OROVILLE RISK ANALYSIS

SUMMARY OF OROVILLE LEVEL 2 RISK ANALYSIS REPORT

This document represents a summary of the Level 2 Risk Analysis Report for the Oroville Dam Complex for public dissemination. Critical Energy Infrastructure Information has been removed.

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Contents

Acronyms

APF: annual probability of failure

AEP: annual exceedance probability

DOE: DWR's Division of Engineering

DSOD: California Division of Safety of Dams

DWR: California Department of Water Resources

FERC: Federal Energy Regulatory Commission

FCO: Flood Control Outlet

IFT: Independent Forensic Team

L2RA: Level 2 Risk Analysis

O&M: DWR's Division of Operations and Maintenance

PFM: Potential Failure Mode

PFMA: Potential Failure Mode Analysis

RIDM: Risk Informed Decision Making

SME: Subject Matter Expert

USACE: U.S. Army Corps of Engineers

Introduction

In 2020, the Department of Water Resources (DWR) received the Oroville Level 2 Risk Analysis (L2RA) report from the independent consultants tasked with its preparation. Since the report contains a significant amount of Critical Energy Infrastructure Information (CEII), the report must be reviewed and appropriate redactions applied before it can be released to the public. The CEII review and redactions protect operational, physical, and security-related information that could be utilized to disrupt operations or damage the facilities.

In order to accelerate the public's access and enhance understanding of the L2RA, DWR has prepared this summary document that provides the L2RA's purpose, background information, process, and results.

Purpose of Oroville L2RA

The Oroville L2RA was performed to support and enhance the 10th Part 12D Safety Inspection Reports for the Oroville Dam complex. The Part 12D Safety Inspection Report is a regular safety assessment FERC Licensees are required to perform and submit to FERC every five years. For the L2RA, the California Department of Water Resources (DWR) implemented the Federal Energy Regulatory Commission's (FERC) Risk Informed Decision Making (RIDM) process to understand qualitative baseline risks and use those risk estimates to inform dam safety decisions.

The primary purposes of an L2RA are to:

- Evaluate the project potential failure modes (PFM) and associated risks
- Identify the need for additional studies and determine the priority for those studies
- Identify and prioritize any data collection, analyses, and study needs;
- Identify operations and maintenance, monitoring, emergency action plan, training and other recurrent needs
- Provide a better understanding of potential failure modes and a basis for future dam safety inspections and activities; and,
- Inform dam safety decisions such as where to conduct additional studies to better define risk and where to implement mitigation measures to reduce risk.

The Oroville Dam Complex includes Oroville Dam, Edward Hyatt Powerplant, Hyatt Powerplant Intake, Bidwell Bar Canyon Saddle Dam, Parish Camp Saddle Dam, Flood Control Outlet Headworks, Flood Control Outlet Chute, Emergency Spillway, River Valve Outlet System, and Palermo Tunnel Outlet. Each of these features was considered in the L2RA. The L2RA report (two volumes) covering all the features, with the exception of the Flood Control Spillway Chute and Emergency Spillway, were published in March 2020. The L2RA report for the Flood Control

Spillway Chute and Emergency Spillway was published in July 2020. Upon receipt, DWR submitted the reports to FERC and the California Division of Safety of Dams.(DSOD) .

Background

On September 21, 2018, the "Energy and Water, Legislative Branch, and Military Construction and Veterans Affairs Appropriations Act, 2019" (H.R. 5895) became law. The Conference Report to accompany H.R. 5895 included language directing FERC to require the licensee of Oroville Dam (DWR) to request the United States Society on Dams (USSD) to nominate independent consultants to prepare a Level 2 Risk Analysis, consistent with FERC's risk informed decision-making guidelines, for use in conducting the 10th Part 12D safety review of Oroville Dam.

DWR engaged the USSD-nominated consultants to plan, lead, execute, and complete the L2RA. The L2RA Facilitation Team, consisting of nominated individuals supported by qualified staff, worked with industry experts to assemble qualified teams of independent subject matter experts (SME) on various topics central to the dam safety evaluation. The independent subject matter experts are distinct and separate from the Board of Independent Consultants required by FERC to conduct and prepare the Part 12D Safety Inspection Report.

The L2RA Facilitation Team prepared a written risk analysis plan to establish the general process for the project and identify key individual roles. The risk analysis plan was submitted to FERC and subsequently accepted by FERC by letter dated January 8, 2019. The plan included numerous improvements to the traditional Potential Failure Modes Analysis (PFMA) process that were identified in the Oroville spillway incident Independent Forensic Team (IFT) Report. PFMA process improvements adopted for the L2RA are summarized below:

- Adopt a broader definition of "failure" to include malfunction or abnormal operation that adversely affects a dam's ability to impound water leading to serious consequences, as well as an unintended release of all or part of the reservoir.
- Provide more time for document review by workshop participants.
- Bring forward all PFMs from prior project PFMAs for discussion in the workshops.
- Apply a structured approach to brainstorming PFMs during the workshops.
- Provide a diverse team to cover relevant technical disciplines.
- Divide the workshops into specialized sessions for different components, while also considering interactions between components.
- Break up the sessions into a series of separate workshops to reduce mental fatigue and burnout.
- Based on qualifications and experience, identify individuals who will be estimating risks, and use a silent risk estimating process.

- For complex structures, supplement the PFMA with a more suitable process (e.g., fault tree analysis).
- Assure that structures related to Oroville Dam (appurtenant structures) receive appropriate attention with dedicated workshops.

The L2RA project also engaged two individuals with United States Army Corps of Engineers (USACE) risk and dam safety experience to provide independent oversight and guidance during the L2RA. The independent oversight advisors attended and observed most of the workshops and provided daily observations, feedback, and advice to DWR and the Facilitation Team.

Risk workshops were held between January and July 2019 and totaled 34 days.

Each workshop was attended by members of the L2RA Facilitation Team, independent oversight advisors, and appropriate independent SMEs based on the facility, structure or topic covered in the workshop. Other workshop attendees included:

- Part 12D Board of Independent Consultants
- DWR SMEs and contributors from the Division of Operations and Maintenance (O&M) and Division of Engineering (DOE)
- Division of Safety of Dams (DSOD) observers
- FERC observers
- DWR Oroville Dam Safety Comprehensive Needs Assessment project observers

Attendance at the workshops varied between approximately 30 and 65 people.

In addition to attending the workshop, participants performed site visits to the facilities, reviewed existing documentation, prepared and received presentations on project facilities and history, brain-stormed potential failure modes, and performed engineering analyses to inform estimates of likelihood and consequence.

The risk estimating process includes a rigorous review of the facilities and development of PFMs which describe a hypothetical, specific chain of events that lead to failure of the dam or structure, uncontrolled release, or other malfunction or abnormal operation with adverse consequences. The Subject Matter Experts were then tasked with providing estimates of likelihood and consequence for each PFM.

Types of Risk

The L2RA considered the following types of risk:

- Non-breach life safety risk

- Failure likelihood, or annual probability of failure (APF) risk [as per FERC (2018), individual life safety risk is approximately represented by the failure likelihood category; the term 'individual risk' was not used in the L2RA]
- Societal incremental life safety risk (qualitative combination of failure likelihood and life loss consequences), which is referred to as annualized life loss (ALL)
- Economic incremental consequence risk
- Qualitative assessment of environmental compliance

These types of risk are summarized below.

