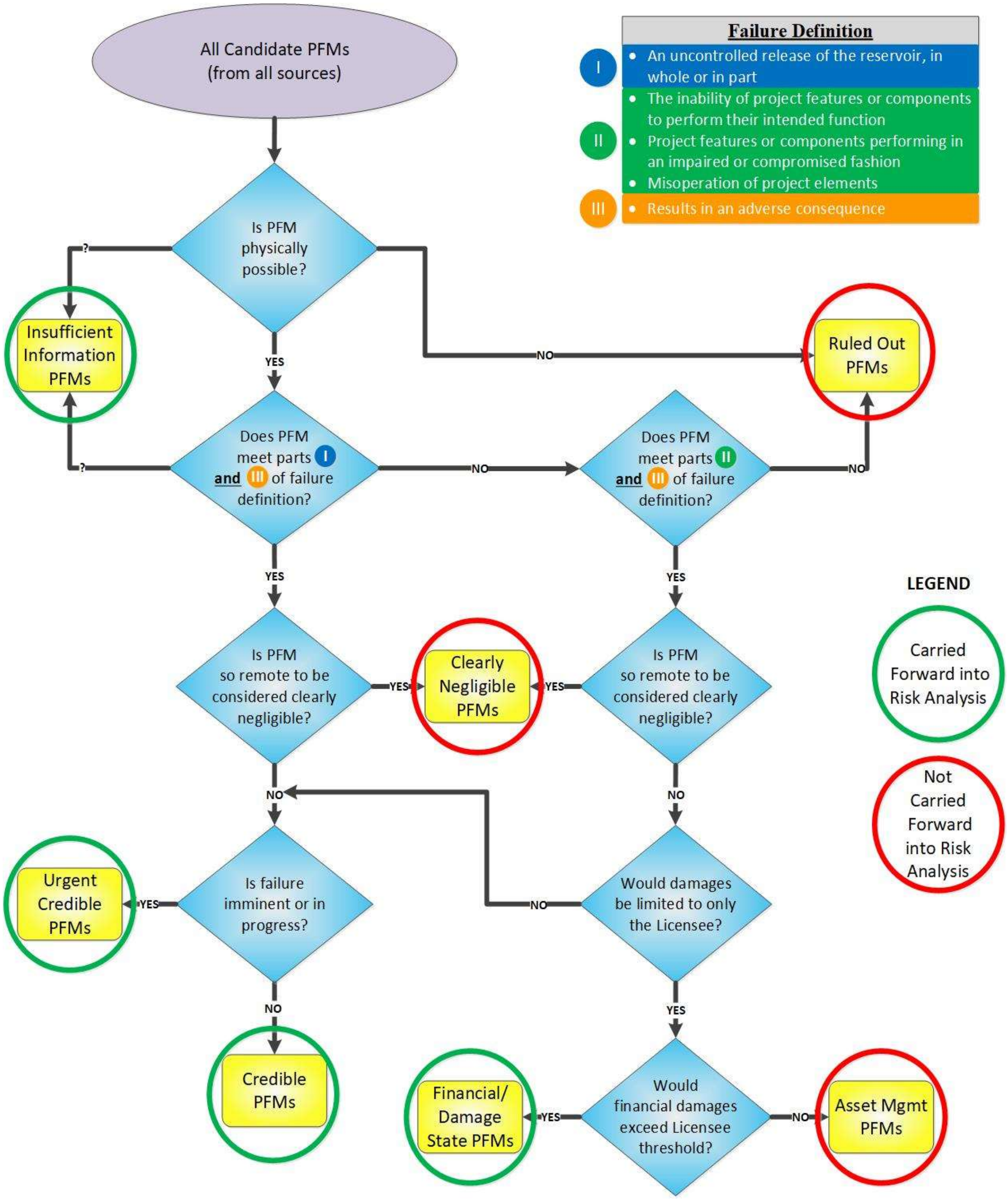

Figure 4: Potential Failure Mode Screening Process

18-7.2 Screening of Potential Failure Modes for Risk Analysis

For most projects, the results of the PFMA will generate a large number of potential failure modes. In most cases, not all of these potential failure modes need to be evaluated in a risk analysis. Only those potential failure modes that substantially contribute to the risk profile of the project need to be evaluated in a risk analysis. This requires screening the credible potential failure modes identified in the PFMA. The goal of screening is to identify those potential failure modes that need to go into the risk analysis process versus those that do not, which allows the participants to focus their efforts on the potential failure modes that contribute to the risk profile.

In addition to the information gained from the PFMA, the screening of credible potential failure modes requires knowledge and understanding of each potential failure mode's estimated:

1. loading frequency (discussed in Section 18-6),
2. likelihood of failure (discussed in Section 18-8), and
3. consequences (discussed in Section 18-9).

The refined screening of credible potential failure modes will result in the potential failure modes further differentiated into potentially significant and insignificant. Potentially significant potential failure modes are those that contribute substantially to the total project. Insignificant potential failure modes are those that after additional evaluation and discussion are considered to be so remote as to be considered negligible (see Chapter 17 of the FERC Engineering Guidelines for additional information). In some cases, after further evaluation and discussion, it is possible that a credible potential failure mode may be revised to an urgent, insufficient information, or ruled out based on the definitions included in Chapter 17 of the FERC Engineering Guidelines. The overall potential failure mode screening process is shown on Figure 5. It is worth mentioning that when performing a Level 2 risk analysis, the screening process performed as part of the PFMA and the refined screening performed as part of the Level 2 risk analysis can be combined into one overall process.

Urgent, potentially significant, financial/damage state, and insufficient information potential failure modes are carried into the risk analysis.

The rationale for why a potential failure mode is classified as insignificant and is not carried forward into the risk analysis is documented similar to the approach used to document clearly negligible potential failure modes from the PFMA process (see Chapter 17 of the FERC Engineering Guidelines for more information and examples).

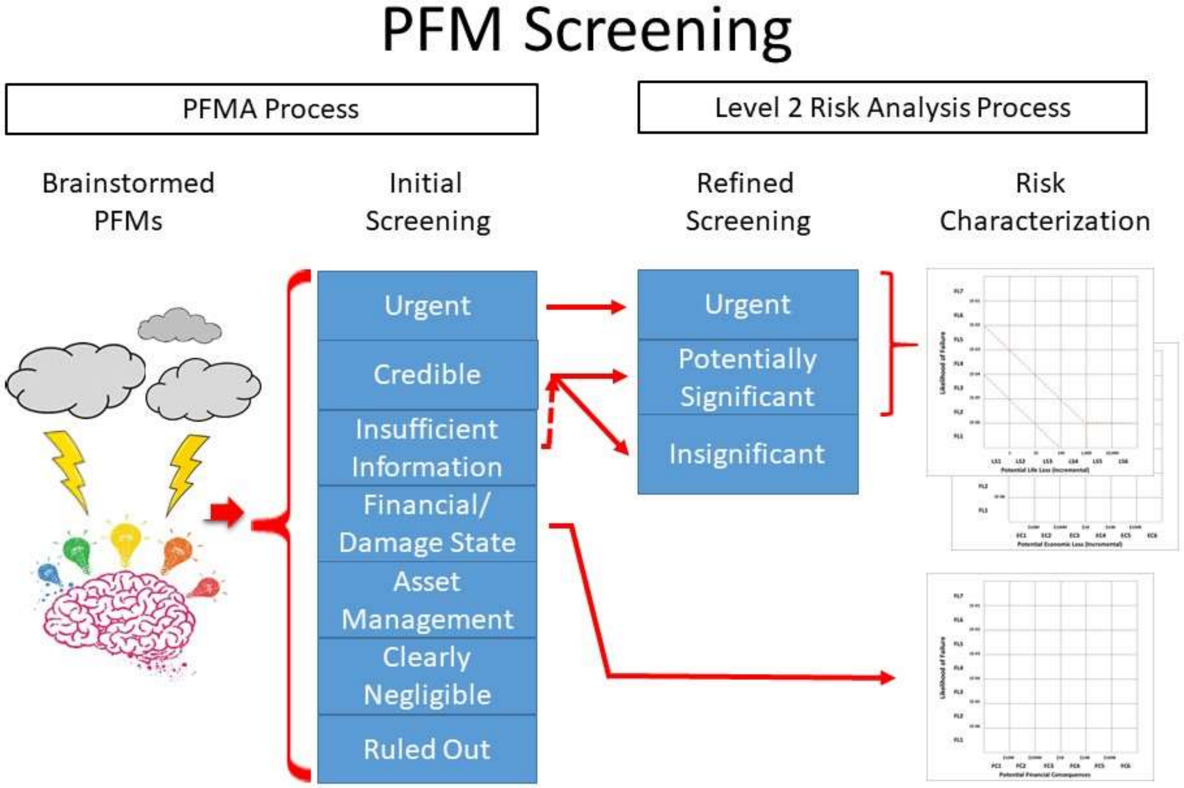

Figure 5: Overall Process of Screening PFMs

18-8 FAILURE LIKELIHOOD

One component of estimating risk is the probability or likelihood of failure. The likelihood of failure is an estimate of the annual probability of failure (APF) based on the strength and weight of the evidence. Dam failure is often characterized by the sudden, rapid, and uncontrolled rapid release of impounded water. Failure likelihood also includes partial or operational failures that may not lead to an uncontrolled release of the reservoir, but can still result in consequences. The likelihood of failure is a function of both the probability of the loading condition that could lead to failure (described in Section 18-6) and the likelihood of failure given the loading condition, described below.

18-8.1 Influence Factors

Part of the effort in developing the information to support the failure likelihood for each potential failure mode carried into the risk analysis is identifying the presence of features or susceptibilities that may lead to vulnerabilities for the dam. A susceptibility is a condition or state of nature (e.g., material can crack, internally unstable gradation, continuous uniform fine sand, untreated foundation contact, steep abutment slope with overhangs). Vulnerability can be a process. For example, an embankment that is susceptible to cracking may become vulnerable to concentrated leak erosion (scour).

Factors that may exacerbate or may mitigate vulnerabilities associated with potential failure modes are identified and evaluated using 'more likely' and 'less likely' factors, and presented in influence tables. Chapter 17 of the FERC Engineering Guidelines provides guidance on developing 'more likely' and 'less likely' factors for each potential failure mode.

For potential failure modes from previous PFMA reports, these 'more likely-less likely' tables, should be reviewed, revised, and expanded, as necessary. For new potential failure modes these factors must be developed, including providing analytical results where applicable, and identifying the key factors, in accordance with the guidance provided in Chapter 17 of the FERC Engineering Guidelines.

Some examples of critical information related to factors that may lead to vulnerabilities include the following:

- Internal erosion failure mechanisms and considerations
    - Concentrated leak erosion (scour): plasticity index, placement moisture content, measured settlement, foundation profile, observed cracking, filters, annual chance exceedance of a flood to reach the elevation of an expected crack or top of filter, embankment erodibility, hydraulic shear stress, etc.
    - Backward erosion piping: continuous fine to medium uniform sand, unfiltered exit, hydraulic gradients, roof material, toe drain or relief well condition, filter compatibility, size and activity of sand boils, etc.

    - Suffusion/suffosion: broadly-graded materials with a flat tail of fines, gap-graded material, material within Sherard's unstable band.
    - Erosion into open rock defects (internal migration): size of the defects, effectiveness of foundation treatment, hydraulic gradient into the foundation, pressurization, etc.
    - Soil contact erosion: coarse layer in contact with fine layer with flow parallel to the contact, filter compatibility, Darcy velocities, etc.

- Instability failure mechanisms and considerations
    - Slope instability: as-built slopes, design factor of safety, seepage and shear strength assumptions, normal freeboard, normal phreatic surface, etc.
    - Foundation or embankment liquefaction: seismicity, triggering ground motion and moment magnitude, expected deformation and cracking, cohesionless soils (gravel, sands, or very low plasticity silts), in-situ index (SPT, CPT, BPT, Vs), fines content, normal freeboard, normal phreatic surface, saturation, etc.
    - Monolith instability: cracks, displacement or leakage along lift joints or other locations, construction methods related to treatment between concrete placements, reinforcement at lift joints or cracks, significant reductions of cross section that could be loaded more than originally designed, performance history, design factor of safety, uplift and drain efficiency, foundation conditions, seismic considerations, etc.

- Hydrologic-related failure mechanisms and considerations
    - Overtopping erosion (flood water level plus wind setup exceeds crest elevation): annual chance exceedance of reservoir elevation, overtopping duration, wind setup, crest width, protection, embankment erodibility, knickpoints, vegetation or other protrusions into the flow, foundation erodibility, etc.
    - Overwash erosion (flood water level plus wind setup does not exceed crest elevation and results in intermittent wave overtopping): annual chance exceedance, threshold flood, freeboard, wave run up, overwash duration, overwash discharge and cumulative volume, see also overtopping erosion.
    - Unlined spillway erosion: annual chance exceedance of control elevation or damage threshold, weir/sill, erodible materials, headcut distance, armoring, velocity, duration, timing of breach, etc.

Uncertainties should not be listed as 'more likely' or' less likely' factors. Uncertainties should be discussed separately, as discussed in Section 18-10.2.

18-8.2 Likelihood of Failure Approaches

Three approaches are available for estimating failure likelihood in Level 2 risk analyses:

1. A descriptive approach in which a relative comparison is made to an anchoring annual probability of failure;
2. A critical load approach that involves a more explicit estimation of the annual probability of failure; and
3. A quantitative approach that uses event trees, fault trees or other quantitative methods more typical of quantitative risk analyses.

Each approach is described in the following sections. In all approaches, the 'best estimate' of the failure likelihood is sought. In some cases, the range of the 'best estimate' can be provided; however, in these cases the estimates should be clearly identified as such.

18-8.2.1 Descriptive Approach

Examination of historical dam failure studies indicates that dams have failed at a rate of approximately 1 in 10,000 per dam year of operation (for both concrete and embankment dams), depending on the failure mode and age of the structure, Douglas et al. (1998), Foster et al. (1998), Hatem (1985), Von Thun (1985), and Whitman (1984). Using this approach, the likelihood of failure is assessed relative to the historical dam failure rate. For example, if the key factors affecting the potential failure mode are weighted toward adverse (more likely), the annual failure likelihood is probably greater than 1/10,000. If weighted toward favorable (less likely), then the annual failure likelihood is probably less than 1/10,000.

For this approach the failure likelihood should be estimated using the information contained in Table 1. **For non-dam structures, it may be appropriate to modify the descriptors and annual failure likelihood, tailoring them to the project being evaluated.**

Failure likelihood descriptors in Table 1 include both the frequency of the load AND the likelihood of failure given the load.

This approach requires less rigor and may be appropriate for potential failure modes where the likelihood of the loading is high (e.g., during normal operating conditions for dams) or hydrologic potential failure modes where a certain flood is very likely to cause failure, as well as making rapid assessments with appropriately facilitated teams. However, it is difficult to assess potential failure modes where there is not a well-defined flood trigger or threshold to initiate and progress to breach. In this case one of the other approaches may be better suited to assess the likelihood of failure.

Table 1: Failure Likelihood Descriptors

Failure Likelihood Category	Descriptors/Evidence	Annual Failure Likelihood
FL7	There is direct evidence to suggest it is certain to nearly certain that failure is imminent or extremely likely in the next few years.	more frequent (greater) than 1/10
FL6	There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is very likely to occur during the life of the structure.	1/10 to 1/100
FL5	There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is likely to initiate.	1/100 to 1/1,000
FL4	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "more likely" than "less likely."	1/1,000 to 1/10,000
FL3	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "less likely" than "more likely."	1/10,000 to 1/100,000
FL2	The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to initiation.	1/100,000 to 1/1,000,000
FL1	Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood such that the failure likelihood is negligible.	more remote (less) than 1/1,000,000

It should be noted that the verbal descriptors in Table 1 do not work well for estimating the likelihood of failure of electrical and mechanical components. One alternate method to estimate the likelihood of failure of mechanical and electrical components is to consider the reliability of the critical components in more quantitative terms as described in Section 18-8.2.3.

For further clarification, a more remote (less than 1/1,000,000) likelihood would be appropriate for the following conditions:

- Remote loading is needed to initiate the potential failure mode. For example, overwash erosion due to inadequate freeboard with the following facts:
    - Potential failure mode elevation is within 3 feet of a 30-foot-wide crest
    - The duration of the potential failure mode peak elevation is only 6 hours
    - AEP of the potential failure mode is less than 1/100,000
- Joint-loading probability is remote (e.g., likelihood of a large earthquake resulting in slope instability with large crest deformations in conjunction with a large storm approaching the potential failure mode).
- Several events must occur in series to cause failure, and the likelihood of those events is remote (e.g., undermining of stilling basin slab, downstream toe erosion, progressive slope failure, and overtopping).

The failure likelihood for each potential failure mode can be estimated using the process outlined in Table 2.

Table 2: Failure Likelihood Development Process

Step	Task
1 – Initial Discussions	Led by the facilitator, the participants discuss the more and less likely factors and other relevant information relative to the potential failure mode. After the participants have completed their discussions the facilitator confirms those individuals who will be providing failure likelihood estimates for the potential failure mode.
2 -Initial Estimates	Initial failure likelihood estimates along with the rationale for the estimates are developed using the guidance in Table 1 above and submitted by individuals identified as estimators.
3- Review and Discussion of Initial Estimates	Initial estimates are collated and presented to the participants. Led by the facilitator, individuals are asked to provide a brief discussion of their estimate and reasoning behind their estimate. This typically prompts discussion among team members.
4 – Development of Consensus Estimate	After the discussion of the initial estimates has died down, the facilitator either: a) summarizes what has been said, proposes a "consensus" likelihood and the reasoning why it makes sense, and then asks if there are any objections, or b) asks the estimators to re-estimate the failure likelihood based on the discussions of the initial estimates. If a consensus cannot be reached through a) or b) above, the range of estimates is captured along with the rationale.
5 - Documentation	The facilitator or designated recorder captures the information, including the likelihood and the rationale for its assignment. The confidence in the rating is also captured, along with the rationale for its assignment and what additional information could be gathered to improve the confidence rating, if applicable.

18-8.2.2 Critical Load Level Approach

In developing estimates for the likelihood of failure, it can be important to determine the critical load level (AEP) for the potential failure mode being evaluated. This is particularly important for potential failure modes where the frequency of the load varies (flood, seismic, etc.). The likelihood of failure is a function of both the likelihood of the loading condition that could lead to failure and the likelihood of failure given the loading condition. For normal operating conditions, the likelihood of the loading is high. However, for floods or earthquakes, the likelihood of the loading could be small. Therefore, the failure likelihood estimate can be improved by considering the likelihood of the loading. This requires identifying the critical loading level for the potential failure mode under consideration. For seismic potential failure modes, the probability of the earthquake and the coincident water level must be considered. At high AEP, the performance of the dam might be expected to be very good; however, as the AEP decreases and the magnitude of the load increases, the performance of the dam may decrease to the point where failure could become likely. Where this expected performance indicator changes is a critical load level.

