Dam Safety Risk Analysis and Risk Management Practice at the Bureau of Reclamation: Lessons Learned from over Two Decades of Experience

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Abstract: The desire to more appropriately prioritize resources within U.S. Department of Interior (DOI) Bureau of Reclamation (Reclamation) and to better understand the risk posed by its dams to the public required Reclamation to move beyond a deterministic assessment of its dams. Risk assessment and risk management were viewed as a logical method to prioritize these resources for the most benefit to the public. Through research and development, Reclamation pioneered the application of risk assessment to its portfolio of 367 high hazard dams. Since the late 1990s, Reclamation has performed over 1300 quantitative and semi-quantitative risk analyses on its portfolio of dams. This paper discusses the evolution of risk analysis within Reclamation's dam safety program to its current state of practice, and some key ongoing initiatives. The focus is on the role of risk-informed decision making within the overall context of a dam safety risk management program.

1 Introduction

The National Dam Inspection Program, formed in 1972 after several prominent dam failures, authorized the U.S. Army Corps of Engineers to provide for a nationwide inspection and inventory of dams. The legislation defined what a dam was and directed inspection of dams that posed any threat to human life or property. It further directed determination of whether a dam constituted a danger to human life or property due to overtopping, seepage, settlement, erosion, sediment, cracking, earth movement, earthquakes, and failure of bulkheads, flashboard, gates on conduits, or other conditions. This legislation only briefly mentions risk, although nearly all the components of risk are discussed in the language. Up to that time, periodic operation and maintenance examinations were conducted on existing DOI Reclamation dams, with the primary goal of identifying obvious performance issues. However, the failure of several dams in the United States in the 1970s, including Reclamation's Teton Dam, led to the development of Reclamation's dam safety program and the Reclamation Safety of Dams Act in 1978. The Act authorized Reclamation's Dam Safety Program and allows for dams to be modified to preserve the safety of the dams when it is determined the structures are inadequate.

Following national legislation, a committee of federal agency representatives commissioned by the President developed the "Federal Guidelines for Dam Safety" (FEMA 93) in 1979 to promote prudent and reasonable dam safety practices among federal agencies. These guidelines recognized risk-based analyses as a new tool for dam safety. As stated in the guidelines:

> *Risk-based analytical techniques and methodologies are a relatively recent addition to the tools available for assessing dam safety. With further refinement and improvement, risk-based analyses will probably gain wider acceptance in the engineering profession and realize potential as a major aid to decision-making in the interest of public safety agencies should be encouraged to conduct research to refine and improve the techniques and to develop the methodologies and base of expertise necessary to apply them to dam safety evaluations. On existing dams, a risk-based analysis should be considered in establishing priorities for examining and rehabilitating the dams, or for improving their safety. The agencies should individually and cooperatively support research and development of risk-based analysis and methodologies as related to the safety of dams. This research should be directed specifically to the fields of hydrology, earthquake hazard and the potential for dam failure. Existing agency work in these fields should be continued and expanded more specifically into developing risk concepts useful in evaluating safety issues.*

In response to the Teton Dam failure, the 1978 Act, and the 1979 Federal Guidelines, Reclamation established procedures to assess the safety of its structures. The early emphasis tended towards earthquake and flood concerns, rather than normal operating condition or static loading issues. The engineering approach at the time was focused on deterministic, not probabilistic, evaluations.

In 1979 Reclamation began the Safety Evaluation of Existing Dams, or SEED, program. Teams of engineers spent 10-12 weeks inspecting dams and writing SEED reports that discussed the design and construction details, foundation conditions, loadings, observed performance, and they provided recommendations to address potential deficiencies. Typical recommendations involved conducting deterministic studies and documenting static

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stability. If the SEED reports concluded there could be a dam safety deficiency, based on the deterministic studies, a Modification Decision Analysis (MDA) study was conducted. MDA studies involved more detailed engineering analyses and provided the basis for decision-making regarding modifying a dam to address deficiencies. MDA briefings to upper management of the organization resulted in Decision Memoranda to use dam safety program funding to address the dam safety deficiencies. These early modifications were often related to seismic performance during the Maximum Credible Earthquake (MCE), hydrologic inadequacies during the Probable Maximum Flood (PMF) and static instability concerns where analyses indicated the required minimum factors of safety were not achieved. There was no formal prioritization process – projects were advanced through the SEED, MDA and modification phases as the engineering studies were completed and MDA Decision Memoranda were approved. The SEED and MDA processes continued until the mid-1990s.

