State of Colorado
Department of Natural Resources
Division of Water Resources
Office of the State Engineer

GUIDELINES FOR COMPREHENSIVE DAM SAFETY EVALUATION (CDSE) RISK ASSESSMENTS & RISK INFORMED DECISION MAKING (RIDM)

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Section 1. **Single Page Overview of CDSE/Risk Assessment Process**

CDSE Purpose

- Why are we doing this?
- Better understanding of dam design, performance, and construction history
- To allow for more Risk Informed Decision making:
  - Identify & predict future behavior of latent defects
  - Setting safe storage level
  - Identify focused observation and monitoring points
  - Identify actions, as needed, to reduce potential failure likelihood and potential failure consequences to acceptable levels of risk.

Risk Assessment Steps

- Comprehensive file review (Owner's SME with support from CO DSB)
  - History of construction, performance, and supporting engineering analyses
- Potential Failure Modes Analysis Screening Workshop (All Participants)
  - Jumpstart using list of "typical" PFMs
  - Modify/add PFMs as appropriate for specifics of dam
  - Screen out PFMs as remote with good cause shown
  - Identify Carried forward PFMs
- PFM Information Gathering (Owner's SME with Support from CO DSB)
  - Gather & organize available information related to Carried Forward PFMs to support positive and adverse factors
  - Gather available information related to consequences including Life Loss
- Risk Assessment Workshop (All Participants)
  - Finalize event trees for each Carried Forward PFMs
  - Work through positive and adverse factors for tyical nodes on event tree
  - Assess nodal probabilities
  - Assign best estimate (consensus) failure likelihood and consequence categories
  - Assess confidence for both failure likelihood and consequences and plot on CO Dam Safety Risk Matrix
  - Develop action items for each PFM based on likelihood, consequences, and confidence

Participants

- Facilitator - Independent 3rd party experienced in CO Dam Safety Branch CDSE Risk Assessment Process. Approved by CO DSB.
- Owner Staff, Owner Engineers, & Owner Dam Operations and Maintenance
- Owner's Consulting Engineer serving as subject matter expert (SME) or design engineer
- Notetaker - Owner or SME Staff
- Colorado Dam Safety Branch Chief, Risk SME, and Regional Dam Safety Engineers

Schedule Considerations

- Facilitator procurement
- File review completion
- PFM Screening Workshop
- PFM Information gathering
- Risk Assessment workshop
- Full CDSE Risk Assessment Report

In depth Guidance

- Remainder of this document: *Updated Guidelines for Comprehensive Dam Safety Evaluations, Risk Assessment Workshops, and Risk Informed Decision Making, January 29, 2021*

Section 2. Purpose and Expected Outcomes

2.1 Background and Need

The Colorado Dam Safety Branch is statutorily responsible for determining the ***safe storage level*** for all reservoirs impounded by dams in the State of Colorado. This authority has historically been executed by Dam Safety Branch Engineers primarily through visual inspections. However, this historic process is less effective at identifying slowly developing dam safety defects in existing dams. In addition, the process is inherently re-active. Within our organization and across the dam safety industry, a more pro-active approach that identifies, documents, and evaluates credible potential failure modes and associated consequences is becoming the industry accepted standard of practice for understanding the risks posed by a dam. The Comprehensive Dam Safety Evaluation (CDSE) Risk Assessment process was developed by the Colorado Dam Safety Branch in 2015 using Federal (USBR and USACE) best practices as a foundation. Since 2015 the CDSE process has evolved to fit the unique needs of a State dam safety program.

Many of Colorado's high hazard dams are approaching or are well over 100 years of age. As these dams have continued to age, the population continues to increase below them. Historical, standards-based engineering design to ensure safe dams have built upon continued observation and study of how existing dams behave, respond to varying loads, and also fail. Hence the development of "potential failure modes" (PFM's) analysis (PFMA) as a way to assess the likelihood of a given dam failing in ways similar to those observed historically. Standards based design and dam safety rules can result in requirements for defensive designs to address credible PFM's. However, assessing a given dams' compliance against a standard or rule as a measure of the dams safety does not adequately address the uncertainties associated with its design, construction, and performance history.

Moreover, while design standards and rule requirements have evolved to keep up with best practices, 100+ year old dams have not necessarily evolved. In most cases the standards to which they were built are not as conservative or defensive as what is considered the standard of practice today. Additionally, some dams have been re-classified as high hazard due to downstream development and may have been designed and built to less stringent standards. Developing and implementing this CDSE risk assessment process allows for a more complete view of how existing dams were designed, construction and have performed and what improvements, if any, are needed to ensure the dam now presents an acceptable level of risk. In other words, it is entirely possible that a dam may not meet all modern standards based design requirements, but it does not present an unacceptable level of risk to the downstream public. Conversely, the more comprehensive review and evaluation involved in completing a full CDSE report could bring to light a previously unknown concern that does present an unacceptable level of risk that requires a risk reduction action.

The importance of this approach and developing a more complete understanding of the dam has recently been highlighted by:

- Emergency spillway incident at the largest dam in the US, Oroville Dam, 2017.
- Spencer Dam failure in Nebraska, 2019.
- Edenville & Sanford Dam failures in Michigan, 2020.

2.2 Expected Outcomes

The primary intent of the CDSE process is to consistently develop PFM's and understand their impact within an acceptable level of risk framework. That information is used to make risk informed decisions for:

- Setting the safe storage level as an interim risk reduction measure.
- Working with partners to reduce the potential for consequences downstream.

- Supporting dam owners in making decisions to modify or rehabilitate their dams when risks are considered unacceptable.
- Providing a basis for obtaining additional information that will increase knowledge and confidence in risk assessment.
- Assess the risk posed by existing dams in terms of Rules and Risk-based frameworks.
- Help inform the design of new dams and the repair/modification of existing dams in concert with our January 1, 2020 Rules and Regulations for Dam Safety and Dam Construction.
- Assess the impacts of any potential dam raises or increases in water storage on the existing structure.

2.3 Roles and Responsibilities

The full CDSE process is best utilized through a team effort that leverages the strengths of the Colorado Dam Safety Branch engineers, dam owners, a dam owner's engineer, a Facilitator and a trained notetaker in a Risk Assessment Workshop setting. Briefly, the Risk Assessment workshop includes a Potential Failure Modes Analysis, judgement of likelihood of failure and associated consequences, and an assessment of confidence. Some key strengths of CDSE team members are described below.

- Colorado Dam Safety Branch Engineers – Dam engineering and dam safety subject matter experts (SME) and access to digital repository of information about dams in Colorado.
- Dam Owners – Extensive hands-on knowledge of the operation, maintenance and performance of their dams.
- Dam Owner's Engineer – Brings an outside perspective, dam engineering expertise (SME), and knowledge of past investigations and analyses specific to the dam. In addition, junior engineers (if a consulting firm is utilized) can be used as appropriate for economic efficiency and to train new generations of engineers.
- Facilitator – A trained and experienced Facilitator can draw out the key points of the various potential failure modes and consequences in a workshop setting to get the most out of the assembled CDSE team. They also keep the PFMA sessions moving to avoid stalemates or roadblocks and work to obtain consensus.
- Notetaker – Adequate documentation of the CDSE Risk Assessment process is critical to creating a transparent record of the known state of the risk at high hazard dams and of the decisions made based on those risks. The CDSE Risk Assessment workshop setting can be stressful on a notetaker, so good computer skills and patience are essential qualities.

It is also key that Colorado Dam Safety Branch engineers work with dam owners during these processes. Through the workshops conducted to date the value of this collaboration has been demonstrated. Dam Safety engineers and dam owners alike ALWAYS come away knowing more about the dams they regulate and own, respectively. Making decisions together, based on an objective look at the available information allows consensus decisions that set expectations of all going forward and improves the overall safety of the dam and downstream public. This is the essence and power of this process to reduce the risk of dams in Colorado.

Section 3. <u>**Colorado Dam Safety Branch Risk Tools (CDSE Process)**</u>

3.1 History

The intent of the Colorado Dam Safety Branch risk process was not to create another acronym with "CDSE", but rather to create a process for a "comprehensive" look at dams within our existing high hazard inventory. The intent of the name was to capture the concept that being able to make a risk informed decision on a high hazard dam requires a significant effort. It is not just a potential failure modes analysis, it is not just a risk assessment, it is not just a deep file review, updated inspection, updated analyses, and it is not just coordination with dam owners, engineers, and emergency managers. Such an analysis, in order to be comprehensive, must include all these things.

As a matter of priority, the Colorado Dam Safety Branch is focusing on completing CDSE's for high hazard dams. However, the process can be applied to make better decisions on dams of all hazard classifications.

With respect to Risk and Dam Safety management, the State of Colorado Dam Safety Branch recognizes the value and importance in completing:

- Full review of all available documentation to obtain better understanding of dam design, construction, performance, and operational history,
- Potential failure modes assessment in a repeatable/efficient manner,
- Consequence assessment,
- Portrayal of the identified PFM's in a risk matrix that informs dam safety decision making consistent with our mission as dam safety regulators.

RISK ASSESSMENT

Our regulatory program deals with a wide range of staff, owners, and consulting engineers who may have limited experience in the concept of risk and potential failure modes analysis (PFMA), so a key theme of consistency and objectivity has been important in developing our CDSE Risk Tools. This has resulted in:

- Full CDSE Risk Assessment Report templates,
- Typical PFM lists for earthen and concrete dams used for initial screening, as well as,
- PFM Worksheets and Event Tree Libraries, and;
- Recommended actions for risk reduction.

It should be noted that the typical PFM lists and event tree libraries are not considered all-encompassing and should be adapted and expanded as needed to suit site-specific conditions. They should not limit imagination of what may be physically possible. With that said, the templates were created in an attempt to be consistent with the physical mechanics of common failure modes and for ease of entry into the PFMA process for the uninitiated. It is common for engineers experienced solely in standards based design to be unfamiliar with potential failure modes analyses as related to dams.

Therefore, it is fully expected that owners and consultants completing this process for dams regulated by the Colorado Dam Safety Branch will utilize the report, screening, PFM library, and risk matrix templates as described within this guidance.