For example, tailwater can significantly affect the critical load level. The maximum high pool may result in a lower differential hydraulic head for initiation of a potential failure mode and breach at that reservoir level and may result in lower incremental life loss due to warning and evacuation of the population at risk (PAR) for uncontrolled spillway releases prior to breach. In this case, a reservoir level at the spillway crest may be more critical for differential hydraulic head and result in higher incremental life loss. If the AEP of the flood for the critical load level (from a reservoir stage-frequency relationship) is virtually certain to cause failure, then the annual probability of failure is essentially equal to the AEP of that flood.

It is suggested to start the failure likelihood with the AEP of the critical load level, and then reduce that probability based on the likelihood of the step-by-step progression leading to failure (i.e., subsequent nodes in an event tree have probabilities less than one). With this approach a more precise estimate of the range of annualized probability of failure can be made than the semi-quantitative/descriptive approach. An example of this is shown graphically on Figure 6. Estimating the critical loading level can be difficult, especially when the performance is not well understood for the full range of loading and there is not a well-defined trigger or threshold to initiate and progress to breach.

For example, the AEP becomes smaller at higher and higher reservoir water surface elevations. An overtopping potential failure mode is typically not a concern until the reservoir elevation approaches the dam crest elevation or some other critical elevation. This may occur before the reservoir elevation reaches the PMF elevation. More frequent floods than the PMF may result in overtopping, erosion, breach, and failure of the dam.

The following is a simplified example. Consider a potential failure mode of foundation liquefaction for an embankment dam. The probability of the seismic load from a probabilistic seismic hazard analysis (PSHA) is shown on Figure 7. Seismic and deformation analyses have been performed for the dam for various seismic loads and the results indicate that for levels of ground shaking below 0.2g, liquefaction is very unlikely. For ground shaking above 0.9g liquefaction and dam failure is very likely. For ground shaking of 0.5g, liquefaction and dam failure is likely. From this information the probability of failure given certain levels of shaking was estimated and is shown on Figure 8. So, the question is, what is the critical load level that should be considered in the risk analysis?

By inspection of the curves on Figures 7 and 8, the answer to that question may not be immediately obvious. Is the critical load case a result of the highest level of shaking or is it for a lower level of shaking?

Starting at the highest load level, the annual exceedance probability (AEP) is 1 x 10^{-5}. The likelihood of failure at this load level is 1, so the approximate annualized probability of failure (between 1 x 10^{-5} and 1 x 10^{-4}) is 8.6 x 10^{-5}. The next lowest load level the AEP is 1 x 10^{-4}. The likelihood of failure at this load level is 0.9, and the approximate annualized probability of failure (between 1 x 10^{-4} and 1 x 10^{-3}) is 4.1 x 10^{-4}. This can be done for each load level as shown in Table 3. This quick evaluation shows that the second to the highest load level is the critical load level.

Table 4 shows the various load levels used in the example and the resulting failure likelihood ranges indicating a higher failure likelihood for the critical load level in bold text.

The information and rationale for determining the critical load level for each potential failure mode should be captured and documented in the report.

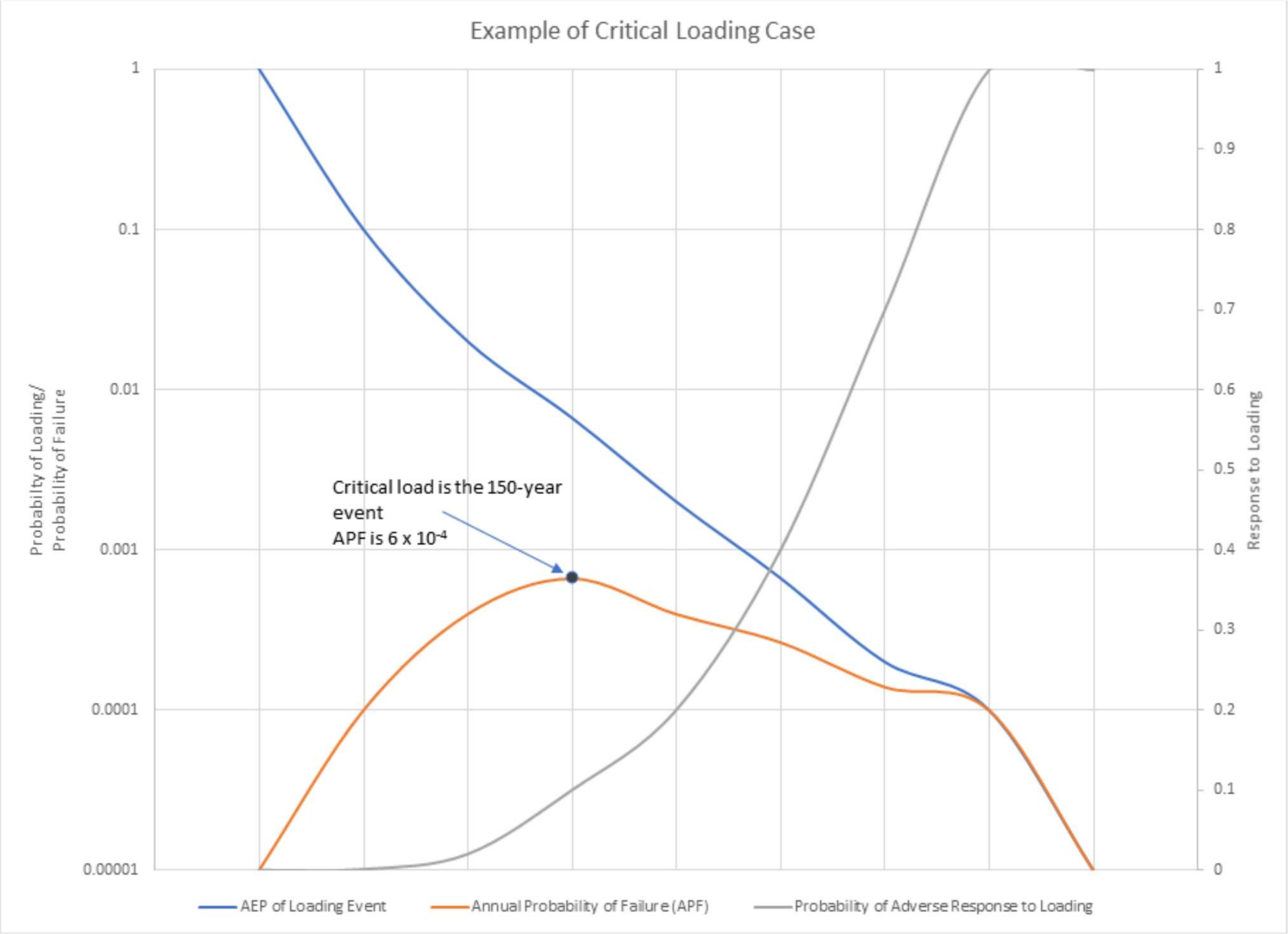

Figure 6: Graphic Illustration of Critical Load Case

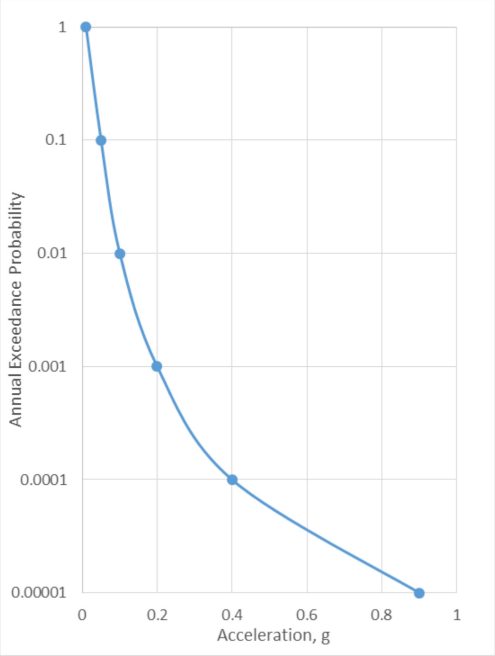

Figure 7: Probabilistic Seismic Hazard Loading Curve

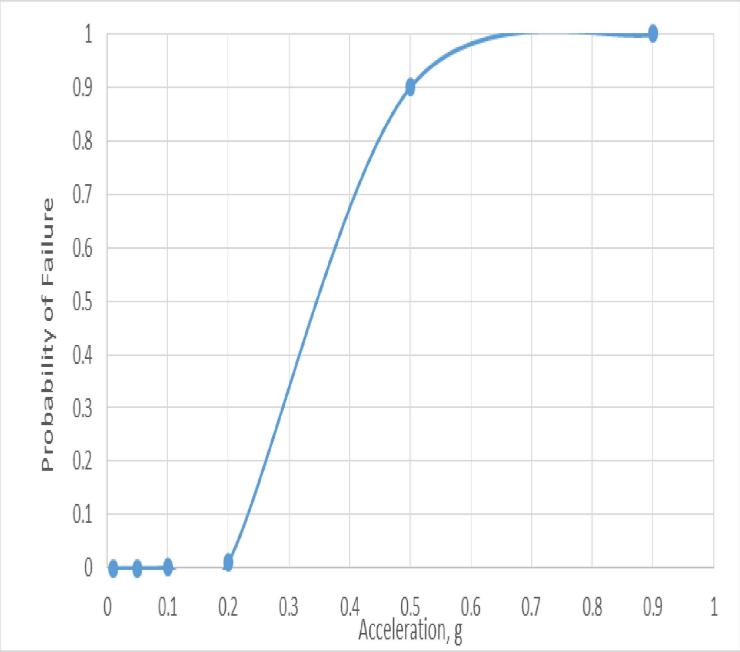

Figure 8: Probability of Embankment Failure for Various Levels of Shaking

Table 3: Critical Load Level Example

AEP	Acceleration, g	Emb. Failure Estimate	Annual Prob. of Load Range	Avg. Prob. of Failure	Annual Prob. of Failure	Comments
1	0.01	0				
			0.9	0	0	
0.1	0.05	0				
			0.09	0.0005	4.5×10^{-5}	
0.01	0.1	0.001				
			0.009	0.0055	5.0×10^{-5}	
0.001	0.2	0.01				
			0.0009	**0.455**	**4.1×10^{-4}**	**Critical Load Level**
0.0001	0.5	0.9				
			0.00009	0.95	8.6×10^{-5}	
0.00001	0.9	1				

Table 4: Critical Load Level Example with Failure Likelihood

<table>
<tr><th>AEP</th><th>Acceleration, g</th><th>Embankment Failure Estimate</th><th>Annual Probability of Failure</th><th>Failure Likelihood Range</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">0.01</td><td rowspan="2">0</td><td></td><td></td></tr>
<tr><td rowspan="2">0</td><td rowspan="2">None</td></tr>
<tr><td rowspan="2">0.1</td><td rowspan="2">0.05</td><td rowspan="2">0</td></tr>
<tr><td rowspan="2">4.5 x 10^{-5}</td><td rowspan="2">1 x 10^{-4} to 1 x 10^{-5}</td></tr>
<tr><td rowspan="2">0.01</td><td rowspan="2">0.1</td><td rowspan="2">0.001</td></tr>
<tr><td rowspan="2">5.0 x 10^{-5}</td><td rowspan="2">1 x 10^{-4} to 1 x 10^{-5}</td></tr>
<tr><td rowspan="2">0.001</td><td rowspan="2">0.2</td><td rowspan="2">0.01</td></tr>
<tr><td rowspan="2">**4.1 x 10^{-4}**</td><td rowspan="2">**1 x 10^{-3} to 1 x 10^{-4}**</td></tr>
<tr><td rowspan="2">0.0001</td><td rowspan="2">0.5</td><td rowspan="2">0.9</td></tr>
<tr><td rowspan="2">8.6 x 10^{-5}</td><td rowspan="2">1 x 10^{-4} to 1 x 10^{-5}</td></tr>
<tr><td rowspan="2">0.00001</td><td rowspan="2">0.9</td><td rowspan="2">1</td></tr>
<tr><td></td><td></td></tr>
</table>

18-8.2.3 Quantitative Approach

If one finds difficulty estimating the failure likelihood using the previously discussed approaches, then an alternate approach could be to use event trees or fault trees. Event tree analysis is a commonly used tool in dam safety risk analysis to identify, characterize, and estimate risk. Quantitative estimates for probability of breach or failure and the resulting consequences can be obtained using event trees. Qualitative depictions of potential failure modes and consequences can also be developed using event trees.

For some it is common practice to develop detailed event trees for individual potential failure modes to clearly identify the full sequence of steps required to obtain failure or breach. If the potential failure mode description is complete, then construction of an event tree should be relatively straight forward. A logical progression of events is represented by the event tree beginning with an initiating event and continuing through to a set of outcomes. A typical progression might include an initiating event (flood or earthquake) followed by a system response (breach or non-breach) resulting in potential consequences (life loss, economic). Additional contributing events such as inoperable spillway gates (initiating event), flood fighting (system response), and exposure (consequences) should also be considered in the event tree. In the case of using an event tree for the failure likelihood the consequence part of the event tree would not be included.

An event tree consists of a sequence of interconnected nodes and branches. Each node defines a random variable that represents an uncertain event (a crack forms in the embankment) or state of nature (existence of adversely oriented joint planes). Branches originating from a node represent each of the possible events or states of nature that can occur. Probabilities are estimated for each branch to represent the likelihood for each event or condition. These probabilities are conditional on the occurrence of the preceding events to the left in the tree. Nodal estimates can be estimated by subjective probability using Table 5.

Table 5: Subjective Probability Descriptors

Descriptor	Associated Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Risks are typically annualized (e.g., probability of breach per year or annual life loss) in the event tree by using annual probabilities to characterize the loading conditions. The conditional structure of the event tree allows the probability for any sequence of events to be computed by multiplying the probabilities for each branch along a pathway. The branching structure of the event tree, which requires that all branches originating from a node be mutually exclusive and collectively exhaustive, allows the probability for any combination of events (e.g., total failure probability for a potential failure mode) to be computed by summing branch probabilities across multiple pathways.

Event trees can be developed for individual potential failure modes to clearly identify the full sequence of steps required to obtain failure or breach. Each potential failure mode is decomposed into a sequence of component events and conditions that all must occur for the breach to develop. This ensures that due consideration is given to each event in the failure sequence. It also supports the identification of key issues contributing to the risk. A typical event tree structure for an internal erosion potential failure mode is illustrated on Figure 9. A challenge with estimating event tree probabilities is remembering that each branch is conditional on predecessor branches.

Additional guidance on use of event trees for dam safety risk analysis is provided in Best Practices in Dam and Levee Safety Risk Analysis, Chapter A-5 Event Trees (BOR/USACE, 2019).

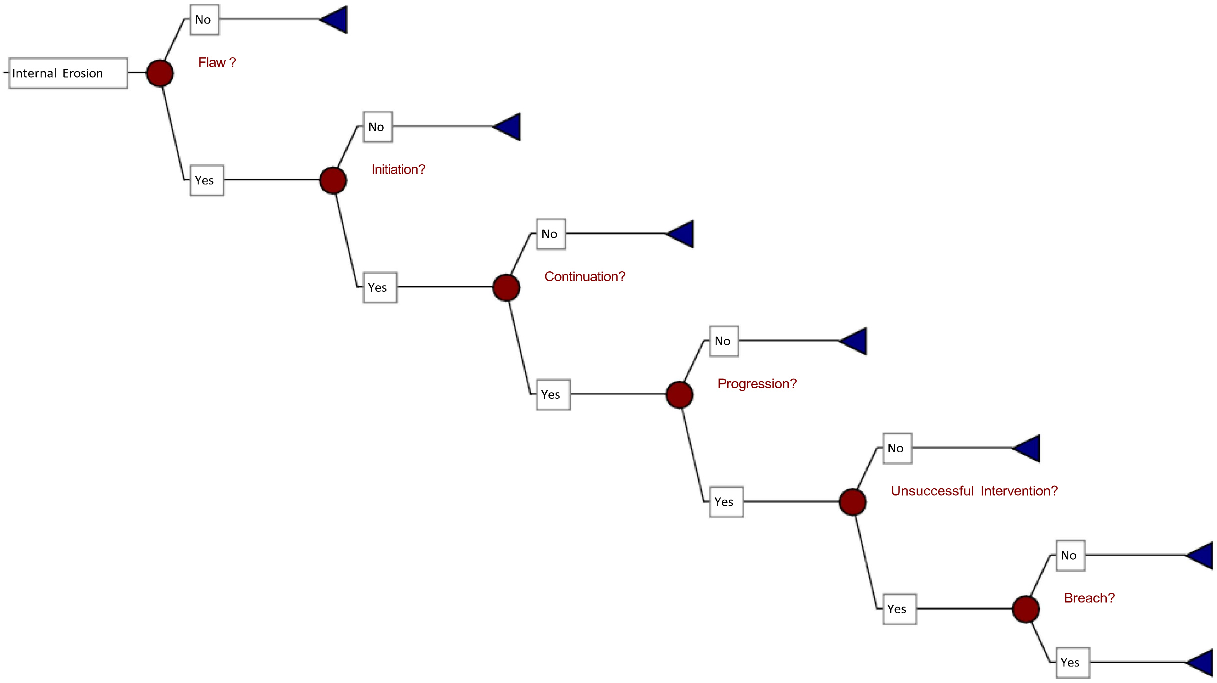

Figure 9: Example Internal Erosion Potential Failure Mode Event Tree

18-8.3 Intervention

The potential for intervention to reduce the likelihood of failure must be considered when estimating the failure likelihood. In some cases, it may be appropriate to consider cases with and without intervention. The likelihood that intervention is successful should be based on realistic estimates, considering whether procedures are in place, materials are available, and personnel are adequately trained, among other factors. Successful intervention is not guaranteed even with the most qualified responders.

18-8.4 Failure Likelihood Justification

The rationale for the selected failure likelihood for each potential failure mode should be synthesized from the pertinent information from the background, performance, and more likely/less likely table to build the case for the failure likelihood. As discussed above, the rationale should include critical information related to susceptibilities that may lead to vulnerabilities. It should also include a discussion of the key pieces of evidence that drove the team's assigned descriptor for failure likelihood. The rationale should clearly document the team's assumptions and understanding so that future reviewers of the information and discussion can understand what the team was thinking and whether there are changed conditions, improved knowledge, or improved state of practice that would affect the risk assessment.