2 Transition to Risk Assessment

Through the 1980s, there were some early risk analysis efforts initiated under the guidance of Larry Von Thun. Von Thun authored a key whitepaper that studied causes of dam incidents and failures and evaluated statistical data and trends that could be used to inform dam safety decisions (Reclamation 1985). Risk concepts were explored and developed, and training was provided to staff, but no formal risk methodologies or risk guidelines existed. Risk was not part of the SEED/MDA decision making process, although risk-based decision analysis reports were prepared for several dams. The risk analyses of these dams compared the total cost (construction cost plus risk cost, also called economic risk) for different alternatives to reduce dam safety risk. Life loss risk was not part of the risk evaluation in these early studies. The economic risk concept continued to be applied on a few dams through the early 1990s to determine justifiable levels of modification, particularly related to economic damages from deterministic PMF floods. Progress on dam safety risk was generally limited because there was little precedent and few practical published methodologies for use. With the apparent success of the SEED and MDA processes (i.e. dam safety was being evaluated and those dams with deficiencies were being modified) the advancement of risk-based analytical tools that was called for in the 1979 Federal Guidelines stalled.

Between 1993 and 1995, Reclamation began cooperating and sharing risk concepts with BC Hydro. Similarly, BC Hydro shared risk concepts that Australia was developing. One of the key concepts that came from this international cooperation was the notion of using life loss risk as a measure of dam safety risk, rather than economic or cost risk. These discussions re-energized efforts at Reclamation to push forward risk analysis as a tool for managing the dam safety program.

In current practice, potential failure modes (PFMs) form the basic units of meaning in a dam safety risk analysis (see, e.g., Galic 2017). Although the topic had been introduced as part of several dam safety projects in the 1970s and 1980s, it was not until 1995 when potential failure modes analysis, and shortly thereafter risk analysis, became a standard part of all dam safety evaluations at Reclamation. The SEED report process was eventually replaced by the Comprehensive Facility Review (CFR) process. CFRs were performed on a 6-year cycle (recently changed to an 8-year cycle) and involved three separately written reports for each dam; (1) Examination Report, (2) Performance Parameters Report, and (3) Report of Findings. With the Performance Parameter evaluations, there was an increased emphasis on seepage and internal erosion concerns, which was a shift from the deterministic stability, seismic and hydrologic concerns of the 1980s. By 1997 Reclamation had published its first risk guidelines document (Reclamation 1997) and risks were being quantified in CFR reports. For a given PFM, risk was defined as the probability of adverse consequences, and measured in two ways: annualized failure probability (AFP) and annualized life loss (ALL), where:

1. AFP = *(probability of load)* x *(probability of failure given load)*
2. ALL = (AFP) x *(life loss consequences given that a failure occurs)*

The risk threshold values described in Reclamation's 1997 guidelines included an annualized failure probability value of 1 in 10,000, and an annualized life loss value of 1 in 1000, applicable to each individual facility. These values were consistent with guidance that other international organizations had implemented to manage dam safety risk and continue to be used by Reclamation today. As shown on Figure 1, risk estimates are plotted logarithmically to facilitate their comparison to the guideline values. The preferred plotting style evolved over time, and today Reclamation uses the so called fN ("little f-n") chart to display risks. The standard fN chart includes a vertical AFP (f) axis, a horizontal life loss (N) axis, and a series of diagonal ALL contours. The points plotted on the chart represent the AFP-life loss coordinates of the individual PFMs, and the AFP-ALL coordinates of the total (summed) risk estimate are also shown. Reclamation has found that the fN format provides a summary of the results of a risk analysis and serves as a convenient visual aid for decision makers (see Galic 2018 for additional considerations).