3.2 Application and Use

3.2.1 Issue Specific Risk Evaluation Use by Dam Safety Engineers

Elements of this process have and will continue to be used by Dam Safety Branch Engineers for evaluating issue-specific PFM's as related to safe storage level. This is in accordance with Rule 5.2 of the January 1, 2020 Rules and Regulation for Dam Safety and Dam Construction. Evaluating observed conditions that may lead to a storage restriction, or restriction lifting in a Risk Assessment framework is valuable for gaining consensus and justification for regulatory actions.

3.2.2 Issue Specific Risk Evaluation Use by Owners and Owner Engineers

Owners and their engineers can also use the CDSE tools to address issue specific PFM's, in collaboration with the Colorado Dam Safety Branch as described in Section 4 below. Dam owners and their engineers will need to follow the process of evaluating a specific PFM by working through the Risk Assessment Workshop process with experienced Engineers and Facilitators as described in this guidance document. This process has been used to provide justification to dam owner leadership (Ag Boards, HOA's, etc.) for making necessary dam safety investments.

3.2.3 Application of Full CDSE Risk Assessments across an Inventory of Regulated Dams

Since this process was first initiated by the Colorado Dam Safety Branch in 2015, its application has proven invaluable in assessing existing dams within the high hazard inventory. In some cases, issues were found that required action and in other cases it provided justification to eliminate perceived risks. Application of the process has evaluated perceived and previously unknown latent defects in existing dams, helped construction projects stay on budget and within reasonable risk, and helped owners better understand their dams in general, allowing them to focus financial resources.

Given our diverse inventory of dam owners, it is ***NOT*** considered realistic that:

- All High hazard dam owners will have the financial resources to complete a full CDSE Risk Assessment Report with the aid of experienced consulting Engineers and Facilitators through a Colorado Dam Safety Branch regulatory directive.
- It is also not realistic that the current staff of 12 Colorado Dam Safety Branch Engineers working to complete the annual duties described in their position descriptions will be able to complete full CDSE Risk Assessments Reports for the current inventory of nearly 396 High Hazard dams. A significant increase in staffing would be required to complete this effort internally, similar to that initiated by the California Division of Safety of Dams in 2020.

However, it is essential to keep a long-term goal of completing a full CDSE Risk Assessment Report evaluating all credible potential failure modes for a dam for our full inventory of High hazard dams for the reasons stated above. Therefore, Colorado Dam Safety Branch leadership is pursuing options to complete an eventual full high hazard dam inventory risk assessment (i.e. full CDSE Risk Assessment Reports). Current plans include:

- Owner will reach a critical decision making juncture OR recognize this is a valuable process to limit their own risk exposure and work to complete a full CDSE Risk Assessment Report with an experienced consulting engineer and Facilitator. It should be noted that several forward-thinking dam owners within the State have already voluntarily initiated this process for their own portfolio of dams.
- Through a variety of Federal and State grants, the Colorado Dam Safety Branch will contract with experienced consulting engineers and Facilitator to complete a full CDSE Risk Assessment Report on behalf of and in coordination with dam owners. These efforts will include developing a high hazard dam ranking system so that the order of full CDSE risk assessments is prioritized.
- The Colorado Dam Safety Branch will require full CDSE Risk Assessment when an existing dam increases in hazard classification to High Hazard.

3.3 About this Guidance Document

As previously described, the Colorado Dam Safety Branch began development of the CDSE processes in 2015 and have been using a "learning by doing" approach to guide continuous incremental improvements. As such, this guidance should be considered a living document that is expected to be updated as more CDSE risk assessments are completed and improvements and adjustments are made based on knowledge and insight gained through application and practice. A "revision date" will be applied to each updated version. Users should periodically check the Dam Safety Branch website to be sure they are using the latest version.

3.4 References

Based on our on-going review of the state of the practice, the following documents are recommended for review prior to performing CDSE risk assessments. The reference list below is clearly not all-inclusive. The references shown most aligned with the Colorado Dam Safety Branch application of risk principles and style of dam safety regulation.

- US Department of Interior Bureau of Reclamation/USACE, Best Practices & Risk Methodology, July 2019.
- Strategic Framework for Dam Safety Regulation, State of Victoria Department of Environment, Land, Water, and Planning, April 2014.
- Guidance Note on Dam Safety Decision Principles, State of Victoria Department of Environment, Land, Water, and Planning, March 2015.
- Tolerable Risk for Dams: How Safe is Safe Enough? David S. Bowles. USSD 2007.

Section 4. Issue Specific PFM Risk Evaluation vs. Full CDSE Risk Assessments

It is readily acknowledged that a full CDSE Risk Assessment Report process is no small task. Understanding this, there are intermediate steps to completing a full CDSE report that can be utilized by the Colorado Dam Safety Branch engineers, owners, and consulting engineers to address identified issue specific potential failure modes that may be of higher concern.

4.1 Issue Specific PFM Risk Evaluation

This is the direct approach to seeing immediate benefit from the CDSE tools. In this case, the risk tools are used to make difficult decisions regarding isolated concerning or uncertain issues identified during seemingly routine efforts by the Dam Safety Engineer or Owner such as:

- Visual inspections
- Instrumentation reviews
- Storage restriction reviews
- End of construction reviews
- Emergency planning efforts
- Engineering analyses
- Owner elected upgrades/modifications to the dam.

Stepping through an issue specific PFM evaluation can be a valuable risk informed decision making tool for making the day to day decisions required of state dam safety programs and dam owners. However, this does not change the long term goal of identifying and evaluating ***all credible potential failure modes*** through the full CDSE report process. The knowledge gained from the issue specific PFM risk evaluation will need to be incorporated into an eventual comprehensive PFMA and CDSE report for the given dam. Issue specific Risk Evaluations should be considered "Building Blocks" for the full CDSE process.

Once the concerning issue or required decision making has been identified through activities described above, it is considered important to identify the most appropriate failure mode(s) from the CDSE Typical PFM Screening List adapted to the site specific mechanism/issues. Decisions required of state dam officials that might require actions from dam owners should be made in coordination with the dam owners for transparency and to avoid surprises.

The steps described in the following sections for a full CDSE report also apply for the evaluation of that issue specific PFM, including retaining experienced Engineers and Facilitators, identification of risk category level, and identifying consequences.

Applicable portions of the CDSE Report Template should be used to summarizing background information, conclusions and recommendations. Other work products of the process including the PFM Screening List Selection, PFM Worksheets, consequences (life loss) calculations, and a plot on the risk matrix should be included. These documents together provide the basis for responsible dam safety decision making and actions to resolve PFMs and issues of concern.

4.2 CDSE Evaluation of all Credible PFMs and Consequences

As described, the goal of the Colorado Dam Safety Branch is to have all High Hazard dams evaluated within a CDSE Risk Assessment framework and a complete CDSE report produced. This involves experienced Engineers (SME's) and Facilitator's working alongside dam owners and operators and using Screening List and PFMA Worksheets to develop and evaluate all credible potential failure modes that apply to the dam site in a Risk Assessment Workshop setting. Guidance for completing this effort is provided below.

Once the CDSE report, summarizing the overall risk for the dam is complete, it is considered a living document that allows dam safety engineers, dam owners, and consulting engineers to completely assess safe storage level, focus future actions and monitoring on risk driving issues, and inform risk based design alternatives and evaluation.

Inspections will still be conducted annually by the Colorado Dam Safety Branch, but with a renewed focus on:

- Area or components of the dam relevant to risk driving potential failure modes identified in the overall CDSE report,
- Instrumentation changes related to those PFMs,
- Physical changes observed related to those PFMs,
- Careful observation for other new changes that may be related to PFM's carried forward in the process,
- Upkeep on routine maintenance for issues that could potentially initiate or become a PFM if left unchecked,
- Annual review of consequences downstream, and
- Annual review of Emergency Action Plans (EAPs) to ensure consequence reduction.

Recommended actions will be tracked through their association will an identified PFM. The focus being on risk driving issues, while tracking any changes or identified concerns within the living document CDSE Risk Assessment report framework. This will ultimately make the physical inspection process more efficient, freeing dam safety engineer and owner time for other activities.

More detailed guidance can be found in the following pages for preparing, completing, and documenting CDSE Risk Assessments for dams within the State of Colorado inventory.

Section 5. File Review and Background Information

In preparation for completing a CDSE and associated Risk Assessment Workshop (whether for issue specific or all credible PFMs), an in-depth file review should be completed and documented as described below. It is typically recommended that the Owner's consulting engineer obtain all available information from Owner and the Colorado Dam Safety Branch files to complete this effort. It should be considered part of the consulting engineer's scope to obtain the files from the various sources, review this information, summarize key design, construction and performance highlights appropriately, and be knowledgeable about it leading into the PFMA/risk assessment workshop. The CDSE report template should be used, but other summary document formats that provide clear, concise information properly referenced to the sources document are acceptable. Additionally, it is expected that the responsible Colorado Dam Safety Branch Engineer will also review the available information in preparation for the

Risk Assessment Workshop. The goal is to have everyone involved in the risk assessment workshop knowledgeable about the history, performance, and existing analyses for the dam. The risk assessment workshop is NOT the time for beginning to review background data.

Procedural Steps – General Overview of Templates/Review Process

5.1 Complete File Review and Summarize into CDSE Report Template

a. The goal is to summarize the key elements of design history, construction history, and investigations done through the life of the dam, and the performance history into a single living document.
b. The summary document will create an "outline" of the dam's key defensive features and also key weaknesses (relative to modern design) that will allow decisions for the PFM process. This process is iterative and the first cut should be relatively high level. Evaluation of individual PFM's later in the process often result in additional detailed review, and refinements and additions to the various elements in these sections is typical.
c. It is important to keep the PFM screening list evaluation in mind when reviewing and summarizing the documents and to keep in mind "what is your failure mode"? Different failure modes require different information for their assessment. Being familiar with the PFM pathways and initiating mechanisms will allow extraction of key details of the dams history and a more efficient summation of the known information.

For reference, example excerpts of those sections of the CDSE Report summary document are shown below.

d. While it is important to understand design history, it is also important to recognize that design and as-constructed conditions can be and often are different. It is important to first document the construction history of the dam including original construction and any subsequent modifications.