18-9 CONSEQUENCES

18-9.1 General

Another component of estimating risk is consequences. The consequences of failure, as failure is defined in Chapter 17 of the Engineering Guidelines, can be varied. Consequences are not limited to only the sudden, rapid, and uncontrolled release of impounded water, but also include partial or operational failures that can result in significant adverse consequences. Traditionally, life safety consequences have been the primary and often the only consequence considered as a result of failure; however, there can be other types of consequences. Life safety is considered paramount and other consequences should be considered as that information can serve to help prioritize dam safety actions.

Similar to the likelihood of failure estimate, a consequence estimate is based on the strength and weight of the evidence.

Factors that may increase or decrease the magnitude of the consequences associated with potential failure modes are identified and can be considered in the ‘more likely’ and ‘less likely’ evaluation factors and presented in influence tables. Chapter 17 of the FERC Engineering Guidelines provides guidance on developing ‘more likely’ and ‘less likely’ factors for each potential failure mode.

Each type of consequence is described in the following sections. For all types of consequences, the best estimate order of magnitude range of the consequences is sought. In some cases, the range of the best estimate can be provided; however, in these cases the estimates should be clearly identified as such.

Consequence estimates should include both direct and indirect losses. For example, for life loss consequences, direct life loss, as defined in Chapter C-1 of Best Practices in Dam and Levee Safety Risk Analysis (BOR/USACE, 2019), is the loss of life caused by direct exposure to the physical effects of the flood. More specifically, direct life loss is that caused by drowning or being crushed by a building that collapses due to flooding. Indirect life loss includes those people that lose their life due to other flood related issues such as stress leading to heart attack or suicide, illness, or prolonged exposure to the elements at an emergency evacuation location (e.g., attic, overpass, etc.).

18-9.2 Life Safety Consequences

An evaluation of dam failure case histories (Graham, 1999) indicates that the number of fatalities is primarily dependent on:

1. The population at risk within the dam-break inundation boundary,
2. The severity of the flooding, and
3. The amount of warning time the population at risk has to evacuate the area.

The population at risk can be broadly categorized by the size of the towns and development within the inundation zone as well as transient activity (e.g., seasonal campgrounds). The severity of flooding is a function of the potential destruction to structures and infrastructure within the floodplain. The warning time is a function of when the warnings are issued and the time it takes for the flood wave to reach the population at risk. Other significant considerations include the degree to which the population at risk understands the seriousness of the potential flooding and the availability, the clarity and effectiveness of the warning, the time it takes for people to mobilize, and clarity of possible evacuation routes.

The potential for evacuation must be considered when estimating the life loss consequence. In the case of breach risks, incremental consequences (consequences over and above those that would occur without failure) are considered when assigning the consequences. For non-breach risks associated with planned operational releases, total consequences drive the consequence estimates.

The essential elements of evaluating life safety consequences include the following:

- Initial distribution of people
    - Primary impact areas: communities, residential / commercial / industrial, state / county
    - Estimated population at risk
    - Distance downstream from dam
    - Spatial location and population density

- Redistribution of people (evacuation effectiveness)
    - Threat recognition and warning issuance: flood forecast or hazard (failure mode) detection, hazard communication and warning issuance delays (relative to breach initiation), initial non-breach warning (double-warning scenario).
    - Warning diffusion: Factors that most influence how quickly an alert or warning spreads through a community (number and mix of warning channels, frequency of distribution, ability to wake people up, and modern technologies). Warning channels include EAS, sirens, reverse 911 but also improvements by word-of-mouth due to dense urban environment, sheriff door-to-door or drive-by announcement.
    - Protective action initiation: Factors that most influence how quickly someone takes the recommended protective action after receiving a warning (message content and style, message spoken by a person, and messages frequently repeated).

  - Evacuation potential (ability to get to safety before water arrives): distance to clear inundation limits, special evacuation assistance facilities, available road network or routes, traffic density and jams, etc.

- Flood characteristics
  - Flood wave arrival time, depth, and velocity (all from hydraulic model) if available

- Shelter provided by final location
  - Potential for vertical evacuation and shelter in-place: number of stories
  - Survivability: structure damage, human stability, and vehicle stability

Similar to the failure likelihood process described in Section 18-8.2, this process is repeated to arrive at a life safety consequence estimate for each potential failure mode. It is especially important during this process to note differences between the likely breach flows associated with a potential failure mode and what has been assumed in the breach inundation studies. In many cases, the breach outflow associated with a potential failure mode would be considerably less than assumed in the worst-case inundation studies.

Three general approaches are available for estimating life safety consequences in Level 2 risk analyses:

1. A descriptive approach based on verbal descriptions,
2. An empirical approach that uses the results of case history data to estimate fatality rates, and
3. A simulation approach that models estimated life loss.

18-9.2.1 Descriptive Approach

For this approach the life safety consequences should be estimated using the information contained in Table 6. This approach may be appropriate where little to no consequence information is available. If no significant impacts to the population at risk other than temporary minor, non-life-threatening flooding of roads or lands adjacent to the river, then no consequence category should be assigned. In this case, the rationale should be documented, but those potential failure modes would be considered non-risk drivers since there is no life safety risk.

The case for consequences must be built as rigorously as for the failure likelihood and for this level of risk analysis, an order-of-magnitude of estimated life loss is more important than discrete values.

Table 6: Life Safety Consequences

Life Safety Consequence Category	Incremental Life Loss	Description
LS0	None expected	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river
LS1	Less than 1	Although life-threatening releases occur, direct loss of life is unlikely due to severity or location of the flooding, or effective detection and evacuation
LS2	1 to 10	Some direct loss of life is likely, related primarily to difficulties in warning and evacuating small population centers
LS3	10 to 100	Large direct loss of life is likely, related primarily to difficulties in warning and evacuating smaller population centers, or difficulties evacuating large population centers with significant warning time
LS4	100 to 1,000	Extensive direct loss of life can be expected due to limited warning for large population centers and/or limited evacuation routes
LS5	1,000 to 10,000	Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes
LS6	Greater than 10,000	Catastrophic direct loss of life can be expected due to little to no warning for very large population centers and/or limited evacuation routes

The case for consequences must be built as rigorously as for the failure likelihood and for this level of risk analysis, an order-of-magnitude of estimated life loss is more important than discrete values.

18-9.2.2 Empirical Approach

Several empirical approaches have been developed to estimate life loss consequences. Probably the most familiar method in the U.S. is the Reclamation Consequences Estimating Methodology (RCEM) (Reclamation, 2015). RCEM relies on 60 dam failure and other flooding cases as a basis to estimate a total of 79 data case history points that are used to develop estimated fatality rates. Flooding intensity (the intensity is quantified by DV, which is the maximum depth (D) of flooding multiplied by maximum velocity (V) of the flood flow) and warning time are the key parameters that affect fatality rate selection. Strong emphasis is placed on a team approach to the development of assumptions, fatality rate selection, building the case and identifying sources of uncertainty. RCEM is a revision to the DSO-99-06 (Reclamation, 1999) method, also developed by Reclamation. DSO-99-06 was in use by Reclamation from 1999 to 2014, prior to the development of RCEM. More information on RCEM can be found at:

https://www.usbr.gov/ssle/damsafety/references.html

Other empirical methods are also available, some of which rely on RCEM as the basis of their approach.

Additional guidance on developing consequence estimates can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter C-1 Consequences of Flooding (BOR/USACE, 2019).

Empirical approaches could be considered when there is little consequence information available and when the empirical case history data (flooding characteristics, mobilization and evacuation assumptions, etc.) used to develop the fatality estimates is similar to the project.

Similar to the failure likelihood, the rationale for the consequences selected should be synthesized from the pertinent information from the background, performance, and more likely/less likely table to build the case for the consequences selected. The rationale should clearly document the team's assumptions and understanding so that future reviews of the information and discussion can understand what the team was thinking and whether there are changed conditions, improved knowledge, or improved state of practice that would affect the risk assessment.

18-9.2.3 Simulation Approach

HEC-LifeSim. LifeSim is an agent-based simulation model that tracks the movement of people and their interaction with flooding through time. It includes an integrated transportation simulation algorithm to model the evacuation process and evaluates loss of life based on location of people when the water arrives, and important factors related to building, vehicle, and human stability. Fatalities are estimated by grouping people into high or low hazard "zones." Each zone has a corresponding fatality rate, which were developed based on an extensive review and analysis of historic flood events. Additional guidance on developing consequence estimates can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter C-1 Consequences of Flooding (BOR/USACE, 2019). More information on LifeSim can be found at:

http://www.hec.usace.army.mil/software/hec-lifesim/

Life Safety Model. The Life Safety Model is a simulation model that tracks movement of water and movement of people. Fatalities are estimated based on various factors including building destruction, vehicle toppling and drowning. The Life Safety Model has an integrated transportation model but does not use empirical-based fatality rates. More information on the Life Safety Model can be found at:

http://www.lifesafetymodel.net/index.html.

Other simulation models and approaches are also available.

Simulation approaches should be used when the information and assumptions for the descriptive and empirical approaches are not valid. The use of simulation approaches should also be considered for the following conditions:

1. If more detailed risk analyses are planned for the near future.
2. For projects with a time sensitive emergency action plans (EAP). The results of the simulation model can provide valuable information to confirm or revise the time-sensitive EAP assumptions and to provide additional information that can be valuable for developing more focused warning and evacuation plans.
3. Where the results of the simulation model can provide additional information to improve the understanding and planning for EAPs and emergency responders.

18-9.3 Economic Consequences

For some projects, economic losses can be significant and may be an important consequence to consider in helping to prioritize the results of the risk analysis. Economic considerations include both the direct losses and other economic impacts on the regional or national economy (USACE, 2014).

Direct losses include the damage to property located downstream from the dam due to dam failure. These include damage to private and public buildings, contents of buildings, vehicles, public infrastructure such as roads and bridges, public utility infrastructure, agricultural crops, agricultural capital, and erosion losses to land. The sudden loss of the reservoir due to a dam failure could result in losses to property and infrastructure within the reservoir area (upstream of the dam). Direct losses also include the value from the loss in services provided by the dam such as hydropower (incremental cost to replace lost power), water supply (municipal, industrial, irrigation), flood damage reduction, navigation (incremental cost for alternate transportation, if available), and recreation.

Another category of direct losses are the costs associated with the emergency response for evacuation and rescue and the additional travel costs associated with closures of roads and bridges. These losses are commonly included in computing direct economic loss due to dam failure.

Another potential direct loss is the cost of repairing the damage to the dam. This is a complicated issue and to some degree depends on the extent of damage to the dam. If the dam can be repaired, these repair costs may or may not be counted as a direct economic cost (loss). In the case of catastrophic failure, these rebuilding costs are typically not included in the direct costs, as the decision to rebuild the dam depends on the post-failure benefits (which the dam owner would have to evaluate separately) (USACE, 2014).

Indirect economic impacts are those associated with the destruction of property and the displacement of people due to the failure. The destruction due to the failure flood can have significant impacts on the local and regional economy as businesses at least temporarily close resulting in loss of employment and income. Similarly, economic activity linked to the services provided by the dam will also have consequences. These would include economic impacts on business that provide goods and services for the recreation activities associated with the reservoir. All these indirect losses then have ripple or multiplier effects in the rest of the regional and national economy due to the resulting reduction in spending on goods and services in the region. In this way, a dam failure can have widespread economic losses throughout the region. These losses are the incremental losses that would have occurred had the dam not failed. These are often difficult to estimate or substantiate.

Economic considerations that result in financial consequences to the licensee due to failure of structures and components that do not result in any other consequences to other entities and result in a damage state should be considered separately. These financial losses might include both direct and indirect impacts. Some examples might include lost or reduced generation revenue, repair costs, losses/ costs associated with operational limitations or changes that may result.

Three general approaches are available for estimating economic consequences in Level 2 risk analyses:

1. A descriptive approach based on verbal descriptions,
2. A simulation approach that models economic life loss, and
3. A quantitative approach.

18-9.3.1 Descriptive Approach

For this approach the economic consequences should be estimated using the information contained in Table 7.

Likewise, financial losses to the licensee should be estimated using the information contained in Table 8.

Table 7: Economic Consequences

Economic Consequence Category	Incremental Economic Loss ($)	Description
EC0	None expected	No significant economic or other impacts.
EC1	Less than 10M	Downstream discharge results in limited property and/or environmental damage.
EC2	10M to 100M	Downstream discharge results in moderate property and/or environmental damage.
EC3	100M to 1B	Downstream discharge results in significant property and/or environmental damage.
EC4	1B to 10B	Downstream discharge results in extensive property and/or environmental damage.
EC5	10B to 100B	Downstream discharge results in extremely high property and/or environmental damage.
EC6	greater than 100B	Downstream discharge results in catastrophic property and/or environmental damage.

For both of the tables above, these are relative rankings and are not tied to tolerable risk guidelines. **They are in no way to be equated to the life loss descriptors to arrive at a value for human life.** In a general sense, each descriptor represents an order of magnitude range in economic or financial consequences. This approach may be appropriate where little to no consequence information is available.

The case for consequences must be built as rigorously as for the failure likelihood and for this level of risk analysis, an order-of-magnitude of estimate is more important than discrete values.

Table 8: Financial Consequences

Financial Consequence Category	Financial Loss/Cost ($)	Description
FC0	None expected	No significant financial loss or cost or other impacts.
FC1	Less than 10M	Results in limited financial loss or cost.
FC2	10M to 100M	Results in moderate financial loss or cost.
FC3	100M to 1B	Results in significant financial loss or cost.
FC4	1B to 10B	Results in extensive financial loss or cost.
FC5	10B to 100B	Results in extremely high financial loss or cost.
FC6	greater than 100B	Results in catastrophic financial loss or cost.

18-9.3.2 Simulation Approach

Some life safety consequence models, such as the LifeSim discussed in Section 18-9.2.3, can also be used to develop estimates of economic consequences. Additional information on using LifeSim for economic consequence estimates can be found at http://www.hec.usace.army.mil/software/hec-lifesim/.

Other simulation models may be available to develop estimates of economic consequences.

18-9.3.3 Quantitative Approach

Some dam owners have internal or external resources or reference information and estimates of potential economic consequences. This information can be used to develop quantitative estimates. In this case, it is strongly recommended that the analysis of economic considerations be performed by qualified economists. Except in special circumstances, quantitative estimates of economic consequences are typically beyond the scope of semi-quantitative risk analyses.

18-9.4 Environmental and Other Non-Monetary Consequences

Other types of consequences should be considered and evaluated in the risk estimates.

A dam failure has both direct and indirect consequences that cannot be measured in monetary terms (USACE, 2014). These stem from the impacts of the failure flood and loss of reservoir on environmental, cultural, and historic resources. In most cases, the assessment of the impacts of dam failure will be the reporting of area and type of habitat impacted, habitat of threatened and endangered species impacted, number and type of historic sites impacted, and the number and type of culturally significant areas impacted.

An additional indirect non-monetary consequence could be the exposure of people and the ecosystem to hazardous and toxic material released from landfills, warehouses, and other facilities. An estimate of the locations and quantities should be compiled identifying where significant quantities are concentrated. A potential additional source of hazardous and toxic material is the sediment accumulated behind the dam. Identifying and enumerating these indirect hazards could be important enough to require additional consequence studies including estimating additional fatalities due to exposure to theses hazards. Although these non-monetary consequences may not provide the sole basis for risk reduction, they can provide additional information for decision making. They can also be used to identify risks to be managed separately from dam modifications.

Intangible consequences are those that have no directly observable physical dimensions but exist in the minds, individually and collectively, of those affected. Such consequences are real and can support decisions. Intangible consequences may include (ANCOLD, 2003):

- The grief and loss suffered by relatives and friends of those who die;
- The impact of multiple deaths on the psyche of the community in which they lived;
- The stress involved in arranging alternative accommodations and income;
- The sense of loss by those who enjoyed the natural landscape destroyed; and
- The fear of lost status and reputation of the dam owning/regulating organization(s) and their technical staff.

Where these other consequences are considered to be significant and may be an important consequence to consider in helping to prioritize the results of the risk analysis, qualitative impacts from these types of consequences should be identified and described.

No environmental or non-monetary risk matrix is used to present this information. Instead, these consequences are described, and their significance is evaluated, in qualitative terms.

18-10 OTHER CONSIDERATIONS

18-10.1 Confidence

An essential part of the evaluation is to capture the confidence in the selecting the failure likelihood and consequences. Confidence as used in this case is related to the confidence in the risk estimate relative to the decision to take action or not to take action and is not to be confused with how confidence is typically defined in statistical terms. Decision confidence is a qualitative measure of belief that the information, engineering analysis results, and risk estimate is reasonable. Decision confidence is used to describe how sure the risk analyst/team is about the risk estimate and the associated decision. Decision confidence estimates are used by decision makers to inform the potential need to take (or not take) action to reduce risk or to reduce sources of uncertainty.

Factors that influence decision confidence include:

- Quantity and quality of the information available
- Representiveness of the information
- Information/analysis results accurately capture the expected performance

Decision confidence categories and qualitative descriptors should be provided for both the failure likelihood and consequence categories using the categories and descriptors provide in Table 9.

Table 9: Decision Confidence Categories

Decision Confidence Category	Description
High	The individual/team is confident in the assigned order of magnitude descriptor and it is unlikely that additional information would change the estimate to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
Moderate	The individual/team is relatively confident in the assigned order of magnitude descriptor, but key additional information might possibly change the estimate to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
Low	The individual/team is not confident in the assigned order of magnitude descriptor and it is entirely possible

	that additional information would change the estimate to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

A potential failure mode rated with ‘low’ confidence, particularly if risk-reduction actions are indicated, would probably require additional investigations or analyses before taking risk-reduction action. However, if it is rated with ‘high’ confidence, it may be appropriate to go directly to interim risk-reduction actions or in some cases long-term risk reduction actions. In some cases, the team will have ‘low’ confidence in an assigned descriptor but cannot think of any additional information that could be collected to improve their confidence. These cases are documented. The lack of information is not low confidence. When assigning confidence descriptors, the reasoning behind the descriptor and the information that could be gathered to improve the rating should also be captured in the documentation.

18-10.2 Accounting for Uncertainty

Uncertainty is the result of imperfect knowledge. Uncertainty is used to portray variability or a range of values for loads, consequences, failure likelihoods, and risk estimates.

It is acknowledged that given the limited information and resources available for risk estimates and the qualitative nature of these estimates, uncertainty about the risk estimates can be high. The estimates of risk are provided for the expected value/mean value of risk for each potential failure mode. Likewise, the uncertainty about the expected value/mean value of risk is what should be provided and not the overall uncertainty that would be provided by the wider range of all possible outcomes.