Non-Breach Life Safety Risk

Non-breach risk is the risk that exists even if the Oroville Complex performs its intended function without failing. The primary source of non-breach risk is related to "normal" or "as planned" operation (i.e., following the 1970 Water Control Manual reservoir operations plan) of the dam when reservoir and drainage basin hydrologic conditions dictate large spillway releases that exceed the downstream channel capacity. Downstream life loss consequences would be expected once channel capacity is exceeded, and the magnitude of the life loss would be dependent on many factors including, but not limited to, flow quantity, performance of levees, public awareness of danger, warning time and evacuation effectiveness.

Failure Likelihood/Annual Failure Probability

Failure likelihood is the risk of failure expressed as a qualitative failure likelihood category, defined by a quantitative probability range. It represents the annualized (i.e., probability in any given year) failure probability for the structure. For hydrologic and seismic PFMs, the magnitude of the loading (i.e., reservoir elevation, acceleration) and Annual Exceedance Probability (AEP) for the loading is considered semi-quantitatively along with the conditional failure likelihood.

Societal Incremental Life Safety Risk/Annualized Life Loss

Incremental risk is the likelihood and consequences associated with the presence of the structure, should the structure breach or undergo component malfunction, where the consequences considered are over and above the non-breach consequences associated with structure performing as intended. In other words, incremental consequences are those that would occur separate from consequences associated with normal operation of the feature, prior to failure.

Societal incremental life safety risk, expressed in terms of annualized life loss, is the risk represented by the semi-quantitative probability of a life loss consequence category. It is the combination of failure likelihood and the resulting incremental life loss consequences.

Economic Incremental Consequence Risk

In addition to the incremental life safety risk, there are incremental economic consequence risks. Incremental economic consequences are those that would occur separate from economic consequences associated with normal operation of the feature, prior to failure (non-breach consequences). Economic consequences include direct impacts of exceeding channel capacities downstream, and other indirect economic impacts on the regional or national economy. Potential direct economic losses are associated with property damage (buildings and infrastructure), emergency response costs, and repair costs. Potential indirect economic losses are associated with disruption of businesses, employment and income due to destruction of property and displacement of people. Some (but not all) of these components of economic risk were estimated for the L2RA.

Environmental Compliance

Similar to incremental life safety and incremental economic consequences described above, incremental environmental consequences are those that would occur separate from environmental consequences associated with normal operation of the feature, prior to failure (non-breach consequences). Environmental consequences include direct and indirect impacts of exceeding channel capacities downstream. Potential direct environmental consequences include damage to habitat, culturally significant resources or historic sites. Indirect environmental consequences include potential release of environmentally damaging waste or other materials from other downstream facilities damaged as a result of exceeding channel capacities downstream. For the L2RA, environmental consequences were measured in qualitative terms of environmental compliance and were not quantified.

Risk Estimating Process

The FERC guidelines specific to Periodic Level 2 Risk Analysis are under development. FERC provided DWR a draft of the procedures (version 1.1, June 2018) to inform the L2RA effort. The overall L2RA project followed the procedures in the draft L2RA document (FERC 2018), RIDM Guidelines (FERC 2016), and Best Practices in Dam and Levee Safety Risk Analysis (Reclamation/USACE, 2018).

The L2RA process is summarized as follows:

1. Train / coach participants in RIDM concepts and the L2RA process. Key risk reference documents and training presentations were provided at the start of the risk workshops.
2. Review of project information. Several hundred documents were provided to participants electronically via a shared website for review in advance of the workshops. The information included inspections reports, engineering, hydrologic and geologic studies, drawings and specifications, construction documentation, photographs, prior PFMA and Part 12D reports, specialized inspection results, and project correspondence. The shared website was updated during the workshops as additional information and presentations became available.
3. Develop and review loading estimates. Loading estimates were developed for hydrologic loading and seismic loading and represent the flood reservoir elevation and the seismic ground motions (respectively) for varying annual exceedance probabilities (i.e., higher flood reservoir elevations and higher earthquake accelerations are associated with more remote annual exceedance probabilities).
4. Brainstorm, review and develop PFMs. PFMs from prior PFMAs were reviewed and new PFMs were developed via survey prior to the workshop, and brainstorming sessions during the workshops.
5. Evaluate and screen PFMs. PFMs were either ruled out, excluded, or carried forward to the risk analysis. **Figure 1** reproduced from the FERC (2018) draft RIDM guidelines provides a graphical depiction this evaluation and screening process. Additional description of this important step is provided below.
6. Develop consequence estimates for PFMs. Inundation mapping and USACE LifeSIM software was used to estimate the potential life loss for various breach scenarios.
7. Develop failure likelihood and consequence categories. Factors making each PFM more likely and less likely were identified, along with supporting studies and references. The frequency of hydrologic and seismic loading was considered in estimating failure likelihood, while inundation mapping and LifeSIM results were utilized to estimate consequences. A “blind” estimating process was followed in which individuals estimating the failure likelihood for a given PFM did so initially without knowing others’

estimates. A consensus was reached on the failure likelihood category, or a range of categories, and the rationale was documented in the workshop notes. The level of confidence in the failure likelihood category was also discussed and recorded. Consequence categories were proposed for each PFM based on the consideration of specific inundation scenarios that were developed and then simulated in LifeSIM to generate life loss estimates. A life loss category was proposed and agreed to by consensus. The rationale for the estimated category and the level of confidence in the estimate was documented in the workshop notes.

8. Identify, discuss and document potential interim risk reduction measures and dam safety management actions.

9. Document and portray risk results. During the risk workshop, dedicated recorders captured key information through the use of a PFM template from the L2RA draft procedures (FERC 2018). The notes and templates provided the starting point for drafting the L2RA report. The Facilitation Team authored the report, with the independent SMEs contributing and providing reviews. The L2RA considered several measures of risk.

Further Description of Step 5 –Evaluate and Screen PFMs

With a list of all candidate PFMs for each structure, PFMs were first evaluated to determine whether they could be ruled out. PFMs were only ruled out if they were either not physically possible; did not meet the minimum threshold limit for consequences; or if they were not complete PFMs but rather contributing factors that could influence other candidate PFMs. The remaining PFMs were evaluated and discussed to determine if they could be excluded because they were considered negligible. In many cases, even initial discussions of PFMs resulted in (1) detailed development of the PFM to achieve a broad understanding of the PFM, and (2) consideration of more likely and less likely factors in the process of reaching consensus on whether a PFM should be excluded or not. If a PFM could not be excluded relatively quickly, it was carried forward into risk analysis for further evaluation. PFMs that were not ruled out or excluded were also carried forward into risk analysis.

Many PFMs were initially brainstormed separately under normal operation, hydrologic loading and seismic loading conditions. However, the reservoir exceedance curve is a continuum that spans from normal operating levels all the way to reservoir levels that would only occur during an extreme flood. In addition, the Oroville Dam reservoir operation includes variable seasonal flood storage, which makes the distinction between “normal” and “flood” conditions somewhat artificial. Therefore, rather than separating risks associated with normal operating levels from risks associated with flood events, embankment PFMs and some non-embankment PFMs were evaluated over the full range of reservoir levels. The term “full reservoir range” is used to reflect the approach for estimating PFM likelihood based on the probability of different reservoir levels.

