RISK ANALYSIS FOR DAM SAFETY EVALUATION:

HYDROLOGIC RISK

By

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This report was initiated under the U.S. Army Corps of Engineers' Dam Safety Research Program. The report was prepared to fulfill part of several work units in the research program. These work units focused on outlining dam safety standards, developing risk and uncertainty concepts, and specifically studying aspects of risks of failure involving dams and spillways constructed by the Corps.

The purpose of this research project was to demonstrate the application of quantitative risk assessment techniques to hydrologic risk of dam safety analysis. A review of traditional and alternative methodologies is given, as is a discussion of some basic risk analysis concepts, tools, and techniques. The report proposes a method for analyzing hydrologic risk in application to dam safety, and demonstrates through use of a sample analysis. The report should be viewed as an investigation into the application of risk analysis techniques to dam safety analysis. This report is not intended as guidance for performing dam safety analysis. Furthermore, it is not suggestive of using risk analysis in place of traditional methods of analysis, rather it does suggest that risk analysis and the products thereof provide additional information and serve as an aid in the decision making process.

The report consists of five chapters, a bibliography, and two appendices. The chapters provide background information on the evolution of dam safety analysis, a general framework of quantitative assessment of dam safety, and a sample analysis demonstrating how such an analysis is performed. The first appendix is an annotated bibliography of relevant research in the field, while the second appendix technically describes the model used in the sample analysis.

This report was prepared by Jery Stedinger, David C. Heath, and Kay Thompson of Cornell University under terms of a contract with the U.S. Army Corps of Engineers Institute for Water Resources. Dr. Eugene Z. Stakhiv was the initial contract manager for the report and was succeeded by Dr. David A. Moser of the Technical Analysis and Research Division and program manager of the Risk Analysis for Water Resources Investments Program. The Chief of the Technical Analysis and Research Division is Mr. Michael R. Krouse and the Director of IWR is Mr. Kyle Schilling. Mr. Robert Daniel, Chief of Economics and Social Analysis Branch, Planning Division, HQUSACE, Mr. Earl Eiker, Chief of Hydrology and Hydraulics Branch, Engineering Division, HQUSACE, and Mr. James Crews, HQUSACE, served as technical monitors for the research program. Numerous field reviewers provided valuable insights and suggestions to improve early drafts.

Presently, based on historical and methodological development, the safety standard for high hazard dams is the Probable Maximum Flood (PMF). The PMF is assumed to provide, in effect, a “zero-risk” of failure, thereby ensuring the safety of downstream populations. This gauge of maximum flood is principally based upon the conservative application of the Probable Maximum Precipitation (PMP); an estimate of the maximum possible precipitation depth over a given catchment in a given length of time. It is calculated by maximizing the moisture of a given storm in relation to the specified catchment over the duration of the event and the affected area, based upon historical record. However, the PMF design standard has been questioned for two reasons. One, estimates of the PMF have changed over time as data is collected. This change in the PMF estimates detracts from its conceptual premise that a design meeting this standard yields one of zero risk. Second, the PMF standard does not allow for any trade-off among costs, economic benefits, and risk.

Budgetary concerns relating to large dam retrofit decisions in the U.S. have created a demand for justifying scarce appropriations. This has resulted in greater interest in risk-based analyses and possibly has caused an easing of standards. Recently, risk-based procedures have been encouraged for retrofit decisions when a structure has not passed the latest PMF estimate, but still might be deemed safe enough, or used to evaluate whether the cost of upgrading to full PMF is justified. The debate is not over safety, rather it is concerned with the best allocation of the Nation’s scarce resources. Risk-based analysis has been proposed as both an alternative and a complement to the PMF analysis and design standard. However, traditional risk-based methodologies have difficulty in application to this problem stemming from the possibility of low risk catastrophic events. A project solely designed on risk-based analysis invites the possibility of a catastrophic failure at a low risk. Furthermore, the reliance on expected value calculations in traditional risk-based analysis inherently depreciates the importance of catastrophic losses through its means of computation. Consequently, research continues on developing risk-based decision variables that adequately account for the catastrophic consequences of failure.

This research contributes to the evolution of risk-based dam safety assessment methods by illustrating how dam safety risk assessment analysis might be improved by employing more detailed stochastic descriptions of the rainfall and runoff processes, and improving the performance of warning systems, dams, and other structures. The products of a stochastic analysis, such as that explored, will provide further insights into the complexities of dam safety problems than traditional deterministic methods alone. These products include the pathways to failure and their associated relative likelihoods, overall failure probabilities, and the trade-offs between safety and costs. Using a detailed stochastic analyses will give decision-makers more information about the implications of adopting alternative solutions to dam safety problems, thus ameliorating the evaluation process.

The report develops and illustrates the concepts needed to perform a thorough probabilistic analysis of the dam safety issue, including the calculation of the probability of dam failure and the distributions for dollar damages and loss-of-life as a result of the combinations of the many factors that result in large releases from a dam, and possibly as a result of actual structural+ failure. Such an enterprise is both complicated and controversial as it requires that probability distributions or particular values be assigned to meteorological and hydrologic variables, the status and performance of the structure, and the response and impact of releases from the dam on human populations and their possessions. Quantitative risk assessment such as this described is based upon the premise that man-made systems can fail. Thus, it suggests that in times of scarce resources, engineering analyses should consider how to reduce the costs and consequences of failure in balance with the cost of such efforts. However, the analysis is not advocating the use of risk analysis in lieu of traditional design standard analysis. Rather, it proposes the use of quantitative risk analysis as a complement to current design standard analysis. Using quantitative risk analysis as an aid or tool in the decision making process, or as an integral component of traditional design standards, gives decision-makers more information about the implications of adopting alternative solutions to dam safety problems, and should aid in the evaluation of alternatives.

List of Figures

List of Tables

CHAPTER 1 - INTRODUCTION

Selecting appropriate and reasonable design safety standards for high-hazard dams in the United States has posed a dilemma for the U.S. water resources engineering community. The failure of a large structure built by the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, or the Tennessee Valley Authority due to extraordinary floods would result in the loss of an expensive structure, the services it provides, and would, in many cases, cause immense economic costs and loss-of-life associated with the flood which would pass downstream. The emergency spillway of such a structure and the flood storage zone should be sized to survive a theoretical flood of a certain magnitude, providing both a reasonable level of safety and an acceptable compromise between construction costs and the possible consequences of dam failure. The modern challenge is to quantify the costs of construction, the damage resulting from major floods, and the probability that floods of different magnitudes might occur, so that the trade-off between the costs of construction, operation and maintenance, possible damage due to failures, the benefits of flood damage prevention, and other services of the dam can be evaluated quantitatively.

Chapter 1 of this report provides a general overview of the evolution of dam safety standards and the relative merits of three different approaches. This discussion is supplemented by the annotated bibliography in Appendix A. Chapter 2 develops a general framework for quantitative probabilistic assessment of dam safety issues using an event diagram paradigm. The paradigm describes the interaction of the various factors which contribute to the determination of the inflow flood, a reservoir's operation, and downstream damage. It also serves as the foundation for the specialized Monte Carlo procedure used to calculate the probabilities of various failure events, the distribution of damage, and loss-of-life. Chapter 3 discusses methods suggested in general risk literature and water resources literature to display and communicate the results of risk studies. The ideas of frequency, annual probability, expected damage, and partial expected damage are developed, the Partitioned Multi-objective Risk Method (PMRM) is discussed, and a simple example is used to illustrate the ideas. A stochastic dam safety analysis is presented in Chapter 4 to show how the many factors that contribute to the inflow hydrograph and the performance of control structures can be incorporated into risk analysis. It also illustrates the use of criteria developed in Chapter 3. Going through the steps necessary to develop a stochastic dam safety analysis prototype provides experience useful for identifying what additional factors need to be researched, how an operational model might work, what it should include, and how useful probabilistic results might ultimately be.

Background and Alternative Methodologies

At the turn of the century, the selection of design inflow floods for dams using the *flood-of-record* and *flood frequency* methods were found to be unsatisfactory; available records could not be trusted to reveal the possible severity of the unusual and intense meteorological events that cause the extraordinary floods which are of concern [Myers, 1967]. At the other end of the scale, flood-frequency techniques have been successful for traditional floodplain mapping and the design of levees, bridges, roads, and traditional flood-control structures [Feldman, 1981]. These structures are designed to meet less severe standards than high-hazard dams.

In the 1930s, the storm transposition approach was developed for estimating a spillway's design flood from the worst rainfall observed in a region, transposed to the reservoir's catchment. For high-hazard dams, the safety standard has become the Probable Maximum Flood (PMF), which is derived by conservative application (in terms of antecedent moisture, streamflow, snowpack, storm placement, and the time distribution of rainfall within the storm) of the Probable Maximum Precipitation (PMP). The PMP is an estimate of the maximum possible precipitation depth over a given size catchment in a given length of time. It is calculated by maximizing the moisture in the worst storms of record, the transposition of those storms to the catchment (adjusting for maximum moisture, and barrier and terrain effects), and finally the use of an envelope curve over the duration and area to define a maximum possible precipitation for the duration and drainage size of interest [Myers, 1967; Stallings et al., 1986].

Budgetary concerns relating to large dam retrofit decisions in the U.S. have created a demand for justifying scarce appropriations; this has resulted in greater interest in risk-based analyses and possibly has caused an easing of standards [Krouse, 1986]. Recently, a National Research Council committee reviewed the standards and methods for dam safety evaluation [NRC, 1985]. Risk-based procedures have been encouraged for retrofit decisions when a structure has not passed the latest PMF estimate, but still might be deemed safe enough, or to evaluate if the cost of upgrading to the full PMF is justified. Von Thun [1987] discusses the U.S. Bureau of Reclamation's dam-safety risk-evaluation methodology, which incorporates this idea, and illustrates the calculation of “risk costs.” Two conferences in 1985 addressed dam safety and risk assessment [McCann, 1986; and Haimes and Stakhiv, 1986; also see Bowles, 1987, and Moser and Stakhiv, 1987]. Appendix A reviews many of these papers and other published studies. Terry Coomes [McCann, 1986, p. 4-4] has put the question clearly: “The debate is over money and the best allocation of the Nation's resources.”

The general application of risk assessment to dam safety evaluation will require estimation of the frequency of very unusual and extreme events on the order of the PMF. One approach is to assign the PMF an exceedance probability from 10^{-4} to as little as 10^{-6}, and then to extend a flood-flow frequency curve from the 100-year flood out to the PMF. The results depend on the probabilities used and the method of extension employed. Stedinger and Grygier [1985], Haimes et al. [1988], and Karlsson and Haimes [1989] show that the selection of a distribution can affect the ranking of retrofit alternatives.

An alternative approach is to attempt to estimate the frequency of large storms and floods using regional storm data. Such an analysis is described by Yankee Atomic Electric Company [YAEC, 1984], which estimated the probability that the Harriman Dam in Vermont would be overtopped by a flood. A 1988 NRC Committee on Techniques for Estimating Probabilities of Extreme Floods recommended several approaches to increase the available data pool and ways to focus on extreme flood and rainfall events [NRC, 1988]. Foufoula-Georgiou [1989] illustrate the derivation of the exceedance probabilities of extraordinary precipitation depths for two catchments in Iowa.

Langseth and Perkins [1983] demonstrate risk-analysis procedures for dam safety evaluations. Following the 1985 NRC Committee's charge to develop dam safety criteria, Stedinger and Grygier [1985], Von Thun [1987], Resendiz-Carillo and Lave [1987], Haimes et al. [1988] and Petrakian et al. [1989] illustrate such procedures and discuss issues that arise. The Bureau of Reclamation [1986], Stakhiv and Moser [1986], and the Task Committee on Spillway Design Flood Selection [1988] provide examples of more comprehensive risk-analysis methodologies. Bohnenblust and Vanmarcke [1982], Kreuzer and Bury [1984], McCann et al. [1985], Bury and Kreuzer [1986], and Bowles [1987] employ risk-analysis methodologies which include a variety of possible causes for dam failures, including piping, structural, and earthquakes.

Dam safety issues often fall into two categories:

1) setting safety standards for proposed dams

2) deciding whether existing structures provide adequate levels of safety, and if not what modifications are justified.

The 1985 NRC Committee [NRC, 1985] suggests that decision-makers need not apply the same safety criteria to both categories and recognizes three major approaches to setting dam safety standards:

1) The deterministic probable-maximum-precipitation/probable-maximum-flood standard which requires that all new and existing high-hazard structures be able to survive their estimated PMF.

2) The probabilistic approach which prescribes that a structure's probability of failure not exceed some standard for a particular failure mode or set of failure modes. A prescribed failure probability would then correspond to a flood with that exceedance probability. The American Nuclear Society [1981] has used 10^{-6} as a safety target for hydrologic events. Many states use a 1,000-year event as a design standard for small, low-hazard dams.

3) Quantitative risk-analysis procedures which attempt to quantify both the probabilities of extreme hydrologic events and the consequences and incremental damage from the passage of those floods, including incremental damage from dam failure. Risk analysis for an existing structure attempts to find a reasonable balance between safety improvement costs and the resulting decrease in flood damage and losses.

Comparing the approaches for addressing dam safety problems is facilitated by considering different criteria. In particular, this report will consider:

a) the potential quality of the results relating to their economic or social efficiency and stability over time,
b) practical considerations, including the complexity of the analysis and the availability of required inputs, and
c) the procedure's acceptance by the engineering community and the public.

The Potential Quality of Results

Of concern is the stability of a method's solutions over time with the accumulation of new data, and the duration of the solutions over the life of the structure. Because of the lack of long-term flood records available in practice, all three methods suffer some stability problems. Past experience has shown that PMF estimates can increase significantly over the life of a dam, necessitating (expensive) retrofits. Experience has also shown that difficulties exist in applying the flood-frequency approach. Short historical records yield imprecise estimates of probability distributions for floods. The instability of solutions in the risk-analysis method could result from changes in the population and property values downstream from the dam, as well as changes in the estimated flood-frequency curve for extreme events.

Every dam safety decision is an implicit decision about the allocation of resources in the society. Money spent building a new dam or upgrading an existing one leaves less money for other socially beneficial projects. This trade-off is especially evident when an agency has limited funds to improve dam safety. In this case, the agency may want to maximize the benefit of available money by using those funds efficiently. Neither the deterministic method nor the probabilistic method really attempts to efficiently allocate resources in the dam retrofit situation.

In the case of the deterministic approach, estimating the magnitude of the PMF often leaves engineers with little knowledge of the PMF's quantitative probability. Dam safety guidelines designed to meet their respective PMF estimates certainly vary. Using the flood-frequency approach is an attempt to make the probability of failure more uniform across sites, but it still causes inefficient allocation of resources by not accounting for the fact that the costs of failure (in terms of lives lost and dollar and environmental damages) vary from project to project. The deterministic and flood-frequency methodologies do attempt to deal with this last issue by incorporating crude classification systems which, for example, categorize dams as high, medium, or low hazard; these approaches, however, fail to address the issue with any precision. A given budget allocation could result in a lower probability of risk by explicitly acknowledging the probabilities and consequences of floods and failures and allocating funds as efficiently as available cost and damage data allows.

In contrast to the deterministic and flood-frequency methods, the risk-analysis approach directly addresses the resource allocation issue. This approach provides a more site-specific analysis than the deterministic and flood-frequency approaches by incorporating pertinent damage information. Analysts can use estimated damage probabilities to minimize the expected cost to society with a given budget. Of the three methods, only risk analysis provides an estimate of the cost effectiveness of an allocation or combination of allocations. By balancing costs and losses and their probabilities, risk analysis provides a method for estimating the optimal allocation of resources. But the analyst does pay a price for the ability to achieve greater efficiency by way of added complexity.

Practical Considerations and Complexity of the Analyses

When choosing a method to apply to dam safety problems, engineers should consider the complexity of the analytical methods and the resources needed to conduct a study. The best method should reflect a trade-off between the quality of the results, the time the analysis requires, the staff resources and managerial effort required, and the cost of the analysis.

The deterministic approach requires historical meteorological information which has been organized and published by the U.S. Weather Service, as well as hydrologic models to predict how the chosen regional storm will impact the basin in question. All of the methodologies generally require a somewhat complicated hydrologic analysis, but the deterministic method alone requires little quantitative probabilistic information.

The flood-frequency approach uses quantitative information about the probability of extreme events. Often, analysts estimate a distribution for extreme rainfall and use a hydrologic model to route a selected rainfall with the prescribed exceedance probability. Even the assignment of a prescribed probability to the PMF and extension of a frequency curve out from more common events, such as the 100-year flood, requires that one first estimate a PMF. This probably constitutes the simplest method for building a probability distribution for extreme floods.

Alternative methods of constructing distributions would need substantially more work given that researchers have not developed the required frequency-based rainfall databases [NRC, 1988]. This situation would likely improve if engineers used the risk method more widely [Task Committee on Spillway Design Flood Selection, 1988].

Risk-analysis methods incorporate the occurrence probabilities used by the flood-frequency approach and also employ quantitative estimates of the damage caused by floods of different magnitudes. Estimating quantitative damage requires a site specific study of resources in a dam's floodplain. In general, using the risk-analysis approach requires more resources and effort than either the deterministic or flood-frequency methods. In particular, analysts and engineers should emphasize developing better estimates of the likely character of dam operation, failures, and incremental damage.

These three methods possess different degrees of complexity which will affect the desires of engineers and decision-makers to use them. Engineers and decision-makers who do not have a good understanding of probabilistic and statistical principles may resist working with probability-based methods. They may feel uncomfortable with the assumptions employed in quantitative risk studies. Some decision-makers have also pointed at the possibly high cost of risk analysis, resulting from the analysis' complexity, as an argument against its use [Cooper, 1987].