Sources of uncertainty and potential actions that could be taken to reduce that uncertainty should both be identified.

18-10.3 Potential Dam Safety Management Activities

After the decision confidence and uncertainty has been assessed, potential dam safety management activities should be discussed and documented for each potential failure mode. The knowledge and understanding gained from identifying, evaluating, and estimating the risk can help identify potential dam safety management activities for each potential failure mode. These dam safety management activities include:

- Potential Risk Reduction Measures,
- Inspections,
- Surveillance and Monitoring,
- Emergency Action Plan,

- Follow-up Studies, and
- Other.

Each of these are discussed in more detail in Section 17-4.7.10 of Chapter 17 of the FERC Engineering Guidelines.

18-10.4 Close-out Activities

Similar to conducting only a PFMA, at the end of the risk analysis session, the facilitator should ask the participants to reflect on what they learned during the risk analysis process. After a few minutes the facilitator should ask the participants to state what were the Major Findings and Understandings (MFU) they gained during the risk analysis session. Typically, this is done by going around the room and asking each participant to provide an MFU and then starting again with the first person until all participants have had the opportunity to express their findings. MFUs may relate directly to a potential failure mode or may reflect a more general understanding about the dam or the risk analysis process.

The Licensee must notify the FERC-D2SI Regional Engineer, in writing within five days of completing the risk analysis session, of any serious dam safety issue identified during the risk analysis session.

The Major Findings and Understandings should be documented immediately after the session. The items noted during the session are typically abbreviated and should accurately reflect what the individual participants stated as their major finding or understanding gained during the session. Where the MFU relates to a potential failure mode, a brief discussion (three to five sentences) relating the MFU to the potential failure mode should be prepared and included with the MFU. The write up of the major findings and understandings is then sent to the facilitator and the other core team members for review. Alternately, the major findings and understandings can be captured at key times throughout the course of the risk analysis session so as not to forget important findings and not to leave this important task to the very end of the session when memories may have faded and participants are exhausted.

See Chapter 17 of the FERC Engineering Guidelines for an example write-up of major findings and understandings.

18-11 ESTIMATING AND PORTRAYING RISKS

18-11.1 Risk Estimates

Risk estimates for each of the risk measures are portrayed and assessed as described in the following sections.

18-11.1.1 Societal Incremental Life Safety Risk

A Level 2 risk analysis matrix has been established to portray the societal incremental life safety risk (due to failure) associated with the identified potential failure modes, with likelihood of failure on the vertical axis (using cell divisions corresponding to the failure likelihood previously described) and the associated incremental consequences on the horizontal axis (using cell divisions corresponding to the consequences previously described). The matrix is similar to the f-Ñ/F-N diagram used to portray societal incremental life safety risk estimated from quantitative risk assessments (see Chapter 3 of FERC's RIDM Risk Guidelines). Figure 10 illustrates the societal incremental life safety risk matrix.

Cells of the societal incremental life safety risk matrix, defining the failure likelihood and consequences, correspond to order of magnitude divisions. Societal risk guidelines are portrayed on the Level 2 risk analysis matrix as dashed red lines and although the results of a Level 2 risk analysis are not sufficiently robust to evaluate the tolerability of risk, the tolerable risk reference lines can provide a sense of reference for the risk results.

Potential failure modes with no life safety consequences can be excluded from the risk matrix or plotted as a line on the vertical axis at the far-left end of the matrix.

Likelihoods of failure less than 1E-07/yr are not explicitly represented on the incremental risk matrix.

Using the appropriate failure likelihood and consequences, each significant potential failure mode is plotted on the risk matrix, as shown on Figure 11. When possible, order of magnitude estimates for each the likelihood of failure and incremental consequences should be plotted. For those instances when the risk analysis team could not reach consensus on a single order of magnitude descriptor, then the range of estimates of the best estimate is plotted on the matrix (e.g., liquefaction potential failure mode on Figure 11) and the rationale for that range is provided in the report. Estimates should be plotted to the closest ½-order of magnitude.

The total societal incremental life safety risk is also plotted on the risk matrix. The total societal incremental life safety risk is the sum of the risks from each of the individual potential failure modes plotted on the risk matrix. The methodology for determining the total societal incremental life safety risk should be in accordance with SQRA Calculation Methodology (USACE, 2018). The total risk box should be plotted on the risk matrix with a height and width of one order of magnitude with the box centered on the computed total risk estimate. It should be noted that the total risk calculation assumes the individual potential failure modes are mutually exclusive, which may not be the case, but is considered conservative for an SQRA level of effort.

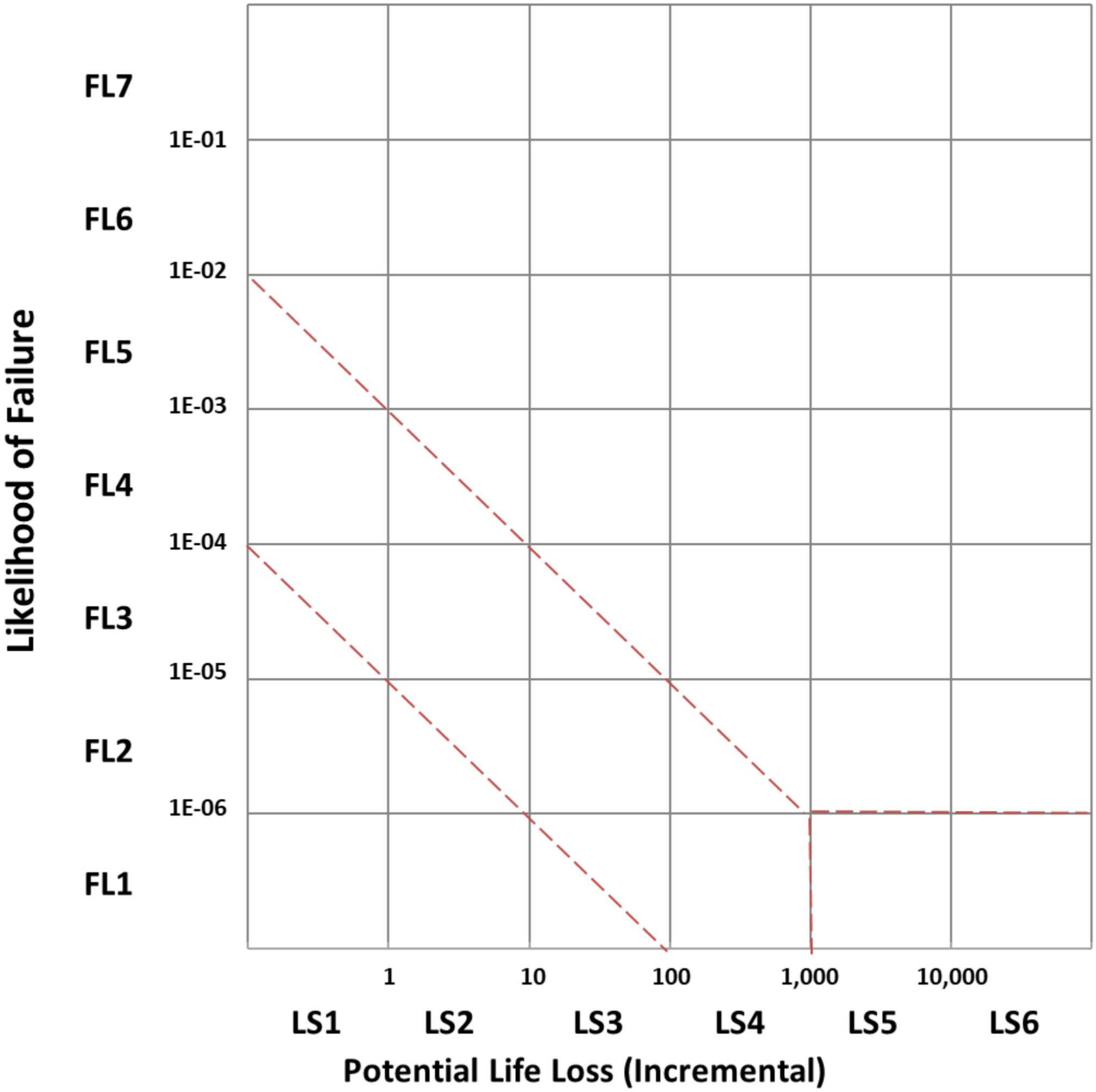

Figure 10: Risk Analysis Matrix for Societal Incremental Life Safety Risk

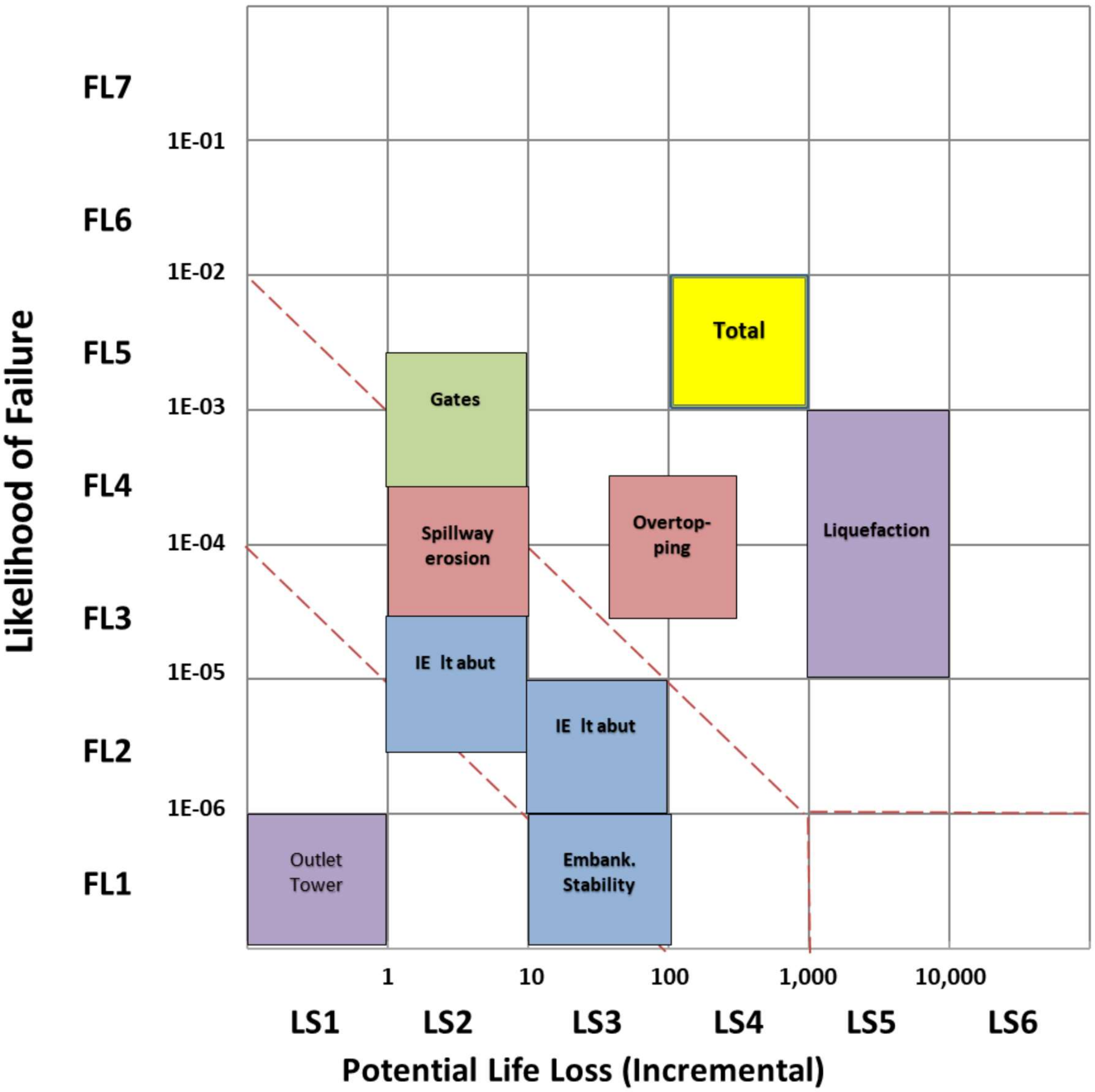

Figure 11: Example of a Risk Analysis Matrix for Societal Incremental Life Safety Risk

18-11.1.2 Non-Breach Life Safety Risk

Non-breach risks are associated with operations, typically involving reservoir release through spillways and/or outlets in order to pass flood flows or overtopping of structures without breach. In some cases, these releases may cause damage and threaten lives.

The AEP when the public would begin to experience flooding due to spillway release and the AEP when life loss would start to occur are important to understand and communicate. The AEP for flooding is typically related to spillway releases. However, the annual probability of when life loss would start to occur depends on the specific situation but is typically less than the AEP for flooding. Failure to consider these larger, less frequent flood events results in an underestimation of the non-breach risk (USACE, 2018).

Warnings that would go out prior to impacting the population at risk with planned releases must be taken into account in assessing the consequences. Total consequences are typically estimated. Thus, the incremental risks of comparing to the case of no dam are not captured. The results are plotted on a separate non-breach life safety risk matrix, as shown on Figure 12. This is similar to the societal incremental life safety risk matrix described previously, but the vertical axis is labeled “Likelihood of Life Loss” and no tolerable risk limit lines are shown since they are not applicable to non-breach conditions. An example plot is shown on Figure 13. The likelihood of life loss or AEP when life loss begins to occur is plotted on the vertical axis of the non-breach risk matrix. For non-breach risks, the same consequence categories in Table 6 are used; however, they are for total potential life loss and not incremental potential life loss. Consequences associated with planned operational releases typically drive the non-breach consequence category.

If there is downstream flood risk management or water supply infrastructure (e.g., dams or levees) that could be overtopped by operational spillway releases, the frequency of the flood that would overtop those structures and the consequences resulting from overtopping (but not due to failure) of those structures are included. Further guidance on estimating non-breach risks is provided in SQRA Calculation Methodology (USACE, 2018).