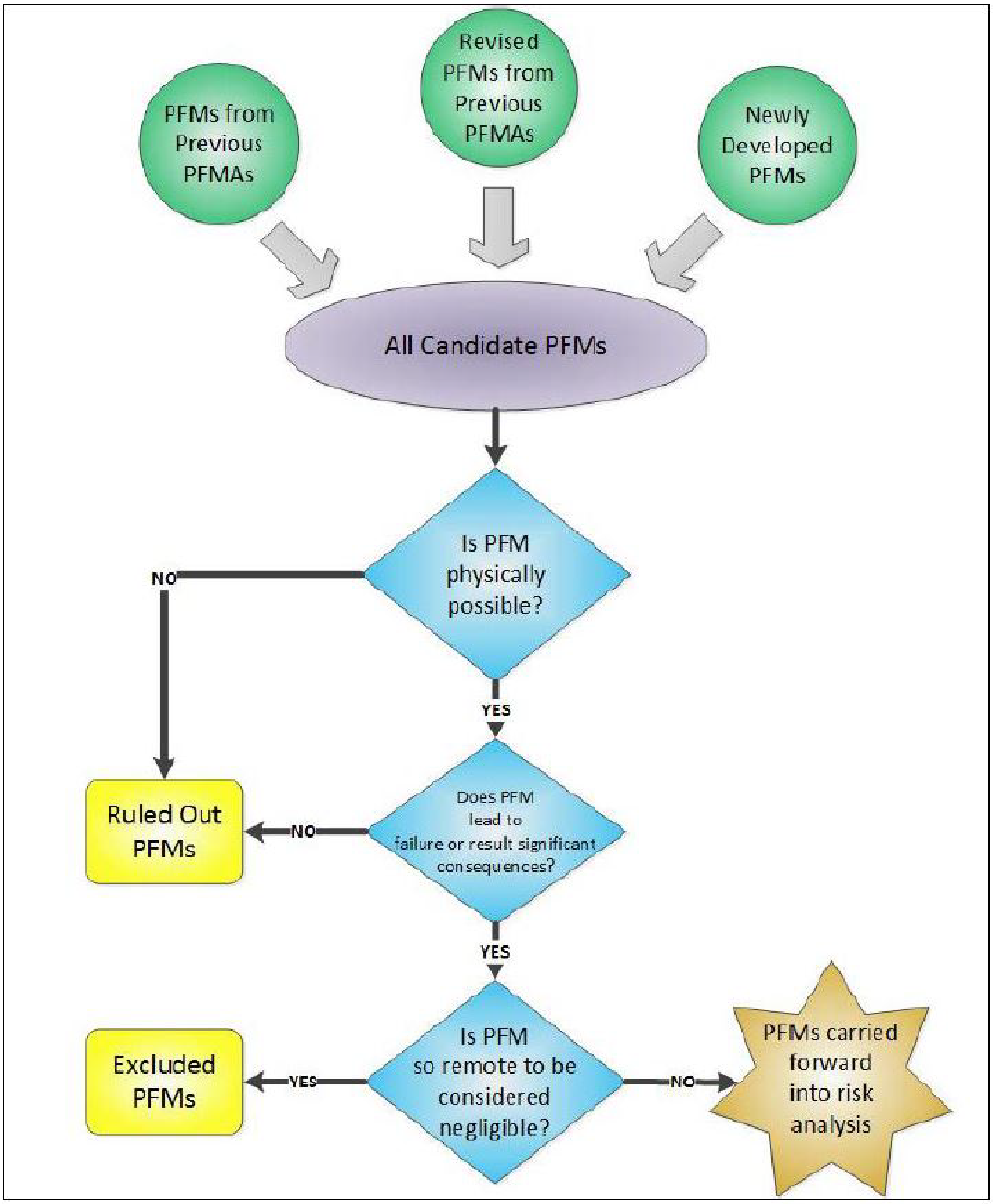


Figure 1 – Potential Failure Mode Evaluation Process (Figure 4 in FERC 2018)

Failure Likelihood Estimates

Failure likelihood for PFMs carried forward to the risk analysis was generally estimated using one of three approaches:

- Estimate considering loading probabilities and associated conditional failure probabilities.
- Estimate more qualitatively considering failure likelihood evidence descriptors (see **Table 1**).
- Estimate relative likelihood by comparison with failure likelihood categories previously estimated.

Each of these approaches is considered acceptable, as long as there is supporting rationale for the estimated failure likelihood category.

FERC (2018) includes eight failure likelihood categories described in **Table 1**. Each failure likelihood descriptor has an associated quantitative annual failure likelihood range and a description of evidence that could be used to help support failure likelihood estimation. For the Oroville Complex L2RA, six failure likelihood categories were considered, ranging from Very High to Remote. A seventh “category” of Negligible was considered for any PFM judged to have likelihood lower than Remote.

The Hyatt Powerplant, Hyatt Intake and FCO gates involve operation of many electrical and mechanical components whose failure could result in inoperable equipment including gates, valves, and generating units. For these components, a fault tree approach was used to evaluate overall vulnerabilities and the potential causes of component failure.

Table 1 – Potential Failure Mode Evaluation Process (Table 2 of FERC 2018)

Failure Likelihood Descriptors		
Failure Likelihood Descriptors	**Annual Failure Likelihood**	**Evidence**
Certain	More frequent (greater) than 1/10	There is direct evidence or substantial indirect evidence to suggest it certain to nearly certain that failure is eminent or extremely likely in the next few years.
Extreme	1/10 to 1/100	There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is very likely to occur during the life of the structure.
Very High	1/100 to 1/1,000	There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is likely to occur.
High	1/1,000 to 1/10,000	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "more likely" than "less likely."
Moderate	1/10,000 to 1/100,000	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "less likely" than "more likely."
Low	1/100,000 to 1/1,000,000	The possibility cannot be ruled out, the fundamental condition or defect is postulated. Evidence indicates it is very unlikely.
Very Low	1/1,000,000 to 1/10,000,000	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	More remote (less) than 1/10,000,000	Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood such that the failure likelihood is negligible.

Life Safety Consequence Estimates

FERC (2018) includes five life safety consequence categories described in **Table 2**. Each consequence category has an associated incremental life loss and description. During each workshop session, life loss consequence subject matter experts presented the results of breach inundation and LifeSIM models for hydraulic cases relevant to the structure being discussed. Workshop participants discussed key observations and findings from the results. After the failure likelihood category for PFMs was estimated, discussions between the life loss consequence subject matter experts and other independent subject matter experts focused on identifying the hydraulic model case(s) and the incremental life loss range that would best represent the expected outcome of each PFM. Factors such as reservoir elevation at the time of failure, likely downstream channel flows, time to detect a breach, time for a breach to develop, and public warning and evacuation assumptions were discussed to select representative LifeSIM model(s).