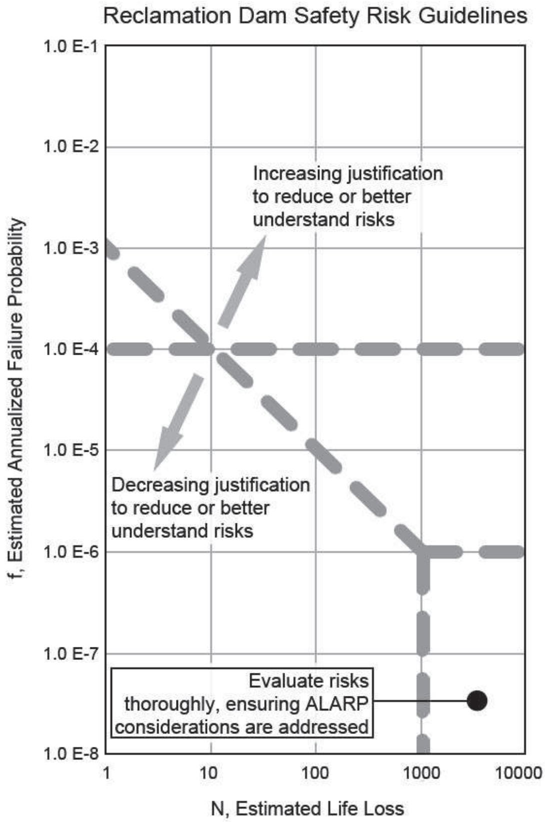

Figure 1. Reclamation fN Chart.

At about the same time dam safety evaluations transitioned from the SEED and MDA to the CFR, Issue Evaluation and Corrective Action Study (CAS) processes, there were other organizational changes within Reclamation that transformed the enterprise structure and delegated new responsibilities. In 1994 the Technical Service Center (TSC) was formed, which separated the dam safety program from those performing the engineering analysis and design related work. Dam safety decision-making authority was delegated to the "triad" of Regional Director, Area Manager, and Dam Safety Office Chief. A peer-review quality control process was implemented within the TSC, eliminating technical reviews of analyses and designs by the organizational upper management. In response to these changes, a Dam Safety Advisory Team (DSAT) was formed in 1995 that consisted of senior technical experts who advised the dam safety program on technical issues and decisions. The DSAT evolved over time and continues to play an important role in advising the dam safety program.

The need for more widespread application of risk analysis as a tool to evaluate dam safety drove the need for consistency in its application and more training of staff whose experience was in deterministic methods. In response to these needs, a group of five senior technical staff with extensive experience in dam design, designated the Reclamation "Risk Cadre", was formed in 1998 and tasked with the development and documentation of risk procedures and methodology. Risk methodologies were documented in the form of "toolboxes" – relatively brief and practical documents that provided information on how to apply risk concepts to evaluate dam safety. Through on-the-job training and continued exposure to risk analyses, staff transitioned into risk-based processes and procedures. Risk analyses did not replace engineering evaluations; the engineering evaluations and engineering judgments became key inputs into the risk analyses.

Construction of major dam safety modifications continued through the 1990s on dams where modification decisions had been made prior to the introduction of risk analysis. By 2000, however, most dam safety modification construction projects followed the recently established risk analysis and risk-informed decision-making processes. Deterministic studies were de-emphasized in identifying dam safety deficiencies, and probabilistic approaches became standard. Risk methodologies were developed, risk guidelines were in place, and decision-makers had a senior group of technical advisors to help them with dam safety decisions.

3 Current Portfolio and Management Approach

3.1 General process

Since 1997, Reclamation has been well-positioned to manage its portfolio of 367 high and significant hazard dams using risk-informed decision making. With the Comprehensive Review (CR, formerly CFR) process in place, engineers apply standardized risk assessment methodologies to analyze risks and compare them to guidelines. A multi-agency training manual (https://www.usbr.gov/ssle/damsafety/risk/methodology.html) was jointly developed with the U.S. Army Corps of Engineers and describes techniques and procedures currently considered to represent the "Best Practices" for estimating dam safety risks. Updates to these "Best Practices" are implemented as significant improvements are developed. From the outset, Reclamation recognized that procedures and data available for dam safety risk analysis, while quantitative, do not provide precise numerical results. This manual strives to present useful information, tools, and techniques, while stopping short of a "cookbook" approach. This allows the risk analyst(s) to use the proper balance of engineering judgment and calculations in estimating risks, and to understand and "build the case" for what influences the risk values the most. The final risk values, while important, are less important than understanding and documenting what the major risk contributors are and why.

The risk guideline values (risk threshold values for annualized failure probability of 1/10,000 and annualized life loss of 1/1000) provide a framework for technical teams and DSAT members to advise decision-makers if additional actions are justified and recommended to reduce or better define risk. If a decision is made at the CR level to take additional action to better define risk, an Issue Evaluation study is performed based on the specific potential failure mode (or modes) of concern, which might include installing additional instrumentation or monitoring; performing field investigations, laboratory testing, and engineering analyses to better evaluate the structure's performance; performing inundation and life loss evaluations to better define consequences; and conducting a more detailed team risk analysis. Once risks have been better defined, with reduced uncertainty and improved confidence, risk estimates are again compared to risk guidelines and the technical team and DSAT advise decision-makers if there is a need to perform corrective action to reduce risk. If there is justification to reduce risk, the project advances through the CAS phase where different structural and non-structural risk reduction alternatives are evaluated. If a decision is made to structurally modify the dam, a preferred alternative is selected, a Dam Safety Modification report is written by Reclamation and approved by Congress, and the project advances through the final design phase and into construction. After construction is complete, risk reduction is verified through a post-construction risk assessment and risk management continues through the established monitoring and periodic inspection and review (i.e., CR) processes.