2.2. Summary of Construction History

Date	C #	Brief Description
1901	N/A	Original construction of dam completed in 1901. There is no information on record pertaining to the original construction. 1962 outlet works replacement and 1991 Dam and Spillway Rehabilitation Project indicate original dam consisted of homogenous earthen embankment with outlet works. Original outlet works located diagonally near center of southern half of dam and consisted of two 3-ft-diameter sewer tile outlet conduits of unknown length on concrete cradle overlying wooden pile supported concrete slab foundation beneath embankment and gate well tower. An inspection report dated 6/1/1903 indicated there was no spillway. At some time after 1903 and before 1960, two spillways (Spillway A and Spillway B) were constructed. Spillway A was located approximately 1,100 ft south (right) of outlet works and consisted of uncontrolled 80-ft-wide earth/rock cut channel with concrete sill and invert elevation 5,207.3 ft. Spillway B was located approximately 1,700 ft north (left) of outlet works and consisted of uncontrolled 150-ft-wide depression in dam crest (2-ft-deep) with invert at elevation 5,210.8 ft.
10/8/1962	C-1034	Original outlet works was removed and replaced with new outlet conduit, new gate well tower, and new inlet and outlet structures. Construction information is limited to a single construction drawing and specifications.
2/20/1984	C-1034A	North and south toe drains were constructed at downstream embankment toe, discharging at outlet structure. Toe drains extend approximately 800 ft north (left) and 800 ft south (right) of outlet structure and consist of 6-in-diameter pipe surrounded by filter material. Construction also included four manholes and two weir boxes. Specifications state quality control testing requirements during construction including soil compaction, field density, and gradation tests; however, there are no test results on record. Construction information is limited to construction drawings and specifications.

Figure 1 - Excerpt from CDSE Report – Summary of Construction History

e. Once the overall construction history of the dam is understood, highlighting the investigations, analyses, and designs that supported any construction elements should be documented. The key is to highlight conclusions of any design efforts as related to the intent of the analyses. Key assumptions and parameters can be included here, if appropriate. It is also important to consider things such as "era of design" because many modern defenses (and weaknesses) can be attributed to defined periods in time. It should be noted that it is not unusual to have poor documentation of "basis of design" for many dams that have been upgraded to high hazard dams. This fact highlights another reason to complete a full CDSE Risk Assessment report process.

2.3. Summary of Investigations, Designs, & Analyses

Report Type	In File? (Y/N)	Author, Date	Brief Summary
Hazard Classification			
Hazard Classification Determination	Y	Division of Water Resources, 6/11/1980	The hazard classification for Stillwater #1 Dam is high based on the determination that the routed peak discharge resulting from dam failure greatly exceeds the channel capacity. If the dam were to fail, loss of life and significant damage to improved properties is anticipated.
Spillway			
Project Drawings	Y	5/10/1939	The spillway is shown on the original project drawings and is south of the dike that is located south of the Main Dam.
Phase I Inspection Report	Y	Hydro-Triad, LTD 11/16/1979	The spillway is described in the 1979 Inspection Report as an earthen channel emergency spillway that is cut south of the right abutment of the dike. It has a bottom width of 125 ft and a crest elevation of 10,290 feet. Discharges from the spillway flow through several depressions or lakes before returning to the Bear River. The rainfall from the Probable Maximum General Storm (PMGS) and Probable Maximum Thunderstorm (PMTS) were determined based on the Design of Small Dams and Hydro-Met Report (HMR) No. 49. The hydrologic study indicated the critical storm was the Design of Small Dams PMTS with total rainfall of 6.6 inches over a duration of 1.0 hour. This results in a peak inflow of 13,308 cfs, a peak reservoir elevation of 10,295.7 ft (5.7 ft depth on spillway), and a maximum spillway discharge of 5,561 cfs. This report presents elevation-discharge capacity table/curve for the emergency spillway assuming the outlet is not discharging.
CO-NM Regional Extreme Precipitation Study (REPS) MetPortal Online Tool	Refer to Appendix D	SEO, 10/2019	In preparation for the SQRA, the SEO used the MetPortal tool to help evaluate the frequency of the IDF. The MetPortal tool provides an annual exceedance probability curve against precipitation depth. The tool indicates 2 and 6 hour thunderstorm depths, each the same at 5.95 inches, which translate to annual exceedance probabilities of less than 10e-7. These results indicate the 1 hour IDF event of 6.6 inches has an annual exceedance probability (AEP) of less than 10E-7.
Geotechnical			
Geology	Y	Hydro-Triad, LTD 11/16/1979	The Phase I Inspection Report describes the geology and soils at the dam site. It describes the topography of the area as a steep sided valley bounded by mesas above. Two types of rock compose the bedrock at the site: sandstone and shale with overlying volcanic rocks (flows and dikes of basalt). Outcrops of the sedimentary rocks are not observed in the area but basalt outcrops are visible at both abutments and in the floor of the valley. The basalt is described as gray to black, hard to soft, and closely jointed. The overburden soils are reddish-brown, poorly graded sands of glacial origin.

Figure 2 - Excerpt from CDSE Report – Summary of Investigations, Designs, & Analyses

f. Once the construction and design history is understood, the next step is to understand what is known about how the dam has performed. With respect to this performance history, the goal is to highlight incidents, concerns, or highlighted deficiencies. It is also key to document the resolution of those issues. Unresolved or improperly resolved incidents, concerns and deficiencies are especially important to document. It is not necessary to summarize every state inspection report or correspondence letter verbatim, but tracking recommended or required actions to know if they were actually completed is important to document. The importance of "resolution" of incidents, concerns and deficiencies is shown by the heading in the table shown in the example in Figure 3 below.

2.4. Summary of Performance History, Incidents & Significant Noted Deficiencies

Date	Description of Deficiency	Action Taken	Resolved?	Reference
1939	Foundation problems were encountered during original construction between Stations 5+00 and 7+00 where up to 34 feet of silt overburden was encountered overlying bedrock. The horseshoe alignment of Stillwater #1 Dam was then adopted to locate the dam around and on the edge of a morainic dike to miss as much of the silt deposit as possible.	Y, "swamp area" investigated and embankment alignment revised	Y	
10/27/1940	Water was observed leaking through cracks in the outlet conduit prior to embankment construction was completed. A grouting plan was implemented to stop or slow leakage into the conduit and to "make conduit more stable and decrease further cracking and settling."	Y, grouting around conduit completed	Y/N, although leakage appears to have been stopped in the upstream portion of the conduit, it continues to leak downstream of where these repairs were made	Letter to Board of Directors of Yampa Reservoir Public Irr. District from Edward Rizer, Civil Irrigation Engineer

Figure 3 - Excerpt from CDSE Report – Summary of Performance History

g. The next step is to review and summarize the available monitoring and instrumentation data. The primary goal when reviewing and summarizing available instrumentation data is to document what data are available and whether or not it has been reviewed and/or analyzed in the past and by whom. A secondary task is to relate that data and analysis to PFMs for use during the risk workshop and after the workshop to focus any future monitoring efforts. It may be valuable to have data graphed or otherwise shown graphically as that will be helpful during the risk assessment workshop. An example excerpt from an instrumentation summary is shown below.

2.6. Summary of Monitoring & Instrumentation

Instrumentation Type	Monitoring Frequency	Reporting to SEO?	Analysis of Data?	Discussion of Trends
Staff Gauge	At least every other day during summer months	Yes	Yes	Reservoir staff gauge located on the upstream slope of the outlet embankment section.
Survey Monuments	Approx. Every Five Years	Yes	Yes	Twelve survey monuments located across the Main Dam crest were installed in 1993 to measure horizontal and vertical movement of the dam. Annual readings available between 1994 and 1996. Readings every 2 to 5 years available between 2005 and 2015. S-2 is located on the right abutment and shows the most movement since installation, even though it was potentially damaged. It shows settlement of close to 0.5 ft between 2005 and 2007.
Parshall Flumes	At least weekly during summer months	Yes	Yes	A 24-inch Parshall Flume measures right abutment seepage. A 3-inch Parshall Flume measures seepage right of the outlet channel. An 18-inch Parshall Flume measures left abutment seepage. Based on seepage data between 2002 and 2019, seepage increases significantly above a gauge height of 39 ft (corresponding to a reservoir elevation of 10,270), specifically observed in the 24-inch and 18-inch Parshall Flumes. Seepage at the 24-inch Parshall Flume increases from about 1 cfs to almost 10 cfs from gauge height 39 ft to 56 ft. Seepage at the 18-inch Parshall Flume increases from about 1.5 cfs to 2-3 cfs from gauge height 39 ft to 56 ft.

Figure 4 - Excerpt from CDSE Report – Summary of Monitoring & Instrumentation

Section 6. Understanding and Describing Loading Conditions

The following are the typical loading conditions that need to be understood and developed by the Engineer prior to the Risk Assessment Workshop process.

6.1 Normal loading conditions

Understanding of range of annual reservoir operations should be developed and clearly documented leading into the Risk Assessment Workshop. This can be supported through historic reservoir gage records from the owner, Colorado Division of Water Resources (CDWR) website as available, or through possible coordination with a local CDWR Water Commissioner.

The normal loading is typically assumed to be the reservoir full to the spillway crest elevation. This is also sometimes referred to as the “static” loading, since it is often the continuous load applied to the dam. PFM’s associated with internal erosion and slope instability are often controlled by a range of normal loading conditions as loading up to the spillway crest is likely to occur annually.

6.2 Hydrologic loading conditions

The hydrologic loading conditions should be based on the reservoir stage hydrologic loading curve that “triggers” or initiates a PFM. For example, the annual exceed probability (AEP) of an extreme storm that results in a depth of overtopping above the dam crest that would initiate the “overtopping” PFM should be documented. A nodal probability estimate for that loading is used when evaluating an overtopping failure mode. As another example, one should consider the AEP of the hydrologic load that results in flow above the spillway crest but below the dam crest that could trigger a slope stability issue.

The steps presented in the Overview of Hydrologic Evaluation & Design Process Guidance that ultimately result in a Reservoir Stage Hydrologic Loading Curve should be developed by that consulting engineer prior to workshop.