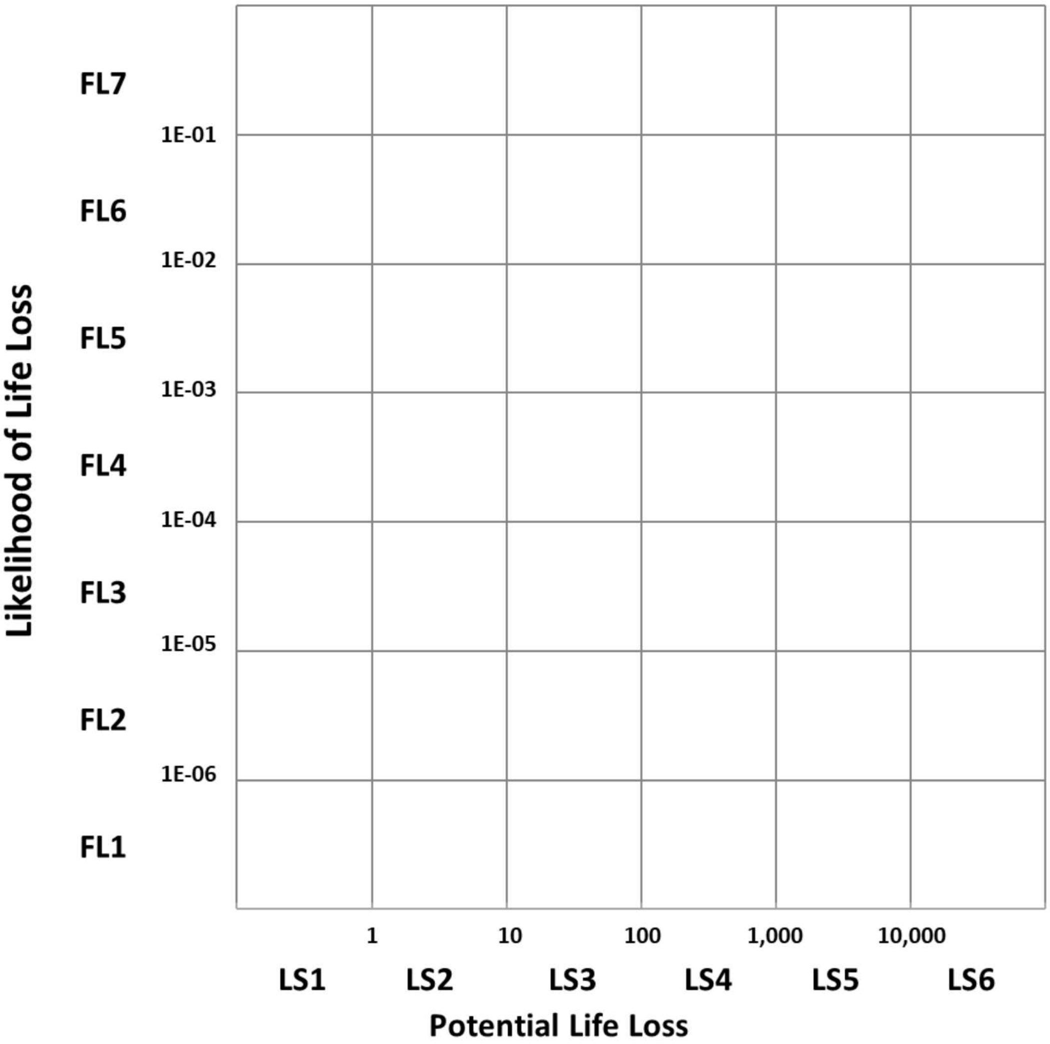

Figure 12: Risk Analysis Matrix for Non-Breach Life Safety Risk

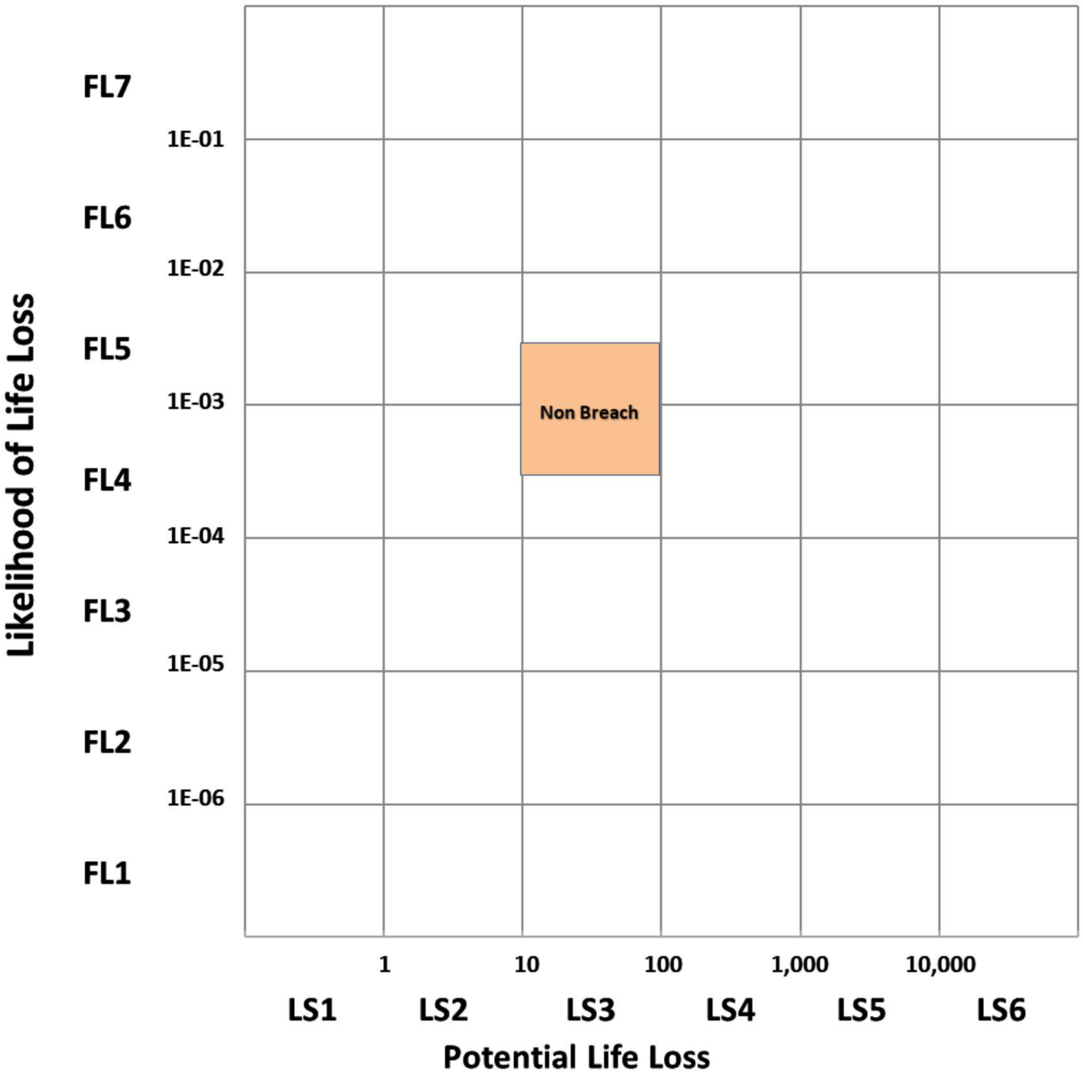

Figure 13: Example of a Risk Analysis Matrix for Non-Breach Life Safety Risk

18-11.1.3 Annual Probability of Failure

Annual probability of failure (APF) is estimated for those potential failure modes associated with the incremental risk. APF is estimated from all potential failure modes associated with all loading or initiating event types. The total APF is calculated by summing the APF estimates for all of the individual potential failure modes. It should be noted that this calculation assumes the potential failure modes are mutually exclusive, which is considered conservative for an SQRA level of effort. Although the combined annual probability of failure of all potential failure modes is to be provided, it is important that the contributions to the APF from the individual potential failure modes, loading types, and loading ranges, etc., are analyzed.

Annualized probability of failure is approximately represented by the likelihood of failure.

18-11.1.4 Economic, Environmental, and Other Consequences

Economic, environmental, and other consequences are evaluated on a case-by-case basis. Additional discussion of economic, environmental, and other consequences can be found in Chapter 2 of the FERC RIDM Risk Guidelines.

Economic risks, when estimated, should be plotted using the risk matrix on Figure 14.

Financial and damage state risks should be plotted using the risk matrix on Figure 15.

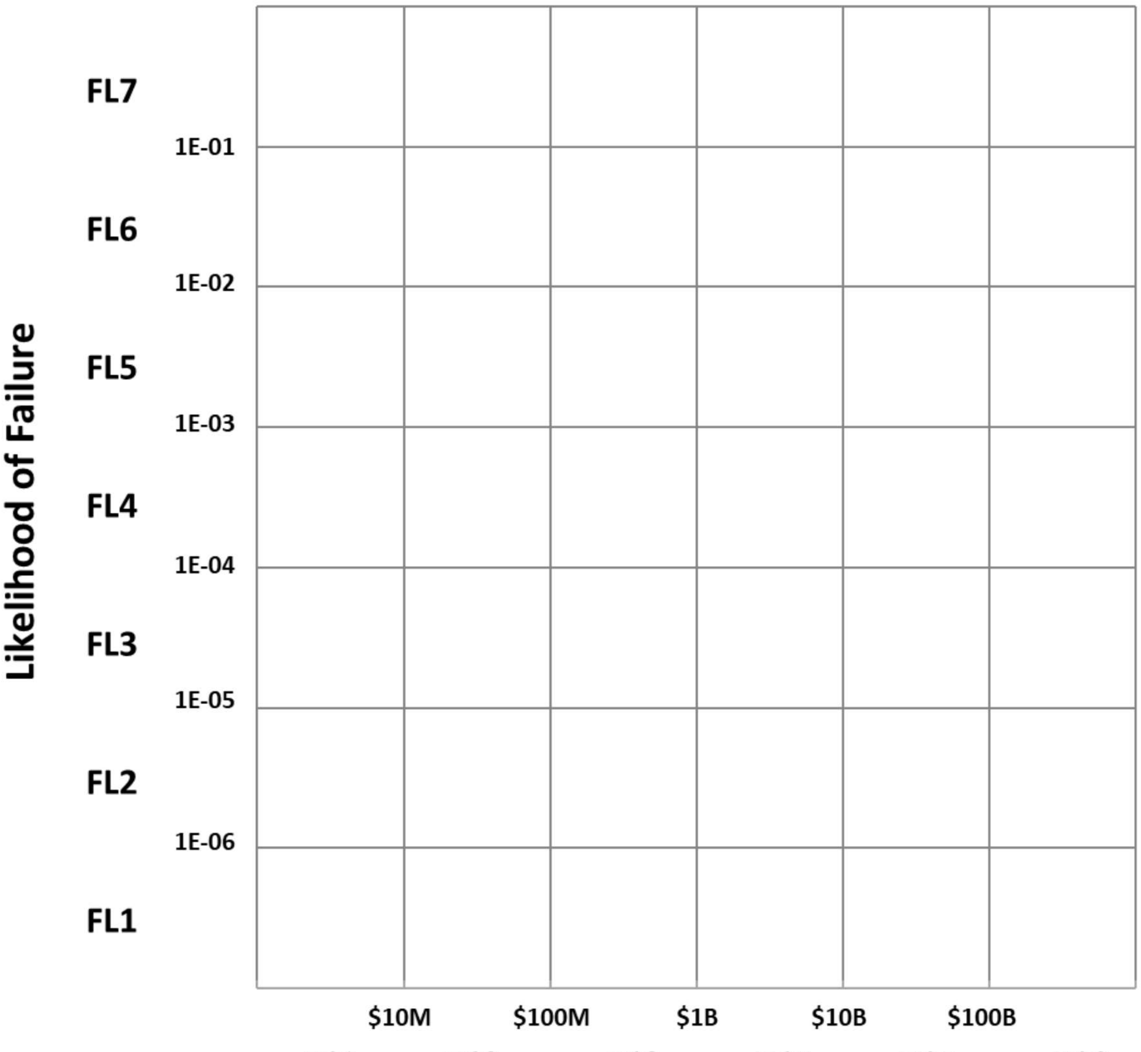

Figure 14: Risk Analysis Matrix for Incremental Economic Consequences

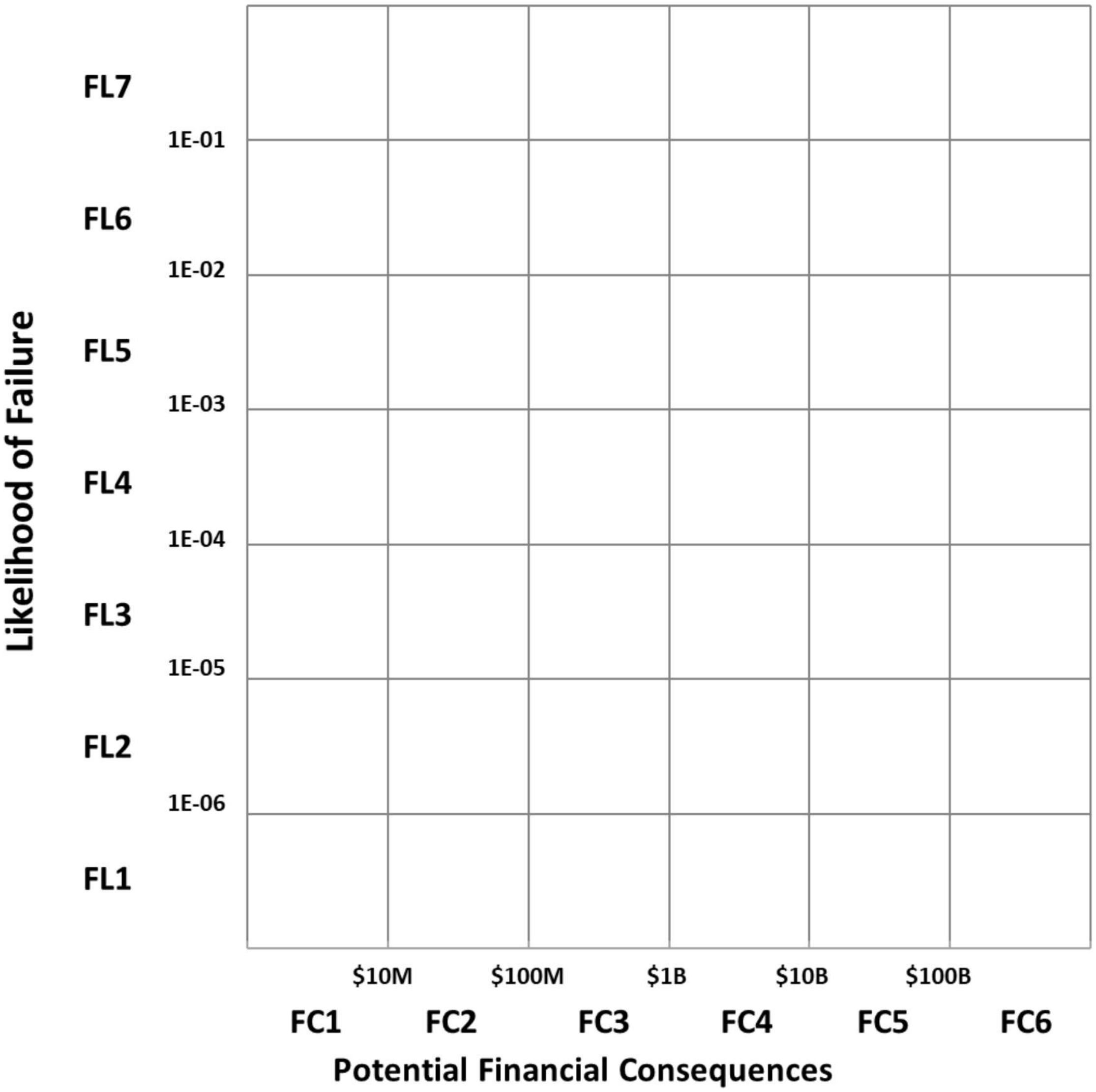

Figure 15: Risk Analysis Matrix for Incremental Financial/Damage State Consequences

18-11.1.5 Individual Incremental Life Safety Risk

Individual incremental life safety risk (assuming that the most exposed individual is exposed all the time) represents the concept that everyone deserves some minimum level of safety regardless of the magnitude of the consequences. Additional information on individual incremental life safety risk can be found in Chapter 2 of the FERC RIDM Risk Guidelines. Because the individual incremental life safety risk is always equal to or less than the annual probability of failure (APF), APF can be used as a conservative estimate of the individual incremental life safety risk for an SQRA level of effort.

18-12 DOCUMENTATION

The objective of the Level 2 risk analysis report is to present clear, thorough, logical, and rational documentation of the assumptions, evaluations, and results that accurately portray the risk estimate and recommended course of action in a manner and style that can be understood by both the dam owner and FERC. The three basic risk components, (i.e., load, response, and consequences) should reflect the dam's existing condition and ability to withstand future loading, the risk estimates, and provide the basis for the recommended actions.

A general risk analysis report outline is provided in Appendix 18-B. The report outline includes both the potential failure mode analysis (discussed in Chapter 17 of the FERC Engineering Guidelines) and risk analysis efforts in one report. The outline should be revised to reflect the project-specific components and evaluations performed for developing the risk estimates.

The documentation for each potential failure mode carried into the risk analysis should follow the template provided in Appendix 18-C or other similar template approved by FERC. Example potential failure mode documentation is included in Appendix 18-D.

The results of the risk analysis are used to place each potential failure mode in the appropriate failure likelihood and consequence box. This requires a clear and complete description of the potential failure modes and an evaluation of the adverse factors that make each potential failure mode "more likely" to occur as well as the favorable factors that make it "less likely" to occur. The rationale and key factors affecting the assigned failure likelihood are documented. Similarly, for consequences, the potential incremental consequences are evaluated and assigned to the appropriate consequence, and the rationale for the assignment is documented. The confidence (and their rationale) as well as the uncertainty are assigned to each, and then each potential failure mode is plotted in the appropriate cell of the risk matrix.

When assigning confidence categories, the reasoning behind the category, and the information that could be gathered to improve the rating should also be captured in the documentation.

The risk estimate documentation should also include the following:

- Summary tables: summarizing the risk results for all potential failure modes in a table(s) provides an easy way to identify and compare the likelihood estimates for each potential failure mode. Use the risk estimate summary table(s) for this purpose. Separate tables can be provided for each risk measure included in the risk analysis. An example of summarizing a societal incremental life safety risk results is provided below.

Potential Failure Mode	**Annual Probability of Failure, APF (failures/year)**	**Average Incremental Life Loss, N (lives)**	**Average Annual Incremental Life Loss, AALL (lives/year)**
PFM 1			
PFM 2			
PFM X			
Total			

- Risk matrix charts: the risk results should also be plotted on the risk matrix chart(s), as discussed in the previous section, and templates can be found as MS Excel files on the FERC D2SI web page.

The risk analysis report should also:

- Describe the estimated incremental risk for the project and the potential failure modes driving the incremental risk along with their likelihood and key evidence. Describe the primary consequence center(s) including proximity to the dam, population at risk, and life loss potential.
- Describe the potential impacts of planned spillway releases on the primary consequence center(s) (e.g., potential impacts to downstream populations due to the entire range of non-failure high flow operational discharge). This information can be presented in a summary table; an example of which is provided below.

Downstream Discharge Condition	**Total Discharge, (cfs)**	**Reservoir Elev., (ft)**	**AEP (1/return period)**	**Estimated Total Life Loss (order-of-magnitude)**
Downstream non-damaging discharge (safe downstream channel capacity)				
Downstream discharge resulting in initial life loss				
Downstream discharge with the reservoir at the top of the dam crest				

Downstream discharge with the maximum reservoir elevation that does not result in breach of the dam or other water retaining structures (pre-incipient overtopping breach)				

As appropriate, additional rows can be added to the table based on available project information, such as flood of record or other historic high discharges or other known or modelled inundation scenarios.

- Describe the confidence in the incremental risk estimate and any major uncertainties related to failure likelihood or incremental consequences.

The basis for the recommended actions should be documented in an objective, transparent manner, portraying the data, evaluations, findings and any associated uncertainties in data or analysis on a factual basis.

It is important to understand that if the risk analysis report does not accomplish the goals of the Level 2 risk analysis – appropriately estimating the risk of each dam's site-specific potential failure modes – at the discretion of the Regional Engineer, the Level 2 risk analysis may be required to be supplemented or redone entirely.

18-13 REFERENCES

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APPENDIX 18-A: APPENDIX NOT USED

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APPENDIX 18-B: RISK ANALYSIS REPORT OUTLINE

The following is the outline for the risk analysis report.