3.2 Evolution of prioritization

As risk estimates were developed and refined for more dams, projects with the highest risk were given priority to advance through the Issue Evaluation and CAS phases. In the early years of using risk values to prioritize projects, some regional offices believed the safety of dams in their regions was being sacrificed as dams in other regions were receiving a greater proportion of the limited funding because those dams had higher risk. Attempts were made to balance dam safety funding across the regions so that the highest risk dams in each region were being addressed through Issue Evaluations, CAS, and modifications if necessary.

Prioritization continued to be based on the risk estimates through the 2000s, and concerns over balancing regional funding diminished as the regions gained an appreciation of the need to lower overall agency risk. Risk was tracked for all dams and priorities were revisited periodically throughout each year. At the same time, some issues were developing that made it more difficult for decision makers to apply consistency to risk-informed decisions. First, it became evident that in some cases the fN chart threshold values were being treated as decision criteria, rather than as risk-informative guidelines. On some projects, risks just above the guideline values were being treated much differently than risks just below the guideline values on other projects. At times, it appeared Reclamation would fall into the risk "trap" of allowing the guidelines to become the decision makers and disregarding the fact that risk estimates are not and were never intended to be precise numbers. Reclamation was striving to achieve consistency in risk estimates through methodology and review; however, complete consistency cannot be expected with the risk estimates.

In 2011, Reclamation added the Dam Safety Priority Rating (DSPR) to the Public Protection Guidelines (Reclamation 2011). The five-level DSPR system was established to prioritize and establish the urgency of risk management activities, without as much reliance on the numerical value of the risk estimate. Greater emphasis was placed on "building the case" for the level of risk, the DSPR, and the recommended actions. The DSPR system, which integrates different levels of urgency, response actions, and confidence in the risk estimates, has facilitated greater consistency in decision making and better overall program prioritization.

Significant incidents within Reclamation's inventory continue to receive high priority such as those relatively recent incidents at Deer Flat Dam, AV Watkins Dam and Red Willow Dam. Today, Reclamation continues to focus on the highest priority dams based on the DSPR, risk estimates, and the case that has been built. However, it is recognized that external factors can also influence prioritization of risk reduction activities. For example, environmental studies or field investigation activities related to design of proposed dam safety modifications on a higher priority dam might take years to complete; allowing work on other lower priority dam modifications (with fewer significant external factors) to move forward more quickly. In these cases, interim risk reduction actions such as reservoir restrictions can help lower the threat of an uncontrolled release for the higher risk dams until more permanent risk reduction modifications can be completed.

3.3 Decisions to take action

When estimated risks are at a level where there is justification to reduce or better define risks, there is much discussion on what exactly the appropriate actions should be, and how much effort in terms of time and resources should be spent on the actions. The fact that risk-informed decision making generates these detailed discussions is one of the most important outcomes of incorporating risk into Reclamation's dam safety program. Typically, decisions informed by the results of CR-level and most Issue Evaluation risk analyses are focused on how to better define risks. Any or all of the components of risk (loading, structural response to loading, and life loss consequences) can be targeted for better definition. The risk analysis process identifies those areas where there is significant uncertainty and may help guide where additional data collection is needed. Sensitivity studies are used to bring focus to potential outcomes after additional information is obtained.

Confidence in the risk estimates plays a major role in deciding what actions should be taken. Facilities with high estimated risks, but low confidence in the risks, typically involve decisions to better define risks through data collection (related to the key components of risk uncertainty) and re-analyze the risks once the new information becomes available. Decisions on facilities with high risks and high confidence are typically focused on reducing risk because spending additional time and money studying the risks is not likely to change the decision. Facilities with low risk and low confidence in the risks may or may not result in decisions to take action to better define the risks – depending on all the site-specific factors. The ultimate goal of the dam safety program is for each dam to have low risk with high confidence, where generally no decisions to take action are needed, or where actions might include low cost prudent actions that will better define or reduce the risk.