The availability of data needed to use each of the methods will also influence decisions about the appropriate dam safety evaluation method. Several methods for estimating PMFs have been developed and have different meteorological data needs. Proposals have been advanced for developing more accurate methods of estimating the extreme probabilities used by the flood-frequency and risk-analysis methodologies [NRC, 1988; Foufoula-Georgiou, 1989]; however, these more sophisticated methods have greater data requirements and are more computationally demanding. The PMF also suffers from a lack of precision.

Acceptability of the Results

The PMF method has a greater acceptability than the other methods because of its long history of use in the engineering profession. The relatively new proposal to use risk analysis may be less acceptable to the profession because it does not have the PMF's historical record to recommend it. Some engineers suggest that the U.S. currently has a good safety record which changes may jeopardize.

The issue of placing a monetary value on human life also affects the acceptability of the approaches. Some decision-makers and engineers have opposed risk analysis because it may explicitly require or suggest the assignment of a monetary value to human lives which the PMF method does not explicitly do. In actuality, any decision to build a dam, even one that can pass its estimated PMF, will put human beings, their property, and the environment at risk, and thus, places a finite value on all three [Baecher et al., 1980]. The PMF method allows decision-makers to conceal the fact that a value has been assigned to human life which is a situation that decision-makers may prefer. The risk-analysis method more clearly shows the monetary value placed on human life.

Goals for this Study

Clearly, this is not the first study attempting to evaluate statistically the exceedance probability of the PMF, distribution of damage, or the chance of a flood overtopping a reservoir and failing. Newton [1983] considers how the return period of PMFs might be calculated. YAEC [1984] describes a stochastic simulation of rainfall events and runoff in their analysis of the likelihood that the Harriman dam might be overtopped. The Bureau of Reclamation has for some time approximated the distribution of damage by extending the floodflow frequency curve beyond the 100-year event out to the PMF, which is assigned some reasonable return period for the analysis; this approach has been recommended for dam safety risk analysis by the National Research Council's Committee on Dam Safety [NRC, 1985], and has subsequently been explored by Grygier and Stedinger [1985], NRC [1988], Karlsson and Haimes, [1989] and others. Thus, this study does not propose a new approach. However, the trend is to take the use of risk analyses in dam safety evaluation more seriously [Bowles, 1987; McCann et al., 1985; Von Thun, 1987; Resendiz-Carrillo and Lave, 1987; Karlsson and Haimes, 1988ab; Haimes et al., 1988; Karlsson and Haimes, 1989; Petrakian et al., 1989]. As a result, there is increasing interest in better refining figures on the actual distribution of extreme rainfall and runoff events [NRC, 1988] and the performance of dams and related control structures, so as to better predict the probabilities of various failures, distributions of dollar damages, loss-of-life, and other criteria.

This research is intended to contribute to the evolution of dam safety assessment methods by illustrating how dam-safety risk assessment might be improved by employing more detailed stochastic descriptions of the rainfall and runoff processes, and improving the performance of warning systems, dams, and other structures. The products of a stochastic analysis should provide better insights into the complexities of dam safety problems than traditional deterministic methods. These products include the pathways to failure and their relative likelihoods, overall failure probabilities, and the trade-offs between safety and costs. Using detailed stochastic analyses should give decision-makers more information about the implications of adopting alternative solutions to dam safety problems, thus ameliorating the evaluation process.

The functions and distributions that have been employed in this study are in many cases straightforward. However, further research is needed to develop better models of many distributions, such as the distribution of rain within a storm and the likely durations and magnitudes of flows a spillway can withstand before failure. Moreover, many details included here will not be needed in operational risk analysis of actual structures once researchers obtain a sense of which factors are important. For example, in the case of a large reservoir where the *volume* of the inflow hydrograph controls the maximum reservoir elevation and outflow, the *distribution of timing* within a storm may be of relatively little importance, whereas for a small structure where the *peak* of the inflow hydrograph controls the peak outflow, *antecedent moisture conditions and initial rainfall losses* may have relatively little effect. For actual dam safety studies it may be found that extending the flood flow frequency curve from the 100-year flood to a PMF with some adopted return period is sufficient. This research is intended to assist in the development of a framework within which such questions can be posed, studied, and resolved.

Because the Probable Maximum Flood (PMF) is based on conservative assumptions about the values of many factors (see Hansen et al. [1982], the World Meteorological Organization [WMO, 1986], NRC [1985], the Task Committee on Spillway Design Flood Selection [1988], and NRC [1988]), it is often thought to be a very conservative design standard [Newton, 1983]. In moving to risk-based analyses, the impact of the many factors which contribute to the probability of dam failure and the magnitudes of damage should be considered (see Newton, 1983, Table 1). In particular, the probability that a flood might occur and exceed some threshold is the sum of the probabilities of all combinations of rainfall depths, rainfall distributions in space, rainfall distributions across time within a storm, and antecedent soil moisture levels that would yield a flood of that size or larger. Whereas the PMP is envisioned to be the worst probable combination of conditions possible and, therefore, is defined by the single storm type that generates these conditions [WMO, 1986]. A probabilistic analysis should include the distribution of less severe storms and the many storm types (winter or summer; hurricane, frontal, or thunder storms) that can lead to such major flood events.

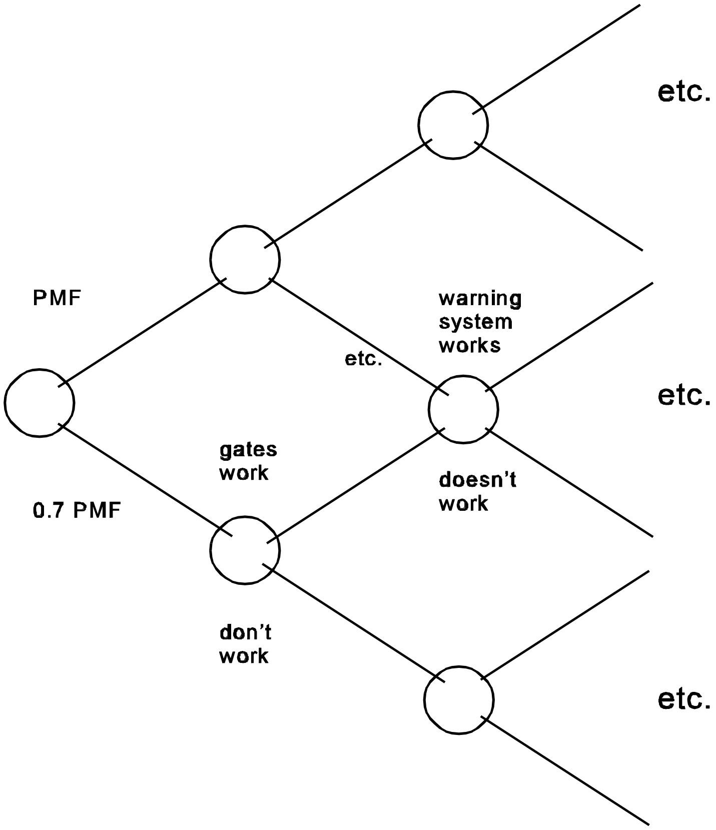
Likewise, the probability that a dam fails or that a given level of damage is exceeded, depends upon all the ways a given outflow discharge rate may be achieved, and thus depends upon the possible inflow floods, the reservoir operating policy, initial reservoir levels, what outflow works and gates are operational, and whether the turbines can be operated at capacity. Whether the structure fails depends on whether the emergency spillway can actually pass its rated discharge without failing; on the margin, it may also hinge on the direction of the wind across the reservoir's pool and the resultant wave run-up on the dam (freeboard) as well as the amount of overtopping the structure can withstand without failure.

Finally, the level of damage that results from the flood may depend on the time-of-year and time-of-day that the flood occurs. Other structures besides the dam and spillway may fail and contribute to loss-of-life and downstream damage. Likewise, flood warning systems have the potential to reduce loss-of-life in major floods; but they may not work perfectly, particularly in the case of dam-break floods [Paté -Cornell, 1984; Paté-Cornell and Tagaras, 1986; Paté -Cornell, 1989].

Using risk-based criteria in dam safety studies requires estimating the probabilities of different events and the resulting damage. Estimates of the probabilities of large floods may be imprecise, and this has made some engineers reluctant to conduct risk analysis studies. Such uncertainties can be handled in several ways. For example, one can integrate the uncertainty of key parameters or events into the analysis by assigning probabilities to different sets of parameters and events, or one can use a sensitivity analysis approach to investigate the impact of different assumptions and parameter sets upon the results by rerunning the basic analysis with the different assumptions. In the example given in Chapter 4, the number of functioning outlet gates is a random variable explicitly describing the uncertainty in the gates mechanical operation. In addition, that analysis considers two alternative distributions for rainfall depth, thus using sensitivity analysis to address concern over the appropriate rainfall distribution. It is also possible to incorporate rainfall distribution parameter uncertainty into the analysis by assigning probability distributions to the values of those parameters and employing the resulting *posterior rainfall distribution* [Stedinger, 1983]. YAEC [1984] explicitly incorporates uncertainty in the parameters and distributions of rainfall into its analysis by assigning probabilities to different rainfall distributions in its Monte Carlo simulation.

Describing Events

Bury and Kreuzer [1986] show how the relationships between events contributing to dam failure, damage, and loss-of-life can be summarized by **event trees**. An event tree is a description of possible combinations of simple events and the values of the various factors that contribute to a flood's magnitude, the dam's operation, and any eventual damage and loss-of-life. An event tree might look like:



In an event tree, for all possible combinations of preceding factors, each new factor is listed and probabilities are assigned to each of the **discrete** values it is allowed to assume. Because each factor is assigned a finite number of discrete values, the total number of combinations of simple events is finite, but perhaps large. A probability for each compound event or combination is determined by the probabilities assigned in the event tree.

Another conceptual framework employed in risk and reliability studies is a **fault tree**. A fault tree describes by simple logical relationships all the ways in which a system can fail. Where an event tree describes all possible combinations of simple events or factors, a fault tree focuses only on those combinations which would cause some failure. System failure may or may not occur, and each component is generally assumed to be working or inoperable. For example, a radio which is part of a flood warning system will fail to function if the output amplifier has failed or the antenna is damaged or the batteries are dead and backup power is not available. Fault tree analyses are based upon a binary logic which is not well suited for dam safety analysis where many factors, such as rainfall, can assume a wide range of values, and where the interest is in the probability distribution for a range of outcomes which include different levels of damage and ways in which the reservoir might fail, consequently causing different levels of damage.

The orientations of both the narrow fault tree analysis framework and the more general event tree make them unsatisfactory for the detailed dam safety analysis conducted in this study. In particular, a paradigm is needed which allows the analysis to include a number of continuous random variables without discretizing their probabilities.

Figure 1 contains an **event diagram** or **influence diagram** describing how several hydrologic and operating factors can contribute to a major flood which would cause downstream flooding, the associated damage, as well as the factors which may combine to result in dam failure. In the lower left corner, the circles describe seasonal and meteorological factors which combine to determine the inflow hydrograph. Such a flood needs to be contained in the reservoir and passed downstream by the reservoir's outlet works, turbines, and emergency spillway, depending upon their ability to operate, and the reservoir's operating guidelines. Such event or influence diagrams have been used to describe the relationships between different factors and to structure decision issues with inherent uncertainties [Howard and Matheson, 1984]. Shachter [1988] provides a rigorous system for the construction and manipulation of such descriptions of stochastic systems when the random variables can assume only a finite number of values, while Shachter and Kenley [1989] consider application to linear-quadratic-Gaussian models.

Many of the factors described by circles in the Event Diagram in Figure 1 are best described by continuous random variables; rainfall depth, the possible temporal distribution of rain within a storm, and initial reservoir levels are three examples. This precludes the simple event tree evaluation in which each event can have only a few values. Likewise, Shachter's evaluation procedures for influence diagrams with discrete random variables are not applicable. If one were willing to substitute a discrete representation for the various continuous distributions and tolerate the resulting approximation error, then the event diagram could be converted into an event tree by ordering the factors described by circles in such a way that the distribution of the events described by each circle is completely specified by factors which appear higher in the list. This would determine the order in which the variables would be introduced in the event tree. In fact, such an ordering is necessary if the event diagram is to serve as a prescription for the generation of floods and possible dam safety events. Thus, for both purposes, the event or influence diagram cannot contain loops or circular references.

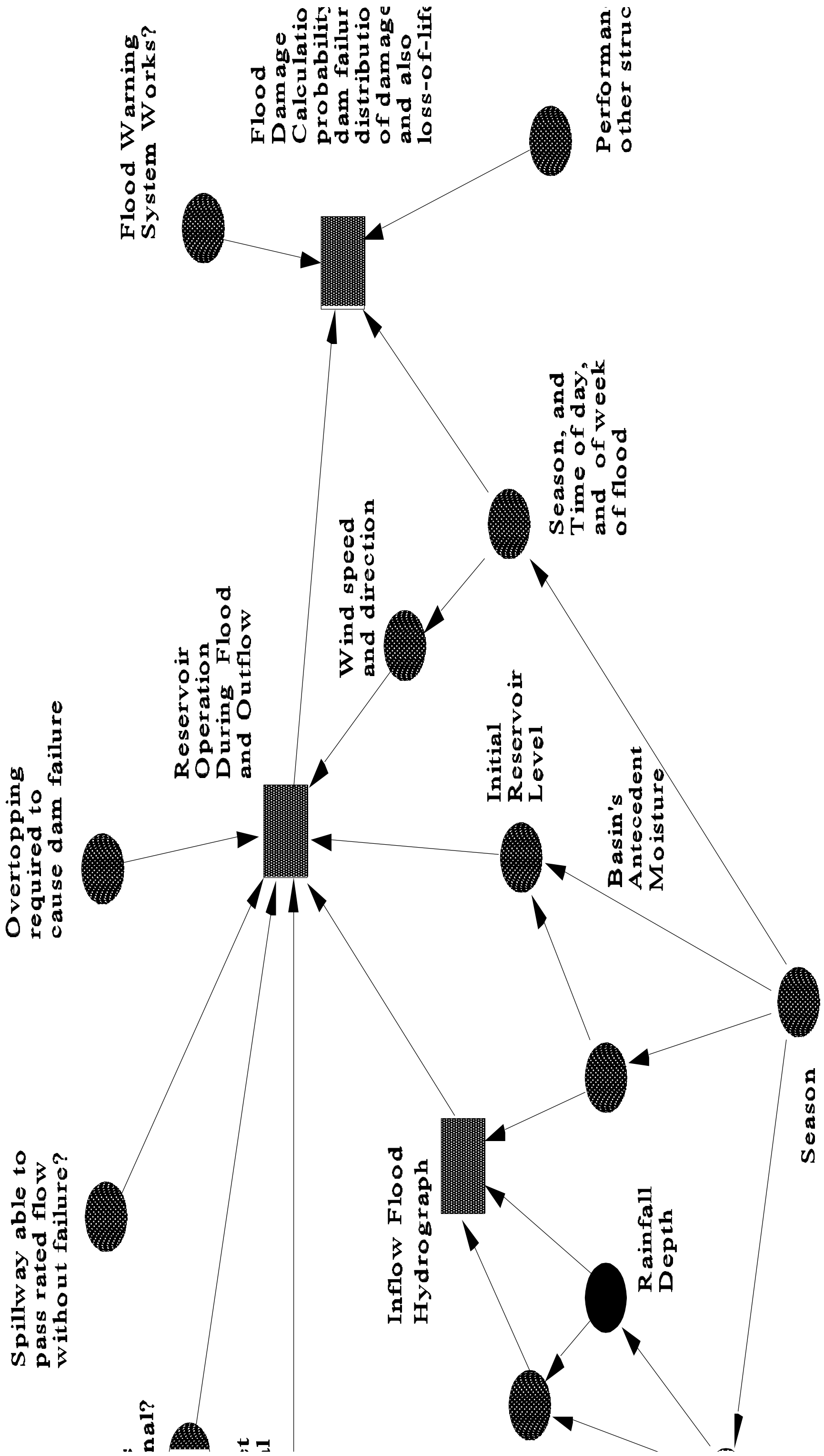


Figure 1. Event Structure for Monte Carlo Simulation

A Computational Procedure

Rather than discretizing the various random variables to evaluate the problem described by an event diagram, one could attempt a straightforward Monte Carlo analysis; because extremely rare events, which may occur with a probability of 1 in 10,000 or more, are the events of interest, this approach would be very inefficient. A hybrid procedure, proposed here, takes advantage of the strengths of both the Monte Carlo approach for continuous random variables and the event tree approach for important discrete events.

Table 1 describes the event diagram simulation procedure. The procedure is based on the premise that the most important, and perhaps dominant random variable in the hydrologic risk of dam failure, is the rainfall depth. Without sufficient rain, a flood won't occur. Therefore, a reasonable hybrid Monte Carlo/analytical evaluation of the event diagram in Figure 1 would randomly draw values of all the random variables in Figure 1, except rainfall depth, to form a single replicate experiment. Conditional on those values, one could analytically obtain the conditional probability of dam failure (which is the probability that rainfall for that season, storm type, and so forth would be sufficient to cause a spillway or overtopping dam failure) and the distribution of damage and loss-of-life. Averaging these conditional distributions yields the distributions of interest.

In step 1 the events were not all generated randomly. Stratification is employed in the Monte Carlo analysis to increase the precision of the results by evaluating the distributions of some discrete random variables analytically. Examples of discrete random variables which could be used to define different strata are whether the flood warning system works, the numbers of gates and outlets working, the season, and the storm type within a season. In a system where the warning system succeeds or fails, and the season is either summer or winter, four strata could be defined:

1) warning system succeeds in summer
2) warning system fails in summer

Table 1. Structure of Monte Carlo Simulation

1. Generate the values of all random variables in Figure 1, except rainfall depth.

2. For those values from step 1, determine the rainfall depth that causes dam failure and calculate for this case:

    a) conditional probability of dam failure,
    b) conditional distribution of damage, and
    c) conditional distribution of loss-of-life.