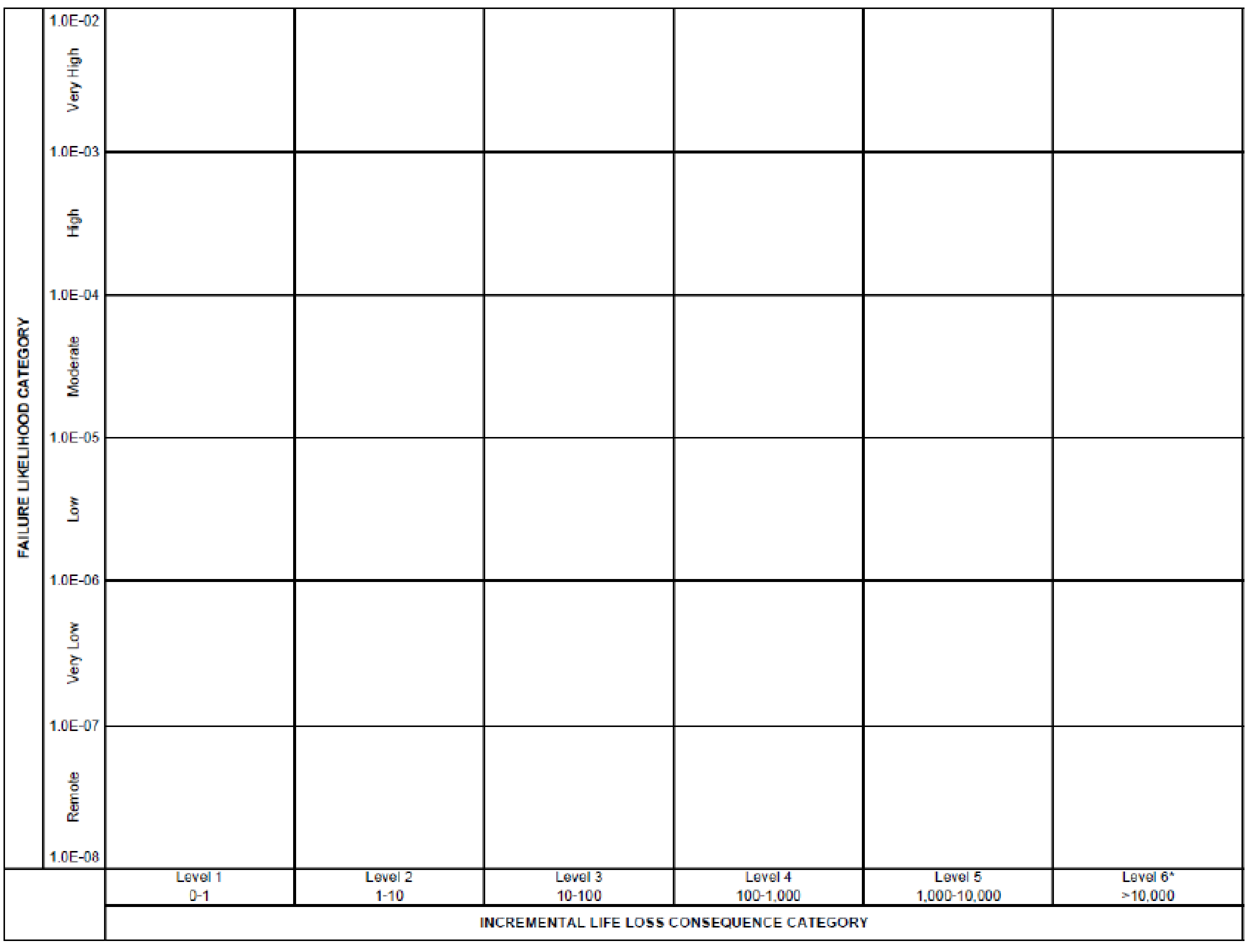
Table 2 – Life Safety Consequence Categories (Table 5 of FERC 2018)

Life Safety Consequence Category	Incremental Life Loss	Description
Level 0	None expected	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river.
Level 1	Less than 1	Although life-threatening releases occur, direct loss of life is unlikely due to severity or location of the flooding, or effective detection and evacuation.
Level 2	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	10 to 100	Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/ travelers and smaller population centers, or difficulties evacuating large population centers with significant warning time.
Level 4	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	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.

Oroville Level 2 Life Safety Risk Matrix

The Oroville Level 2 Life Safety Risk Analysis matrix with the general categories for failure likelihood and consequences is shown on **Figure 2**. Likelihood of failure categories are shown on the vertical axis (using cell divisions corresponding to the failure likelihood categories) and the associated consequences due to breach are shown on the horizontal axis (using cell divisions corresponding to the consequences categories). Cells of the risk matrix correspond to order-of-magnitude quantitative estimates. Potential failure modes are plotted on the matrix as boxes of the same size and represent order-of-magnitude best estimates made by the team.

Figure 2 – Oroville Level 2 Life Safety Risk Analysis Matrix



Notes:
1. *FERC draft PL2RA procedures do not include Level 6. Level 6 was added to the matrix to portray PFMs with life loss potential greater than 10,000 people.
2. Each PFM is positioned in a matrix cell that represents the best estimate failure likelihood category and life loss consequence level. All PFMs within a matrix cell are considered to have equal best estimate risk; the relative position of PFMs within each cell is arbitrary and is not an indicator of relative risk.
3. PFMs positioned to straddle a line between failure likelihood categories or life loss consequence levels represent the best estimate (one order of magnitude) that spans across the category or level.

Important considerations when reviewing the L2RA results (matrices) follow:

1. FERC draft Level 2 RIDM guidelines (2018) do not include Consequence Level 6. Level 6 was added to the L2RA matrix to portray PFMs with life loss potential greater than 10,000 people.
2. Each PFM is positioned in a matrix cell that represents the best estimate failure likelihood and life loss consequence level. All PFMs within a matrix cell are considered to have equal best estimate risk; the relative position of PFMs within each cell is arbitrary and is not an indicator of relative risk.
3. PFMs positioned to straddle a line between failure likelihood categories or life loss consequence levels represent the best estimate (one order of magnitude) that spans across the category or level.

Economic Incremental Consequence Risk

Economic incremental consequence risk is the risk represented by the semi-quantitative probability (annualized) of an economic consequence category. For the L2RA, the same six likelihood categories that were used to describe failure likelihood were used to describe the likelihood of an event (failure or non-failure) that leads to economic consequences, ranging from Very High to Remote.

Table 3 provides the incremental economic consequence categories and the descriptions that were used in the L2RA. PFMs or events with the potential for incremental economic consequences that were estimated to be in any of the six event likelihood categories were portrayed on an economic consequence risk matrix.

Table 3 – Economic Consequence Categories (Table 6 of FERC 2018)

Economic Consequence Category	Incremental Economic Loss ($)	Description
Level 0	None expected	No significant economic or other impacts.
Level 1	Less than 10M	Downstream discharge results in limited property and/or environmental damage.
Level 2	10M to 100M	Downstream discharge results in moderate property and/or environmental damage.
Level 3	100M to 1B	Downstream discharge results in significant property and/or environmental damage.
Level 4	1B to 10B	Downstream discharge results in extensive property and/or environmental damage.
Level 5	greater than 10B	Downstream discharge results in extremely high property and/or environmental damage.

Environmental Compliance

Environmental consequences were estimated in terms of degree of violation of environmental compliance using a relative range of categories. The categories provide a relative ranking of likely environmental damages, as severity of violation generally correlates with the severity of damages. The following environmental compliance categories were considered and each PFM or event was assigned a category:

1. Insignificant (no compliance violation).
2. Minor (minor restrictions or increased oversight).
3. Moderate (violation and fines).
4. High (mitigation to offset impacts).
5. Major (sanctions, lose rights to operate facility).

Facilitation during Estimating

For all PFMs, a "blind" estimating process was followed in which individuals estimating the failure likelihood for a given PFM did so initially without knowing others' estimates. The blind estimating process promotes independent thinking and reduces availability and anchoring bias that can occur if estimators are unduly influenced by a particular individual's initial opinions and estimates.

After the initial estimates were presented to the workshop participants, each estimator was given the opportunity to provide the rationale for their estimate. Following the discussion of estimates, the group agreed on a range, typically spanning two or three orders of magnitude, and occasionally on a single category. The level of confidence in the failure likelihood category and sources of uncertainty were also discussed and documented.