3.4 How many risk analyses?

Reclamation has performed quantitative CR-level risk analysis on each of its high and significant hazard dams, as part of the CR process that has been in place since the mid-1990s. With an initial CR cycle frequency of six years (changed to eight years in 2013), most dams have been through three cycles of quantitative CR-level risk analysis, which is about 1000 risk analyses at the CR level.

When there is justification to better define risks based on the CR-level risk analysis, more detailed Issue Evaluation studies are performed. Reclamation has performed Issue Evaluation risk analyses on about 142 dams, which is 38% of its portfolio. In many cases, several rounds of Issue Evaluation level risk analyses are performed, with decisions made after each round of risk analyses regarding justification to take further action to better define risks, and on what types of additional information can be obtained to reduce uncertainty and increase confidence in the risk estimates. For some dams multiple Issue Evaluations have been performed to address different potential failure modes at different times. In total, Reclamation has completed over 230 Issue Evaluation level risk analyses over the past 20 years.

When the decision is made to perform Corrective Action Studies to reduce risk at a dam, the studies involve estimating how much the risk could be reduced by implementing a variety of structural and non-structural risk reduction alternatives. There are two phases of risk reduction studies, and sometimes more depending on the information available and the types of potential failure modes being addressed. Reclamation has performed risk analyses to support CAS on about 60 dams, with two or more phases of risk analyses performed for each dam, resulting in over 120 CAS-level risk reduction analyses.

Over the past 20 years Reclamation has completed over 1300 risk analyses on its inventory of 367 high and significant hazard dams. Lessons learned from each risk analysis allow Reclamation to improve the understanding of dam safety risk, and ultimately make better organizational decisions for dam safety.

3.5 Dam modifications

Eighty dam safety modifications have been completed under the authorization of the Reclamation Safety of Dams Act. The language of the act states that funds are authorized for dam modifications needed for "new hydrologic or seismic data or changes in the state-of-the-art criteria." With about half of Reclamation's dams built before 1950, and about 90% of the dams built before current design and construction practices, many dams do not have the typical redundant design features that are part of today's state-of-the-art designs. Dam modifications to address changes in the state-of-the-art include reducing risks related to dam foundation concerns (due to lack of foundation treatment during construction), seepage and internal erosion concerns (due to lack of seepage collection and control features), and other similar current practice considerations.

Table 1 below provides some insight into how the types of dam safety issues being addressed through dam safety modifications have changed over time. The table only represents studies that culminated in a dam safety modification, not other dam safety studies.

Table 1. Summary of Dam Safety Modifications 1980s to 2015.

Year Range	Hydrologic Issues	Seismic Issues	State-of-the-Art Issues	Percentage of Dams with Multiple Issues
1980s (deterministic)	50%	15%	35%	18%
1990s (transition)	30%	34%	36%	50%
2000-2015 (risk-informed)	16%	37%	47%	23%

Most dam safety deficiencies identified in the 1980s were related to hydrologic concerns. From a deterministic perspective, it was relatively easy to evaluate whether deterministic hydrologic criteria were satisfied based on new hydrologic data. Therefore, about half of the dam modifications during this period included modifications to address hydrologic deficiencies. Identified seismic deficiencies were less prevalent partly due to the lack of understanding of seismic loadings and the lack of understanding of how to realistically predict structural behavior of dams subject to seismic shaking.

During the transition period of the 1990s, a smaller percentage of dams were modified for hydrologic issues, in part because the dams with the greatest hydrologic deficiencies had been modified, and because risk analysis of dams indicated that it was not efficient to spend limited funding reducing risk for very large, but very remote flood events. The 1990s also saw a sharp increase in the percentage of dams modified for seismic deficiencies. Academic research in all aspects of seismic issues increased significantly, and published guidance became more widely available. In addition, analysis techniques improved greatly because of the widespread availability of powerful desktop computers. A general awareness of faults and the highly seismic environment of the western United States, along with concerns about how quickly weak dam foundation soils subject to seismic shaking could lose strength, resulted in significant seismic concerns from both deterministic and probabilistic perspectives. Unlike the hydrologic deficiencies identified in the 1980s that were mostly associated with large, remote events, a number of Reclamation's dams were judged to have high risk even for small to mid-sized seismic events that were not very remote.

The percentage of dams modified for state-of-the-art deficiencies increased in the risk-informed period after 2000, due to the focus on performance parameters and concerns about potential failure modes that could develop at any time during normal operations. Almost half of the dams modified during this period included modifications to address state-of-the-art concerns.