3. Repeat steps 1 and 2 a sufficient number of times to accurately estimate the quantities of interest.

4. Average the conditional probabilities and conditional distributions obtained in step 2 across generated samples to estimate the expected values.

3) warning system succeeds in winter
4) warning system fails in winter.

If there is a 40% chance the warning system fails and a 60% chance it works and two-thirds of the storms arrive in the winter season and one-third in the summer, then the frequencies that would be assigned to the four strata would be 3/15, 2/15, 6/15, and 4/15, respectively. In the Monte Carlo analysis, each stratum that was employed (corresponding to a set of values for the stratified variables) was sampled with a frequency proportional to its probability of occurrence.

Once a stratum is selected, random numbers for the non-stratified variables (such as the precipitation distribution within a storm and required overtopping to cause dam failure) are generated using the conditional distributions for those variables given that they are in that stratum.[1]

In this way, the model computes individual damage distributions for each stratum. The overall damage distribution is calculated by averaging the individual stratum's distributions, weighted by the probability with which each stratum occurs.[2] This stratified Monte Carlo procedure increases the precision with which the damage distributions can be computed with a given level of effort.[3]

Figure 2 illustrates the kind of information generated by the Monte Carlo procedure proposed in Figure 1. Figure 2 displays the distribution of downstream damage and the cost of dam failure for the original hypothetical dam, and a proposed modification which would widen the spillway and raise the height of the dam. For floods with exceedance probabilities between 10^{-2} and 10^{-4}, widening the spillway increases the damage because of the larger spillway. With the larger spillway and greater height, the dam fails with a probability of approximately 10^{-5}, instead of 10^{-4}, without the modification. However, because the modified dam is higher than the original, if it fails the downstream damage are larger than when the unmodified dam fails. The proposed modification has a construction cost, losses associated with any decrease in the available active storage zone or other operating restrictions, and a small increase in damage for floods with exceedance probabilities in the 10^{-2} to 10^{-4} range and for events with exceedance probabilities less than 10^{-5}.

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[1] Clearly, the distribution for rainfall and antecedent moisture would depend upon the season, whereas the lives lost from dam failure would depend upon whether the warning system worked.

[2] In the program, the number of replicates generated to calculate the damage distribution for each stratum is essentially proportional to the frequency with which that stratum occurs. Thus, the average damage distribution is the straight average across all of the randomly generated damages distributions for all strata. This strategy ensures that if winter storms occur twice as frequently as summer storms, then two-thirds of the replicates will correspond to winter storms and one-third to summer storms.

[3] By ensuring that the stratified random variables occur in the samples with the theoretical frequencies, some of the randomness is removed from the experiment. The precision of the final results depends upon the variability of replicates within each stratum, and the weight assigned to them when they are averaged. If fixing the stratified random variables within each stratum significantly reduces the variances of the statistics being estimated, a significant increase in overall precision can be obtained.

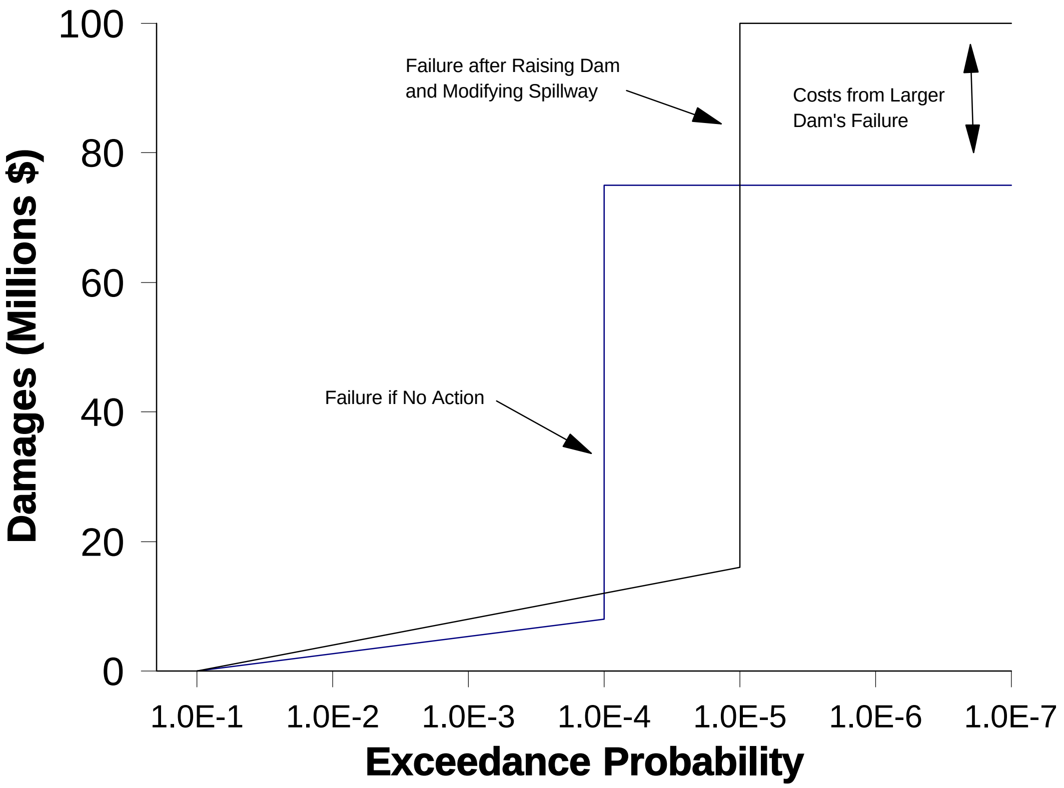


Figure 2. - The Impact on Damage Distribution of Raising the Dam

A display like Figure 2 shows in an uncondensed fashion the probabilities that various damage thresholds are exceeded and possible trade-offs between increased damage for infrequent (10^{-2} to 10^{-4} range) versus very rare events (less than 10^{-5}). The Monte Carlo analysis would also yield the probabilities of dam failure from these large flood events and contributing factors. Other useful and easy to calculate summary statistics include expected damage and loss-of-life, their variance, and the cost per expected life saved. Sophisticated decision methodologies, such as multi-attribute utility theory [Keeney and Raiffa, 1976] or the partitioned multi-objective risk method with the surrogate worth trade-off method or other analysis vehicles [Haimes et al., 1988; Karlsson and Haimes, 1988ab, 1989; Petrakian et al., 1989] could also be employed to help choose among alternatives. Chapter 3 discusses in more detail alternative approaches for displaying the distribution of property damage and loss-of-life.

The purpose of dam-safety risk analyses is not so much to determine the average expected costs or loss-of-life associated with a particular design, as it is to help those interested in a project understand the alternative trade-offs between costs and safety. For the purpose of assisting the decision-making and analysis process, several criteria may be useful. An interesting aspect of such an analysis is the allocation of costs and/or loss-of-life for a particular design between what have been termed high-probability/low-consequence events and low-probability/high-consequence events; thus, one could ask if the total expected damage was primarily due to many "common" floods, which cause modest damage, or primarily due to relatively rare or very unlikely floods, which would cause extraordinary damage. The Bureau of Reclamation [1986] has used risk-cost curves to illustrate this issue. Karlsson and Y.Y. Haimes [1988ab] and Haimes et al. [1988] develop the Partitioned Multi-objective Risk Method (PMRM) which provides a different approach. Recently, Reid [1987] suggested several ways of presenting the **risk spectrum** of a project to illustrate these issues.

Display of Results

The manner and form in which analysts present results from a dam safety risk analysis is important. Neither decision-makers nor the general public are accustomed to working with the very small probabilities of concern in dam safety analyses. Thus, it is important to present results in a manner which:

1) will be as straightforward and intuitive as possible,
2) will be consistent with other presentations of probabilistic results which individuals may have encountered, and
3) will contribute to an understanding of the major issues of concern.

Reid [1987] proposes that results from quantitative risk analyses can be presented graphically in several ways that illustrate:

1) the magnitude of the exceedance probabilities of different events,
2) the relative likelihood of different events,
3) the relative contribution of the total expected damage of events of different magnitudes, and
4) the fraction of the total expected damage which is due to events causing damage less than various thresholds.

These ideas are developed further in the following section.

Frequency and Probability Models of Damage

This study employs the distribution of property damage and loss-of-life in terms of exceedance probabilities based on the probability for the maximum damage which will occur in a given year. Thus, the annual exceedance probability, $p_e(x)$, associated with a damage level x is the probability in a given year that damage due to a single flood within that year will exceed x. Let F(x) denote the cumulative distribution function (CDF), which is the annual probability that damage is less than or equal to x. Then

$$p_e(x) = 1 - F(x)$$

Reid [1987], McCann et al. [1985], and others have done risk analyses and have displayed their results using arrival rates (frequencies). Thus, they have worked with the frequency N(x) with which damage will equal or exceed a given damage level x in any year. This average arrival rate can exceed one for frequent events, which would reflect the fact that on average one or more significant rainfall events or minor floods causing minor damage can occur per year. For relatively infrequent events, there is little difference between the average frequency with which a damage level is exceeded and the probability a given level of damage is exceeded in any year.

The results of the study in Chapter 4 are reported using exceedance probabilities, rather than arrival rates, because exceedance probabilities are more consistent with the way that flood-damage studies are traditionally done and flood-frequency relationships are described. However, to be mathematically correct in the calculation of damage, the underlying calculations are performed using the frequency or arrival rate of flood-producing rains, yielding a description of the frequency with which different damage levels would be exceeded [Ouellette et al., 1985]. This allows for more than one damage-producing event per year. This can be important for events with arrival rates on the order of 0.10 per year or more.

If a damage level x is exceeded with an average annual frequency of N(x), then for independent events the probability that x is exceeded in a year is given by the Poisson distribution, yielding

$$p_e(x) = 1 - \exp[-N(x)].$$

For N(x) less than 10^{-2}, this is essentially equivalent to $p_e(x) = N(x)$. The Monte Carlo analysis determines the frequencies with which different damage levels would be exceeded. The relationship above allows conversion of the frequency distribution for different damage levels into the corresponding annual exceedance probabilities.

Alternative Graphical Displays of the Risk and Losses

Based upon the ideas put forward by Reid [1987], Chapter 4 presents the results of a Monte Carlo study both in terms of the exceedance probabilities of different damage levels, and the expected damage from all events greater than various thresholds. The significance of these two viewpoints is discussed below.

Exceedance Probabilities

One of the most fundamental concepts in probability theory is the assignment of probabilities to events. A fundamental notation is the cumulative distribution function (CDF), denoted $F(x) = 1 - p_e(x)$, which gives the probability that a random variable X will be less than or equal to x. For problems such as flood-frequency analysis and dam safety, which are concerned with very unusual events, it is generally more convenient to work with the complementary CDF, which is the annual exceedance probability $p_e(x)$, or the probability that the random variable X would exceed any value x. Floods are often described by their return period. Thus, a 100-year flood is one with a 0.01 exceedance probability, and the 10,000-year flood is one with an 10^{-4} exceedance probability.

A first choice for describing the distribution of damage and/or loss-of-life is the generation and display of the exceedance probability function p_e as shown in Figure 2. For each damage level, it shows the probability that the prescribed level is reached or exceeded. In Figure 2, a logarithmic scale is used for the exceedance probabilities and a linear scale for damage. In Chapter 4, a linear scale is sufficient to describe loss-of-life, however, dollar damages (which vary over several orders of magnitude) are plotted on a logarithmic scale. It is not clear whether probability or damage should go on the horizontal axis; there is precedence for both. In Figure 2, damage is plotted as a function of flood magnitude, where flood magnitude is represented by the exceedance probability of the event. Thus, damage appears on the vertical axis. In Chapter 4, the exceedance probability is viewed as a function of the damage level, so $p_e(x)$ is plotted on the vertical axis and damage on the horizontal axis. This arrangement also makes the damage-probability plots consistent with the graphical display of expected damage for events which exceed various thresholds, an idea developed in the following paragraphs.

Expected Damage from All Events Greater than Various Thresholds

Reid [1987] proposes the use of the cumulative expected cost distribution (CECD) function, which is the expected costs due to all events whose magnitude is less than x. The cumulative expected cost distribution is a concise visual vehicle for illustrating the relative contribution of small, modest, and extraordinary events to the total expected damage costs associated with a project.

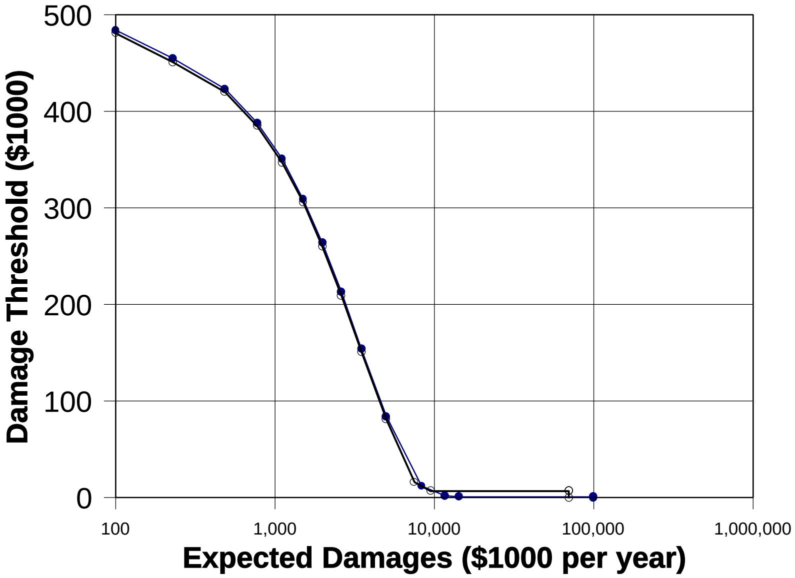
A common outcome of dam safety studies is that the contribution to total expected damage of very large and rare floods can be quite small. The CECD function is a way of illustrating this. However, if the actual expected loss from rare events is small, its relative contribution would be difficult to see in such figures. Thus, the results in Chapter 4 are shown in terms of the expected damage from all events greater than various thresholds x. This is the complement of Reid's CECD function. The expected damage C*(x), from all events greater than a threshold x, was calculated as

$$C^*(x) = \int_x^\infty s \, dF(s),$$

where F(x) is the CDF for the damage. Whereas $p_e(x)$ is the probability of damage events that exceed x in magnitude, C*(x) is the total expected damage caused by events that exceed x. For a non-negative random variable, like damages, C*(0) would be the expected damages from any and all events. C*(x) is called the **partial expected damage function** because it is the fraction or part of the total expected damages due to events whose damage exceeds x in magnitude.

There are several ways that C*(x) might be used. As proposed above, it reflects the absolute level of costs. If one is interested in comparing the relative distribution of costs to different damage levels, then one might consider the *normalized cumulative expected cost function* C*(x)/C*(0). This ratio would reflect the fraction of the total cost attributable to events exceeding different thresholds.

Figure 3 displays C*(x) for the two damage distributions in Figure 2. The upper graph in Figure 3 uses a linear scale for damages and reveals little difference between the two options. Indeed, the total expected damages for each option are relatively close: $480,800 per year for the existing structure and $484,100



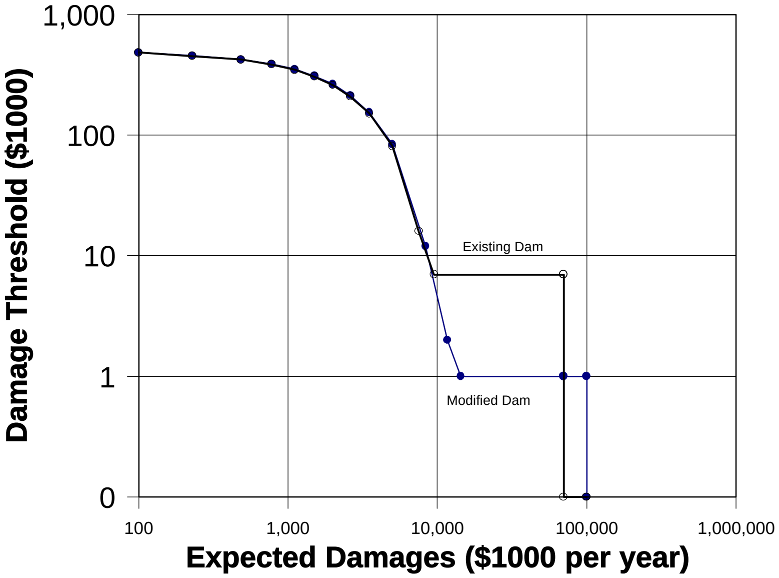


Figure 3. - Damage Distributions Where Expected Damages Exceed Threshold. The upper graph uses a linear scale while the lower graph uses a logarithmic vertical scale.

per year for the modified dam and spillway. The difference is less than 1%. Such differences in expected damage need to be compared with the construction, operating, and opportunity costs associated with various options.

The lower graph in Figure 3 uses a logarithmic scale for damages and shows a difference in the expected damages due to events causing great damage. For events costing more than $70 million, the modified dam has higher expected damages. In fact, the existing structure cannot cause more than $70 million in damages; as indicated in Figure 2, the modified structure causes $100 million in damages when it fails. When considering damages greater than thresholds between $10 million and $70 million, the existing dam has higher expected damages than the modified dam because of the tenfold larger probability that it might fail and cause $70 million in damages (versus $100 million for the modified dam). However, the contribution to total expected damages from damage events in this range is quite small: the total expected damages for damage events exceeding the $20 million threshold is $7,000, compared to some $480,000 in expected damages associated with all events.