6.3 Seismic loading conditions

Similar to hydrologic loading, seismic loading conditions should consider a range of earthquakes and their associated AEP and determine what would initiate a given PFM. The USGS Earthquake Hazards Program Website can be used as a basis to develop curves that should extend from 1/10,000 to 1/50,000 AEP. A typically seismic PFM is “Dynamic Deformation Exceeds Freeboard”. The internal erosion and slope instability PFM’s can also be impacted by a seismic loading scenario as a result of anticipated deformation so they should also be considered during the PFM screening discussion.

Section 7. Understanding and Estimating Consequences

An accurate understanding of dam breach flood consequences should be developed by the consulting Engineer prior to the Risk Assessment Workshop. The Colorado Dam Safety Branch has a tool for determining a conservative estimate of population at risk (PAR) within a dam breach flood inundation zone using inundation mapping shapefiles and US Census Data. Provided inundation mapping shapefiles exist, dam owners and their engineers can request PAR information for their dams from the Colorado Dam Safety Branch. The Federal Emergency Management Agency (FEMA) also supports the DSS-WISE tool for calculating dam breach flood inundation limits and includes a human consequences module (HCOM) that calculates PAR. Engineers can request access to DSS-WISE through the DSS-WISE website.

The Colorado Dam Safety Branch recommends use of USBR Reclamation Consequences Estimating Methodology (RCEM) to evaluate Life Loss consequences. The RCEM uses PAR derived from the sources described above as an input. Other methods of calculating Life Loss such as HEC-LifeSim are also available. Engineers must provide documentation for the life loss estimates utilized in the Risk Assessment Workshop.

Consequences should consider individual failure modes, loading conditions, and regional emergency response understanding. This may result in refinement of consequences during the Risk Assessment Workshop. One intent of RCEM is to develop best estimate range of Fatality Rate and then delve further into the available source case history information to confirm how documented historical dam failure life loss relates to the dam under evaluation.

Section 8. Risk Assessment Workshop Team Members

Although "Roles and Responsibilities" were described above, an additional discussion of the PFMA/risk assessment team is provided here. Generally, the most robust approach to completing a risk assessment is by assembling a team as described herein. This allows gathering enough experts, operators, regulators, and decision makers into the room to allow for open discussion, documentation, and elicitation for defensible risk assessments. Taking this approach will improve the confidence in the overall risk assessment process, resulting in stronger and more defensible decisions and actions.

8.1 Owner Representatives:

- Leadership, Dam Operators, Staff Engineers. It is considered critical that these members from the owner participate in the risk assessment workshop.
- Consulting Engineers serving as Subject Matter Experts (SME) or Design Engineer representing Owner, under contract with the owner.
- The Note taker is an important role in the overall process. This person should be knowledgeable in dam safety and should be familiar with the CDSE templates and the dam.

8.2 Colorado Dam Safety Branch

- Chief of Dam Safety, Regional Dam Safety Engineer assigned to dam, SME's from within Colorado Dam Safety Branch, CDWR Water Commissioners.

- SEO has expertise to facilitate issue specific and/or full Risk Assessment Workshops in unique or emergency situations, but this is not considered a normal occurrence and should not be relied upon.

8.3 Facilitator

The Facilitator is an Owner provided, independent third party. The following are key facilitator attributes:

- Should meet expectation per USBR, Best Practices, 2019, Chapter A-11.
- Have previous experience facilitating dam safety risk assessments.
- Have experience with Colorado Dam Safety Branch risk tools, templates, processes and workshop philosophy. These tools, processes and philosophy form the basis for the workshop.
- Should generally be an impartial party who does not have a vested interest in the project. It is considered acceptable if the Facilitator and SME/Design Engineer work for the same company, but the Facilitator cannot also be an SME during the workshop or be part of the Design Engineering Team.
- The Colorado Dam Safety Branch maintains an Approved List of Risk Facilitators from which an owner can engage and retain a qualified facilitator for a given project.

Section 9. Expectations for Risk Assessment Workshop Behavior

It is understood implicitly that the Colorado Dam Safety Branch is ultimately a dam safety regulator and that opening up this deep dive risk process into a given dam may result in initial frictions with the involved parties. It is important to note that the Colorado Dam Safety Branch considers itself a partner with dam owners wherein BOTH parties have a vested interest in reducing the risk associated with the dam or proposed project. One of the objectives of this process is to build a better understanding and trust between regulator and dam owner as a means to reduce the overall risk dams to the general public.

The primary benefit of completing a Risk Assessment Workshop with the team members described above is to *engage open dialogue about a given dam from expert viewpoints and ultimately try to come to a consensus* as to the actual risk posed by a dam. Involving experts, operators, regulators, and decision makers in a workshop setting allows for streamlined efforts to identify and reduce risk.

The importance of the role of Facilitator in these workshops cannot be overstated. The Facilitator must manage different personalities, varying engineering backgrounds, schedule, and competing interests. Our expectations and our experience is that when parties remain polite, professional, engaged, open to others' ideas, and willing to step through the details of the risk process that positive outcomes result. All parties are encouraged to participate fully and describe and defend their (sometimes strong) opinions about the specifics of potential failure modes, consequences, likelihoods and confidence.

However, our experience also shows that single individuals can also potentially derail, bully, or drive a risk assessment workshop in a preconceived or intentional direction to achieve a predefined end result. The type of behavior undermines the inherent strength of the risk assessment process and will not be tolerated by the Colorado Dam Safety Branch.

An additional role of the Facilitator will be to attempt to prevent this type of behavior. If the Facilitator is repeatedly unsuccessful in re-directing the energy of such an individual, the Colorado Dam Safety Branch reserves the right to call the individual out on their behavior during the workshop and if it remains unchanged, ask them to remove themselves from the process. Examples of such behavior include:

- Aggressive outbursts attempting to diminish the viewpoints of others on the team.
- Repeatedly and consistently talking over others.
- Repeated, aggressive rebuttals with non-specific examples not supported with actual references, evidence or case histories.
- Repeated aggressive walking out of the meeting room or turning off video/hanging up on virtual conference.

While it would be unfortunate if such a removal significantly delayed the risk assessment process, it may be considered necessary in order to achieve a defensible assessment of dam safety risk without undue subjective influence.

Section 10. Risk Assessment Workshop Planning & Execution

10.1 Risk Assessment Team site visit

While it may not always be practical or seemingly cost-efficient, it is considered advantageous to provide all risk assessment team members a site visit to observe conditions, key features, and operations. At a minimum, pictures and a detailed site layout discussion should be provided for the risk assessment workshop team by the consulting engineer with support from the Colorado Dam Safety Branch.

10.2 PFM Screening video conference call

To make the process more efficient, it is considered valuable to have the subject matter experts independently pre-develop PFM screening lists (further described below) and to add any additional PFM's appropriate for the site. This should be done in preparation for the PFM screening call. A video conference call should be held with the ***key members*** of the Risk Assessment Workshop participants to go through the PFM screening list and develop an initial consensus for which PFM's can be considered REMOTE and which should be evaluated more closely (carried forward) during the Risk Assessment Workshop.

Key members for this call would include Facilitator, SMEs, Owner Representative, and Colorado Dam Safety Branch Engineers. If individual organizations want to be more prepared going into this type of meeting, they can coordinate on their own, as long as their conclusions are properly presented to the team during this pre-workshop call. It should be noted that the workshop may bring to light issues that would require previously screened REMOTE PFM's to be reconsidered or reviewed more closely. The CARRIED FORWARD (aka credible) PFM's will be evaluated during the Risk Assessment Workshop and documented as described below.

The PFM screening video conference call should also be used as a driver for identifying data gaps and where additional engineering analysis that could be relatively easily obtained to increase confidence in a likelihood assessments.

10.3 "Data Gap" Gathering supporting engineering analyses

Through the PFM screening process described above, data gaps may be identified. In some cases this will requiring researching available references that can be easily obtained and used to support event tree development or describing positive and adverse factors for a given PFM. In some cases it may be beneficial or even essential to conduct additional engineering analyses in preparation for the Risk Assessment Workshop. The extent and rigor of such analysis that can be accomplished between the PFM screening call and the Risk Assessment workshop will be dependent on factors such as dam owner resources, SME availability, and time. Data gaps that can't be filled before the workshop often become action items that will impact the confidence of a likelihood determination. Those can then be accomplished after the Risk Assessment workshop and then the PFM can revisited and the likelihood revised as appropriate.

Section 11. Typical PFM List for Screening Evaluation

A typical PFM screening list has been developed by the Colorado Dam Safety Branch for both earthen and concrete dams. As described already, this is considered a base list of PFM's that stay true to typical PFM mechanisms. The list should be expanded as specific site conditions dictate. One example being the case where different geologic conditions exist on the right abutment versus the left abutment.

The following section presents the process for screening list evaluation and documentation and keys on the headings provided of the PFM screening list as shown below in Figure 5.

PFM #	PFM Mechanism	Shortened PFM Considerations For Initial Screening	Feature and Loading Condition	PFM Carried Forward or Remote	Justification for Remote Screening or Result of Carried Forward PFM
Internal Erosion through Embankment					
1	Concentrated Leak Erosion (scour) through Embankment	Scour of embankment material along a flaw. Flaws may include a hydraulic fracture crack in a low stress zone in the core, a desiccation crack, differential settlement cracking, a frost damaged layer at a winter shutdown level, the boundary in the embankment created by a closure section, defects due to animal burrows or roots			

Figure 5 - Excerpt from CDSE Typical PFM Screening List

11.1 Loading Condition Column in Screening List Template.

In working through the Typical PFM Screening list, the key loading conditions should be considered for each PFM. As described in Section 6, the three loading conditions typically assessed for each PFM are Normal, Hydrologic and Seismic.

It should be noted that hydrologic & seismic loading conditions have a more remote Annual Exceedance Probability (AEP) (less likely to occur annually) and in an event tree progression will *typically* only decrease the overall probability or likelihood of the PFM. However, in the case where the consequences of dam failure are high or extreme they can play in important role in defining the overall risk.

11.2 Document justification for Remote likelihood or Carried Forward determination

The typical screening list is a valuable resource for documenting why a particular PFM was considered remote by the team and did not require a more in-depth development with PFM worksheets. Additionally, it provides a valuable place to summarize why a particular PFM was evaluated more closely in a Risk Workshop setting.