In the 1990s, half of the dams that were modified included modifications to address multiple dam safety deficiencies. With the decreased emphasis on deterministic evaluations during this time period, engineers became more aware of state-of-the-art related potential failure modes such as internal erosion. Since many of the dams modified during this time period were older dams, not only did they have seismic or hydrologic deficiencies, but it was relatively easy to identify state-of-the-art deficiencies as well. Once the decision was made to perform corrective action on a dam, it was common to take a more detailed look at all dam safety aspects in addition to the concern initially driving the risk. By doing this, some efficiency was gained by not having to do separate dam safety modifications at different times – the team would simply identify all the deficiencies and design one modification that could lower the risk for all of the key potential failure modes.

4 Retrospective

The 1990s saw Reclamation transition from an organization focused on modifying dams based on deterministic deficiencies (while somewhat experimenting in risk) to an organization fully engaged in the practice of risk-informed decision making. Risk-informed decision making continues to evolve due to several factors: (1) risk analysis methodology and our understanding of dam performance and structural response to loadings continues to improve; (2) our understanding of the potential for, and magnitude of, seismic and hydrologic loadings continues to change; (3) the physical performance of some dams changes over time as the structures continue to age, and; (4) the populations at risk downstream of some dams are increasing.

Adopting a probabilistic, risk-informed approach to dam safety, after many years or decades of deterministic approaches, did not occur seamlessly or easily within Reclamation (Engemoen et al. 2015). In some respects, the frame of reference used in traditional engineering analyses slows the transition to risk-informed concepts. That transition involves a cultural change to the way the organization and staff approach dam safety evaluations and decisions. Assigning an actual number (or rather a range of numbers) to the likelihood of an event is predicting a future occurrence, and, there is a natural reluctance to apply this kind of approach. There is little question that a fundamental grounding in the evaluation of potential failure modes helps usher the cultural change to risk-informed thinking, improves the organization's understanding of structural performance, and improves the overall safety of the dams each agency is responsible for. Emphasizing the importance of thinking about how a given dam might fail facilitates a transition toward a probabilistic approach, with the reliance on factors of safety and deterministic loads such as the MCE or PMF set aside, and expanded thought given to other failure mechanisms or loadings that are more critical to performance than extreme (but rare) events. Teams are encouraged to focus on many specifics such as probable initiation location, possible weak links, likelihood of available freeboard, indications of distress and their significance, and many other variables that must combine to lead to failure. By considering the many aspects that would need to contribute to a failure, teams become more aware of the likely and unlikely factors that help determine whether a potential failure mode is likely to lead to an actual dam failure.

In retrospect, the transition to risk-informed decision making was facilitated by constantly reminding risk teams that it is unreasonable to expect that a probability of failure estimated during a quantitative risk analysis be an accurate number with a high level of precision. Reclamation focuses more critically on the balanced case made to support decisions than on the validity of the risk estimates alone. The most helpful outcome from a risk analysis is the improved understanding of a dam's strengths and vulnerabilities that results from the detailed look at the potential failure modes that may apply. It is this enhanced understanding of a dam's potential for adverse performance that greatly aids the understanding of dam safety risks, and helps target additional explorations, studies, and monitoring to best ensure a thoughtful and prudent continued operation of each dam. Emphasizing and re-emphasizing this benefit can also help individuals and teams get comfortable with risk analysis and see the value in the process.

5 Ongoing and Future Initiatives

For over two decades, Reclamation has played an active part in the development of risk analysis methodology and practice. Consistent with its leadership role, Reclamation continues to invest in outreach, support for other agencies, and research on topics of emerging interest. The current incarnation of the Reclamation risk cadre serves as a locus for many of these efforts and forms a vital link between the technical and programmatic branches of the organization, each of which actively contributes to the body of knowledge. As part of its scope, the risk cadre is currently pursuing initiatives intended to develop and expand the methodology for specific subject areas including: (1) guidance for risk management of non-failure (incident type) events, including the application of the ALARP (as low as reasonably practicable) concept to these risks (see Galic and Rocha 2019); (2) guidance for construction risk analysis, and; (3) the use of risk-informed design concepts, which if properly applied can be used to help avoid disproportionate expenditure for loading conditions that do not control the risk. The results of these studies will be incorporated into the next revision of Reclamation's public protection guidelines. Much has changed since the last revision, and both the industry and Reclamation continue to evolve as societal priorities change and as new dam safety threats are identified.

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