The Partitioned Multi-objective Risk Method

Karlsson and Haimes [1988ab, 1989] and Haimes et al. [1988] develop the Partitioned Multi-objective Risk Method (PMRM) which considers explicitly the expected damage associated with relatively frequent and infrequent events. To do this, the PMRM method employs probability ranges (such as exceedance probabilities of 10^{-2} through 10^{-4} or 10^{-4} and less). It then determines the conditional expected damage for the damage events that correspond to these specified probability ranges. The PMRM's goal is to elucidate the relative damage associated with very unusual and with more common events. It attempts to achieve this objective by calculating the conditional damage associated with events in different probability ranges.

Karlsson and Haimes [1989] also explore the calculation of the conditional damage in specific damage ranges; the resultant conditional expectations for the most extreme partition are generally very close to the lower damage bound, and thus vary little across alternative actions. The use of PMRM with specific damage ranges is thought to be less "intuitive" and is not recommended.

Consider four problems associated with the PMRM approach and the corresponding use of the conditional expectations of the damage associated with specified probability ranges.

1) The PMRM method does not make it clear which damage events correspond to each probability range. This can make the interpretation of the conditional means difficult because one does not know to which events they correspond. Moreover, sensitivity analyses that consider modifications of the probability distributions assigned to different events will change the actual damage events associated with the PMRM probability ranges; thus, the expected values assigned to different probability ranges will not be comparable, because they correspond to different sets of events.

2) The natural way to think of probability is the likelihood or frequency assigned to a fixed or specified damage or damage range; the PMRM works the other way around. Thus, it is likely to be difficult to understand. Calculating the conditional expectation of damage in particular damage ranges [Petrakian et al., 1989; Karlsson and Haimes, 1989] doesn't help. A natural and useful exercise is calculating the probabilities associated with important and meaningful damage ranges or the exceedance probabilities of key damage thresholds.

3) A major objective of the PMRM is highlighting the trade-off between low-consequence/high-probability events, and high-consequence/low-probability events, which are combined in the overall expected costs E[X]. In this regard, the PMRM falls short for it still averages together events whose exceedance probabilities range over several orders of magnitude. As a result, it does not provide the resolution of the distribution function $p_e(x)$ for damage or of the partial expected damage function C*(x), which shows continuously as a function of damage level x the expected damage from events of that magnitude and greater to the total expected cost. Moreover, the second function relates a system's expected damage to specific levels of damage, not to wide probability ranges whose relationship to actual events is unclear.

To illustrate the problem with averaging over probability ranges of two orders of magnitude, consider the damage functions in Figure 2. It is fairly easy to select probability ranges which make the relative advantages of the two projects look very different. Consider three natural exceedance probability intervals: $[1, 1x10^{-2}]$, $[1x10^{-2}, 1x10^{-4}]$, and $[1x10^{-4}, 0]$. As shown in Table 2, in all three of these intervals the expected damage of the modified dam is greater than or equal to the original structure. Thus, the modification appears to be an unwise expenditure regardless of which probability range is of interest.

However, if the last two intervals are redefined to emphasize less frequent events, one could consider $[1, 1x10^{-2}]$, $[1x10^{-2}, 1x10^{-5}]$, and $[1x10^{-5}, 0]$. As shown in Table 3, with this choice of probability intervals the modified dam has the lower conditional expected costs for the last interval. In the first case, the modified structure appears to be dominated by the original dam. In the second case, a trade-off is evident. Petrakian et al. [1989, p. 116] also observed such reversals in project ordering with variations in the endpoints of the probability ranges. *With the PMRM approach, the apparent relative advantages of alternative proposals can depend critically upon the selected probability range,* because they determine over which events the conditional average is calculated. This is troubling given that, as observed by Petrakian et al. [1989, p. 113], "the choice of the partitioning points on the probability axis is a somewhat arbitrary process." This alone is sufficient reason to question the method's use.

4) A stated purpose for the PMRM method is to allow decision-makers to make a trade-off between low-consequence/high-probability events and high-consequence/low-probability events. To do so, construction costs and the conditional expected damages associated with different risk intervals should be expressed in units which decision-makers feel comfortable comparing. Were it possible to determine appropriate partitioning probabilities, it is unclear how a decision-maker should rationally trade-off construction costs of perhaps \$15 million, versus expected damages of \$23 million, instead of \$70 million should an event occur with an exceedance probability in the interval $[1x10^{-4}, 0]$, versus expected damages of \$8.18 million, instead of \$7.38 million should an event occur in the interval $[1x10^{-2}, 1x10^{-4}]$. One natural solution is to multiply each conditional expectation by the probability of that interval. This gives the portion of the total expected damages, E[X], associated with each probability interval. The portion of the total expected damages attributable to a given probability interval is what the partial expected cost distribution C*(x) reveals.

Table 2. Expected Damages ($million/yr) for the Initial Partitioning of Probabilities of Damages in Figure 2 for use with PMRM

Probability Range	[1, 1x10^{-2}]	[1x10^{-2}, 1x10^{-5}]	[1x10^{-5}, 0]
Modified Dam	0.4	8.32	100
Existing Dam	0.4	8.02	70

Table 3. Expected Damages ($million/yr) for the Modified Partitioning of Probabilities of Damages in Figure 2 for use with PMRM

Probability Range	[1, 1x10^{-2}]	[1x10^{-2}, 1x10^{-4}]	[1x10^{-4}, 0]
Modified Dam	0.4	8.26	23
Existing Dam	0.4	7.45	70

Background

This chapter presents an example to illustrate probabilistic dam safety risk analysis. The example is based upon the physical characteristics, and hydrologic and meteorological parameters, of a dam in the Northeastern United States. The characteristics of the dam and the distributions used to describe various random meteorological and hydrologic events are described in Appendix B.

The drainage basin for the dam has an area of 600 square miles with an elevation difference of 1,000 feet. The total length of the watercourse is 40 miles. The dam is an earth-filled structure which rises from a ground elevation of 931 feet to an elevation at the crest of 995 feet. An emergency spillway begins operation when the storage level in the dam reaches an elevation of 976.5 feet. When full to the top of the embankment, the storage pool has a volume of 265,500 acre-feet. When full to the spillway crest, the storage pool contains 69,600 acre-feet of water. The total length of the dam is 5600 feet, including the 150-foot spillway. Water can escape from the dam in three ways:

1) through the sluiceway outlet works
2) over the spillway
3) over the the dam's crest, as described in Figure B-2 in Appendix B.

The damage and loss-of-life as a function of release and the reservoir operating policy for the dam are described in Appendix B and Figures B-4 through B-7.

The analysis considers three structural alternatives. The first is the current dam configuration with a 150-foot wide spillway, as described in Appendix B. The second option corresponds to widening the spillway to 450 feet. This alternative would allow the passage of larger floods without overtopping, but would also result in the release of larger volumes of water in all cases when the reservoir level exceeds the spillway crest. The third option is to raise the dam crest 10 feet to an elevation of 1005 feet while retaining the current 150-foot spillway. This allows the dam to store more water before being overtopped.

The analysis considers another issue as well possible uncertainty in the distribution of rainfall using sensitivity analysis. Figure 4 displays the nominal distribution for rainfall depths described in Appendix B with a one-in-a-million-year rainfall depth of 24 inches.

For the purposes of illustration, the analysis also considers an alternative thick-tailed rainfall-depth distribution with a one-in-a-million-year rainfall depth exceeding 50 inches.[4] This allows an exploration of the relationship between the rainfall distribution and the derived damage and loss-of-life distributions, and also the impact of different rainfall distributions on the character of the results. Alternatively, one

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[4] For the thin-tailed rainfall distribution, the probability distribution for rainfall that exceeds a threshold of D_o = 0.9654 inches was $F(D|D \geq D_o) = 1 - [1-k(D-D_o)/a]^{1/k}$ with a = 6556 in. and k = - 0.10; for the thick-tailed distribution D_o = 1.3481 in., a = 0.3689 in., and k = - 0.25.

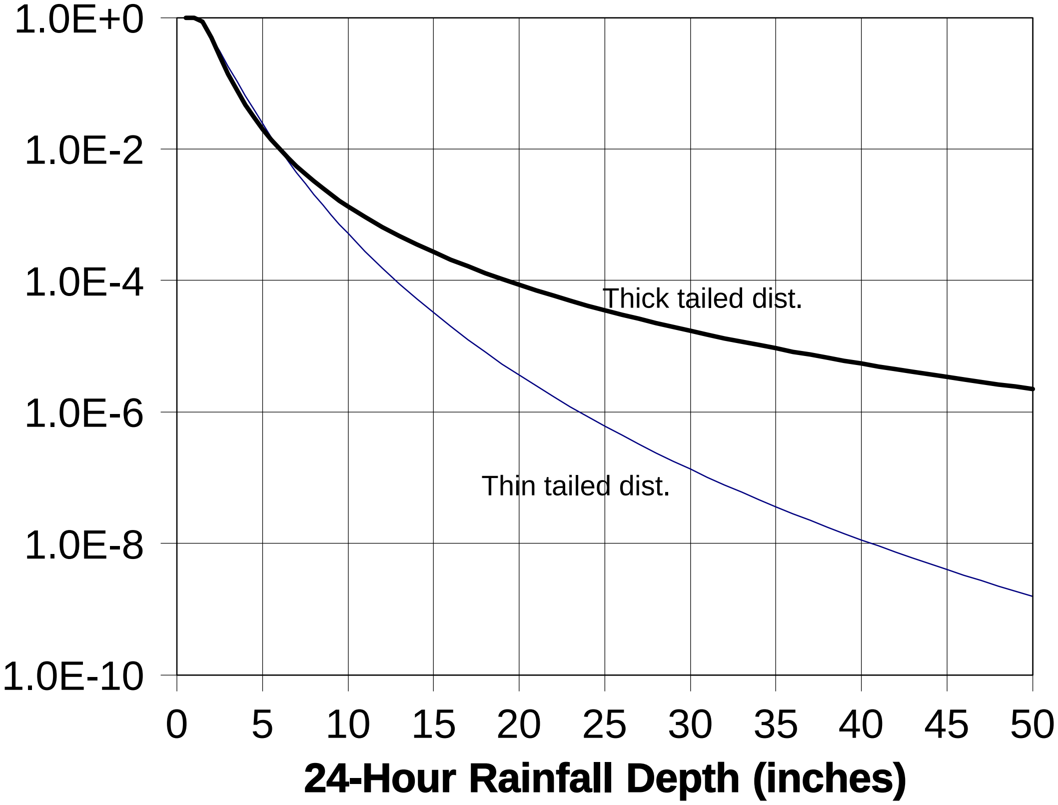

Figure 4. - Exceedance Probability for 24-Hour Rainfall Depth.

could use a rainfall distribution which integrates both natural variability and parameter uncertainty to obtain the posterior risk [Stedinger, 1983].

There is also uncertainty as to how the dam would operate during a flood. This uncertainty is integrated into the analysis by assigning probabilities to different events, such as the number of sluice gates which would be functioning. Continuous distributions are employed to describe the depth of overtopping necessary to cause dam failure and the discharge rate at which the spillway would fail. Likewise, it is assumed that there is only a 50% probability that the emergency evacuation plan would be activated in time. These and the many other assumptions are described in Appendix B.

Discussion of Results

Figures 5 through 8 below illustrate the probability distributions obtained for damage and loss-of-life using the Monte Carlo simulation procedure described in Chapter 2. Table 4 reports three statistics:

1) the overall average probability of the dam's being overtopped and failing, P[Failure]
2) the expected loss-of-life, E[Deaths]
3) the expected damage, E[Damages].

In practice, these numbers need to be compared with the cost of these and other alternatives.

From the statistics reported in Table 4, several anticipated trends manifest themselves. First, the wider spillway does indeed lower the probability that the dam is overtopped and fails. Likewise, raising the dam crest results in a large decrease in the probability that the dam is overtopped and fails. Second, with either of the three options, the probability of dam failure is larger with the thick-tailed rainfall-depth distribution; however, the other statistics change very little.

Table 4. Summary of Monte Carlo Results for Illustrative Dam-Safety Example

Case	P[Failure]	E[DEATHS] (lives)	E[Damages] (Million $)
Thin-tailed rainfall distribution			
150-foot spillway	2.3×10^{-5}	1.47	25.1
450-foot spillway	6.3×10^{-6}	1.52	27.7
Raise dam 10 feet	1.6×10^{-6}	1.47	25.1
Thick-tailed rainfall distribution			
150-foot spillway	2.1×10^{-4}	1.43	30.1
450-foot spillway	8.2×10^{-5}	1.53	32.0
Raise dam 10 feet	3.3×10^{-5}	1.43	30.0

What is perhaps surprising is that with either rainfall distribution combined with the current crest elevation, the expected lives lost and dollar damages are larger with the wider spillway. Also surprising is that with the current 150-foot spillway, the expected loss-of-life and damage are almost independent of whether the dam is raised.

Figures 5 through 8 aid in understanding these results. Figure 5, with some reflection, reveals that for property damages less than $50 million, the emergency spillway does not come into operation. Thus, the damage distributions are the same for all three options. Property damage levels between $50 and

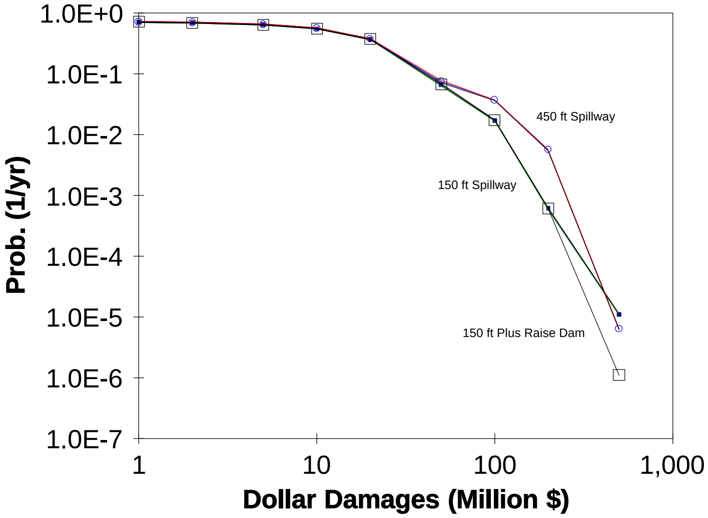

Figure 5a. - Distribution of Damages As a Plot of the Exceedance Probabilities Thin-Tailed Rainfall Distribution

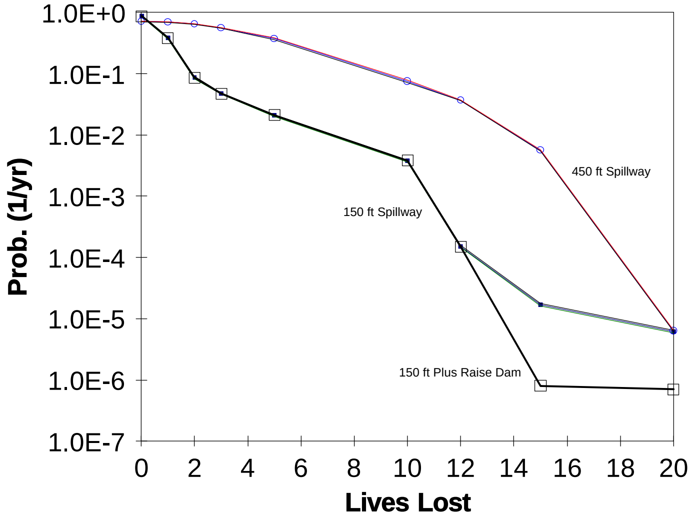

Figure 5b. - Distribution of Loss-of-Life As a Plot of the Exceedance Probabilities Thin-Tailed Rainfall Distribution

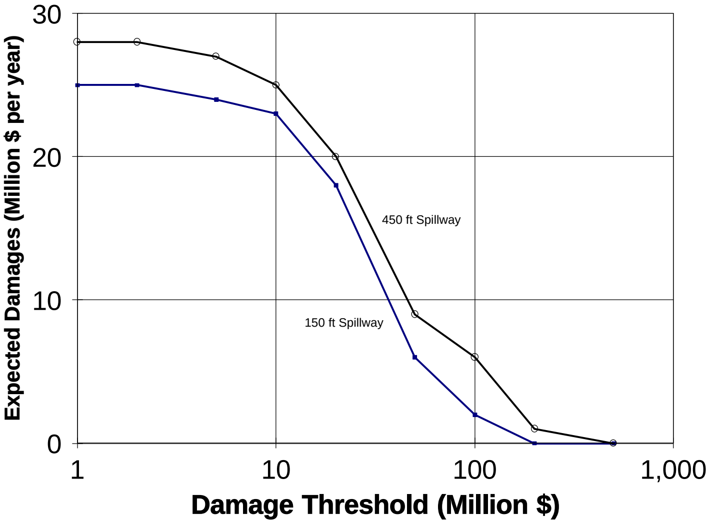

Figure 6a. - Expected Damages From Events that Exceed the Specified Thresholds Thin-Tailed Rainfall Distribution

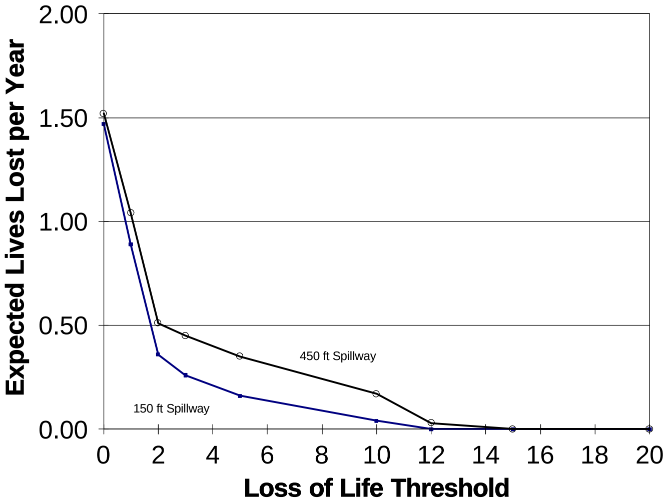

Figure 6b. - Loss-of-Life From Events that Exceed the Specified Thresholds Thin-Tailed Rainfall Distribution