Risk Analysis Report

1.0 Introduction
    1.1 Introduction
    1.2 Scope of Work
    1.3 Project Team

2.0 Description of Dam and Other Key Features

3.0 Previous Studies

3.0 Hydrologic Loading
    3.1 General
    3.2 Background Information
    3.3 Reservoir Elevation Frequency
    3.4 Methodology/Approach
    3.5 Results
    3.6 Non-Breach Scenario

4.0 Seismic Loading
    4.1 General
    4.2 Background Information
    4.3 Methodology/Approach
    4.4 Results

5.0 Consequences
    5.1 General
    5.2 Approach
    5.3 Inundation Scenarios
    5.4 Description of Inundation Area
    5.5 Breach Assumptions
    5.6 Life Loss Estimates
    5.7 Economic Loss Estimates
    5.8 Other Consequences

6.0 Potential Failure Modes
    6.1 Potential Failure Mode Analysis
    6.2 Identification of Candidate Potential Failure Modes
    6.3 Evaluation and Screening of Potential Failure Modes
    6.4 Potential Failure Modes Carried Forward into Risk Analysis

- 7.0 Risk Analysis
  - 7.1 General
  - 7.2 Methodology/Approach
  - 7.3 PFM ##: Short Title (Include separate section for each PFM)
    - 7.3.1 Description
    - 7.3.2 Background/Supporting Information
    - 7.3.3 Performance
    - 7.3.4 Failure Likelihood
    - 7.3.5 Consequences
    - 7.3.6 Decision Confidence and Uncertainty
    - 7.3.7 Potential Risk Reduction Measures
    - 7.3.8 Potential Dam Safety Management Actions
  - 7.X Summary and Evaluation of Risk Estimates
    - 7.X.1 Societal Incremental Life Safety Risk
    - 7.X.2 Non-Breach Life Safety Risk
    - 7.X.3 Annual Probability of Failure/Individual Incremental Life Safety Risk
    - 7.X.4 Economic Risk
    - 7.X.5 Other Consequences

- 8.0 Major Findings and Understandings

- 9.0 Conclusions and Recommendations

Appendices

- A Risk Analysis PFM Worksheets

APPENDIX 18-C: POTENTIAL FAILURE MODE TEMPLATE FOR LEVEL 2 RISK ANALYSIS

Dam Name

PFM Information

Structure	
Loading Condition	
PFM Type	
Location(s)	
PFM Source	
PFM Source Date	

PFM Description

PFM No.	
PFM Title	
PFM Description	(include flaw/initiation, continuation, progression, intervention, and failure)
PFM Classification	☐ Ruled Out ☐ Clearly Negligible ☐ Insufficient Info ☐ Asset Management ☐ Financial/Damage State ☐ Credible ☐ Urgent Credible
Classification Justification	

PFM Sketch(s)

Event Tree (if used)

Additional Supporting Information (if needed)

Performance Monitoring Information

Evaluation Factors

Step/Node	Adverse (More Likely)	Favorable (Less Likely)
Flaw/Initiation		
Continuation		

<table>
<tr><td>Progression</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Intervention</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Failure/Breach</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><th colspan="5">Failure Likelihood Summary</th></tr>
<tr><td>Failure Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><td>Sources of Uncertainty</td><td colspan="4"></td></tr>
<tr><th colspan="5">Consequences</th></tr>
<tr><td colspan="5">Life Safety Consequences</td></tr>
<tr><td>Consequence Description</td><td colspan="4"></td></tr>
<tr><td>Estimated PAR</td><td colspan="4"></td></tr>
<tr><td rowspan="5">Inundation Characteristics</td><td colspan="4"></td></tr>
<tr><td>Location</td><td>Time (hr)</td><td>Depth (ft)</td><td>Velocity (ft/s)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td colspan="4"></td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><td>Sources of Uncertainty</td><td colspan="4"></td></tr>
<tr><td colspan="5">Economic Consequences</td></tr>
<tr><td>Consequence Description</td><td colspan="4"></td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><td>Sources of Uncertainty</td><td colspan="4"></td></tr>
<tr><td colspan="5">Other Consequences</td></tr>
</table>

Consequence Description	
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Sources of Uncertainty	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Potential Risk Reduction Measures	
Inspections and Actions	
Surveillance and Monitoring	
EAP	
Follow up Studies	
Others	
Other Notes/Comments	

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APPENDIX 18-D: EXAMPLE TEMPLATE WRITE UPS

Wontoo Dam

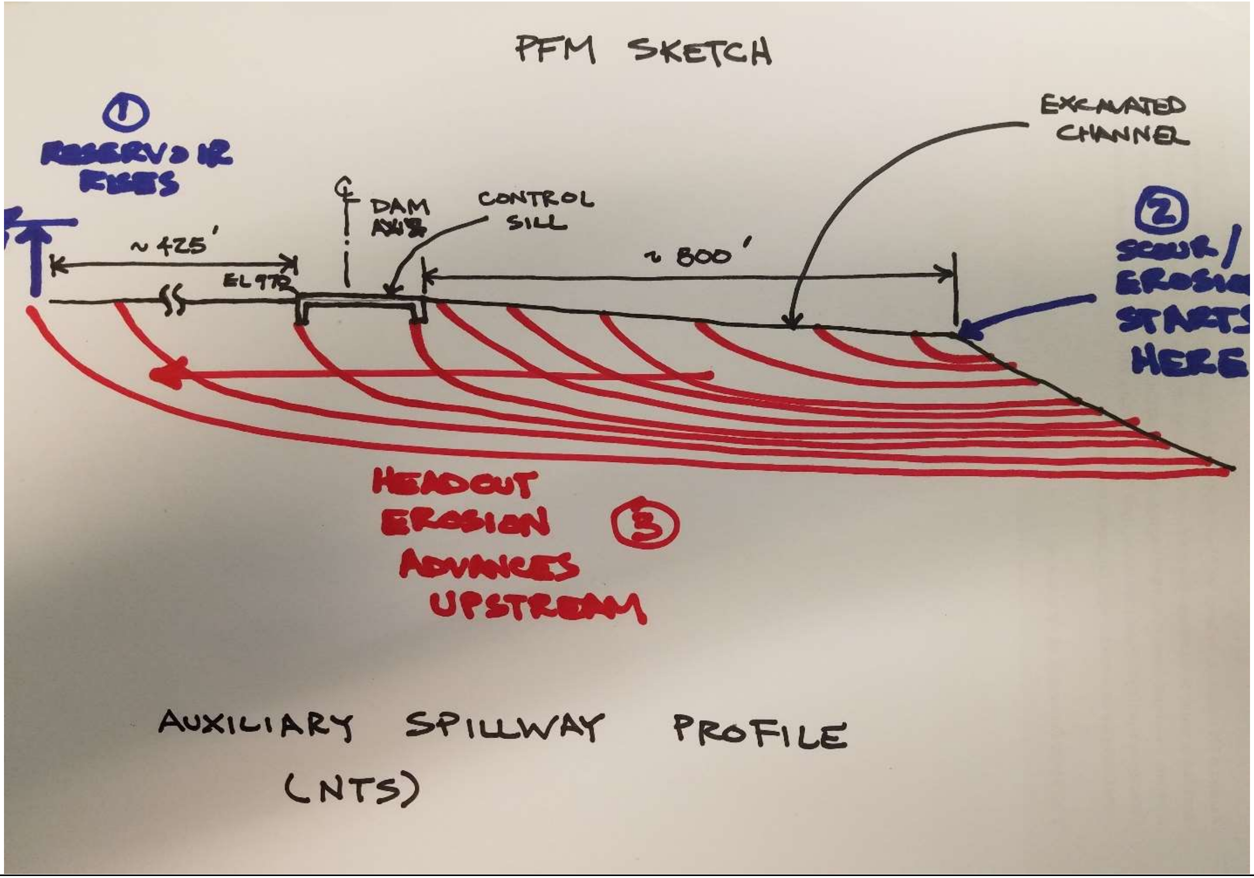
PFM Information

Structure	Auxiliary Spillway
Loading Condition	Flood
PFM Type	Erosion
Location(s)	Auxiliary Spillway

PFM Description

PFM No.	1
PFM Title	Headcutting and erosion of the auxiliary spillway
PFM Description	The reservoir rises above elevation 975 to 980 feet leading to headcut erosion downstream of the spillway control sill. Erosion begins at the knickpoint near the break in slope approximately 800 feet downstream of the control sill. Headcut erosion continues and deepens, undermining the control sill. Headcut erosion continues to advance towards the reservoir leading to breach and partial loss of pool.

PFM Sketch



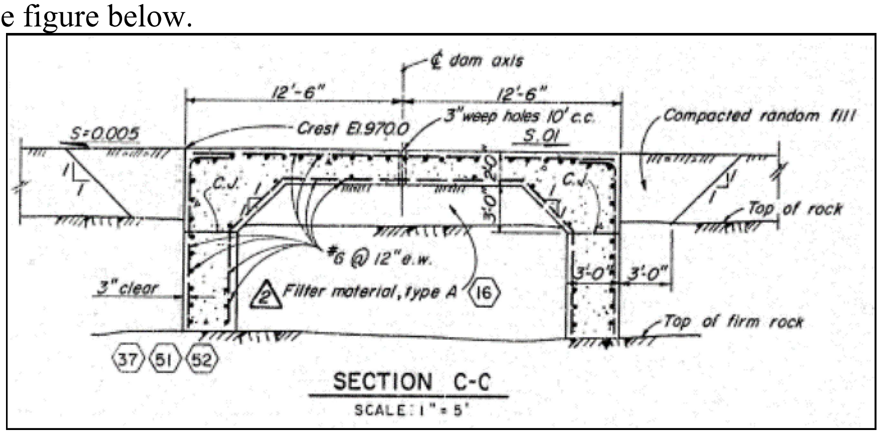
Event Tree (if used)

A sequence of events that can be used in spillway erosion event tree is:

- Hydrologic event occurs and reservoir stage reaches the spillway crest.
- Spillway begins to flow.
- Vegetation is removed (if it is present).
- Concentrated flow erosion begins (downcutting forms headcut).
- Headcut advancement begins (Headcut deepens and advances towards spillway crest/control section).
- Intervention is unsuccessful.
- Headcut advances through crest of spillway and/or headcut undermines control structure/section and flow control is lost.
- Headcut advances into reservoir pool and breaching begins.

Additional Supporting Information (if needed)

The auxiliary spillway is located at the west end of the embankment, with its centerline at dam Station 36+03. The spillway is 300 feet wide with a crest elevation of 970 feet. The length of the excavated spillway is approximately 1,500 feet with 3H:1V side slopes. A retaining wall with a top elevation of 988 feet is located on each side of the spillway and retains the embankment fill. A 25-foot-wide and 300-foot-long concrete slab (i.e., control sill) protects the crest. The slab is turned down at both the upstream and downstream ends to firm rock at a depth of about 8.5 feet, as shown in the figure below.



The spillway floor consists of soft to hard shale materials. The firm rock line is approximately at an elevation of about 959 feet. The excavated spillway channel extends approximately 800 feet downstream of the control sill and 425 feet upstream. An approximately 20-foot fall exists within 175 feet beyond the downstream portion of the excavation.

Performance Monitoring Information

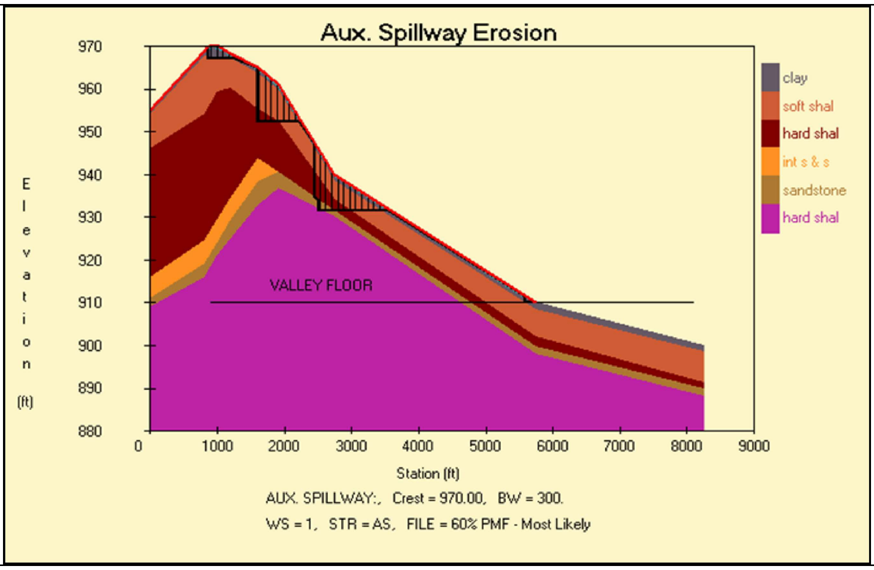
The spillway has never experienced flow. The record pool elevation 964.24 feet is approximately 6 feet below the spillway crest. Surface erosion has occurred downstream of the spillway, as shown in the photo below.

Influence Factors

Event Tree Node (or other designation)	More Likely	Less Likely
	The spillway includes erodible near-surface overburden and weathered shale	Infrequent flood for loss of crest control (i.e., AEP = 5E-04/year to 6E-05/year)
		Exit channel length is 800 to 1000 feet.
		An additional 400 feet of natural materials exist at an elevation of 970 feet, resulting in a total length of 1,200 to 1,500 feet which must eroded before partial breach.
		A concrete sill is founded in firm rock with a depth of 8.5 feet, which is not included in the SITES model.
		Infrequent flood for loss of crest control (i.e., AEP = 5E-04/year to 6E-05/year)

Failure Likelihood Summary

Failure Likelihood	5E-05 to 5E-06
Justification	Based on the spillway erodibility analysis using SITES, the threshold flood for loss of spillway control is approximately 60 to 70 percent of the PMF, as shown in the figure below, which corresponds to an annual exceedance probability (AEP) on the order of 1E-05/year. Therefore, the annual probability of failure (APF) is also on the order of 1E-05/year.

	
Confidence	Low
Rationale	The SITES analysis appears to be conservative and included some sensitivity analyses. The frequency of the PMF seems reasonable. The lower confidence is due to uncertainty associated with the SITES model. Additional boring may improve the geologic profile but would not change the confidence in the estimate.
Consequences	
Life Safety Consequences	
Consequence Description	Wontoo Dam is located on Town Creek, a drainage that joins Lolly Creek approximately 7 miles downstream of the dam. Lolly Creek then flows into Smith Reservoir approximately 26 miles downstream of the dam. Downstream from Wontoo Dam, extending to Smith Reservoir, the valley of Town Creek is narrow with scattered rural residences, seasonal cabins, and much recreation use during the tourist season. The facilities and communities located downstream of Wontoo Dam within the inundation limits include numerous ranches, campgrounds, a dozen or more residences, a Forest Service facility, the Carolina Gulch Picnic Area on the shore of Smith Reservoir, 2.9 miles of railroad track, and 18 miles of roads and trails. Several additional campgrounds and picnic areas exist around Smith Reservoir that could also be affected by potential flooding caused by a breach of Wontoo Dam. Smith Reservoir's flood-surcharge capacity of 21,000 acre-feet and would be able to contain the dam-breach flood volume (up to 15,700 acre-feet) from Wontoo Dam and Reservoir.
Estimated PAR	Wontoo Dam is rated as a high-hazard structure due to the population at risk downstream. It is estimated that about 90 people live within the potentially inundated areas below Wontoo Dam, and a possible total of about 200 people including those seasonally using the campgrounds and other facilities in the floodplain.

Failure of Wontoo Dam has the potential to place many people at risk. The number of people and their location varies substantially depending on the time of year, day of the week, and time of day.

The inundation area for a hydrologic day failure under flood loading conditions would be expected to be slightly higher due to the larger reservoir volume and higher reservoir head available as compared to a sunny day failure. Therefore, the population at risk estimates for a hydrologic failure were increased by 10 percent to account for the larger extent and deeper inundation that would likely be caused by a larger reservoir volume and reservoir head.

An estimated population at risk is provided in the table below.

Reach	Season			
	May-September		October-April	
	Day	Night	Day	Night
Reach 1	44	44	22	22
Reach 2	176	176	77	77
Totals	220	220	99	99
Annualized Total	150			

Inundation Characteristics

Travel times for the leading edge of the flood wave are provided on the inundation maps. The results of that study provide estimates of the leading edge of the flood wave beginning at the time of failure at the dam.

Location	Time (hr)	Depth (ft)	Velocity (ft/s)

Warning/Evacuation Challenges

The area around Wontoo Dam and along the creeks below the dam are popular recreation areas. Based on the inundation maps, the first populated areas and potential dam-failure notification people downstream of the dam appear to consist of several ranches and camps located along the creek within the first 2 miles below the dam. These ranches and camps include both year-round and seasonal residents. There also appear to be some ranches just downstream of the dam that are located above the inundation boundary.

The dam tender is located at Smith Dam, about 25 miles from Wontoo Dam, and visits Wontoo Dam for visual inspections on a regular (at least weekly), year-round basis. The roadway to Wontoo Dam is a good paved highway, except for about 6 miles of gravel roadway near the dam. There is also a locked gate on the access road about 1.6 miles below Wontoo Dam that must be opened. The trip from the dam tenders house to Wontoo Dam takes approximately 30 to 45 minutes, depending on the weather

	conditions. It should be noted that the access road to Wontoo Dam travels up the Town Creek valley below the dam and crosses two bridges over the Creek. The first bridge is located just above the gate and the second bridge is located above the confluence of the creek and the spillway outflow channel. If the spillway is flowing above a relatively low percentage of its capacity, the two bridges and the last 1.7 miles of the access road to the dam could be underwater and impassible, forcing the dam tender to use other routes to reach the dam. Alternate access routes would range from an additional 15 minutes to over 1-1/2 hours to reach the site, depending on what other access routes are also underwater and impassible. Depending on the perceived severity of the situation, other modes of travel to the dam, such as a helicopter, could be used. Telephone communications are available at the dam, and the dam tender has two-way radio communication.
Consequence Likelihood	1-10
Justification	No peak flood flow velocities were provided from the flood inundation studies. Because of the narrow canyon and steepness of the downstream channel, flow depths and estimated flow velocities would likely be high for the majority of the flood flow cross section. Based on crude analyses, it is estimated that the depth-velocity factor for the flood flows for both reaches would be greater than 50. In some places it is likely that the flood severity would be severe. However, due to the steepness of the valley walls and abundant large vegetation, it is likely that the vast majority of the population at risk would be able to make it to higher ground very quickly, therefore only a medium flood severity was used for both reaches. Filling of the reservoir above the current maximum pool would be considered first filling and require 24-hour monitoring of the dam. Therefore, if a failure event occurred during a flood loading, then adequate warning (more than 60 minutes) would be provided prior to failure and breach. Because of the above, fatality rates were estimated to be relatively low with estimated average potential life loss less than 10.
Confidence	Moderate
Rationale	A more detailed life loss study could potentially show slightly higher fatality rates may be justified.
Economic and Environmental Consequences	
Consequence Description	The vast majority of the inundation area is public lands with relatively limited other use (scattered residential). No other major consequences were considered.
Consequence Likelihood	
Justification	

Confidence	
Rationale	
Other Consequences	
Consequence Description	None considered.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Inspect spillway channel after each flow event for signs of erosion.
Surveillance and Monitoring	Consider installing a staff gage in the spillway channel to monitor flow depths. Perform 24-hour monitoring when depth of flow in spillway channel exceeds historic flows.
EAP	Consider preparing inundation maps for breach of the spillway control structure.
Follow up Studies	Consider more detailed life loss studies for breach of the spillway.
Others	
Other Notes/Comments	

New Beaver Dam

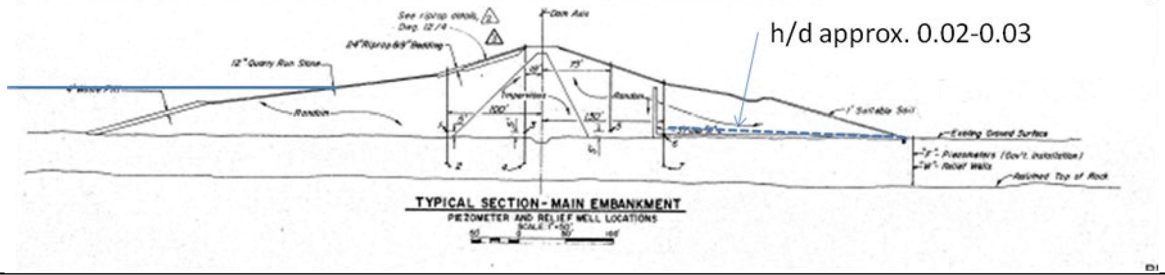
PFM Information

Structure	Main Dam
Loading Condition	Static
PFM Type	Internal Erosion
Location(s)	Sta 14+00

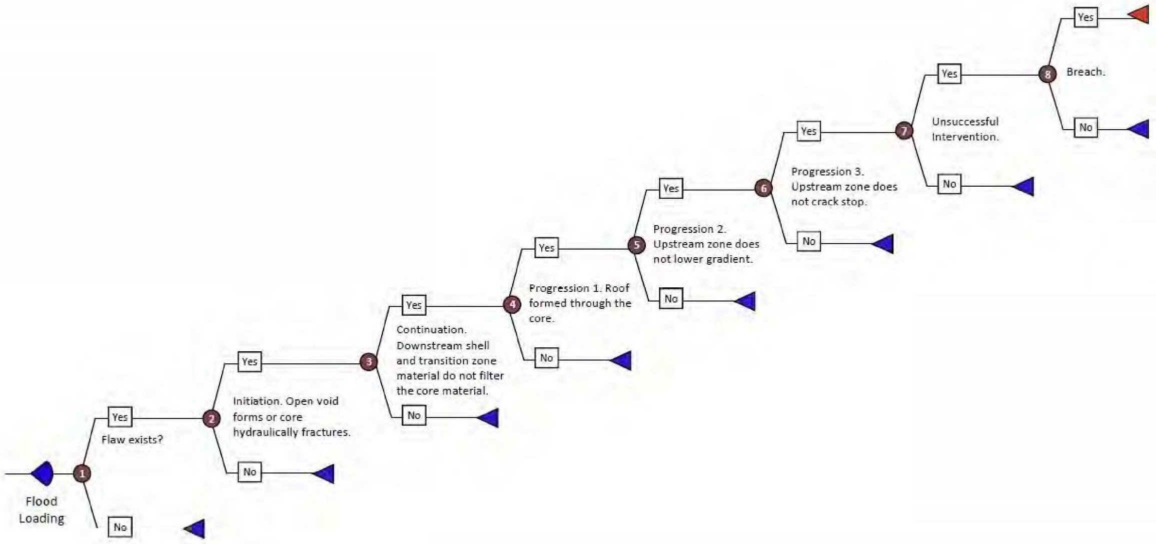
PFM Description

PFM No.	3
PFM Title	Backward erosion piping in foundation near 14+00 (former stream channel)
PFM Description	The reservoir rises above conservation pool of elevation 412 feet overwhelming the capacity of the toe drain system causing foundation pressures to rise to a sufficient level to heave the confining layer, creating an unfiltered exit at the ground surface. Sufficient gradient exists to remove soil particles at the exit initially forming a void. A pipe develops as soil particles are transported into the void as the erosion in the pipe advances upstream towards the reservoir. The fine-grained confining layer supports the roof of the developing pipe. The erosion pipe enlarges as flow increases. Breach initiates as gross enlargement leading to crest collapse and rapid release of the reservoir.