After the initial workshops, the facilitation team led efforts to select best estimate failure likelihood for each PFM. The best estimate failure likelihood category was identified by the facilitation team based on information from the workshops. Maintaining relative risk categories between PFMs was also important in selecting the best estimate category. The best estimate category was sometimes at the low end of the workshop range, sometimes in the middle of the workshop range, and sometimes at the upper end of the workshop range. For the few cases where the best estimate failure likelihood category was outside of the range estimated during the workshop, justification for the change in category from the workshops to the report is documented in the individual PFM discussions. In all cases, the facilitation team and independent SMEs were in agreement with the selected category.

Systems Interactions and Human Factors Approach

In the process of planning for the L2RA, it was recognized that evaluations of dam failure case histories often reveal that system interactions and human factors are key contributors to the failure. During the individual structure workshops, system interactions between structures were identified, documented and set aside for further consideration in the systems interaction and human factors workshop. The intent of the system interactions and human factors workshop was to systematically analyze the system interactions and human factors in order to assess their potential contribution to the PFMs. Neither quantitative nor qualitative risk estimates were developed for any of the system interaction scenarios considered during the workshop. Estimating system risk would not be appropriate for this level of study and was judged to be beyond the scope of the L2RA. The impacts of interaction between human and physical factors were also explored and documented both at a system level and an individual structure level.

L2RA Results

Table 4 summarizes the total number of candidate PFMs for the Oroville Dam Complex, by structure, and which of those were ruled out, excluded, or carried forward into risk analysis. A number of candidate PFMs for each structure included duplicate candidate PFMs; in Table 4 those were combined with PFMs that were ruled out or excluded. Table 5 provides a breakdown (by structure) of the PFMs carried forward into the Risk Analysis.

Table 4 - Identified PFMs for the Oroville Dam Complex

Structure	Candidate PFMs	Ruled Out PFMs, Excluded PFMs, and Duplicate PFMs	PFMs Carried Forward into Risk Analysis
Oroville Dam	86	40	46
Parish Camp Saddle Dam	50	32	18
Bidwell Bar Canyon Saddle Dam	56	23	33
FCO Headworks	208	186	22
Hyatt Intake	40	30	10
Hyatt Powerplant	46	30	16
River Valve Outlet System	18	11	7
Palermo Outlet	25	15	10
FCO Spillway Chute	53	41	12
Emergency Spillway	53	38	15
Total	**630**	**441**	**189**

Table 5 - PFMs Carried Forward into Risk Analysis

Structure	PFMs Carried Forward into Risk Analysis	PFMs on the L2RA Risk Matrix	Negligible PFMs	Other PFMs
Oroville Dam	46	17	25	4
Parish Camp Saddle Dam	18	2	13	3
Bidwell Bar Canyon Saddle Dam	33	2	29	2
FCO Headworks	22	9	6	7
Hyatt Intake	10	0	4	6
Hyatt Powerplant	16	5	0	11
River Valve Outlet System	7	0	3	4
Palermo Outlet	10	1	3	6
FCO Spillway Chute	12	3	6	3
Emergency Spillway	15	4	6	5
Total	**189**	**43**	**95**	**51**

The column on Table 5 titled “Other PFMs” includes the remaining PFMs that were either 1) not estimated due to significant uncertainty, 2) conditionally estimated, 3) estimated for failure likelihood category but had no life loss consequences and therefore were not plotted on the L2RA matrix, or (4) after further consideration, judged not physically possible. The PFM that was “conditionally estimated” pertained to a rapid drawdown event causing slope instability. The likelihood of slope instability and dam breach were estimated, but the rapid drawdown event (i.e. the trigger) and its corresponding likelihood was not estimated.

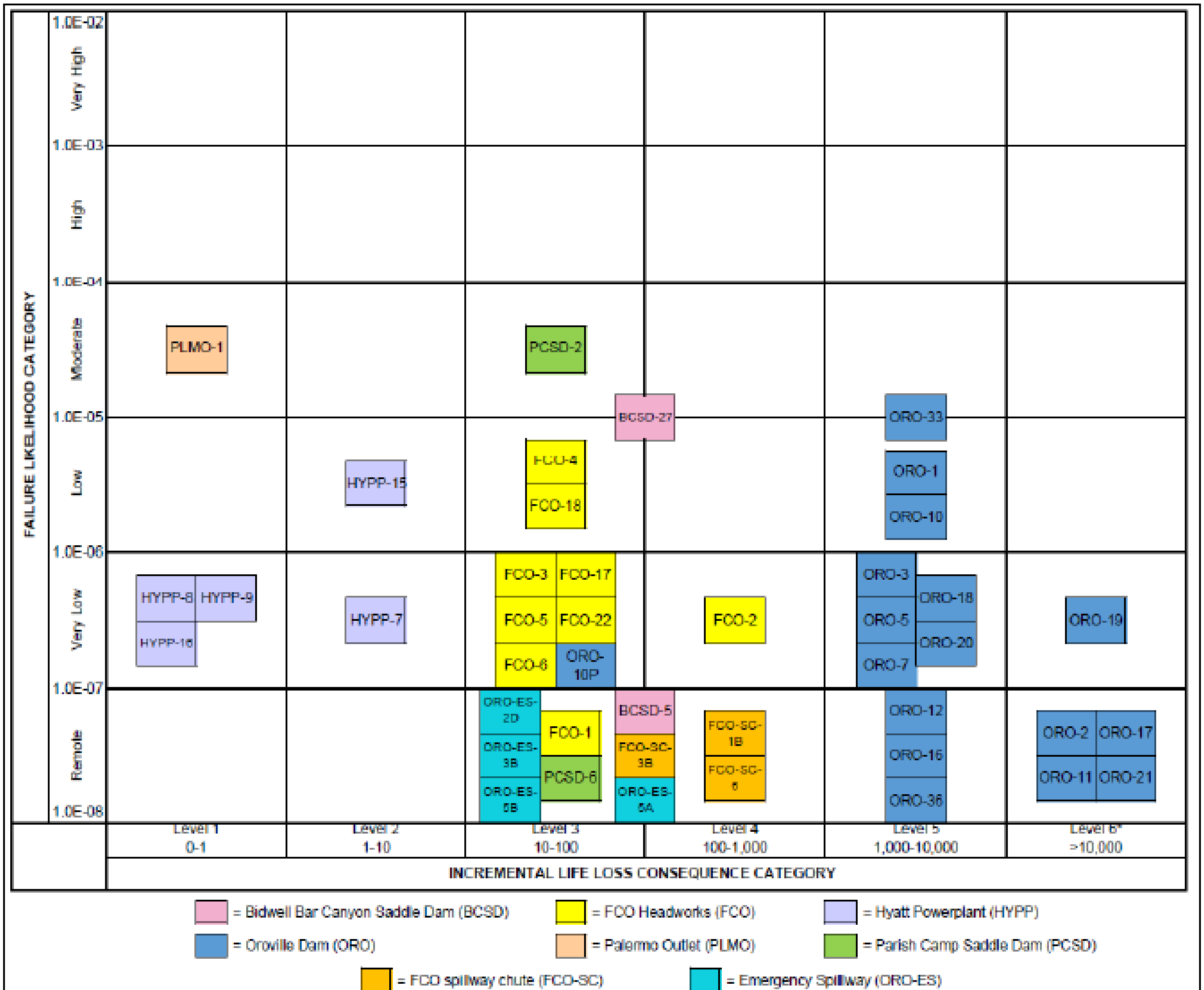
There were at total of 630 candidate PFMs for the Oroville complex L2RA. A total of 189 PFMs were carried forwarded and evaluated in the risk analysis workshops. Of those 189 PFMs, 43 PFMs with life loss consequences were judged to have a best estimate failure likelihood category of Remote or higher and are portrayed on the Oroville Dam Complex risk matrix (**Figure 3**).