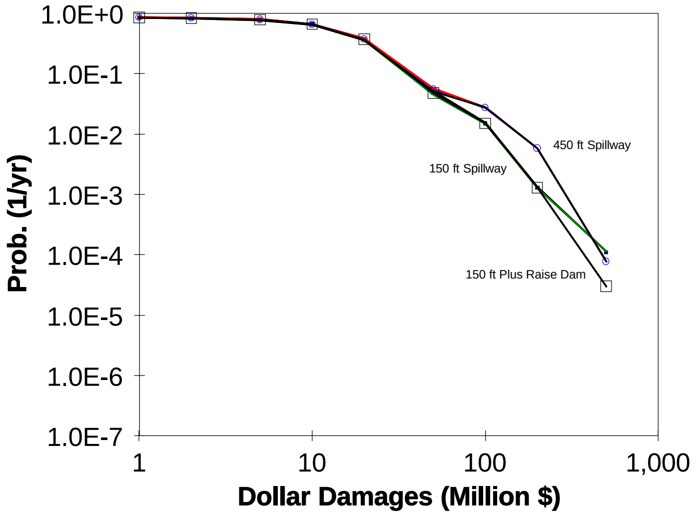

Figure 7a. - Distribution of Damage As a Plot of the Exceedance Probabilities Thick-Tailed Rainfall Distribution

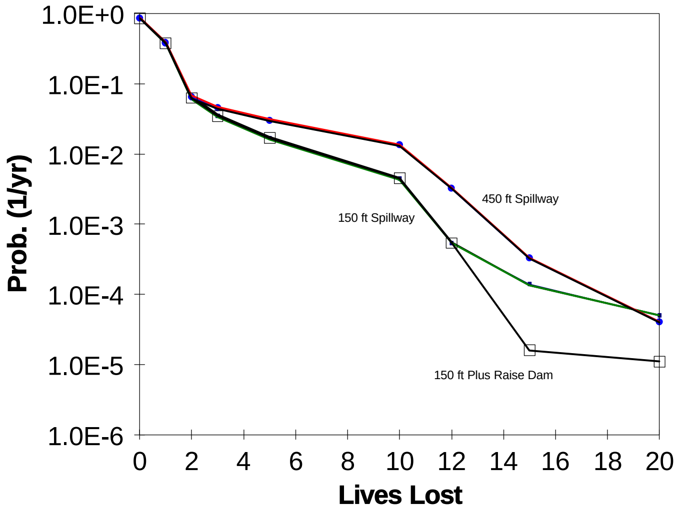

Figure 7b. - Distribution of Loss-of-Life As a Plot of the Exceedance Probabilities Thick-Tailed Rainfall Distribution

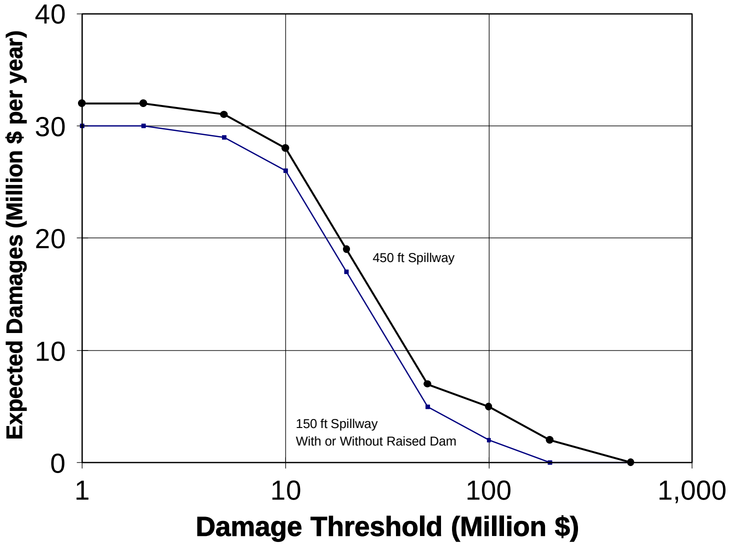

Figure 8a. - Expected Damages From Events that Exceed the Specified Thresholds Thick-Tailed Rainfall Distribution

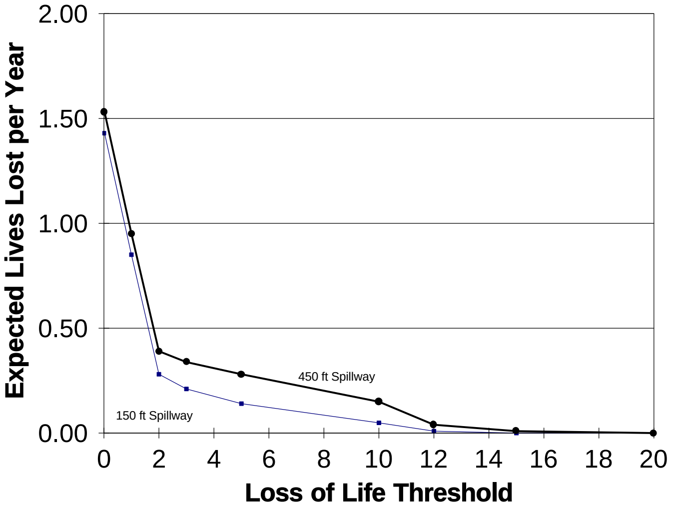

Figure 8b. - Loss-of-Life From Events that Exceed the Specified Thresholds Thick-Tailed Rainfall Distribution

$500 million correspond to events without dam failure but with large damaging floods passed downstream by the spillways. For events in this range, the wider 450-foot spillway causes much greater damage for a given inflow; or, as shown by Figure 5, for any damage level in this range, the 450-foot spillway option has a larger probability of exceeding that level.

Similarly, for loss-of-life events corresponding to less than two lives, the emergency spillway does not come into play and the three options have identical loss-of-life distributions. Floods causing from 2 to 18 deaths still do not correspond to dam failure events and the 450-foot spillway results in a larger probability of each level in that range being exceeded.

Figure 7 shows the damage and loss-of-life distributions for the thick-tailed rainfall-depth distribution. Figure 5 and Figure 7 are very similar, because the damage and loss-of-life thresholds corresponding to spillway operation and dam failure are the same. What changes are the probabilities that the various levels are exceeded. This is why the summary statistics for the two sets of results with different rainfall-depth distributions have essentially the same character.

Figures 6 and 8 display the partial expected value function C*(x) for all losses that exceed the thresholds x indicated on the horizontal axis. The figures indicate that most, if not all, of the expected loss-of-life and damage are due to events that cause less than 3 deaths or $50 million in damages. These correspond to less than the 1 percentile of the corresponding distributions; hence the expected loss-of-life and damage values are insensitive to the rainfall-depth distribution for the very extreme events, in this example.

Likewise, the importance of relatively likely events in the calculation of expected loss-of-life and damage is the reason that the values of statistics for the 150-foot spillway with the current crest level, or the 10-foot higher crest, are almost identical. As Figures 5 through 8 all show, differences in the distributions of damage and loss-of-life between these two options only occur when the original dam is overtopped, a very rare event. In such cases, the dam with the higher crest is better able to contain the flood, thus decreasing losses downstream, except in the even less likely case that the higher dam is overtopped and fails, causing an even larger flood wave than that resulting from the failure of the original dam. While the difference in dam failure probabilities for the 150-foot spillway with the two crest elevations is about an order of magnitude for both the thin-tailed and thick-tailed rainfall distributions, the expected loss-of-life and damage are virtually identical.

Figure 6 (or Figure 8 for the thick-tailed rainfall-depth distribution) actually explains why the 450-foot spillway alternative has larger expected property damage and expected loss-of-life than the 150-foot spillway with the same crest elevation. In the case of property damage, the expected property damage for events in the dam failure range (over $500 million) are not detectable. That is, they are an insignificant proportion of the total expected losses because of the very small probability that these values are incurred. However, the difference in C*(x) in the $50 million to $500 million range is much larger. The 450-foot spillway option has a higher C*(x) than the 150-foot spillway option in this range, reflecting the larger expected costs that would be incurred by the larger spillway due to damage events in this magnitude range. Because of this difference, the total expected costs associated with the 450-foot spillway exceed those of the current 150-foot spillway. In the under $50 million property damage range, the two C*(x) property damage curves are parallel because the probabilities of those damage levels are the same with the two alternatives.

Figure 6 also shows the partial expected value function C*(x) for loss-of-life. Here, the threshold x along the horizontal axis corresponds not to the actual number of lives lost in any flood, but to the expected number of lives lost due to various release rates from the dam. Thus, it is reasonable to consider the expected loss-of-life corresponding to all floods which would be expected to cause more than 0.5 deaths or 2.5 deaths or 10 deaths. In Figure 6, C*(x) for loss-of-life has the same general pattern as C*(x) for damage. The difference between the two partial expected value functions C*(X) for loss-of-life in Figure 6 accumulates in the range between 2 and 12 deaths and is negligible above 12 deaths.

Figure 8 corresponds to Figure 6, but for the thick-tailed rainfall-depth distribution. The only apparent difference is a modest change in the overall levels of the expectations. An anomaly is the decrease in the total expected number of deaths with the adoption of the thick-tailed distribution. This, however, is a result of the thick-tailed distribution having been chosen to yield a Generalized Extreme Value (GEV) annual 24-hour rainfall distribution [Hosking et al., 1985] with the same 2-year and 100-year rainfall depths of 2 and 6 inches, respectively, as the thin-tailed rainfall distribution, but with a shape parameter k of - 0.25 instead of - 0.10. The resultant thick-tailed distribution is thinner in the 2-year to 100-year rainfall range which produces floods causing less than two deaths; see Figure 4. Figures 6 and 8 show that most of the total expected loss-of-life in this example is due to floods which on average cause less than two deaths. Thus, the major loss-of-life risk in this example is due to modest flood events in which only one or two persons die. Of course, such events are not as dramatic as the dam's failure which would on average result in the loss of some 20 lives if the flood warning system also failed.

In conclusion, it is of interest to reflect on how these results might affect public opinion and the decisions of legislators. In terms of the expected damage and loss-of-life, in this example it is unlikely that either of the modifications of the current dam could be justified. However, facilities may still be required to satisfy some target level of safety to avoid the occurrence of failures and the associated catastrophes. In this regard, raising the dam by some amount would allow a higher safety standard to be met without adversely affecting the population immediately at risk below the dam.

Comparison with FEMA/Stanford Approach

McCann et al. [1985] describe a dam safety procedure developed for the Federal Emergency Management Agency (FEMA). The purpose of their analysis is to employ risk analysis as part of a screening procedure for "preliminary safety evaluation," for allocating funds among dams in a given jurisdiction for further study, and for the upgrading of some structures. The techniques used are relatively simple and intended to save money or at least to allocate a budget reasonably. The analysis makes use of general regional relationships and quantitative observations of a dam's state to estimate the relative probability of failure from the various failure modes: foundation and piping, structural, seismic, and hydrologic, including upstream dam failures. They indicate that the procedure is intended to be a "preliminary and simplified approach designed to provide a relative, as opposed to an absolute assessment of risk" [McCann et al., Volume I, p. ii, 1985].

It is not necessarily appropriate to compare the FEMA/Stanford approach presented by McCann et al. [1985] with the Monte Carlo dam-safety risk-analysis procedure described here because they have such different objectives. First, the FEMA/Stanford approach is intended to provide a simple preliminary assessment of failure risk from a very broad and comprehensive list of possible causes of dam failure. The Monte Carlo risk analysis procedures developed here are intended to provide a detailed and careful examination of the probability of failure and the distributions of property damage and loss-of-life from a wide range of flood events, including events which would cause dam overtopping and dam failure; other sources of failure are not considered. Such detailed risk analysis requires a reasonably extensive site-specific evaluation of the likely performance of a dam and reservoir in major floods, as opposed to the general regional relationships and simplified routing relationships employed in the FEMA/Stanford model. The detailed risk analysis described in the previous chapter is appropriate to support the analysis of alternative design options. The FEMA/Stanford model is intended to determine at what sites such studies might be warranted.

To make this point more clearly, an implementation of the FEMA/Stanford model was employed to do a hydrologic risk analysis for a dam which matched closely the example dam employed in this chapter. This implementation was constructed by Moy, Moser, and Stakhiv of the Institute of Water Resources and revised by Heath, Nagarwalla, and Stedinger [1987]. The procedure is basically that described by McCann et al. [1985].

Table 5 below summarizes the description of the basin employed in the FEMA/Stanford model. As indicated at the bottom of Table 5, the FEMA/Stanford analysis indicates that the probability of dam failure with the 150-foot spillway is $9.0\text{x}10^{-4}$ (the reciprocal of the return period of 1,100 years) and with a 450 foot spillway was $4.5\text{x}10^{-5}$. These probabilities are larger than those obtained with the stratified Monte Carlo simulation, even with the thick-tailed distribution. The difference is due to a number of factors, including differences in the flood routing models, descriptions of the operation of reservoir outlet works, the assumed pattern for rainfall in the FEMA/Stanford models, and the probabilities of different temporal distributions employed in the Monte Carlo risk analysis. More importantly, examination of the Monte Carlo risk-analysis statistics for this example, and the distribution variances that occur with different designs, reveal that dam failure events are not the disasters which have the major impact on total expected property damage and loss-of-life. These are issues that the initial FEMA/Stanford screening model as implemented does not address.

Table 5. Information Employed In FEMA/Stanford Analysis

To compare the FEMA/Stanford analysis methodology for dam-overtopping failures with a more detailed hydrologic risk-analysis procedure, the following input is employed at each step in response to the program's requests.

Item	**Data**	**Comments**
Name of Dam	Test 1	
Name Basin	Test 1	
Area of basin	600	sq. miles
Length of water course	40	miles
Elevation difference	1000	feet
Return period	10^6	years critical rainfall for 24 hours
Precipitation	23.5	inches critical rainfall
Return period	100	years second rainfall depth 24 hours
Precipitation	6	inches
Runoff index	2	medium
Dam location	3	East of Rockies
Dam Condition	g	condition of dam is good
Storage @ Crest + 2 feet	298405	acre-feet; corresponds to spillway crest plus 2 feet where failure occurs
Storage initial	5597	acre-feet; corresponds to average condition for Monte Carlo runs.
Spillway rating	47063	cfs; Discharge at Crest full plus 2 feet.
Fraction working	1	Assumes all sluiceway gates working
Crest length	5600	feet; The program assumes spillway length is included in crest length.
Spillway length	150	feet
Height of dam	64	feet (base to crest)

Resultant probability *of dam failure is 1 in 1,100 per year.*

Thoughts on Progress in Dam Safety Risk Analysis

Science and engineering tend to be evolutionary processes with each model, set of theories, or method successively replaced by more sophisticated concepts and procedures. Simplistic flood-frequency analyses and flood-of-record planning have been rejected for determination of the safety evaluation flood for large high-hazard dams because as implemented they are unreliable; subsequently, the PMP-PMF design standard has been adopted. With the availability of larger and longer databases, better statistical modeling concepts, and greater numerical processing capabilities, it is now time to move from use of the implicit risk associated with such a deterministic or selected worst-case design standard to a policy determined by a reasonable and explicit risk target. Even better, decision-makers can try to balance the costs of reducing large floods and dam failure probabilities against the resulting benefits. This requires a thorough risk assessment in terms of the probabilities of various natural phenomena, the likely response of natural and human-engineered systems to those events, and the evaluation of the cost and consequences of the resulting disasters from various social, economic, and environmental perspectives.

Risk analyses have been readily adopted in many decision-making contexts, such as the design of modest flood-control works and floodplain planning. It is profitable to reflect on why progress has been so slow in the safety evaluation of high-hazard dams. Several factors may be relevant.

1) Because the dam safety problem deals with such extraordinary rainfall and flood extremes, far beyond what may actually have occurred in a river basin or a region, the analysis has a high “fantasy factor”; engineers face a challenge imagining and explaining the PMF, without the additional burden of having to also develop the probability distribution of such events.

2) In moving to risk-cost analyses engineers may be trying to fine-tune a spillway design when only rough estimates of the possible magnitude of events with return periods in the hundred-thousand year range are possible; thus, care should be exercised that the precision with which engineers can describe the natural phenomena of interest is commensurate with the sophistication of the analytical tools employed.

3) Use of a systematized PMP/PMF approach may give engineers a sense of accuracy that may or may not exist in the calculation of a design standard. However, the uncertainties associated with the risk approach are more apparent because of the method's ongoing development. The uncertainties associated with the recommendations of quantitative risk analyses are certainly of concern to many engineers.

4) Finally, and probably most importantly, for 50 years the tradition in high-hazard dam spillway design and safety evaluations has been to use a standard which, with various titles, has essentially corresponded to some approximation of a PMP-PMF analysis. That analysis is now widely accepted and agreed upon by the dam design community and is consistent with their desire to build dams that should not fail. To many, there should be virtually no probability that large dams might fail and cause widespread loss-of-life and destruction. With such a mindset, risk analysis is not an attractive or even a reasonable activity. Still, when existing dams are found to fall short of the latest estimate of the PMF, and the costs of a major retrofit are large, many ask: “How safe is safe enough?” and, “What price should we pay for safety?”

Closing Observations

This report has developed and illustrated the concepts needed to perform a thorough probabilistic analysis of the dam safety issue, including the calculation of the probability of dam failure and the distributions for dollar damages and loss-of-life as a result of the combinations of the many factors that result in large releases from a dam, and possibly as a result of its actual structural failure. As one would expect, the enterprise is complicated, requiring that probability distributions or particular values be assigned to meteorological and hydrologic variables, the status and performance of the structure, and the response and impact of releases from the dam on human populations and their belongings. One surprising finding in the course of the study was that the operating rule assumed for reservoir operation could have a major impact on the damage and loss-of-life distributions because of its importance during small and large (but not necessarily extreme) flood events.