Feature and Loading Condition	PFM Carried Forward or Remote	Justification for Remote Screening or Result of Carried Forward PFM
Internal Erosion through Embankment		
Main Dam: Normal	Main Dam: Carried Forward	**PFM 1 – Low Failure Likelihood, Poor Confidence** *Team discussed that the most likely internal erosion mechanism through the main dam embankment is concentrated leak erosion, and the most likely initiator is a construction flaw resulting in a potential weak seam along an embankment lift line.*
Main Dam: Hydrologic	Main Dam: Remote	**Positive:** • IDF reservoir level (elevation 8,536.1 ft, 2012 datum) only results in about 8% increase in head from the maximum normal reservoir level (elevation 8,523.4 ft, 2012 datum), which would not be expected to significantly change conditions from the normal loading condition. • IDF event is remote, and limited duration of hydrologic loading would not likely progress internal erosion through the main dam embankment to failure.
Spillway Dike: Normal and Hydrologic	Spillway Dike: Remote	**Adverse:** • Spillway dike embankment has no engineered filter. **Positive:** • Spillway dike has a relatively uniform foundation profile, limiting the potential for embankment cracking due to differential settlement. • Maximum normal reservoir level is near the upstream toe of the dike. Thus, dike retains limited normal pool and seepage gradients through the dike embankment would be low.

Figure 6 - Excerpt from CDSE Typical PFM Screening List – Example of Remote Screening and Carried Forward Documentation

Section 12. PFM Event Tree Development and Workshop Elicitation

12.1 Complete PFM Worksheets

The CDSE PFM Worksheets are templates that allow for documentation of all elements required to assess and document the risk of any given failure mode. The following sections describe each step of the Risk Assessment Workshop process in detail and how they are documented within the PFM worksheet templates. This workshop process occurs following the PFM screening video call and data gathering phase. By this point, all the data that is going to be available is available.

The first step is to fully develop an event tree for a given carried forward PFM. Every event tree generally consists of the following essential "nodes".

- Loading Condition
- Flaw Exists
- Initiation
- Continuation
- Progression
- Intervention
- Breach

Some key points to consider when developing a PFM event tree include:

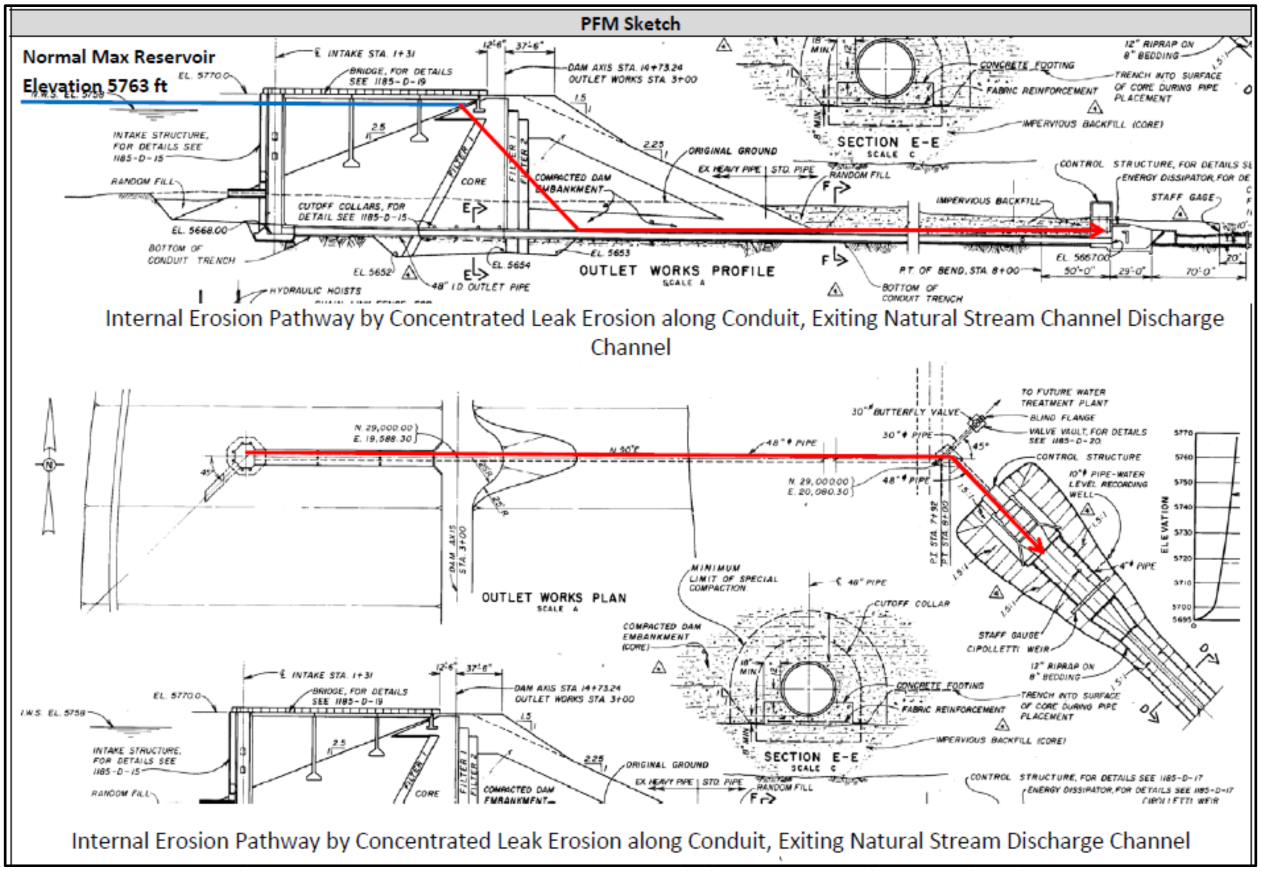
- The developed event tree must fully represent the specific site conditions.
- Use italicized footnote references within the library event trees as starting point and modify the site specific event tree accordingly. Add/remove any other steps shown in the library examples as appropriate. An example event tree is shown below in Figure 7.

PFM Suite: Internal Erosion through Embankment	
PFM #1	Concentrated Leak (Scour) Erosion through Embankment
Loading:	• Reservoir level *rises up to normal operating pool elevation XXXX ft*[1].
Flaw Exists:	• *A defect*[2] exists through the embankment.
Initiation: (seepage velocity is high enough to erode material)	• Concentrated seepage develops through the *defect*[2]. • Seepage gradient and resulting velocity of flow through the *defect*[2] is sufficient to erode embankment material.
Continuation: (unfiltered exit)	• No effective filter is present to prevent removal of eroded material. • Eroded material exits at *downstream groin near Seep Weir 2, just right of concrete drain headwall*[3].
Progression: (void/sidewalls support the flaw)	• Erosion progresses as embankment materials are capable of holding a void.
Progression: (no flow limitation)	• No *features are present to restrict flow*[4] through the *defect*[2], which allows the defect to enlarge.
Progression: (no self-healing material)	• There is no *self-healing material*[5] in the upstream portion of the seepage path. • Erosion pipe forms and progresses toward the upstream face, eventually reaching the reservoir.
Intervention:	• Developing failure mode is not detected, or if detected, intervention is unsuccessful.
Breach:	• Flow through the pipe increases and pipe enlarges. • Uncontrolled release of the reservoir occurs due to gross enlargement of pipe or collapse of crest above pipe sufficient for water to flow over the embankment. • Embankment erodes down to *stream level*[6]. • Downstream consequences result.

[1] Define a threshold reservoir level below which it is judged that there is insufficient head to initiate the internal erosion. Alternatively, define this as the normal annual maximum pool or a flood pool (if flood load is being considered separately).
[2] Define the defect as specifically as possible. Examples of defects that may cause Concentrated Leak Erosion: a crack above an abrupt change in rock slope on an abutment, a hydraulic fracture crack in a low stress zone in the core, a desiccation crack, differential settlement cracking, a frost damaged layer at a winter shutdown level, the boundary in the embankment created by a closure section, defects due to animal burrows or roots.
[3] Indicate proximity of suspected exit location of defect if known.
[4] Flow limiters are natural or manmade, non-erodible features within an embankment that would prevent gross enlargement of a developing pipe, such as a cutoff wall.
[5] Specify any self-healing characteristic or feature, if present, that would need to be ineffective. Crackstopper zones in embankments may be an engineered cohesionless, filter-like material upstream of the core, or a granular upstream shell that is fine-grained enough to flow into pipe. Self-healing can also occur due to filter gradation of eroding material relative to gradation of filtering material (see "some erosion" boundary per Foster and Fell, 2001) or size of defect.
[6] The bottom of the breach may be different from stream level depending on particular circumstances; adjust as necessary.

Figure 7 - Excerpt from CDSE PFM Worksheet – Adaptable Event Tree

- Develop a sketch showing the PFM at pertinent section/location of the dam so that all Risk Assessment Team members understand how PFM could progress to failure. **This is a critical step and may require multiple attempts to ensure all participants are in agreement.** An example sketch is shown below in Figure 8.



Internal Erosion Pathway by Concentrated Leak Erosion along Conduit, Exiting Natural Stream Channel Discharge Channel

Internal Erosion Pathway by Concentrated Leak Erosion along Conduit, Exiting Natural Stream Discharge Channel

Figure 8 - Excerpt from CDSE PFM Worksheet – Example PFM Sketch

12.2 Develop Positive and Adverse Factors

Once an event tree is written and agreed upon by the workshop participants, the next step is to develop lists of positive and adverse factors for each node of the event tree (i.e. initiation, continuation, progression, intervention, breach). **The process of documenting positive and adverse factors is considered the most important element in developing an informed PFM likelihood estimate.** These factors can and should be both quantitative (i.e. stability analyses, overtopping duration, etc.) and qualitative (i.e. intervention discussion) in nature. An example of positive and adverse factors for each node of an event tree is shown on Figure 9.

12.3 Estimate Potential Failure Mode Likelihood

Eliciting the team's consensus of potential failure mode likelihood is the most challenging aspect of the Risk Assessment Workshop and will require a skilled Facilitator to reach a consensus or at least document a range of likelihoods.