Risk Tabulation and Portrayal

Following FERC guidance and the practices of other federal agencies, the L2RA utilized a risk matrix to portray risks. The best estimate of risk associated with each PFM analyzed is portrayed as a single box on the Oroville Level 2 Life Safety Risk Analysis matrix (**Figure 3**). Likelihood of failure categories are shown on the vertical axis (using cell divisions corresponding to the failure likelihood categories) and the associated consequences due to breach are shown on the horizontal axis (using cell divisions corresponding to the consequences categories). Cells of the risk matrix correspond to order-of-magnitude quantitative estimates. Potential failure modes are plotted on the matrix as boxes of the same size and represent order-of-magnitude best estimates made by the team.

The size of each potential failure mode box on the risk matrix is intended to be the same and is not intended to portray any uncertainty. The risk for any PFM positioned in a matrix cell is equivalent to the risk of any other PFM positioned in the same cell, regardless of their relative positions in the cell.

PFMs with the potential for life loss that were estimated to be in any of the six failure likelihood categories were portrayed on the risk matrix. PFMs judged to have failure likelihood lower than the Remote category were judged to have negligible failure likelihood and were not portrayed on the risk matrix.



Notes:
1. *FERC draft PL2RA procedures do not include Level 6. Level 6 was added to the matrix to portray PFMs with life loss potential greater than 10,000 people.
2. Each PFM is positioned in a matrix cell that represents the best estimate failure likelihood category and life loss consequence level. All PFMs within a matrix cell are considered to have equal best estimate risk; the relative position of PFMs within each cell is arbitrary and is not an indicator of relative risk.
3. PFMs positioned to straddle a line between failure likelihood categories or life loss consequence levels represent the best estimate (one order of magnitude) that spans across the category or level.

Figure 3 – Oroville Dam Complex Life Safety Risk Matrix Failure Likelihood and Non-Life Loss Consequence

Summary of Results and Key Findings

A key finding from the L2RA is an improved understanding of the potential for life loss if the Oroville Complex performs its intended function without failing. Downstream life loss consequences would be expected once channel capacity is exceeded, and the magnitude of the life loss would be dependent on many factors including, but not limited to, flow quantity, performance of levees, public awareness of danger, warning time and evacuation effectiveness.

The analyses performed for the L2RA indicate there would be non-zero life loss for any flood more remote than annual exceedance probability of 1/1,000 because downstream releases dictated by the Water Control Manual for an event of this magnitude would exceed the capacity of levees. A critical assumption in this non-breach analysis is the downstream levees can be loaded to the crest without failure. There could be life loss for floods more frequent than 1/1,000 if downstream levees breach prior to overtopping.

PFMs with the Largest Incremental Life Loss Potential

PFMs with the largest incremental life loss potential are associated with failure of Oroville Dam. Peak breach outflows are approximately 35 million cfs. Eleven PFMs were estimated to have a life loss consequence category of Level 5 (incremental life loss estimate of 1,000 to 10,000). Ten of those eleven PFMs are associated with either internal erosion or slope instability: six involved internal erosion through the embankment, three involved internal erosion and the foundation, and one involved upstream slope instability. Generally, slope stability and internal erosion PFMs occurring higher in the embankment would progress to failure more rapidly than PFMs occurring deeper in the embankment or deep in the foundation. Life loss would likely be towards the lower end of the Level 5 range for PFMs that take longer to progress to failure, compared to PFMs that progress more rapidly because there would be additional time for downstream warning and evacuation of the population at risk. One of the eleven PFMs (ORO-33) is associated with dam failure by overtopping. There would likely be life loss occurring as a result of downstream flood releases (in accordance with the Water Control Manual) prior to failure; therefore, incremental life loss for the dam overtopping PFM would likely be in the middle of the Level 5 range.

Five Oroville Dam PFMs were estimated to have a life loss category of Level 6 (incremental life loss >10,000). All of these PFMs are seismic-related and involve internal erosion through the embankment or foundation. There is significant uncertainty related to being able to estimate how quickly an internal erosion PFM might develop due to seismic ground motions that cause damage. The reservoir level at the time of the event, the location of the damage and the amount of damage are variables that influence the rate of progression to failure, which impacts the time for warning and evacuation. Warning and evacuation immediately after an earthquake can be a challenge if normal lines of communication are compromised and limited. These considerations tend to support an incremental life loss estimate toward the higher end of the

HEC LifeSIM case results, which approximately corresponds to the lower bound of the Level 6 consequence category.

The three non-embankment PFMs with the highest potential for life loss are FCO-2 (sliding of headworks under flood loading), FCO-SC-1B (chute slab damage caused by uplift leads to headcutting erosion and breach of FCO headworks), and FCO-SC-6 (fault rupture causing chute damage that leads to headcutting erosion and breach of FCO headworks). The life loss consequence category for these three PFMs was estimated to be Level 4 (incremental life loss of 100 - 1000) because breach outflows from FCO Headworks monolith failure would be added to pre-failure spillway release flows and would contribute to downstream levee overtopping (and possibly levee failure), impacting a large population at risk. This is an upper bound estimate that assumes the FCO Headworks breach occurs just as the capacity of the levees is reached.

PFMs Driving the Total Failure Likelihood (Annual Probability of Failure)

For a quantitative risk analysis, the total mean annual failure probability can be computed by summing the mean failure probability of all PFMs (with adjustments for common cause factors and system interaction factors, as appropriate). With semi-quantitative risk estimates in terms of failure likelihood categories, the total annual failure probability could be estimated by quantitatively summing the mean values for all PFMs. However, for this type of risk analysis, one important outcome is to understand the PFMs and factors driving the qualitative risk, rather than having a well-defined estimate of the total quantitative risk based on summing mean values, which may or may not be representative.

The first step in understanding what is causing or "driving" the total failure likelihood is to simply review the PFMs in the highest failure likelihood categories, regardless of the life loss consequence category. There are two PFMs in the Moderate failure likelihood category, and two PFMs straddling the Low to Moderate failure likelihood categories:

- Moderate: PLMO-1, Failure to control water to pass through Palermo Tunnel
- Moderate: PCSD-2, Flood overtopping and breach of Parish Camp Saddle Dam
- Low to Moderate: BCSD-27, Flood overtopping and breach of Bidwell Canyon Saddle Dam
- Low to Moderate: ORO-33, Flood overtopping and breach of Oroville Dam

Qualitatively, these four PFMs contribute the majority of the failure likelihood risk. Three of the four PFMs involve flood overtopping failure of embankments, i.e. PCSD-2, BCSD-27 and ORO-33. The failure likelihood for these three overtopping PFMs is driven by the hydrologic loading, which indicates the potential for embankment overtopping for a flood with an annual exceedance probability of approximately 1/40,000 years. The fourth PFM driving the total failure likelihood risk is PLMO-1, which involves the failure to control water to pass through

Palermo Tunnel. A fault tree approach was used to consider the numerous components or factors that could contribute to the inability to control water through the tunnel. The likelihood of this PFM was judged to be Moderate and its consequence category was estimated as Low.

There are five PFMs in the second highest failure likelihood category of Low; one for Hyatt Powerplant (HYPP-15, seismic coupling failure), two for the FCO Headworks (FCO-4, and FCO-18), and two internal erosion PFMs for Oroville Dam (ORO-1, ORO-10).