Quantitative risk assessment such as that described here is based upon the premise that man-made systems can fail. Thus, engineering analyses should consider how to reduce the costs and consequences of failure in balance with the cost of such efforts. Such an outlook is a rational and responsible position to adopt. In particular applications, current economic and statistical analysis techniques, and the databases available for estimating the probabilities of extraordinary precipitation events and their spatial and temporal character, may not be sufficiently developed to support detailed risk analyses. However, as ASCE's Task Committee on Spillway Design Flood Selection [1988] notes, this situation should change as the profession gains experience and confidence with the use of quantitative risk analysis for dam safety evaluations, builds the required databases, and develops the necessary techniques. Detailed risk analyses may never have the desired analytical precision to make definitive design decisions, but uncertainties often remain when design decisions are made.

In any case, quantitative risk analysis is ready to complement current design standard formulation. It provides insights into the complexities of dam safety problems. Products of risk analysis include the pathways to failure and their relative likelihoods, overall failure probabilities, and trade-offs between safety and costs. Using quantitative risk analysis as a decision tool or as an integral component of traditional design standards, should give decision-makers more information about the implications of adopting alternative solutions to dam safety problems, and should aid in the evaluation of alternatives.

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EVALUATING PROBABILITIES OF PRECIPITATION AND FLOODS

National Research Council, Committee on Techniques for Estimating Probabilities of Extreme Floods, *Estimating Probabilities of Extreme Floods, Methods and Recommended Research*, 136 pp., National Academy Press, Washington D.C., 1988.

Applying risk-analysis techniques to the problem of dam safety requires estimates of rare flood probabilities. The Committee's report provides a review and critique of the approaches currently used to approximate these probabilities. The Committee expresses doubts about applying current estimation techniques in practice. It states, "Decisions based on risk analysis have become more common in science, engineering and public decision-making, yet techniques for estimating the probabilities and associated confidence limits of rare floods need to be improved considerably" [p. 3]. The committee notes that, "a framework which allows a range of floods and their probabilities to be estimated is preferred to an approach that focuses on a single, large flood" [p. 3].

The Committee suggests employing three principles to help with statistical analysis for flood probability estimation:

1) Substitute space for time.
2) Increase structure in the statistical and simulation models (for example, by making strong assumptions about the event recurrence model).
3) Focus on extremes. Models which describe the distribution of common events well may not work as well as models which focus on describing extreme events. The processes involved in producing extreme and common events probably differ.

The Committee also recommends using all available data, including historical and paleo-flood data, and regional analysis. Using meteorological data in conjunction with runoff models may further improve probability estimates. Probability estimates should include the results of an uncertainty analysis, which would incorporate uncertainty resulting from the models employed in the analysis.

Dawdy, D.R., and D.P. Lettenmaier, Initiative for Risk-Based Flood Design. *Journal of Hydraulic Engineering, 113*(8), 1041-1051, 1987. Discussions by O. Pfafstetter and V. Myers appear in *Journal of Hydraulic Engineering, 115*(3), 416-422, 1989.

The authors criticize the PMF approach because, "...PMF-based methods tend to lead to a false sense of security and to misallocation of resources for dam safety improvements" [p. 1041]. These problems with the PMF occur because many people view the PMF as a deterministic, upper limit on possible floods. Because engineers do not use a single, standardized method for PMF computation, "...the true failure risk...varies from site to site. Therefore, there is an implicit discrepancy in the allocation of public resources for dam failure protection" [p. 1042]

They further criticize a recent inter-agency report for concluding that no viable alternatives to the PMF exist; the authors, however, claim that the action agencies do not fund studies which would lead to better methods. They suggest that this conclusion is a self-fulfilling prophecy, and that agency promotion of research in the area would improve techniques and viable alternatives.

In an attempt to break the no-research no-alternatives cycle, the authors propose that the agencies promote research to develop methods for using risk information in spillway design. They suggest four potential areas of research which could lead to better estimates of the extreme flood magnitudes and probabilities needed in risk analysis:

1) Estimation of empirical exceedance probabilities for PMFs,
2) Use of regional index flood distributions with regional hydrologic information to estimate extraordinary flood risks,
3) Simulation of floods from extreme rainfall events with analysis of regional rainfall frequencies and their spatial distributions, and
4) Use of paleo-flood and historical flood data to extend gauged records in flood-frequency analyses. They give an outline of the related technical issues.

Pfafstetter cites precipitation-frequency work which suggests the authors' estimates of the exceedance probability of large flood events are too low and indicates that estimating exceedance probabilities of rainfall makes more sense than estimating these large floods.

Myers notes that, as *originally conceived*, a "PMP magnitude is a jury decision. A team of professionals saturate themselves with knowledge of the climate and storm behavior, and also with knowledge of consequences of dam over-toppings." He recommends going "probabilistic" because it will clear up identification of the goal of the analysis, allow development of a consensus standard for existing dams, and because the data and computing power are now available. In their reply, both Myers and the authors discuss the need for a trial study.

Foufoula-Georgiou, E., A Probabilistic Storm Transposition Approach for Estimating Exceedance Probabilities of Extreme Precipitation Depths, *Water Resour. Res., 25*(5), 700-815, 1989.

This paper develops a probabilistic storm transposition method which systematically uses storm and basin data to estimate extreme precipitation frequencies. The author views this as a first step to estimating the extreme flood probabilities needed to apply many risk-analysis methodologies. The method is applied to two hypothetical catchments in Iowa. The tail of the resulting depth-exceedance probability curve is smooth and well behaved, suggesting that extrapolating the curve to very rare events may be promising.

Wagner, D.P., M.L. Casada, and J.D. Fussell. Flood Risk Analysis Methodology Development Project Final Report, Oak Ridge National Laboratory, Oak Ridge, TN, 1982.

This report develops a methodology for estimating the effect of floods on nuclear power plant risk, which can be appended to a probabilistic risk assessment. The authors discretize the flood damage function into mutually exclusive "damage levels". They propose using the decomposition philosophy intrinsic to fault tree and event tree methods to calculate the probability and frequency of these damage levels. This method requires knowledge of the probabilities of the sets of events leading to each damage level. The authors note that determining the sets of events which cause failure in a complex system may be "impossible or impractical"; this difficulty limits this method's use in practice.

EVALUATING PROBABILITIES OF FAILURE

Bowles, D.S., Verde River Risk Assessment: an Interim Solution Study, paper presented at the 8th annual USCOLD Meeting, Phoenix, AZ, January 1988.

Pointing to risk assessment's explicit handling of quantitative risk, the author advocates using this approach to solve dam safety problems in three cases:

1) to determine the appropriate safety level for low-hazard dams,
2) to assess options for reducing risk at dams with insufficient spillway capacity, and
3) in cases where decision-makers question the applicability of the usual design standards.

Risk assessment provides probabilistic, economic and safety information which helps to establish useful alternative solutions. The author outlines other roles of risk assessment in dam safety evaluation, the development of risk models using event tree analysis, and the estimation of the probabilities and outcomes of pertinent events.

The author uses the example of the Verde River Risk Assessment Project, which was established to find interim solutions to an inadequate spillway problem for a dam located on the Verde River. The author states that, "Such an approach does not challenge the need for permanent solutions that meet the currently accepted design standards, rather it challenges the wisdom of doing nothing while waiting for the 'ultimate fix'" [p. 5-36].

Prendergast, J.D., Probabilistic Concept for Gravity Dam Analysis, Special Rep. M-265, 68 pp., Construction Engineering Research Lab., U.S. Army Corps of Engineers, Champaign, IL, 1979.

The author discusses the value of a probabilistic approach in the area of dam safety and presents models to evaluate the safety of concrete gravity dams. Engineers traditionally design dams conservatively because they have little quantitative information about the forces a dam faces or the resistances it exerts. Although dams have many possible failure modes (including piping and overtopping) there currently exists "no systematic way of analyzing the degree of uncertainty and its effect on the safety of a design" [p. 9]. Moreover, due to a lack of scientific knowledge engineers usually do not know the factors of safety for each failure mode. However, the author states that, "lack of statistical data is not a valid reason for rejecting probabilistic concepts and methods. Indeed, it is only through probabilistic models that the significance of objective information, or lack thereof, can be properly assessed and combined with engineering judgment to provide a quantitative assessment of the safety of a dam" [p. 63].

The author provides load and resistance models to evaluate safety in terms of the uncertainty in a system's parameters. Uncertain parameters include the height of the water in a reservoir and the earthquake acceleration coefficient. The models use reliability theory to approximate failure probabilities to the first order given probability distributions for all of the system's parameters. Deciding which distributions to use presents a problem because of the limited data available to describe distributions for the extreme events of interest. Furthermore, the distributions chosen may affect results when the failure probability is small. Prendergast applies the models he develops to two simple examples.

Cheng, S., B.C. Yen, and W.H. Tang, Overtopping Risk for an Existing Dam, *Civil Engin. Studies, Hydraulic Engin. Series No. 37,* 195 pp., University of Illinois at Urbana-Champaign, Urbana, IL, 1982.

The authors state that the US dam safety inspection program "lacks the systematic and scientific basis for quantitative assessment of the safety of dams" [p. 4] and suggest that safety studies require a probabilistic approach. They compare several methods for estimating the risk of overtopping at a dam, including Direct Integration, Monte Carlo, Mean-Value First-Order Second-Moment (MFOSM), and Advanced First-Order Second-Moment (AFOSM) analyses. The authors examine several geophysical forces which may cause overtopping of a dam. They then concentrate on floods and wind and only touch on landslides and earthquakes. To estimate the probability of overtopping, the authors use fault tree analysis and assume that the extreme events that may cause overtopping arrive with a Poisson process.

The MFOSM approximates the dam's performance function by using a Taylor Series expansion about the mean value of the performance function; the AFOSM method uses a Taylor Series expansion about the failure point (an extreme area of the performance function). They conclude that while the Monte Carlo method is superior with respect to accuracy, invariance, and sensitivity, the AFOSM method's lower computational costs make it the best overall. The paper includes a demonstration of the AFOSM procedure using an example earth dam. The authors note difficulty in finding the true risk because most models neglect variables which may be important. In their study, flooding causes most overtopping; wind has a much smaller effect.

Kreuzer, H., and K. Bury, A Probability Based Evaluation of the Safety and Risk of Existing Dams, *Proceedings of the International Conference on Safety of Dams,* 61-71, Coimbra, Portugal, 1984.

Typically engineers calculate safety factors using single deterministic values for load and resistance and use the ratio of their means to describe the degree of safety for a project. In reality, a dam's load and resistance are uncertain. The authors develop a probabilistic method for evaluating dam safety. They elect to use failure probability as the safety criterion. The five failure modes considered are:

I. Aging
II. Persistent Overtopping
III. Transient Overtopping
IV. Earthquake
V. Foundation Instability

They consider three means for resisting failure: Material Strength, Shear Resistance, and Erosion Resistance.

For each failure mode, the probability of dam failure due to that mode is estimated analytically: First, the authors decide which mechanisms will resist failure and employ a normal probability distribution function to describe that resistance. Second, they use a Gumbel distribution to describe each load. Both of these steps use experimental data to estimate the parameters of the distribution. Third, they calculate the interference of these two distributions, the probability that the load exceeds the resistance. At this point, engineers can compare these failure probabilities for the different failure modes to determine which is most likely. Finally, the sum of the failure probabilities provides an approximation of the dam's safety. decision-makers can use this number to compare safety levels of different dams. The authors suggest that modifying the distributions or the failure probabilities can account for failure modes which lack analytical descriptions.

GENERAL RISK METHODOLOGIES

Bernier, J.M., Elements of Bayesian Analysis of Uncertainty in Hydrological Reliability and Risk Models, in *Engineering Reliability and Risk in Water Resources*, Duckstein, L., and E. Plate (eds.), pp. 405-422, M. Nijhoff, Dordrecht, the Netherlands, 1987.

The author states that two types of uncertainty exist in water resources problems:

1) Natural uncertainty due to nature's randomness, which includes precipitation and river discharge. Probability distribution functions can represent this uncertainty.
2) Technological uncertainty results from measurement error, inadequate modeling, and other similar errors.

This paper explores the ways in which classical decision theory and Bayesian statistical methods can deal with technological uncertainty.

The author sets up a reliability model for a system where failures occur as a Poisson process with a natural failure rate, but where the decision-maker can choose to reduce the failure rate at a cost. The problem is then to decide how much to reduce the failure rate. Bernier also discusses including decision rules (especially Bayes' Rules) to map the observed system behavior into decisions, and ranking the decision rules in terms of value using the "risk function" (the expected loss associated with a decision rule). Bernier considers using pre-posterior analysis to determine the value of information and experimentation.

Haimes, Y.Y., and W.A. Hall, Sensitivity, Responsivity, Stability and Irreversibility as Multiple Objectives in Civil Systems, *Advances in Water Resources, 1*(7), 71-81, 1977.

The authors propose that water resources management models should consider sensitivity, responsivity, stability, and irreversibility as objectives in a multi-objective analysis framework where:

> *Sensitivity* relates changes in the system's performance index (or output) to possible variations in the decision variables, constraint levels and uncontrolled parameters...
>
> *Responsivity* represents the ability of the system to be dynamically responsive to changes...in the decisions...
>
> *Stability* relates to the degree of variation of the mean system response to fixed decisions...
>
> *Irreversibility* measures the degree of difficulty involved in restoring previous states or conditions once the system has been altered by a decision.

They suggest that these characteristics can be given quantitative values, and that decision-makers should explicitly control them. The authors assert that an easily calculated, pertinent, and understandable "index" should represent each of the characteristics in multi-objective analyses.

Errors affect a model's characteristics. The authors identify six sources of error:

1) model structure

2) model parameters
3) model scope
4) data
5) optimization techniques
6) human subjectivity.

The authors assume that analytical functions relate the errors to the system characteristics.

Hashimoto, T., J.R. Stedinger, and D.P. Loucks, Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation, *Water Resour. Res.*, *18*(1), 14-20, 1982.

The authors argue that the mean and variance of a system's outputs, often used in practice to choose between alternative water resource system proposals, may not adequately describe system performance. The mean and variance may not illustrate the severity and frequency of failures in systems and cannot tell whether an alternative with an improved mean output but higher variance is an overall improvement.

They advocate using risk-related performance criteria to better communicate how a water resource system might operate. Reasonable criteria include:

Reliability - the system failure probability
Resiliency - the speed with which the system returns to a satisfactory state after a failure
Vulnerability - the likely severity of failures when they occur

Use of these criteria with traditional expected benefits and costs in multi-objective analyses may allow decision-makers to see the trade-offs between conflicting objectives and attributes of system performance. Decision-makers should realize that attempting to increase reliability (for example by raising the height of a dam) may also increase vulnerability (the damages and loss-of-life which occur if the dam fails). Pointing to the need to recognize low-probability but high-consequence failures, the authors suggest that vulnerability should be an important criterion in project planning.

Fiering, M.B, A Screening Model to Quantify Resilience, *Water Resour. Res. 18*(1), 27-32, 1982.

The author defines resilience as a system's ability to accommodate and recover after surprises. Establishing a water resource system by simply minimizing cost may lead to "brittle" (unresilient) systems.

The author studies the problem of locating reservoirs among 8 possible parallel sites. The results showed that the system's resilience increases with the number of design options. Systems with more options are also more amenable to political and institutional negotiations. The author concludes that simple cost criteria may not capture the importance of a system's redundancy, which has a significant influence on its flexibility in unusual situations, and its ability to return to normal after a disaster.

Hashimoto, T., D.P. Loucks, and J.R. Stedinger, Robustness of Water Resources Systems, *Water Resour. Res.*, *18*(1), 21-26, 1982.

The authors propose "robustness", a "measure of the likelihood that the actual cost of a proposed project will not exceed some fraction of the minimum possible cost of a system designed for the actual future conditions" [p. 21], as a criterion for project planning. A project which engineers can modify in a cost-effective manner to meet a range of actual conditions may be considered more desirable than one that is cost effective only for the most likely demand condition" [p. 21]. Decisions should account for possible (adverse) effects which may result when future conditions do not match those anticipated during the project's planning.

The authors show that using expected project costs and cost variance to choose between alternatives may not adequately account for this uncertainty. Their criterion, "robustness", describes the ability of a design or proposed project to deal with uncertain future conditions. Adapting a robust project to conditions different from those for which the system was designed should cost less than if a less robust design had been adopted.

Duckstein, L., E. Plate, and M. Benedini, Water engineering reliability and risk: a system framework, in *Engineering Reliability and Risk in Water Resources*, Duckstein, L., and E. Plate (eds.), pp. 1-20, M. Nijhoff, Dordrecht, the Netherlands, 1987.

The authors set up a general framework which decision-makers can use to compare the consequences of alternative decisions and operating rules in a multiple-criteria analysis. A discrete-time, discrete-state model approximates the system's behavior. The framework consists of the following components:

1) Inputs, both controllable and uncontrollable
2) System state variables
3) The state transition function
4) Output (performance indices)
5) The output function, which may be a "figure of merit" (some combination of performance indices, calculated from sequences of observances).

An "incident" occurs when the load on the system exceeds the system's resistance. The authors suggest 10 performance indices and illustrate their calculation with alternative operation rules for a reservoir in the Black Forest in Germany.

Reid, S.G., Frequency-Cost Curves and Derivative Risk Profiles, *Risk Analysis, 7*(2), 261-67, 1987.