PFM Factors		
Event Tree Node	**Adverse Factors (PFM More Likely to Occur)**	**Positive Factors (PFM Less Likely to Occur)**
Loading	• Reservoir is full every year to the principal spillway elevation of 9965, Em. Spwy = 9970, Dam Crest = 9978 • Cyclical loading (peak normal load to 9965 is about 5 months). • Typical Lowest reservoir elevation is 9945 (about ½ full) • Highest Pool of record is right at the principal spillway (9965). The emergency spillway has never run.	• Outlet capacity of 600cfs. • Drainage area = 5.4 square miles at about 10,000 ft. • Spillway is a PMP spillway, 3,800 cfs.

Flaw Exists	• Review of 1971 Geologic Report maps 2 faults within the vicinity of the outlet and near Piezometers 1A & 3A.
	• The same report indicates that there is highly altered, highly fractured basalt within this area that likely are at the base of the cutoff trench.
	• The grout curtain efforts do not appear to have continued right into the area of the highly fractured basalt and faults.
	• March 9, 1972 Geologic report (pg 3).
	  o "foundation problem … is area of fractured and faulted rock with numerous clay seams…which occurs in the vicinity of the creek in the deepest part of the reservoir.
	  o "this convinces us this area is to receive special attention if potentially dangerous seepage is to be prevented".
		• Project included significant efforts to map and understand the foundation geology including complicated basalts, glacial moraines, and faults.
		• Likely concerns with reservoir seepage losses through left abutment basalt were addressed by implementation of a grout curtain essentially left of the outlet towards the abutment.

Initiation	• Photos indicate a deep excavation for the outlet works was performed with a base elevation at the gate chamber of about 9859. • There is no evidence so far that would indicate that the cutoff trench would have extended below/removed the entirety of the altered/fractured basalt. • Thorough review of piezometer data in 2021 is what initiated this PFM review process, summary as follows: • 1A is a foundation piezometer near the crest, constructed to isolate 15-ft of foundation (downstream of cutoff) • Since construction, the nominal high piezometer elevation has increased by 15-ft for similar reservoir elevations. • In 2021, a calculated gradient between the two inline piezometers has increased over time as the rate of rise for P 1A is faster. The piezometer data indicates that this could likely continue to increase the gradient in the future. • As noted by the Geologic (1972) report, this continued rise in piezometers could likely be associated with removal of clay infilling within the fractured basalt and would be scouring the base of the cutoff trench, could be moving that and the clay infilling into deeper fracture systems OR the mapped fault systems. • Initial data shows that there is phreatic surface a significant height up into the Zone 1 (Peak elevation about 9942-ish). This would indicate that this Zone 1 has a moderate permeability (given its cross section on drawings) and could be made up of potentially more erodible material.	• The design included construction of a wide cutoff trench "to firm bedrock from left abutment to STA 10+50 (close to location of piezometers 1 & 3) and then transitioning to 15-ft deep in the moraine continuing to the right abutment. • No flow has ever since construction been observed in the toe drain system (that is obviously tied to the horizontal blanket). o In order for this to become a continuing failure mode, would expect that the toe drain system/elevation would likely need to see observed flow. • Designers did try to construct zoned dam with focus on select less pervious materials in the core.
Continuation	• If we have eroded clay infilling in the basalt foundation, aside from the cutoff trench Zone 1 material, the next portion in contact with fracture system is the horizontal blanket drain. Depending on direction of flow, would continue to easily scour the overlying cohesionless sandy blanket drain. • Blanket drain orientation would not likely provide any filter function. • No filter on downstream side of cutoff trench.	•
Progression (3 nodes)	•	• Zone2 would likely not hold a roof, but would likely erode. • Upstream zone 2 could limit erosion rate, but likely not act as a true crackstopper.

Intervention	• In winter, no access/monitoring
	• Caretaker goes up and down every other day from Spring into Fall.
	• During summer months, when res is full, camp 45 minutes away. No cell service at camp. They have sat phones, but we can't call them.
		• Gate operations
		  o Operates annually
		  o Good maintenance program.
		  o Historically have used its moderate to large capacity to control normal reservoir level.
		• Very good dam owner program with frequent monitoring and engagement with DSE.
		• Outlet capacity is considered sufficient for normal pool capacity of 7161 AF, would likely meet the 5 ft in 5 days drawdown

Breach	• Full breach expected based on dam construction and geometry.	•

Figure 9 - Excerpt from CDSE PFM Worksheet – Example Documentation of Positive & Adverse Factors for each PFM

A combination of two methods is recommended to develop the best estimate of PFM likelihood, as follows:

12.3.1 <u>Comparative Analysis</u>

For this approach, reference Chapter A-4 of 2019 USBR Best Practices. To summarize the key points of this approach: In a comparative analysis, the failure likelihood is assessed relative to the historical failure rate of dams. For example, if the key factor affecting the PFM are weighted toward adverse (more likely), the annual failure likelihood is probably greater than 1/10,000. This approach requires less rigor and may be appropriate for PFM's where the loading likelihood is high as well as for making rapid assessments. Table 1 below shows the baseline for making a comparative analysis decision of PFM likelihood.

12.3.2 <u>Critical Loading Approach (aka linear nodal probability estimate)</u>

Also reference Chapter A-4 of 2019 USBR Best Practices for more information on the application of this approach. The goal is to use increased knowledge of loading conditions and estimates of probability for each node on the event tree to arrive at an estimate of annual probability of failure for a PFM (described in detail below).

In practice, the Colorado Dam Safety Branch has determined that the best approach is to use both the comparative analysis and the linear nodal estimate approach to arrive at the team's consensus best estimate of failure likelihood for a PFM. The linear nodal probability estimate approach also provides the opportunity to complete a sensitivity analysis for a given node on the event tree. Ultimately the qualitative descriptors provided in Table 1 below (Very high, High, Moderate, Low, Remote) are used to represent this best estimate of failure likelihood, supported by any nodal estimate analyses. The Qualitative descriptors are used to represent level of uncertainty associated with these kinds of risk assessments. In general, these likelihood estimates will be within an order of magnitude, but the confidence that may be represented with very “accurate” quantitative estimates is likely not supported.

Table 1: PFM Failure Likelihood Rating

PFM Failure Likelihood Rating	PFM Failure Likelihood Description
VERY HIGH	The annual failure likelihood is more frequent (greater) than 1/1,000 (10^{-3}). There is direct evidence or substantial indirect evidence to suggest it has initiated or is likely to occur in the near future.
HIGH	The annual failure likelihood is between 1/10,000 (10^{-4}) and 1/1,000 (10^{-3}). The fundamental condition or defect is known to exist; indirect evidence suggests it is credible; and key evidence is weighted more heavily toward “more likely” than “less likely”.
MODERATE	The annual failure likelihood is between 1/100,000 (10^{-5}) and 1/10,000 (10^{-4}). The fundamental condition or defect is known to exist; indirect evidence suggests it is credible; and key evidence is weighted more heavily toward “less likely” than “more likely”.
LOW	The annual failure likelihood is between 1/1,000,000 (10^{-6}) and 1/100,000 (10^{-5}). 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.
REMOTE	The annual failure likelihood is more remote than 1/1,000,000 (10^{-6}). Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood.

12.4 Thoughts on Workshop Elicitation

Strong facilitation skills are a basis for a robust risk assessment workshop. After review of many approaches for elicitation from “voting” members and dealing with “strongly opinionated” workshop members, the SEO generally prefers the following approach to arrive at consensus likelihood estimates:

- Open dialogue from all workshop participants presenting their side of view (supported with information available to all) and capturing as documentation, as appropriate.
- While straw polls or anonymous “voting” may serve an initial purpose to open dialogue or “break the ice” for risk evaluation, ultimately it is preferred that workshop participants speak their viewpoint on what is their best estimate of likelihood/consequences and provide support to that viewpoint. This could include a best estimate with a range as well.
- From there, it is incumbent on the Facilitator to get the team to discuss any significant misunderstandings or viewpoints that vary significantly.
- If no consensus can be reached amongst the group, documentation for the ranges of best estimates and reasoning behind the differing viewpoints should be captured and any required data should be obtained to bring the estimates as close as reasonably possible.

12.5 Guidance for Completing Nodal Probability Estimates

The initial element of this process is to estimate the Annual probability of loading for a given PFM and loading condition being evaluated. Considerations for this are discussed in Section 6, above.

Overall, the PFM process and Event Tree is written in the negative and presumes each preceding node of the event tree occurred to move to the next (i.e. linear). It is worth noting that the intervention node is the exception. Intervention is typically considered to be a floating node that can occur at any step in the event tree, although caution should be used in relying solely on intervention to limit progression of a potential failure mode.

This linear nodal probability estimate allows for the teams judgement to estimate the probability of any given node occurring. It is considered acceptable to use the appropriate number of nodes that represent the physical process of the event tree. This may include breaking the essential nodes into smaller elements to more accurately represent those smaller elements. Caution should be taken in creating multiple nodes that don't reflect the physical event tree that could artificially change the accuracy of the risk estimate. The CDSE Event Tree libraries within each PFM worksheet have been carefully constructed to represent the actual number of physical nodes that would be present on each given event tree. Any deviation from these nodes should be documented within the Risk assessment workshop.

The likelihood of each node should be based on the Verbal Description of Probability Value in Table 2 presented below.

Table 2: Verbal Description Probability Values

Verbal Description	***Corresponding Probability Value***
Certain	1
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
Impossible	0

Remember, the intervention node is based on the likelihood that intervention is NOT successful. Therefore, a lower likelihood of example Very Unlikely (0.01) means that intervention is likely to be more successful. ***Additionally, it is appropriate to leave detection and intervention as a single node on the event tree estimate for this linear nodal probabilistic approach.***

The estimated probabilities of all nodes on the event tree are multiplied to arrive at an estimated annual probability of failure for the PFM. A key benefit of this approach is to allow for a sensitivity analysis on nodes in questions to help inform the team's decision making for likelihood and confidence.

The **combination of comparative analysis and nodal probabilities** is then used to arrive at a reasonable consensus of PFM likelihood as described in Table 1.