PFM Sketch



Event Tree (if used)



Additional Supporting Information (if needed)
Beaver Creek, just prior to construction of the dam, ran diagonally across embankment footprint from north to south prior to construction from approximately Station 13+00 to 15+00. The thickness of the alluvium was generally 15 to 20 feet pinching out at the abutments. A 5-foot deep inspection trench with 1H:1V side slopes and a 12-foot wide base was located in this section of the dam from Station 11+00 to 17+00. The alluvium consists primarily of fine-grained, plastic soils with more pervious soils classified as SM (silt sands) and SC (clayey sands) with very little to no SP (poorly graded sands) soils. The original design included 7 relief wells and a toe drain system, and 4 more relief wells were added before 1979. To lengthen the potential seepage path, the upstream channel was filled with waste fill from the first stage dike to the second stage dike approximately 1,200 feet along Beaver Creek and approximately 500 feet from the upstream toe. Waste fill was also placed in the downstream channel for a distance of 280 feet up to an elevation of about 900 feet (the top of original ground outside the channel.) The channel bottom was cleaned/de-mucked and widened to 30 feet with 4H:1V slopes. According to as-built drawing C-2-12/5, the channel was backfilled with random fill up to a minimum elevation of 900 feet (bottom of blanket filter). Zoning in the remainder of this section remained as designed with impervious fill placed in the center portion of the dam flanked by random fill. “Boils” were noted on the construction photographs showing de-mucking operation. This operation appeared to extend below the water table in the area and should have resulted in flow into the excavation. Some areas were noted as being backfilled with material placed by D8 dozer to provide stable base for subsequent compacted lifts.
Performance Monitoring Information
Seepage was first noted as “pinhead boils” near Station 11+25 in June 1986 after a significant increase in reservoir pool level during initial filling (weir flow 0.4 gpm). A total of 9 relief wells were installed between Stations 11+25 and 18+58 in June 1990. According to a 1991 Inspection Report, the seepage condition at the downstream toe improved, but seepage was still visible in old channel further downstream. Following installation of the 9 relief wells, piezometric levels dropped 0 to 5 feet. A 1993 Inspection Report describes a high pool in October 1982 with no seepage noted (seepage condition: “no apparent change”). Following the October 1982 high pool, piezometers responded to pool but then remained relatively unchanged (e.g., B-4 and B-6 at approximately 400 feet). A 1995 Inspection Report indicates no seepage in the notes (seepage condition: “no apparent change”). Following the new record pool of 414.14 in May 1994, piezometers responded to pool but remained relatively unchanged (e.g., B-4 and B-6 returned to approximately 400 feet). According to the high pool inspection report, a new boil was noted 150 yards southeast of the embankment toe with bubbles. A “wet area” was noted near Station 17+00 (piezometers B-5), and “bubbles” were noted near Station 18+00 (piezometer B-7). Boils and associated seepage were also noted during a high pool of 414.08 in May 1998. Piezometers responded to pool but then remained relatively unchanged (e.g., B-4 and B-6 returned to approximately 401 feet). During a high pool of 415.25 feet in June 2002, several boils up to 3 inches in diameter were observed in the former Beaver Creek channel, and a small boil was observed in the second toe drain ditch east of the stilling basin. According to Inspection Report (August 2002), the old river channel adjacent to service road was backfilled. During the 2005 record pool of 416.24 feet, a wet area was noted at the downstream toe near Station 12+00 that extended from the right abutment approximately 300 feet towards the east.

Influence Factors		
Event Tree Node (or other designation)	More Likely	Less Likely
	Embankment and/or confining layer can support a roof.	B-5A max reading at 2 feet above the ground surface (401.4).
	“Boils or bubbles” noted near penetrations or in area of potentially thinner confining layer at B-5 and B-6 and at ditch near Station 12+00.	Relief wells and toe drain system regularly maintained and cleaned at an interval less than 5 years.
	Sands beneath the fine-grained confining layer are fine-grained. Limited samples of SM have 100 percent passing the No. 40 sieve, with fines contents ranging from 20 to 40 percent.	Foundation consists predominantly of fine-grained soils.
		Path of channel prior to construction suggests sinuous/lengthened seepage path.
		High tailwater (for pools greater than about 412.6 feet).
		Base width of embankment is about 250 feet and provides an average gradient of approximately 0.1 at 419 feet (PMF).

Failure Likelihood Summary	
Failure Likelihood	1E-06 to 1E-07
Justification	The ratio of head-to-seepage path length (i.e., gradient) indicates low values, as shown in Figure 7.5, and actual data from piezometers indicated even lower values under the downstream portion of the dam. Graphs of piezometric levels during the 2002 high pool were compared. The effect of tailwater on the piezometers was suggested to be more of a factor than previously thought. B-6 indicates a lower pressure head of about 2 to 3 feet at normal pool levels from early readings after initial filling to those recorded lately. This indicates the drainage systems have been improved, or the reservoir has silted in. A record of drain flows would help in determining the cause of this improved condition. The foundation drainage systems (toe drain and relief wells) for the dam as well as several piezometers become submerged during high releases. A more detailed review of the foundation piezometers is needed to verify this finding. The site visit revealed that tailwater currently enters the toe drain system directly at the lowest manhole even though the outfall for the toe drain has a flap gate. During the site visit, water was observed exiting this drain outfall, but no water was entering the inlet on the berm. Photographs from the 2002 high water event revealed that the toe ditch became flooded. Based on the drawings, it would appear that the filter blanket starts to

<table>
<tr><td></td><td>become inundated when tailwater at the toe ditch gets above 414.5 to 415 feet. At the PMF of 419 feet, the APF will be less than the AEP of 5E-06/year. Spillway crest is 412 feet, (AEP of 3E-02/year) which had satisfactory performance with no boils noted (i.e., SRP less than 1E-04). Therefore, the APF is estimated to be (5E-03/year)(1E-04) or about 5E-07/year to 1E-06/year. At the conservation pool of 412 feet, the APF is also expected to be less than 5E-07/year to 1E-06/year. Therefore, the total APF is likely to be on the order of 1E-06/year to 1E-05/year.</td></tr>
<tr><td>Confidence</td><td>Moderate</td></tr>
<tr><td>Rationale</td><td>The team felt moderately confident in the magnitude of the estimate, some key information might possibly influence the estimate.</td></tr>
<tr><td colspan="2">Consequences</td></tr>
<tr><td colspan="2">Life Safety Consequences</td></tr>
<tr><td>Consequence Description</td><td>New Beaver Dam is located on Beaver Creek upstream of New Beaverdale. Beaver Creek is one of three principal tributaries of Scott's River. The breach of New Beaver Dam main embankment would cause a major flood and inundate several towns, with the most significant impacts to New Beaverdale. The flood wave would travel down Beaver Creek to the confluence with Scott's River and then continue to the Monster River where flows would be contained within the banks of the river. Regional impacts of a dam failure would be observed approximately 25 miles downstream to the confluence with the Monster River, with the deepest inundation occurring within the first eight miles downstream of the dam. Potentially impacted facilities include a school, communication facilities, fire and police stations, electrical substations, and a health care facility.</td></tr>
<tr><td>Estimated PAR</td><td>PAR was estimated from overlaying the inundation area over GoogleMap images. Limited field truthing was done. Estimated PAR is provided in the table below:
<table>
<tr><th>Distance Downstream</th><th>Day PAR</th><th>Night PAR</th></tr>
<tr><td>0-8 mi.</td><td>6</td><td>8</td></tr>
<tr><td>8-18</td><td>2</td><td>1</td></tr>
<tr><td>18-25</td><td>1</td><td>1</td></tr>
</table></td></tr>
<tr><td>Inundation Characteristics</td><td>Beaver Creek downstream of the dam follows an incised channel in the flood plain before discharging into Scott's River. The relatively narrow flood plain includes some farm fields and dense trees. The inundation area downstream of the confluence with Scott's River is a much broader and gently sloping flood plain.
<table>
<tr><th>Location</th><th>Time (hr)</th><th>Depth (ft)</th><th>Velocity (ft/s)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
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</table>

Warning/Evacuation Challenges	The dam is not attended full-time. The dam owner visits the site once a day to confirm reservoir elevation, gate settings, and other tasks. The dam is not visited on the weekends or holidays. The dam has no video camera facilities. The first indication of a problem would likely be a reservoir level warning or high flow warning on the stream gage ½-mile downstream of the dam on Beaver Creek. The first inhabited structures are located 2 miles downstream of the dam.
Consequence Likelihood	1-10
Justification	Life loss is anticipated to range between 2 and 6 for this PFM, depending on the time of day and day of the week.
Confidence	High
Rationale	It is very difficult to envision a life loss less than 1 or greater than 10 for this PFM.
Economic and Environmental Consequences	
Consequence Description	Economic consequences were not estimated.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Other Consequences	
Consequence Description	No other consequences were estimated.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue to monitor seepage and boils during periods of high pool.
Surveillance and Monitoring	Consider installing recorders on select piezometers that collect and transmit data daily for evaluation. Consider installing a high-level alarm on the seepage collection weir. Consider installing video cameras to observe conditions along the downstream toe of the dam.
EAP	Consider using this PFM during the next table top or functional exercise.
Follow up Studies	Evaluate the need for additional piezometers to evaluate seepage gradients near the downstream toe.
Others	
Other Notes/Comments	

Old Man Dam

PFM Information	
Structure	Main Dam
Loading Condition	Static
PFM Type	Slope Stability
Location(s)	

PFM Description	
PFM No.	7
PFM Title	Downstream slope instability due to excessive foundation pore pressures
PFM Description	The reservoir rises causing an increase in foundation pore pressure and a decrease in effective stress, resulting in downstream slope instability, deformations and embankment cracks extending across the dam. Overtopping due to failure at crest is thought to be less likely than embankment cracking, and thus cracking is proposed as part of failure. Concentrated leak erosion through the crack initiates with an unfiltered exit above the filter or below the filter if it is severely damaged so that it does not function. Leakage flows and erosion increase, progressively enlarging the crack. Gross enlargement and lateral erosion of the opening occurs until the reservoir is rapidly released through opening, and the dam erodes to the base of the embankment.

PFM Sketch

See sketch of failure surface in Additional Supporting Information section.

Event Tree (if used)

- The reservoir rises
- Foundation pore pressures increase and effective stresses decrease
- Downstream embankment slope fail resulting in deformations leading to embankment cracking
- Concentrated leak erosion through the crack initiates
- Flow continue to erode cracks, progressively enlarging the cracks
- No crackstopper upstream
- Gross enlargement and lateral erosion of the cracks progress until the reservoir is rapidly released through opening
- Intervention unsuccessful
- Dam breaches.

Additional Supporting Information (if needed)

The downstream slopes are 3H:1V to 6H:1V to 3.5H:1V. Internal seepage control features include blanket/chimney drain at the section in the valley bottom and in addition relief wells between Stations 110+00 to 119+00. An updated stability analysis using as-built shear strengths was reported in the 1991 Stability Analysis Report. The factor of safety for the end-of-construction condition was 1.25.

<table>
<tr><td colspan="4">The factor of safety for steady-state seepage with a pool of 963 feet and tailwater of 896 feet was 1.43. This analysis had the filter in the “as-built” location 120 feet downstream of dam centerline, whereas an earlier analysis had the filter located further upstream and higher.</td></tr>
<tr><th colspan="4">Performance Monitoring Information</th></tr>
<tr><td colspan="4">No instability was observed at record pool. Piezometer B-4 increases 5 to 8 feet at 962.5 feet which is about 2 feet above ground surface. Tailwater has an effect on this rise. No instability was noted during or at the end of construction. Instrumentation indicated that construction-related pore pressures were generated in the embankment as well as the foundation in some locations but have since drained and now reflects drained conditions (e.g., B-3 and B-5 in the embankment and B-7 in the foundation). It was noted that foundation pore pressures at Section B (B2 and B4) indicate higher pressures than at sections A, C, or D. This condition has been present since the instruments began responding to initial filling of the reservoir in the late 60’s.</td></tr>
<tr><th colspan="4">Influence Factors</th></tr>
<tr><td>Event Tree Node (or other designation)</td><td colspan="2">More Likely</td><td>Less Likely</td></tr>
<tr><td rowspan="3"></td><td colspan="2">There is no cut-off trench to rock.</td><td>Significant construction pore pressures were generated with no instability noted.</td></tr>
<tr><td colspan="2">Some CH soils are present in the foundation with potentially lower strength.</td><td>3H:1V to 6H:1V to 3.5H:1V relatively flat slopes with an intermediate berm.</td></tr>
<tr><td colspan="2">Free water has been observed at toe.</td><td>No significant movement up to the record pool has been observed.</td></tr>
<tr><td rowspan="3"></td><td colspan="2"></td><td>The road at the downstream toe appears to be elevated slightly and may provide additional resistance to sliding.</td></tr>
<tr><td colspan="2"></td><td>The filter blanket and chimney, relief wells, and toe drain system provide drainage of embankment and foundation.</td></tr>
<tr><td colspan="2"></td><td>Significant construction pore pressures were generated with no instability noted.</td></tr>
<tr><th colspan="4">Failure Likelihood Summary</th></tr>
<tr><td colspan="2">Failure Likelihood</td><td colspan="2">1E-06 to 1E-07</td></tr>
<tr><td colspan="2">Justification</td><td colspan="2">At the PMF of 988 feet, the APF will be less than the AEP of 5E-06/year. At the record pool of 962.24 feet with an AEP of about 3E-02/year, no instability was observed (i.e., SRP less than 1E-04). Therefore, the APF for record pool is approximately 3E-06/year, and the APF for the full range of loading would be on order of 1E-05/year to 1E-06/year. The key factors for this estimate are the lack of deformation noted to-date under end-of-construction pore pressure conditions as well conditions associated with the record pool which was slightly above the flood control pool; the stability provided by the relatively flat slopes; and the apparent control of pore pressures as a result of the drainage systems and apparent upstream control.</td></tr>
<tr><td colspan="2">Confidence</td><td colspan="2">Moderate to High.</td></tr>
</table>

Rationale	Pore pressure at pools greater than the record pool are somewhat uncertain and might lead to unexpected behavior. Team was not aware of any case histories for this PFM.
Consequences	
Life Safety Consequences	
Consequence Description	Old Man Dam is located on the Timothy Draw drainage, which joins with Ginger Creek approximately four miles downstream of the dam. Ginger Creek then flows into the Gold River approximately 15 miles downstream of the dam. Timothy Draw and Ginger Creek flow through a sparsely to moderately populated area comprised mostly of farm land with the owner's houses. There are no concentrated population centers along the drainage. The inundation area is fairly wide immediately downstream of the dam, but within two or three miles, becomes fairly channelized (1/4 to ½ mile wide) by bluffs located on both sides of Ginger Creek that rise on the order of 90 feet above the creek. The inundation area does not encroach upon the nearby town of Hazel, but passes entirely to the east of the town. The inundation area remains fairly confined to the Ginger Creek drainage until reaching the Gold River. The inundation area flows over state highway 119 just prior to the confluence of Ginger Creek and Gold River, where the flood waters widen considerably. The majority of this area is sparsely populated. From this point downstream along the Gold River, there is no population at risk (PAR) until reaching Elbert, approximately 35 miles downstream of the dam. At this point, the Gold River meets the Whiskey River and the inundation area again becomes fairly broad. Several roads are impacted, as well as the southern portion of Elbert. Beyond this point, the flood waters are minimal and do not present a significant risk further downstream
Estimated PAR	Failure of Old Man Dam has the potential to place many people at risk. The number of people and their location varies substantially depending on the time of day. The overall PAR was estimated by using inhabitable structure estimates based on 2018 GoogleMap files within the estimated inundation limits obtained from the most recent inundation study. Data from the 2010 Census indicates 3.05 residents/house in county. Recent Census data indicates a 4.2 percent population increase in the county from 2010 to 2018, or about a half percent increase per year. Assuming an inhabitable structure estimate from 2018, accounting for a half percent population increase per year, and assuming 3.05 residents/structure results in a PAR of approximately 503 within the downstream inundation limits. This estimate is based on a hydrologic failure mode and would be expected to vary depending on the day of week and time of day.