The paper discusses the presentation of the risk and cost information from a risk-analysis study and suggests that total expected costs and the distribution of expected costs should have great importance to decision-makers. He indicates that the commonly used frequency-cost curves (which actually show cumulative or exceedance frequency versus cost) do not show expected costs and may even conceal rare, catastrophic events which may contribute significantly to total expected costs.

The author suggests the use of total expected costs and several new functions: the "frequency density function", the "expected cost density function", and the "cumulative expected cost function". The author gives graphical examples of the functions he recommends based on a widely quoted example from a Nuclear Regulatory Commission study. The study includes a frequency-cost curve showing that 100 nuclear power plants and meteorites result in quantitatively similar risk spectrums.

The author derives the "frequency density function" which shows the frequency of occurrence of different events as a function of their magnitude. In constructing a frequency density function for the NRC example, the author extends the frequency-cost curve into extreme damage levels. The resulting frequency density function for this example suggests that meteorites will result in catastrophic losses more often than the power plants.

The author derives a third type of function, the "expected cost density function", which shows the distribution of expected costs as a function of costs. Using the NRC example, the author constructs the appropriate expected cost density function which suggests that the density of expected costs for the power plants becomes small at fatality levels greater than 10^4. By contrast, the expected cost density function for meteorites does not reach such small levels until fatalities are greater than 10^7.

Integrating the expected cost density function over cost yields a fourth function, the "cumulative expected cost function". For large costs, this function approaches the total expected costs due to all events. For the NRC example, the cumulative expected cost functions suggest that meteorites will cause significantly more fatalities per year than 100 nuclear power plants, with most of the expected costs due to events causing 1000 or fewer fatalities.

ECONOMICS AND PLANNING

Task Committee on the Reevaluation of the Adequacy of Spillways on Existing Dams of the Committee of Hydrometeorology of the Hydraulics Division, Reevaluating Spillway Adequacy of Existing Dams, *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 99,* No. HY2, 337-372, 1973.

When evaluating actions to modify dam spillways, the Committee proposes that an economic analysis of risk costs and modification costs determine the appropriate modification. The best modification will minimize the sum of these costs. They also make the controversial suggestion that engineers should assign a monetary value to human life in the analysis, stating that "the engineering profession should delay no longer the use of monetary human values in the economics of spillway design" [p. 341].

They extend the proposal to new dams, stating that "standards to judge adequacy of spillways of existing dams should not differ from standards for the design of proposed new dams" [p. 339]. The Committee criticizes the use of the PMF as a design standard because it "overlooks the difference between the loss of a few lives or many lives and offers no measure of the magnitude of property damage" [p. 341]. The authors illustrate use of the procedure with a study of an example dam.

Baecher, G., M.E. Paté , and R. de Neufville, Risk of Dam Failure in Benefit-cost Analysis, *Water Resour. Res., 16*(3), 449-456, 1980.

The authors propose that benefit-cost analyses for new dams incorporate the economic costs of dam failure by deducting the expected cost of failures from net project benefits. Economic failure costs include property damage, the value of lost future dam benefits, lost economic activity, and emergency costs. Failure costs change over time in response to economic development. The analysis does not account for possible changes in downstream demographics and the location of property after a dam failure. They note that adoption of a project whose failure would cause loss of human life at least implicitly assigns some value to such losses.

The authors conduct an analysis of dam failure data and find that about half of all dam failures occur within five years after construction, with the other half distributed fairly uniformly with age. However, pending further studies they suggest that economic analyses use a constant failure rate of 10^{-4}/year.

Paté -Cornell, M.E., and G. Tagaras, Risk Costs for New Dams: Economic Analysis and Effects of Monitoring, *Water Resour. Res.*, *22*(1), 5-14, 1986.

Paté -Cornell and Tagaras [1986] continue the argument made by Baecher et al. [1980] for including risk costs in cost-benefit analyses and expand the methodology for risk cost evaluation to dams in a series. In the case of a project consisting of building a new dam in sequence with an existing dam, they state that the cost-benefit analyses should consider the marginal risk cost associated with the new dam, which includes its interaction with other structures.

As illustrated by three real-world examples, (Teton Dam in Idaho, Dickey-Lincoln School Project in Maine, and Auburn Dam in California) the authors show that risk costs (expected costs) can have an important effect on a project's benefit-to-cost ratio when the dam has a large or heavily populated floodplain and the project costs and benefits are relatively small. The dam failure probability and the value of life used in the analysis can be important. Including risk costs in analyses with large failure probabilities (10^{-3}/year) and/or a $1 million value per life markedly decreases the benefit-to-cost ratios for Teton Dam and Auburn Dam. Accounting for the expected cost of failure allows the decision-maker to more nearly maximize expected social utility. The authors argue that managers can implement warning systems which can, while imperfectly, still decrease risk costs and the expected loss-of-life.

Paté -Cornell, M.E., Warning Systems in Risk Management: the Benefits of Monitoring, in *Risk Analysis and Management of Natural and Man-made Hazards*, pp. 253-67, Haimes, Y.Y., and E.Z. Stakhiv (eds.), American Society of Civil Engineers, New York, NY, 1989.

The author presents a methodology for probabilistically evaluating and optimizing warning systems. Models describing a warning system's signal, response, and consequences are combined to formulate warning system benefits. A Bayesian framework is used to calculate the value of warning information for a hypothetical earth-filled embankment dam, neglecting the effect of false alerts on people's willingness to respond (the cry-wolf effect).

Focusing on human response to warnings, the author distinguishes between systems with frequent warning events and those in which warnings occur rarely. In the former case, memories of past warning system performance will affect response. To describe this effect, the author discusses 3 models: a non-parametric Markov model, a parametric model, and a normative model. The optimal system sensitivity depends on the trade-off between early warning and the cry-wolf effect. When warning events occur rarely, the cry-wolf effect will not be important, and the author discusses psychological and sociological response models for such situations.

RISK AND COST BASED PLANNING METHODOLOGIES

McCann, M.W., Jr, J.B. Franzini, E. Kavazanjian, and H.C. Shah, Preliminary Safety Evaluation of Existing Dams, Vol. 1-2, Rep. 69, John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA, 1985.

This report, prepared for the Federal Emergency Management Agency, proposes a screening procedure using risk analysis for allocating funds to upgrade safety across a set of dams. The techniques used are relatively simple and intended to save money, or at least allocate a budget reasonably. The authors stress that these techniques only predict relative, not absolute, risk.

Volume I contains the theory behind the screening process which combines Bayesian analysis with classical decision theory. This process can prioritize dams for allocating funds either to upgrade safety or to do more extensive studies. The prioritizing process constitutes an example of decision-making under uncertainty. The process consists of two steps: 1. assessing safety and 2. creating a rule for ranking the dams. Volume II provides a users manual for the screening process. This method is primarily intended to help dam safety managers who must upgrade safety within a budget.

National Research Council, Committee on Safety Criteria for Dams, Water Science and Technology Board, *Safety of Dams: Flood and Earthquake Criteria*, 276 pp., National Academy Press, Washington, D.C., 1985.

The report provides an overview of dam safety criteria and issues. The Committee discusses three alternative approaches to evaluating dam safety:

1) The Deterministic Approach with its safety criteria based on the PMF
2) The Probabilistic Approach with its safety defined as a flood with a specified exceedance probability
3) Risk Analysis which determines the appropriate level of safety from an economic analysis of risks and prevention costs

While the Committee feels that risk analysis might be useful, they note that actually applying risk analysis in practice has several problems. Risk-analysis studies may be expensive to conduct and the results may be sensitive to imprecisely known probabilities of extreme hydrologic events.

With regard to the PMF (deterministic) criteria, the Committee notes several problems with that approach too. For many regions of the country, estimates of the PMF have increased in recent years due to increased data and new estimation methods. This has necessitated reevaluation of dam safety and the need for remedial actions. In addition, designing for the most recent PMF estimate may not provide as much safety as the phrase "probable maximum flood" implies. The Committee notes that a dam which could pass the latest estimate of the PMF for the site is not necessarily safe for any possible flood. The inability of the method to allocate economic resources efficiently is another problem. "Some Committee members felt such a design basis, in some cases, results in extravagant use of resources...." [p. viii]

The Committee recommends that engineers continue to use the PMF as the Safety Evaluation Flood (SEF) for proposed new high-hazard dams. It stresses the importance of using incremental damages

(damages in excess of those which would occur if the dam did not exist) for safety analyses. They recommend that engineers use an SEF smaller than the PMF in cases where the PMF would not cause more (incremental) damage than the lower SEF.

Engineers may use different standards for existing dams. For existing high-hazard dams which cannot pass their SEF, the Committee recommends using risk analysis to aid in (retrofit) decisions. The Committee notes that risk analysis provides a site-specific and rational method for allocating (retrofit) funds.

Task Committee on Spillway Design Flood Selection, Surface Water Hydrology Committee, Hydraulics Division, *Evaluation Procedures for Hydrologic Safety of Dams*, American Society of Civil Engineers, New York, NY, 1988.

The Task Committee proposes methods for determining safety design floods for both new and existing dams based on a quantitative risk assessment, which use the likelihood and consequences of dam failures. The consequences of dam failure and the effort required to select a safety design flood form the basis for the Committee's proposal to place dams into three categories. For Category 1 dams, failure would have very high consequences, and the Committee recommends using the Probable Maximum Flood (PMF) as the safety design flood. Failure of Category 3 dams would result in modest damages, and the dam owner would suffer all or most of that damage. In this case, the safety design flood may be lower than the PMF if a lower safety design flood would benefit the dam owner economically. Both Category 1 and Category 3 dams require only a "reconnaissance level" investigation to determine failure consequences. Category 2 dams have damages somewhere between Category 1 and Category 3 damages, and the Committee recommends a detailed study to select a safety design flood based on failure probability, failure consequences (monetary and other costs), and retrofit and construction costs.

With respect to Category 2 dams, engineers should estimate the PMF and use the economic and social consequences of failure in a decision-making process based on a quantitative risk analysis. The appropriate safety design flood for Category 2 dams is the PMF unless risk analysis justifies a lower standard. Although quantifying probabilities for rare events presents a problem for risk analysis in dam safety, "The committee concludes that it is possible to define flood probabilities throughout the full range of potential flooding with sufficient accuracy to make the comparisons necessary for the safety design flood selection" [p. 4]. Failure costs should only include incremental costs, that portion of the flood damage attributable to dam failure.

The Committee makes the controversial proposal that Category 2 dam owners should at all times maintain the funds necessary to pay the prospective victims of a dam failure for potential financial losses (indemnification). The report also recommends considering social and environmental consequences, but not in the indemnification calculation. Dam owners can achieve indemnification by an insurance policy, self insurance, or an escrow account. They state that, "The cost of indemnification, rather than the flood damage itself, is taken as the proper measure of damages sustained by parties other than the dam owner...." [p. 19] The Committee anticipates that if the proposed quantitative risk-analysis process is generally adopted, the technical aspects of the analysis will improve with use. [p. 4]

Bureau of Reclamation, Guidelines to Decision Analysis, *ACER Technical Memorandum No. 7*, U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, 1986.

This report summarizes the Bureau of Reclamation's recommended guidelines for dam safety studies. It provides general and simple step-by-step instructions for performing an analysis to evaluate alternative solutions to engineering problems, and the resolution of dam safety issues in particular. This framework can be used to evaluate new dams or modifications to existing dams. The evaluation focuses on determining risk costs: "the expected value of the risk and adverse consequences for a given hazard." The framework consists of the following steps and associated questions which determine the appropriate analysis for a project:

1) Define the Problem
2) Describe the Pertinent Site Conditions
3) Identify the Potential Loading Conditions
4) Determine the System Response

Will the system fail under the prescribed loading?

5) Perform the Hazard Assessment
    i) For failure events, are the downstream consequences worse than the non-failure consequences?
    ii) Is a risk cost analysis required?
6) Calculate the Risk Costs
7) Develop and Evaluate Alternative Actions

Establish appropriate decision criteria (see below) and repeat analysis in steps 4-6.

8) Prepare Appropriate Documentation

A sensitivity analysis comprises an integral part of the framework. It should show the importance of uncertain parameters, functions, and models used to calculate risk costs. An example analysis for an embankment dam illustrates the use of this decision analysis framework. Factors which are appropriate for objective, comprehensive, and informed decisions, in "recognition of costs and benefits" include:

1) potential loss-of-life and any change,
2) potential property damage and significant change,
3) probability of dam failure and its value relative to historical failure rates and those for an average dam,
4a) relative magnitude of the failure and the owner and region's ability to tolerate such a loss,
4b) potential loss of public confidence and potential suits against government officials,
5) benefit-cost (and B/C ratio) economic analysis
6) relative size of modifications to total project, funding availability, and confidence in modification, and
7) other factors, including site-specific issues and precedents.

The report concludes that such "decision analysis should serve as the primary technical input to the decision-making process."

Stakhiv, E.Z., and D. Moser, Guidelines for Evaluation of Modifications of Existing Dams Related to Hydrologic Deficiencies, IWR Report 86-R-7, Office of the Chief Engineer, U.S. Army Corps of Engineers, Fort Belvoir, VA, October 1986.

The authors propose a hazard assessment procedure to aid in spillway retrofit decisions. The method aids in decisions between alternatives, based on a comparison of the economic consequences and possible loss-of-life with and without each alternative under both failure and non-failure conditions. Phase I of the procedure includes a screening process to determine if a dam's spillway needs upgrading to the PMF and a method for evaluating alternative remediation plans for those dams which require remediation. Phase I includes:

Describing the Physical Project Characteristics
Determining the Existing Threshold Flood
Determining Total Flows and Downstream Inundation from the Threshold Flood "with and without" Dam Failure and from Lesser Floods
Determining Hypothetical Maximum Flooding
Preparing Inundation Maps and Collecting Data on Damageable Property and Populations for the Hypothetical Maximum Flooding, the Threshold Flood, and lesser events
Determining Economic Losses from the Threshold Flood and Specified Lesser Floods
Determining Dam Failure Warning Time
Displaying Existing Condition Results and Proposing Additional Action
Identifying Alternatives to Reduce the Dam Safety Hazard to People and Property
Evaluating the Costs of Modification Alternatives
Evaluating the Alternatives in Terms of their Effectiveness in Reducing the Hazard
Determining the Base Safety Condition
Recommending an Alternative to Meet the Base Safety Condition
Determining whether Breaching the Dam should be Evaluated as an Alternative

The authors include an illustrative example of the Phase I procedure. Phase II presents risk-cost analysis techniques.

SAMPLE RISK STUDIES

Langseth, D.E., and F.E. Perkins, The Influence of Dam Failure Probabilities on Spillway Analysis, *Proc. of the Conference on Frontiers in Hydraulic Engineering*, 459-464, American Society of Civil Engineers, New York, NY, 1983.

Traditionally, engineers have designed spillways by choosing a spillway design flood based on the flood record. This approach implicitly accounts for the probability of failure. However, the paper shows that this approach ignores important complexities in the trade-off between spillway size and safety. The authors employ a water routing model for a catchment, with runoff emptying into a dam, out into a river channel, and by potential damage sites. Their model assumes a known distribution for reservoir inflow, antecedent reservoir conditions, the reservoir state at which overtopping failure occurs, and the state at which non-overtopping failure occurs. The simplicity of their model (only three random variables, all independent of each other) allows the authors to estimate a distribution for damages using direct enumeration. This technique discretizes the events into intervals, assigning a "representative" event and probability to each range. For every possible combination of representative events the model yields a damage level, and for each damage level probability theory yields a probability.

To illustrate the model's use, the authors apply it to four earth-filled dams in New England which have different levels of safety. Results show that expected damage at a site does vary with spillway size, but not in the way that engineers have traditionally assumed. Engineers have generally thought that safer dams have larger spillways. [p. 464]. However, the interaction between non-failure damage (which increases with larger spillways) and overtopping failure damage (which decreases with larger spillways) results in total expected damages which can "increase, decrease, or pass through a minimum as the spillway size increases" [p. 464]. The distribution of damage depends on the damage function and the dam characteristics. The authors conclude that the risk analysis approach may provide valuable insights that traditional deterministic methods do not.

Stedinger, J.R., and J. Grygier, Risk-Cost Analysis and Spillway Design, in *Computer Applications in Water Resources*, edited by H.C. Torno, pp. 1208-17, American Society of Civil Engineers, New York, NY, 1985.

The authors elaborate on their proposal in the National Research Council report [NRC, 1985] to use risk analysis for balancing between economic damages due to floods and dam failure, and the cost of structural and other modifications in spillway retrofit decisions. Using a simple example dam (whose current spillway cannot pass the most recent PMF estimate), they examine the sensitivity of risk analyses to several parameters, including the PMF's return period and magnitude. They estimate the frequencies of rare floods by extrapolating from a known frequency distribution for common floods to a PMF with an assumed return period.

The results of their example show that the return period assigned to the PMF in the analysis and the distribution function chosen to extrapolate from the known frequency curve to the PMF can influence the ranking of alternatives primarily because of its impact on the probability assigned to the less rare floods in the indicated range. Making an error with respect to the damage function seems less important.

Resendiz-Carrillo, D., and L.B. Lave, Optimizing Spillway Capacity with an Estimated Distribution of Floods, *Water Resour. Res.*, *23*(11), 2043-2049, 1987.

The authors argue that emergency spillways for large dams should be sized to minimize total social cost by

1) estimating the distribution of peak flows from historical data,
2) estimating the relationship between spillway capacity and cost,
3) estimating the losses from dam failure and also lesser floods which would not cause dam failure, and finally
4) minimizing net social cost, which is the sum of construction costs and the present value of expected damages due to floods and dam failure.

They observe that "preventing dam failure is not an end in itself, but rather a way of controlling flood losses and preserving an expensive investment."