Of the nine PFMs judged to qualitatively be driving the total failure likelihood risk, three PFMs are related to flood overtopping (PCSD-2, BCSD-27 and ORO-33), two are related to seismic structural failure (HYPP-15 and FCO-18), two involve structure component failure under normal loading (PLMO-1 and FCO-4) and two involve internal erosion (ORO-1 and ORO-10). The hydrologic loading embankment overtopping PFMs qualitatively drive the failure likelihood risk; but after those PFMs, there is no other loading or structure trend that significantly drives the failure likelihood risk.

PFMs Driving the Societal Incremental Risk (Average Annualized Life Loss)

The first step in understanding what is driving the total annualized life loss risk is to view the matrix cells in terms of equal annualized life loss that run diagonal across the matrix from the upper left to the lower right. For example, from a qualitative perspective, the matrix cell corresponding to High failure likelihood and Level 2 consequences generally has the same annualized life loss risk as the matrix cell corresponding to Very Low failure likelihood and Level 5 consequences. Quantitatively, there is significant variability from cell to cell because each cell represents an order of magnitude of failure likelihood and consequences.

Using the diagonal equivalent matrix cell approach, there are four Oroville Dam PFMs that drive the annualized life loss risk; ORO-33, ORO-1, ORO-10 and ORO19.

- ORO-33: Flood overtopping and breach of Oroville Dam
- ORO-1: Internal erosion though transverse crack
- ORO-10: Internal erosion at the FCO / embankment wrap-around location
- ORO-19: Seismic initiated internal erosion at the foundation contact

The combination of Low to Moderate failure likelihood and Level 5 consequences for ORO-33 presents the highest annualized life loss risk PFM. The remaining three PFMs have qualitatively equivalent annualized life loss risk with ORO-1 and ORO-10 having Low failure likelihood and Level 5 consequences and ORO-19 having Very Low failure likelihood and Level 6 consequences.

At the next tier down of qualitatively equivalent annualized life loss risk, there are 11 PFMs contributing to the risk: PCSD-2, BCSD-27, and 9 Oroville PFMs. The two embankment PFMs PCSD-2 and PCSD-27 have Low to Moderate failure likelihood (similar to ORO-33) but the life loss consequence category is lower (thereby lowering the annualized life loss risk compared to

Oroville Dam), reflecting the fact that a complete breach of the saddle dams would only partially release the reservoir. Of the 15 PFMs contributing significantly to the annualized life loss risk, there are no concrete structure PFMs; all PFMs are related to either embankment overtopping (3 PFMs) or Oroville Dam internal erosion (12). Three FCO PFMs (FCO-4, FCO-18 and FCO-2) along with three Oroville Dam PFMs (ORO-12, ORO-16 and ORO-36) are another tier lower and do not contribute significantly to the total annualized life loss risk compared to the 15 embankment PFMs.

Similar to the total annual failure probability risk, hydrologic flood overtopping is a major contributor to annualized life loss risk, with internal erosion PFMs also contributing significantly.

PFMs Driving the Non-Life Loss Consequences Risk

As described above, non-life loss consequences were estimated in terms of environmental compliance and incremental economic impacts. The non-life loss risk discussion below is focused on incremental economic impacts. Environmental compliance is briefly discussed at the end of this section.

Similar to the average annualized life loss risk discussion above, in order to understand what is driving the total incremental economic risk, the matrix cells can be viewed in terms of equal annualized economic risk that runs diagonal across the matrix from the upper left to the lower right (See **Figure 4**). Quantitatively, there is significant variability from cell to cell because each cell represents an order of magnitude of likelihood and consequences.

Using the diagonal equivalent matrix cell approach, there are seven PFMs or events that drive the annualized economic risk: ORO-ES-1, ORO-ES-2A, ORO-ES-2B, HYINT-7, ORO-33, FCO-19 and PLMO-1.

- ORO-ES-1: Erosion downstream of secant pile wall blocks channel.
- ORO-ES-2A: Erosion downstream of secant pile wall.
- ORO-ES-2B: Erosion and damage or failure of secant pile wall.
- HYINT-7: Seismic failure of intake channel walls.
- ORO-33: Flood overtopping and breach of ORO.
- FCO-19: Seismic gate damage scenario.
- PLMO-1: Failure to control water to pass through Palermo Outlet.

Economic losses from Emergency Spillway damage states were discussed in the Non-Life Loss Consequence workshop and information from the damage states was applied to the Emergency Spillway PFMs developed and estimated after the Non-Life Loss Consequence workshop. Emergency Spillway PFMs (High likelihood; Level 4 economic consequences, for PFMs ORO-ES-

1, -2A and -2B) were judged to be significant contributors to the overall annualized economic risk because of the relatively high likelihood and significant economic consequences. The High likelihood is driven by the estimated annual exceedance probability (~ 1/500-year event) of activating the Emergency Spillway. The significant economic consequences are driven by eroding materials that partially or fully block the Feather River channel, increasing tailwater and subsequently flooding Hyatt Powerplant, resulting in significant repair or replacement costs and a multi-year outage of the plant.

HYINT-7 (High likelihood; Level 4 economic consequences) and ORO-33 (Low to Moderate likelihood; Level 5 economic consequences) have the same qualitatively equivalent annualized incremental economic risk as the Emergency Spillway PFMs. FCO-19 and PLMO-1 are at the next tier down of qualitatively equivalent annualized economic risk with Moderate likelihood and Level 4 economic consequences. Of these seven PFMs, ORO-33 is the only one that involves dam failure.

The other measure of non-life loss consequences considered in the L2RA was environmental compliance. All but one of the seven PFMs driving the incremental economic risk were judged to have a category 4 (High) environmental compliance consequence. The one PFM that involves dam failure, ORO-33 (flood overtopping) was judged to have category 5 (Major) environmental compliance consequences. While costs were not developed for the increments of environmental compliance, the categories do provide a relative ranking of likely environmental damages.