<table>
<tr><td></td><td>There are no significant transient population areas within the inundation limits (i.e., no fishing, camping, picnic areas) other than regional transportation corridors. Therefore, the PAR estimates do not include transient populations.

The inundation area for a sunny day failure under static or seismic loading would be expected to be slightly smaller due to the smaller reservoir volume and lower reservoir head available as compared to a hydrologic failure. However, due to the broadness of the inundation area within the first three miles downstream of the dam, the presence of the greatest PAR within the first three miles downstream of the dam, and the relative small percentage of difference between the reservoir height and volumes between the sunny day and hydrologic failure scenarios, the inundation area for the hydrologic failure was conservatively used to estimate the inundation area for the sunny day failure scenarios.</td></tr>
<tr><td>Inundation Characteristics</td><td>Travel times for the leading edge of the flood wave are provided on the inundation maps. The results of that study provide estimates of the leading edge of the flood wave beginning at the time of failure at the dam. This includes a travel time of 4 to 6 hours to reach the Gold River and 15 to 35 hours to reach Elbert.
<table>
<tr><th>Location</th><th>Time (hr)</th><th>Depth (ft)</th><th>Velocity (ft/s)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td>District personnel are stationed at the office and maintenance facility located at the downstream toe of the dam on a daily basis. In addition, recreationalists use the reservoir and other facilities at the reservoir on a daily basis during spring, summer, and fall months. In addition, a fairly well traveled state highway is located very close to the left and downstream portions of the dam. However, typically the dam and reservoir area are not occupied during nighttime hours. Therefore, the following assumptions were made in regard to detection of an event leading to failure of the dam. For a slow failure scenario (daytime or nighttime), initial detection would be made at the dam, therefore some warning would be provided prior to failure and breach of the embankment.</td></tr>
<tr><td>Consequence Likelihood</td><td>10-100</td></tr>
<tr><td>Justification</td><td>For the assumed slower failure scenario and adequate warning, a relatively low fatality rate was applied to the PAR that resulted in an average estimated potential life loss in the range of 15 to 25.</td></tr>
<tr><td>Confidence</td><td>High</td></tr>
<tr><td>Rationale</td><td>It’s not expected that a more detailed life loss study would yield substantially higher or lower (order of magnitude) estimates for potential life loss.</td></tr>
</table>

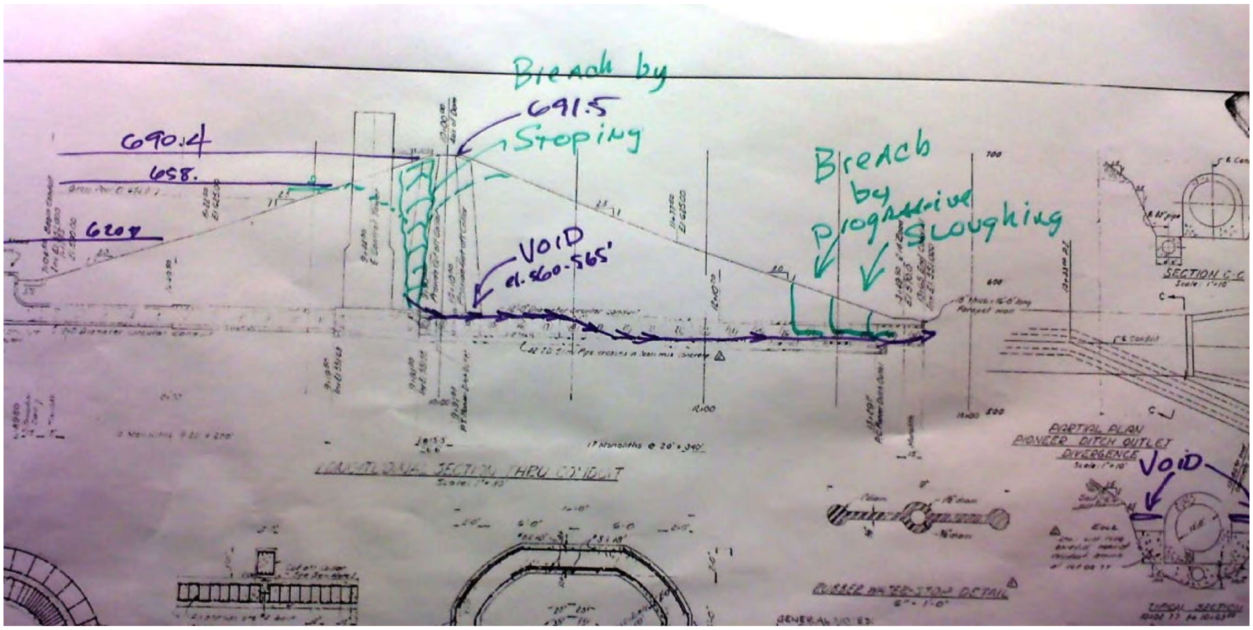
Economic and Environmental Consequences	
Consequence Description	Not considered
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Other Consequences	
Consequence Description	Not considered
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue weekly, monthly, and annual inspections of the dam looking for cracks, bulges, offsets or other signs of slope instability.
Surveillance and Monitoring	Continue to read piezometers and survey monuments. Consider installing additional piezometers along the maximum section of the dam.
EAP	Signs of slope instability should be apparent prior to a failure and failure is anticipated to develop relatively slowly due to the highly plastic nature of the embankment materials.
Follow up Studies	
Others	
Other Notes/Comments	

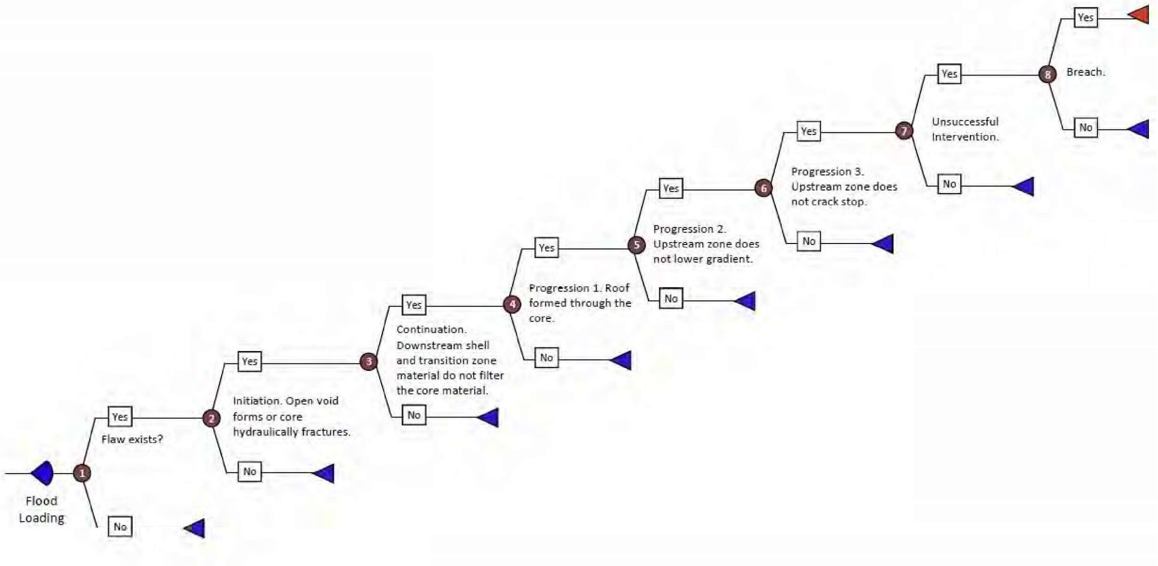
Long Draw Dam

PFM Information	
Structure	Main Dam
Loading Condition	Flood
PFM Type	Internal Erosion
Location(s)	At Outlet Works

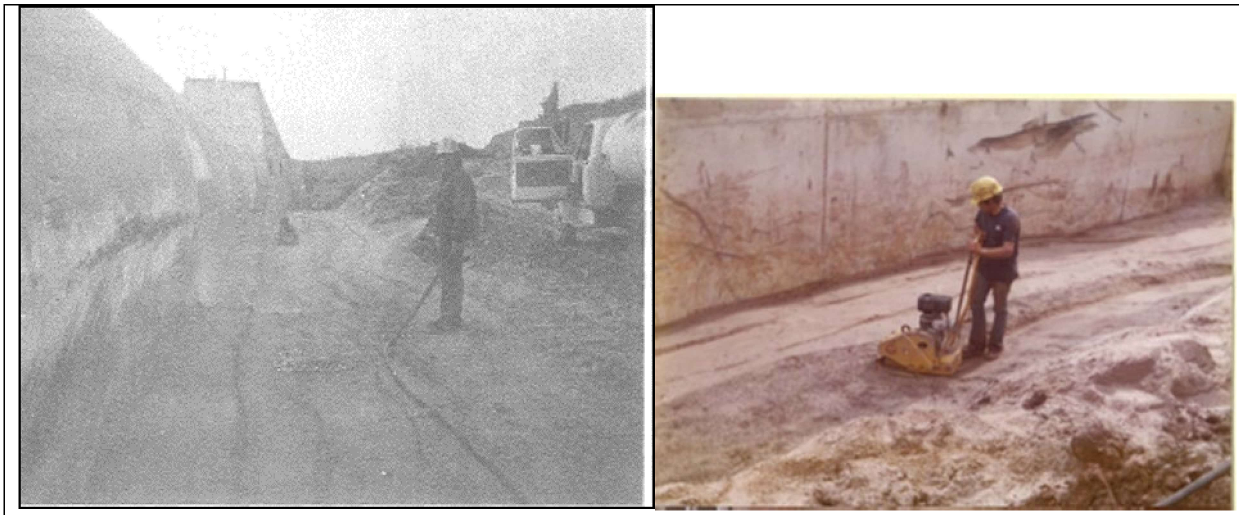
PFM Description	
PFM No.	13
PFM Title	Concentrated leak erosion in transverse crack above conduit and filter
PFM Description	The reservoir rises above 951.4 feet (conservation pool). A defect, such as a crack or hydraulic fracture, due to a low density zone exists in the embankment above the conduit. A concentrated leak develops, and an unfiltered exit exists above the top of the chimney filter (also at 951.4 feet). Leakage flows and erosion increase, progressively enlarging the crack. Gross enlargement and lateral erosion of the opening occurs until the reservoir is rapidly released through opening, and the dam erodes to the base of the embankment.

PFM Sketch

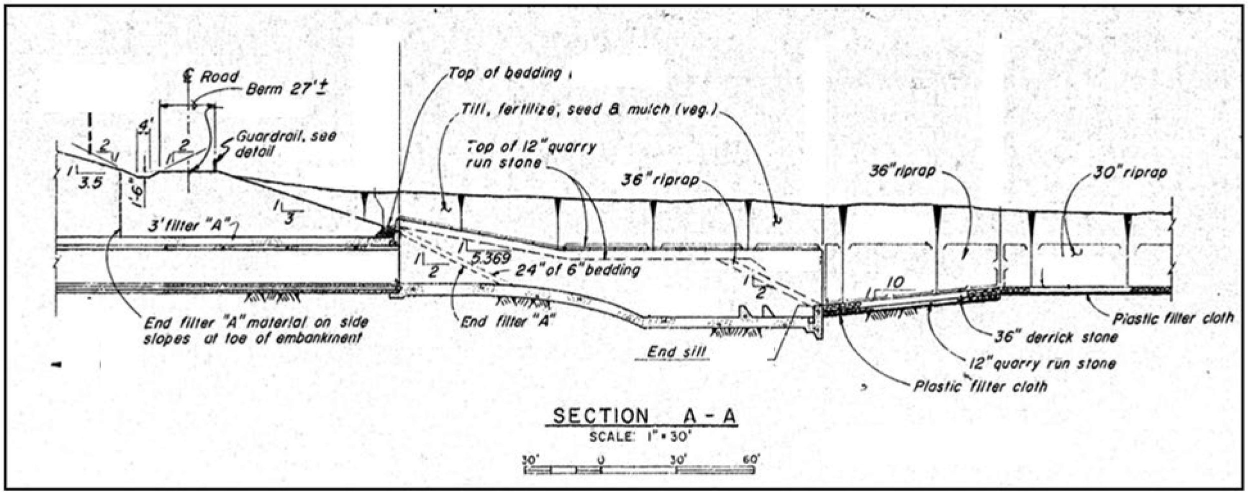


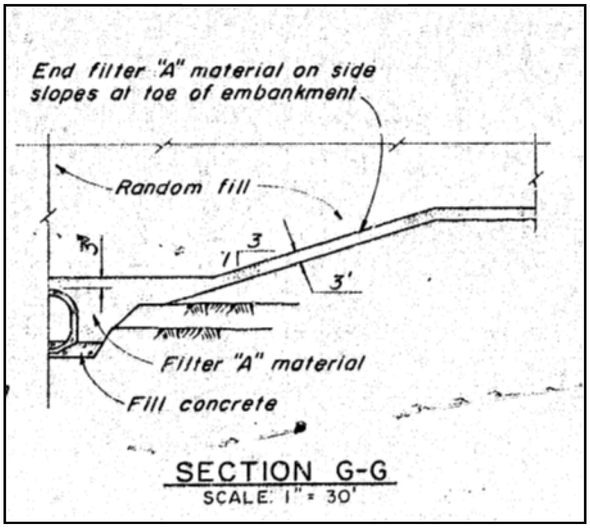
Event Tree (if used)


Additional Supporting Information (if needed)
 Construction Photograph of Outlet Works Excavation



Construction Photographs of Filter Placement around the Conduit





"As-Built" Details of Filter around the Conduit

Performance Monitoring Information
No instrumentation exists along the conduit. No seepage or leakage has been observed at the downstream toe along the conduit.

Influence Factors		
Event Tree Node (or other designation)	More Likely	Less Likely
	Unfiltered exit exists above 951.4 feet.	Top of the outlet conduit and top of weathered rock are at similar elevations so any differential settlement should be negligible.
		Majority of field moisture contents were wet of optimum (average moisture content).
		Embankment plasticity index is greater than 20, with an average of 20 to 30.
		No seepage was observed up to record pool of 964.24.

Failure Likelihood Summary	
Failure Likelihood	1E-06 to 1E-07
Justification	There is no compelling evidence to suggest that a crack exists. Key evidence is weighted against a crack or hydraulic fracture. The top of the conduit and top of weathered bedrock adjacent to the conduit excavation are at similar elevations, and any differential settlement should be minor. Compaction using a vibratory-plate compactor was specified for Filter “A” material around and over the top of the conduit. The embankment soils were placed wet of optimum with average plasticity index greater than 20. No cracking or seepage has been observed in this area up to the record pool of 964.24 feet, which extended about 12 feet above the top of the filter.
Confidence	Moderate to High.
Rationale	The evidence was fairly compelling for the selection of the likelihood. Since the dispersive characteristics of the clay were unknown, the confidence was extended to moderate.

Consequences	
Life Safety Consequences	
Consequence Description	The primary consequence center is Howard, Texas which is located between the toe of the dam and about 22 river miles downstream along the Mainstem River. In Howard, the northern and western portion of Titan Industrial Park is inundated. Merry, Texas is located about 50 river miles downstream of the dam, but only the MHP breach scenario inundates Merry. Howard has less than 1 hour for the MHP breach flood wave arrival time (2-foot rise), and the flood wave arrival time for Merry is about 7 hours.
Estimated PAR	The PAR for a MHP breach ranges from 280 (day) to 390 (night); the PAR for a TAS breach ranges from 200 (day) to 280 (night); and the PAR for a

<table>
<tr><td></td><td colspan="4">sunny day breach is about 30 to 120. The majority of the PAR is in Howard. The incremental PAR for MHP breach is 184 (day) and 255 (night).</td></tr>
<tr><td rowspan="5">Inundation Characteristics</td><td colspan="4">The majority of the single family homes observed during the risk team’s site visit were single story, with most multi-family structures being 2-story buildings. The estimated depth of flooding for MHP breach within Howard typically ranges from 8 to 14 feet but as deep as 20 feet in populated areas. In Merry, the estimated depth of flooding for MHP breach typically ranges from 5 to 10 feet. Based on these depths, single-story structures will not provide safe shelter, and for a depth of flooding of 20 feet, two-story structures will not provide safe shelter either.</td></tr>
<tr><td>Location</td><td>Time (hr)</td><td>Depth (ft)</td><td>Velocity (ft/s)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td colspan="4">There are several facilities in Howard requiring special evacuation assistance within the spillway and embankment breach inundation zones including hospitals, schools, and correctional facilities.</td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4">10-100</td></tr>
<tr><td>Justification</td><td colspan="4">The breach parameters compare favorably with the team’s estimated parameters.

Due to the proximity of the large PAR to the dam, the life loss estimates are not sensitive to warning time. The estimated incremental life loss ranged from about 60 (MHP breach) to 10 (TAS breach) to about 13 to 40 (sunny day).

The life loss estimate is based on the Emergency Alert System (EAS) only. The warning effectiveness may be better than EAS for two reasons. The dense urban development facilitates warning dissemination between neighbors and family, and the PAR will likely have heightened awareness of the reservoir filling given its recent storage history and the extended period of drought and near-drought conditions in this part of Texas. Because of the urban environment, numerous evacuation routes are available, many perpendicular to the river in the residential areas, except for those near the toe of the dam and the river. The maximum distance to evacuate is less than 2 miles nearest the confluence of Smith Creek and less than 1 mile for other areas.</td></tr>
<tr><td>Confidence</td><td colspan="4">Moderate to High</td></tr>
<tr><td>Rationale</td><td colspan="4">Given the close proximity of the large PAR to the dam, there is a potential for significant life loss and it is unlikely that the estimated life loss will change by an order of magnitude.</td></tr>
</table>

Economic and Environmental Consequences	
Consequence Description	There are four endangered mussels in the area.
Consequence Likelihood	Environmental consequences were considered qualitatively.
Justification	Loss or reduction in upstream pool would potentially be considered a benefit as the pool is drawn down periodically to allow vegetation to be established to augment the aquatic habitat. If the pool loss occurred in the winter (unlikely since locking does not occur), the potential separation of off channel pools from the river and lower water levels would be an impact to the ability of the aquatic species to survive the winter freezing period.
Confidence	Low
Rationale	
Other Consequences	
Consequence Description	None.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue to inspect along downstream toe where outlet works penetrate the embankment.
Surveillance and Monitoring	Consider installing piezometers along profile of outlet works from the core to the downstream shell to verify the phreatic surface.
EAP	Initial breach might be limited due to effects of outlet conduit. Might also impact use of outlet to drawdown the reservoir in the event the PFM activated at this location.
Follow up Studies	
Others	
Other Notes/Comments	