An example of a linear nodal probability estimate calculation spreadsheet is presented in Figure 10 below:

PFM No.:	PFM 1:	**Nodal Probability Estimate**	
PFM Title:	Concentrated Leak Erosion Through Embankment	Normal Pool	Flood Loading
PFM Description: 1	Reservoir reaches threshold level	1	0.01
2	A flaw exists	0.01	0.01
3	Erosion Initiates	0.01	0.01
4	No Effective filtered exit	0.1	0.1
5	Materials can hold a roof	0.99	0.99
6	No effective flow limiter	0.99	0.99
7	No self healing upstream material	0.5	0.5
8	Intervention is Unsuccesful	0.2	0.2
9	Dam Breaches	0.9	0.9
	Annualized Probability of Failure:	8.82E-07	8.82E-09

Figure 10 - Example Calculation of Linear Nodal Probability Estimates

12.6 Elicit Team Consensus of PFM Consequence Estimates

The Colorado Dam Safety Branch recommends using the Reclamation Consequence Estimating Methodology (RCEM) to estimate the life loss consequences for the evaluated PFM/loading condition. This methodology is referenced and discussed further in the USBR Best Practices, July 2019, Chapter A-4.

The ranges of environmental damage shown in the Table 3, Consequence Categories, below are not intended to be equated to the life loss ranges to obtain a value for a human life; they are intended for use to aid categorization and in some cases their inclusion may result in an increase in the level estimate. Dam owners should evaluate consequences that apply to their individual operational and economic considerations within their organizational risk tolerance. Dam owners may wish to consider factors such as impact to water users if reservoir is lost, impact to owner revenue if reservoir is lost, cost to rebuilt infrastructure, impact to organizational reputation and community trust, etc. These additional dam owner specific factors could provide justification to an increase in the consequence level selected for the risk assessment.

12.7 Elicit Team Consensus of Confidence for both PFM Likelihood & Consequence Estimates

Evaluation of the confidence of PFM likelihood and consequence estimates is critical to the risk informed decision making process. Confidence is used in the CDSE Risk Assessment process as a measure of the uncertainty around the available information, interpretation and professional judgements of the risk assessment team. Strong confidence corresponds to low uncertainty, and poor confidence corresponds to high uncertainty. Providing confidence estimates for both likelihood of failure and consequences is necessary because of the way these estimates are portrayed in the risk matrix (described below). Changes in confidence can result in changing the overall risk estimate on the matrix and impact actions and next steps to reduce risk.

The three confidence levels used in the CDSE Risk assessment process are shown in Table 4. It should be noted that part of the confidence level determination includes evaluating if the impacts of some new information could change the likelihood or consequences estimate ENOUGH to affect likelihood or consequence level determination and therefore change actionable decisions.

Table 3: Consequence Categories

Consequence Categories	
LEVEL 1	Downstream discharge results in limited property and/or environmental damage. Average life loss is less than 1. Although life-threatening releases occur, direct loss of life is unlikely due to severity of location of the flooding, effective detection and evacuation.
LEVEL 2	Downstream discharge results in moderate property and/or environmental damage. Average life loss is in the range of 1 to 10. Some direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers.
LEVEL 3	Downstream discharge results in significant property and/or environmental damage. Average life loss is in the range of 10 to 100. Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers, or difficulties evacuating large population centers with significant warning time.
LEVEL 4	Downstream discharge results in extensive property and/or environmental damage. Average life loss is in the range of 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.
LEVEL 5	Downstream discharge results in extremely high property and/or environmental damage. Average life loss is greater than 1,000. Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes.

Table 4: Confidence Level Descriptions

Confidence Level	Description
STRONG	The team *is confident* in the risk characterization, and it is *unlikely that additional information would change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
MEDIUM	The team *is relatively confident* in the risk characterization, *but key additional information might possibly change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
POOR	The team *is not confident* in the risk characterization, and it is *entirely possible that additional information would change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

Documentation of what information could be gained to improve confidence is considered key part of risk reduction action plan development.

12.8 Documentation of Key Rationale

Each PFM worksheet allows capturing of key points for:

- Why the chosen PFM likelihood and Confidence levels were chosen by the team.

- Why PFM Consequences and Confidence levels were chosen by the team.
- What information could be obtained to improve confidence and potentially change the likelihood or consequence level determinations?

PFM Executive Summary				
Failure Likelihood		Likelihood Confidence		
Consequences		Consequence Confidence		
PFMA Participants:				PFMA Date
PFM *Likelihood* Decision: Key Factor Summary Statement				
PFM *Confidence* Decision: Key Factor Summary Statement (list of possible further analysis or information to collect)				

Figure 11 - Excerpt of PFM Worksheet for Documenting Key Decisions

Although not technically the purview of a Risk Assessment Workshop, it is sometimes beneficial to brainstorm potential modifications as risk reduction actions with the risk assessment team all in the room together. These would typically be presented as preliminary or potential next step actions and would not impact the assessed risk.

Section 13. Portrayal of Risk for Colorado Dam Safety Branch Regulated Dams

The Colorado Dam Safety Branch has considered many agencies' approaches to portraying risk and the results of the risk assessment process. Various methods are used but all include developing a Risk Matrix and associated Risk Categories. The Colorado Dam Safety Branch portrayal of risk general follows those referenced, but with some differences to be more effective in the state dam safety regulator environment with a broad range of dam owners. The Colorado Dam Safety Branch Risk Matrix, shown below in Figure 12, was developed to best portray risk, confidence, and ultimately Acceptable vs. Unacceptable levels of risk. As a regulatory agency, it might be considered more conservative than owner derived portrayals. It is also designed to illuminate and illicit immediate risk reduction actions from dam owners. The following provides supporting documentation to explain the Colorado portrayal of Risk.

- Represent individual PFM Risk
    - o The most actionable and risk driving elements tie specifically to PFM's and allow both owner and regulator to develop actionable risk reduction items to address the likelihood and consequences of that risk driving PFM.
- Represent Risk Categories with color.
    - o Colorado has a broad inventory of dams, owners, consulting engineers, and emergency management partners. Our work to date has shown that simple communication of PFM risk level through color provides an immediate and effective means to portray urgency of risk for all partners.
- Why "bins" are used instead of smooth lines
    - o The methods most often being used to estimate likelihood and life loss consequences include comparative analysis, nodal probability estimates, and verification checks against historical failure incidents. In a generally conservative, state regulatory environment it is not considered realistic or necessary to achieve an uncertainty and confidence bounds consistently less than an order of magnitude using these methods. Therefore, it is considered appropriate to tie risk category colors to square "order of magnitude" bins that represent the confidence and uncertainty levels achieved through our chosen process. It may be that a full Quantitative Risk Assessment is the most appropriate risk assessment method to more accurately define PFM Risk level for

certain complicated or extreme consequence dams. The Colorado Dam Safety Branch process would not preclude the use of those more accurate but resource intensive efforts as might be appropriate for certain combinations of likelihood and consequence.

- Comparison to other agencies to "tolerable/actionable/acceptable" risk limits
  - SEO did a thorough review of dam safety agencies (dam owner and regulator) risk limits and we are in general agreement with dam safety industry standards.
  - Intent for acceptable risk limit for both existing and new dams. In other words, how is the "acceptable risk limit" applied for risk informed design of new dams and modifications to existing dams?
  - A new or an existing dam should generally meet the intent of the green boxes OR if in yellow should be ALARP (see below for further discussion of ALARP principles). By this line of reasoning this Risk Matrix Decision chart is applicable for the risk informed design consideration of new/modification designs.
  - Prescriptive design criterion for high hazard dams were historically intended for 'Extreme' hazard dams with consequence levels 4-5. A risk-informed decision process can sometimes serve as justification for relaxed design criteria for structures that pose lower consequences. That process must be documented and presented as the basis for waiving any Rules.
  - Design and construction of a new project, or construction of repairs presents a unique opportunity for defensive measures to be incorporated at a relatively low expense. Opportunities for further risk reduction should always be considered and implemented if they do not pose a significant additional financial burden on the owner.

- Why is Life Loss less than 1 on the risk matrix?
  - Applicable for future Significant Hazard dam evaluations and those PFM's that don't result in full breach of a dam but where the owner would like to consider and represent to portray the risk to their infrastructure, revenue and water resources or habitat.
- Non-breach Risk
  - Spillway flows and high outlet works releases can sometimes pose an unacceptable risk to life and property downstream. In addition, failure of individual components of a dam can also result in downstream consequences. Including this consequence level in the risk matrix allows for those scenarios to be evaluated in a risk framework can identify risk reduction actions that might not otherwise be considered.

Each evaluated PFM should be portrayed in the Risk Matrix as shown below. The assessment of confidence should make a best effort to determine which direction the likelihood estimate might change with stronger confidence. This is portrayed with a simple arrow in the risk matrix. If it is unknown or unclear whether the estimate could move up <u>or</u> down, the more conservative confidence estimate should be applied. A confidence estimate of strong means that the PFM likelihood/consequence estimate will stay within the order of magnitude box in the matrix. The risk matrix legend shown in Table 5 shows the immediate response to assignment of risk level within the matrix. It should be noted that for PFM's assigned to green matrix boxes, traditional dam safety best practice activities of observation, monitoring and maintenance still apply. An assessment of "acceptable risk" does not alleviate the ongoing need for state-of-the-practice dam safety activities at all dams.