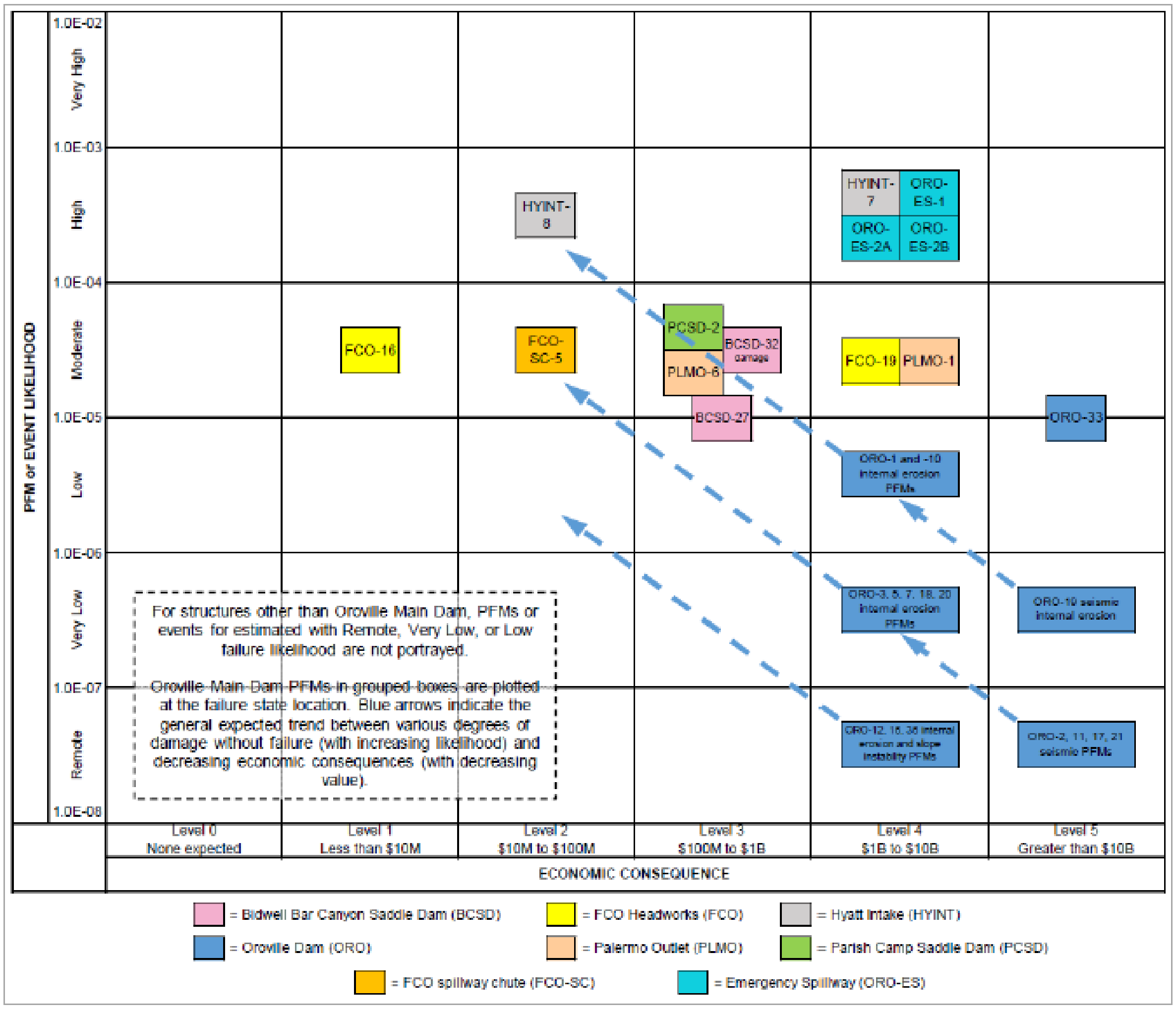


Figure 4 – Oroville Dam Complex Economic Consequence Risk Matrix

System Interaction and Human Factor Considerations

Systems interactions and human factors were considered in a dedicated workshop. The approach for this workshop was to first identify the primary and secondary relationships between the components/structures of the Oroville Dam Complex. The goal of this first step was to identify dependencies between the various components/structures and discover general vulnerabilities within the system. This process was also helpful in identifying influence factors that could positively or adversely affect performance of other structures within the system. The primary and secondary relationships provided building blocks that could be used to construct scenarios to capture the interactions among structures. After these initial efforts, some specific scenarios were developed which considered more complex interactions among system components more completely. This improved the understanding of system complexities and potential feedback loops and interdependencies. Risk estimates and failure likelihoods were not developed for any of the system interaction scenarios developed during the workshop. It was concluded that establishing relationships between structures was an appropriate level of effort for the L2RA, and that estimating risk would be beyond the scope and expectations for the L2RA. System interactions and chain reactions have high levels of complexity that can only be captured in fully quantitative risk analyses.

Another effort in the workshop was to consider the interaction of human and physical factors. Human factors were considered in general accordance with the Human Factors framework outlined in Appendix J of the IFT Report. Workshop participants brainstormed factors that could contribute to the potential for failure, such as pressure from non-safety goals, human fallibility and limitations, and system complexity. Numerous human factors or errors were discussed; however, the risk impacts of human factors were not quantified as part of the workshop.

The efforts in this workshop resulted in a better understanding of some key linkages within the Oroville Complex system, and a better understanding of system vulnerabilities. Some of the key findings and vulnerabilities included:

- Considering failure likelihood or risk for individual PFMs, isolated from system considerations, likely underestimates the overall risk. There is a need to consider system interactions and explicitly account for interaction of physical and human factors in the system model to estimate the overall risk and identify critical combinations of events.
- Having a clear understanding of how components interact is invaluable during an emergency when contemplating intervention and can help avoid unintended consequences. For example, a decision to hold releases at 150,000 cfs (within downstream channel capacity) to allow more time for downstream evacuations could have unforeseen negative consequences that would offset the apparent benefits. The delay in making releases exceeding channel capacity would create a steep ramping rate of flow increases after the hold was lifted which could increase the lethality to any populations not evacuated. Additionally, the net impact downstream could be a larger peak release for a given event and a wider inundated area. Exercising “what if” scenarios can help visualize the most likely path through the system interactions. Decisions related to FCO operations, especially decisions to increase releases above 150,000 cfs, could be difficult and will require balancing competing priorities and careful consideration of risk tradeoffs. These decisions will likely be made under stressful conditions, which further elevate the potential for human error. Decision makers must be comfortable making decisions in light of complexity, uncertainty and ambiguity, and should be aware of the potential outcomes of decisions that they are making.
- Not only does the Oroville Complex operate as a system, the system is larger than the Oroville Complex itself and includes downstream levees and the Thermalito Complex.
- The FCO is a critical component of the system. The reservoir water surface elevation under flood loading conditions is very sensitive to the available spillway release capacity. If the FCO cannot be operated to its full capacity, the AEP for higher reservoir elevations decreases, which increases the risk for many PFMs such as embankment internal erosion PFMs. In addition, the frequency of operating the Emergency Spillway

will increase. The Emergency Spillway has a unique set of vulnerabilities (e.g. erodibility) and consequences associated with operation. Investing in redundancy and increased maintenance for the FCO is an important qualitative system risk reduction measure.

- Use of the Emergency Spillway has impacts on the Hyatt Powerplant and the River Valve Outlet System (RVOS). Operation of the Emergency Spillway will increase tailwater elevations at the Powerplant and RVOS, because of an increase in the total flow in the Feather River channel. Erosion of the Emergency Spillway and deposition of material in the Feather River channel will likely increase tailwater further. Flooding of Hyatt Powerplant has significant non-life loss consequences in terms of financial and economic costs and could result in life loss consequences.
- Although the Thermalito Forebay Dam is not a structure associated with this L2RA, it is part of the Oroville Complex system, and it can be impacted by Oroville Dam releases.
- Human decisions, actions and inactions and the interaction of human and physical factors play an important role in the overall system performance and can influence the ultimate outcome. Key categories of human factors identified for the Oroville Complex included: normalization of deviance, impacts of large-scale regional incident, reservoir operation decision-making, information/communications, preparedness and resource availability, maintenance decisions, and human error in operations.

Areas of Uncertainty

There is uncertainty in all risk estimates; however, uncertainty is not explicitly portrayed on the L2RA matrix. Instead key sources of uncertainty are described with individual PFMs. The level of detail in a semi-quantitative risk analysis is insufficient to consistently quantify uncertainty and portraying a range of uncertainty using order of magnitude categories presents a challenge. In general, results of lower level risk analyses (screening level, FERC Level 2, etc.) are expected to have greater uncertainty than those coming from more detailed, quantitative risk analyses. Estimating uncertainty in a detailed quantitative risk analysis is commonly accomplished through the use of probability distribution functions, variable system response curves or fragility curves, and Monte Carlo risk simulations – tools that are not applicable to a semi-quantitative risk analysis approach.

References

FERC, 2016; Risk Informed Decision Making Guidelines

FERC, 2018; Periodic (Level 2) Risk Informed Decision Making Guidelines, version 1.0 (draft)

U.S Bureau of Reclamation and USACE, 2018; Best Practices in Dam and Levee Safety Risk Analysis.