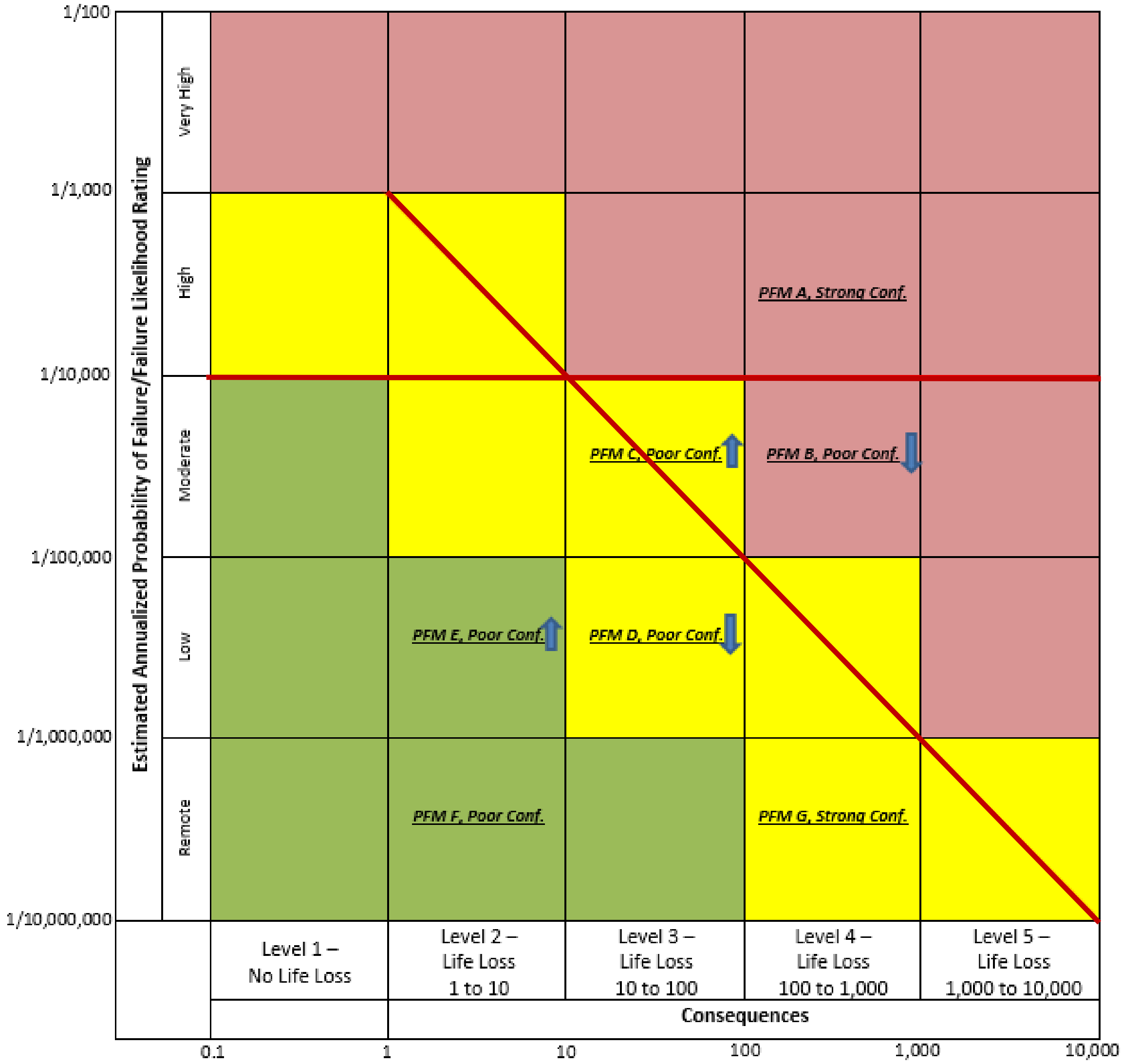


Figure 12 - Colorado Dam Safety Branch Risk Matrix (colored boxes) and PFM Confidence Portrayal (blue up and down arrows).

Table 5: Colorado Dam Safety Branch Risk Matrix Legend

	Unacceptable level of risk. Actions required to reduce risk.
	Increased justification to reduce or better understand risks. ENSURE ALARP principles are addressed.
	Risk monitoring zone, decreased justification to reduce or better understand risks. REVIEW ALARP.

Section 14. Risk Categories and Expected Risk Reduction Actions

Table 6 below presents the possible actions associated with the levels of risk, ranging from acceptable to unacceptable, portrayed in the risk matrix. As with the PFM screening lists and PFM templates, the actions described in this table are pulled from case histories at existing dams and provide a starting place to determine actions for immediate and incremental risk reduction at dams under review. Final actions and schedule for risk reduction at a given dam will be coordinated with the Colorado Dam Safety Branch and based on the level of risk, urgency, dam owner resources, etc.

Table 6: Risk Categories and Expected Risk Reduction Actions

PFM Risk Category, Best Estimate	Possible Regulatory Actions to Reduce Probability of Failure	Possible Actions to Reduce Consequences
Red	Strong Confidence (will stay in order of magnitude box) • Storage Restriction order to mitigate PFM risk, expediency concurrent with level of urgency. • Develop and submit PFM Observation and Monitoring Plan to SEO with specified reporting frequencies. • Develop a Compliance Plan with strict deadlines to complete investigations, designs, and construct repairs needed to mitigate potential for failure. Expediency of this process is concurrent with level of urgency.	• Ensure that emergency action plan and inundation mapping are current and tabletop tested for initiating event. Consider functional exercise testing. • Initiate intensive emergency management coordination including calls and situational awareness reports based on continuous monitoring, concurrent with level of urgency. • Develop early warning system program (EWSP) specific to PFM and engage all EWSP stakeholders.
	Poor to Medium Confidence (could possibly move to a lower Risk Category level) • **Same considerations as above for Strong Confidence, except:** o Develop a compliance plan listing the action to take including information gathering, additional PFMA workshops, and appropriate actions to resolve PFM. o Owner/engineer can obtain additional information as identified during PFMA. o Conduct a follow-up risk assessment workshop to incorporate the new information. Workshop results could provide justification to change PFM to a lower category level or resolve at current level.	
Yellow	Strong Confidence (will stay in order of magnitude box) • Engineering judgment to consider possible storage restriction order if bordering red risk category OR required conditions that would allow full storage if bordering the green risk category to ensure ALARP principles. • Develop a compliance plan to identify and document additional risk reduction actions and set timelines. • Develop and submit PFM Observation and Monitoring Plan to SEO	• Ensure that emergency action plan and inundation mapping are current and tabletop tested for initiating event. • Coordinate with local emergency managers as needed for situational awareness.
	Poor to Medium Confidence (Risk Workshop indicates it could possibly move a ***higher*** risk category level) • Storage Restriction order to mitigate PFM, concurrent with level of urgency. • Develop a compliance plan to identify and document additional risk reduction actions and set timelines. • Develop and submit PFM Observation and Monitoring Plan with specified reporting frequencies. • Based on Compliance Plan actions items, Owner/engineer can obtain additional information as identified during PFMA and provide justification to that risk could change to a lower category level with a follow-up Risk Assessment Workshop.	• Ensure that emergency action plan and inundation mapping are current and functionally tested for initiating event. • Initiate intensive local and state emergency management coordination and provide situation reports based on continuous monitoring, concurrent with level of urgency. • Develop early warning system program (EWSP) specific to PFM.
	Poor to Medium Confidence (Risk Workshop indicates it could possibly move to a ***lower*** Risk Category level) • Owner/engineer to obtain additional information identified during PFMA and provide justification to SEO that risk could change to a lower category level. • Use Engineering Judgment to consider Conditional Full Storage OR Full Storage • Long term monitoring & instrumentation plan focused towards PFM to assess for worsening conditions.	• Ensure that emergency action plan and inundation mapping are current and tabletop tested for initiating event.
Green	Strong Confidence (will stay in order of magnitude box) • Full Storage • Continue routine dam safety risk management activities, normal operation, and maintenance. • Keep PFMs on list to indicate they have been evaluated. • Focus regular inspection visits on highest ranked PFM issues.	• Ensure that emergency action plan and inundation mapping are current and tabletop tested for initiating event.
	Poor to Medium Confidence (Risk Workshop indicates it could possibly move to a higher Risk Category level. • Strict Dates for Compliance Plan to complete investigations and analyses to increase confidence in PFM and support justification for remediation and remediation design, as appropriate. • Conduct regular inspections and heightened monitoring specific to highest ranking PFMs.	• Ensure that emergency action plan and inundation mapping are current and tabletop tested for initiating event.

Section 15. Definition, Use, and Expectations of ALARP Principles

ALARP is an acronym for "As Low As Reasonably Practicable". When applied to dam safety in a risk assessment framework, this term applies to those actions that one might take to reduce risk. The general ALARP risk concept is that risk reduction actions beyond a certain level may not be justified if further risk reduction is impracticable or if the cost is grossly disproportional to the benefits obtained by the risk reduction. A dam owners might say, "We've taken actions to get the risk of our dam to a level that is "as low as reasonably practicable". Put another way, if an owner gets to this point, them spending additional sums of money would result in no appreciable additional reduction in risk.

ALARP considerations may be taken into account when risks are lower than the risk guidelines, for those risks above the risk guidelines that have potentially extraordinary circumstances, or for those cases of very low failure probability but very large consequences. ***ALARP only has meaning in evaluating risk reduction measures – it cannot be applied to an existing risk without considering the options to reduce that risk.***

By definition, consideration of ALARP is a matter of judgement. Simply throwing out the term "ALARP" is not considered justification. To make an objective judgement on whether or not dam risks have actually been reduced to a state that is as low as reasonable practicable (ALARP) through some defined actions, the following should be taken into account:

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

Again, the general intent of ALARP practices and principles is to evaluate whether risks should be reduced, and if so, how far and by what means. A balance between equity and efficiency is implied by using the principle. USBR and State of Victoria (see Reference Section 3.4) have explored the past and present uses of ALARP principles and the societal issues surrounding them. The Colorado Dam Safety Branch's intended use of ALARP principles in our dam regulation environment are consistent with how others are currently applying them.

Section 16. Risk Informed Design Considerations and Allowances

In general, if the risk assessment for an identified PFM or set of PFMs' shows and unacceptable risk that requires some modification to the dam to appropriately reduce the risk, the intent is that the owner will engage a design engineer and engage in Rule 7 standards-based procedures specific to that PFM or set of PFMs. Generally, designs for modifications or new dams provide enough modern design redundancy to land comfortably in the green risk zone, OR in the yellow zone with strong confidence for higher consequence dams. As discussed above in the ALARP section, there may be isolated situations where that is not practical and additional dam owner resources will not appreciable reduce the assessed risk. In situations where the Rule 7 requirements are judged to be impractical either due to extremely improbable loading conditions or low level consequences, etc., then risk informed design considerations may be applied on a case by case basis. Additional dam safety Rules are being contemplated to enable incorporation of Risk Informed Design principles. The Rules will be subject to an abbreviated Rule making process and added by addendum. Until such time as the Rules are amended, completion of this process may require a formal waiver from the State Engineer of the specific Rule being considered.