The authors provide an illustrative example for a hypothetical dam on the Rio Grande River at Embudo, New Mexico. Based on a naive and sample-specific analysis, they argue that 20 years of annual flood data would be sufficient to provide a "reasonable characterization" of the 500-year flood for the site using maximum likelihood estimators for the extreme value type 1 (EV1) distribution [which are known to be stable estimators, but are only accurate if the data is actually from an EV1 distribution]. The example also assumes that flood damages do not vary with spillway and dam size, and that the damages caused by a dam-failure flood would be no worse than those caused by the flood had the dam not failed; thus, the issue is only how big to build the spillway given the replacement cost of the structure should it be destroyed by overtopping.

Their analysis does not consider either the interaction between spillway size and reserved flood control storage capacity or the volume and timing of inflow hydrographs, which together determine if there is sufficient capacity to store the difference between inflow and outflow in the dam without overtopping. In their conclusion, the authors note that sizing dam spillways is an important and difficult decision, and that their method offers a "systematic approach that uses available data and can be subjected to scientific evaluation."

Haimes, Y.Y., Petrakian, R., P.-O. Karlsson, and J. Mitsiopoulos, Multi-objective Risk-partitioning: an Application to Dam Safety Risk Analysis, IWR report 88-R-4, 106 pp., U.S. Army Institute for Water Resources, Fort Belvoir, VA, 1988.

The authors suggest that while traditional statistical techniques may be appropriate for assessing risk, they may not constitute an appropriate method for solving risk-management problems. The traditional expected value approach "is inadequate and may lead to fallacious conclusions when applied to risks associated with extreme and catastrophic events and where public policy issues are involved" [p. ix]. They note that expected values commensurate events of low probability and high consequence with those of high probability and low consequence. This commensuration "... distorts, and almost eliminates, the distinctive features of many viable alternative policy options that could lead to the reduction of the risk of dam failure" [p. xi].

The authors endorse using traditional expected values in conjunction with a conditional expectation that represents the consequences from low-probability events. Analysts can use the partitioned multi-objective risk method (PMRM) to generate the conditional expectation. Evaluating the applicability of the PMRM to a real "idealized" dam "...showed that the PMRM was indeed superior to the use of the unconditional expected value" [p. x].

Sensitivity analyses of the results show that the PMRM's conditional expectation is sensitive to both the return period assigned to the PMF and the distribution chosen to extrapolate between the flood frequency curve and the PMF. The traditional unconditional expectation demonstrates little sensitivity to these factors. The authors state, "Contrary to the conclusions advanced by the traditional unconditional expectation of risk, the proper and representative value of the return period of the PMF used in the analysis of dam safety has major significance" [p. xii].

Karlsson, P., and Y.Y. Haimes, Risk-Based Analysis of Extreme Events, *Water Resour. Res.*, *24*(1), 9-20, 1988.

Problematic decisions which involve risk have traditionally been based on mathematical expectations. The authors state that this approach is "not appropriate for decision-making that affects public policy because it conceals extremes by commensurating events of different magnitudes and probabilities of occurrence" [p. 7]. They argue that people have an aversion to catastrophes, and because of this, decision methodologies should give catastrophes greater weight than they receive using traditional expected costs.

The partitioned multi-objective risk method (PMRM) provides a set of conditional risk functions which represent the loss, given that the exceedance probability for the damage event falls within specific probability ranges. The authors advocate using such conditional damage functions in the decision-making process. They derive a closed form expression for the conditional damage function when only a single random variable affects damage.

Karlsson, P., and Y.Y. Haimes, Probability Distributions and Their Partitioning, *Water Resour. Res.*, *24*(1), 21-29, 1988.

The PMRM (discussed above) partitions a probability distribution function's probability axis into ranges to define conditional risk functions. The authors show that the risk functions depend on the chosen probability ranges and on the distribution used to fit the available data to the original, unpartitioned probability distribution function. The authors quantify the sensitivity with respect to the partition ranges and provide several approximate formulas.

Petrakian, R., Y.Y. Haimes, E. Stakhiv, and D. Moser, Risk Analysis of Dam Failure and Extreme Floods, in *Risk Analysis and Management of Natural and Man-made Hazards*, pp. 81-121, Haimes, Y.Y., and E.Z. Stakhiv (eds.), American Society of Civil Engineers, New York, NY, 1989.

The authors apply the PMRM to a dam safety example with the Surrogate Worth Trade-off Method (SWTM). They examine the sensitivity of the method's results to the partitioning of the probability axis, the return period assigned to the PMF, and the extreme flood distribution. They conclude that the PMRM/SWTM combination can be implemented easily and that it can improve decision-makers' understanding of problems. Their analysis shows that the results are sensitive to the PMF's return period and the chosen flood distribution. The conditional expectations for the partitions exhibited what is thought to be an "undesirable" sensitivity to the choice of partitioning points, and reversals in the ranking of alternatives occur, especially when failure damages are of the same order as non-failure damages. The authors suggest partitioning the damage axis as a possible solution.

Karlsson, P.-O., and Y.Y. Haimes, Risk Assessment of Extreme Events: Application, *J. Water Resources Planning and Management, 115*(3), 299-320, 1989.

Using a revision of Stedinger and Grygier's 1985 example, the paper explores the use of PMRM, and PMRM based upon partitioning of damages by calculating the conditional expected damages given that an event is in a damage range. With damage partitioning, the conditional expectations of damages in the high-risk interval vary little from alternative to alternative and are not much larger than the lower endpoint of the most extreme interval. The authors also see the results as being less intuitive. They develop analytical approximations for the low-probability partition's conditional expectation, f_4, which are useful for problems with a single random variable (such as flow) and a continuously differentiable and monotone loss function. Calculations of f_4 (partitioning at the PMF so that only larger events are considered) and of the unconditional expected damages illustrate trade-offs among six alternatives with five different flood distributions and two PMF return periods. When f_4 corresponded to floods greater than the PMF, the authors observe that fitting a thin-tailed distribution between the 100-year flood and the PMF with a specified return period (the two-point method) yields smaller f_4 values than if a thicker-tailed distribution is used; this is in contrast to Haimes et al. [1988] who observe the opposite when considering only floods less than the PMF in the calculation of f_4. The paper also observes that the unconditional expected damage is very sensitive to the chosen flood distribution (as it should be).

DISCUSSIONS OF RISK METHODOLOGIES

Fan, S., Hydrologic Evaluation of Dam Safety, *Proc. of the Conference on Frontiers in Hydraulic Engineering*, 451-458, American Society of Civil Engineers, New York, NY, 1983.

The author presents a general overview of the many techniques used to determine inflow design floods (IDFs) and their history. The discussion focuses primarily upon the hydrometeorological approach used to obtain PMPs and PMFs, with a few comments upon frequency analysis methods. The author emphasizes the importance of hazard evaluations and the information that they provide about damage, fatalities, and lost revenue.

The author concludes that hydrologic evaluations should include economic information and the dam's design and operation. Lack of data can render flood frequency analyses unreliable, while land use and possible climate changes can undermine the reliability of historical data used by both the hydrometeorological and frequency analysis methods. Hazard analyses should include the potentially significant effects of accumulated sedimentation on dam-break damages. The author advocates using a "cost effective" approach (like risk analysis) to determine inflow design floods for low- and medium-hazard dams.

Cooper, C.L., A Case for Selecting Only Deterministic Spillway Design Floods for High Hazard Dams, *Water Power '87: Proceedings of the International Conference on Hydropower,* 1148-1157, American Society of Civil Engineers, New York, NY, 1987.

In this article, the author expresses his opinion from his perspective as a Federal official. He argues that the use of deterministic probable maximum floods for high-hazard dams where failure would be "unacceptable" over flood frequency methods and risk analyses is supported by Federal Energy Regulatory Commission (FERC) project files, the 1984 Federal Guidelines for Accommodating Inflow design floods, the 1985 National Research Council Report on Safety Criteria for Dams, and the 2-year study conducted by a Inter-agency Advisory Committee which issued its report in 1986 and which concluded that literature indicates that "extrapolation of the frequency curve does not provide experimentally defensible estimates of flood probabilities much beyond those defined by the length of record." He is concerned with the human error rate in flood studies, which he judges would be lower with PMF studies. He concludes that "flood probability and risk analyses used to select spillway design floods do not provide the necessary confidence that public safety requires for the design of high-hazard dams...."

Moser, D.A., and E.Z. Stakhiv, Risk Analysis Considerations for Dam Safety, in *Engineering Reliability and Risk in Water Resources*, Duckstein, L., and E. Plate (eds.), pp. 175-200, M. Nijhoff, Dordrecht, the Netherlands, 1987.

The authors provide an overview of the many problems which arise when applying different decision criteria and risk-analysis methodologies to the evaluation of remediation alternatives to improve dam safety. Public decision-making has incorporated risk analysis into dam safety analyses using three distinct philosophies:

a) regulatory-type decision processes based on fixed safety standards which designs must satisfy resulting in least-cost deign and cost-effectiveness analyses,
b) normative decision-making with explicit or implicit decision rules (including benefit-cost analysis, and maximization of net benefits as in WRC's "Principles and Guidelines"), and
c) "eclectic, relativistic decision-making" based on a multiple objective decision processes which explicitly derive importance factors reflecting articulated preferences (multi-objective optimization, multi-criteria utility theory).

Many practicing engineers are reluctant to replace traditional, deterministic worst-case analysis for dam planning with risk analyses. Public decision-makers may favor using conservative, "worst-case" planning because they are responsible for public safety and legally liable for their decisions. Risk-analysis methods often rely on an expected value which "implicitly weights the outcomes in a manner which may not be relevant to the evaluation of a low-probability, high-consequence event, such as dam failure. For such events a 'min-max' or 'worst-case' approach seems to be more appropriate than an 'expected value' viewpoint" [p. 177].

The authors also discuss the sources of uncertainty in dam safety analysis including the actual size of the PMF, the exceedance probability of the PMF, the probability distribution for floods over the relevant range, the depth of overtopping needed to cause failure, breaching characteristics of any failure, estimates of the population at risk and loss-of-life, the operation of warning and evacuation systems, the economic losses of such an extreme and unique event as a dam failure, and its impact on a region's economy.

An example using real reservoir data makes the authors' point that safety proposals often present an uncomfortable trade-off because "...decision-makers must consider an incommensurable substitution of more frequently occurring economic damages (widening the spillway) for a more remote possibility of an even greater magnitude catastrophic dam failure (raising the dam)...." [p. 191] The authors conclude that the appropriate handling of risk depends on the type of risk, especially whether exposure is voluntary or involuntary. When risk is voluntary, its effect can be included in a cost-benefit analysis "by modeling individual choices under uncertainty" [p. 198]. Decisions involving involuntary risk should include equity as an objective as well as economic efficiency.

Introduction

An example in the text illustrates the probabilistic dam-safety risk-analysis procedures proposed in this report. That example employs physical dam characteristics and hydrologic and meteorological parameters similar to a dam in the Northeastern U.S. The characteristics of the hypothetical dam and the distributions used to describe various random meteorological and hydrologic events are described below. These data are a composite of data describing the dam and its drainage basin, general regional meteorological and hydrologic parameters, and reasonable values assigned to complete and to create an illustrative example. This study has drawn heavily upon the report by McCann et al. [1985, Volumes 1-2], *Preliminary Safety Evaluation of Existing Dams* for the flood routing and dam break models.

Physical Characteristics of the Dam

The basic dam is an earth-filled structure which rises from a ground elevation of 931 feet to a crest elevation of 995 feet. The emergency spillway begins operation when the storage level in the dam reaches an elevation of 976.5 feet. When full to the top of the embankment, the storage pool has a volume of 265,500 acre-feet. When full to the spillway crest, the storage pool contains 69,600 acre-feet of water. The total length of the dam is 5,600 feet, including the 150 foot spillway.

Basin Characteristics and Storm Hydrograph

The drainage basin for the dam has an area of 600 square miles with an elevation difference of 1,000 feet (HW). The total length of the watercourse is 40 miles (LW).

The storm hydrograph for rainfall impacting upon the basin was constructed using the model proposed by McCann et al. [1985, Volume 2, p. 3-7 through 3-9]. Using the Kirpich equation that they recommend, the time of concentration (TC) is

$$TC = [11.9(LW)^3/HW]^{0.385}$$

[McCann et al., 1985, Volume 1, p. 3-12]. For LW =40 miles and HW = 1000 feet, this equation yields a time of concentration for the basin of

$$TC = 12.8 \text{ hours.}$$

McCann et al. recommend that the duration of the design storm should be a function of the time of concentration. In this case, the design storm would have a length (DSTORM) of 24 hours. The overall hydrograph was constructed from 12 individual triangular unit hydrographs each corresponding to rainfall of duration, DUNIT, of 2 hours, which is calculated as DSTORM/12. The time-to-peak for each unit hydrograph was DUNIT/2 + 0.6*TC, or 8.72 hours for our basin. The total length of each unit hydrograph was (8/3) times the time-to-peak, or 23.2 hours for our basin. The peak discharge for the unit hydrograph was 484 *AREA/TP in cfs, for a basin area AREA in square miles and a time to peak, TP in hours, or 23,300 cfs for our basin.

Following McCann et al. [1985], runoff depended upon the excess precipitation in each two-hour period which results from the total rainfall R_i in each period times both a runoff and dropoff coefficient. The dropoff coefficient was assigned a nominal value of 0.80. The runoff coefficient had a value of 0.4 in the dry season and 0.9 in the wet season. In future work, time-dependent loss rates may be employed, and the relationship between antecedent moisture conditions and loss rates and the distribution of initial reservoir storage volumes could be modeled.

Reservoir Storage Capacity

A critical element of the reservoir model is the storage capacity of the reservoir as a function of elevation h of the storage pool. Storage is given by the simple power function:

$$\text{Storage-Capacity}(h) = \begin{cases} 0 & h \leq 940 \text{ feet} \\ 0.361(h-940)^{3.37} \text{ [acre-feet]}, & h > 940 \text{ feet} \end{cases}$$

This yields a storage volume of 69,600 acre-feet for an elevation of 977 feet, just above the top of the spillway. For an elevation of 995, it yields 265,000 acre-feet at crest full. See Figure B-1.

Initial Storage Volume

The initial volume of water in storage is modeled as a random variable whose distribution depends upon the season in question. The model considers a wet and dry season. In both cases, the initial height has a beta distribution with a = b = 3. In the dry season, the range of the initial elevation is 950-955 feet. In the wet season, the range is 955-960 feet. For such a beta random variable, the mean height would be the middle of the indicated ranges, while the standard deviation would be 19% of the interval's width.

Functions for Releases from the Dam

Water can escape from the dam in three ways:

1) through the sluiceway outlet works,
2) over the spillway, and
3) over the the dam's crest if it is overtopped.

The characteristics of each are described below.

Sluiceways. Discharge from the dam is allowed by two semicircular conduits when the elevation of the storage pool is above 948 feet and six sluice gates when the elevation of the storage pool is above 960 feet. The potential release as a function of elevation h is:

$$\text{Sluice-Outflow}(h) = \begin{cases} 0, & h < 948 \text{ feet} \\ 12{,}000(h-948)/(960-948) & 948 \leq h \leq 960 \text{ feet} \\ 12{,}000+(21{,}000-12{,}000)(h-960)/(995-960) & h > 960 \text{ feet} \end{cases}$$

As noted below, an operating policy was assumed that resulted in smaller releases through the sluiceways and conduits.

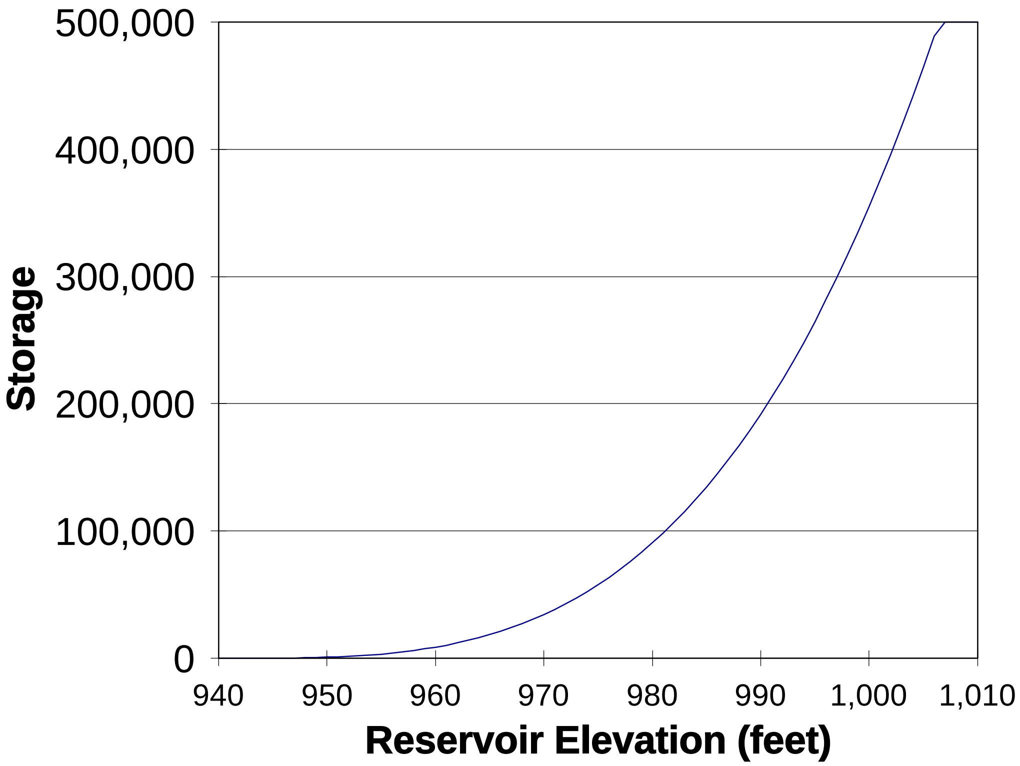

Figure B-1. - Storage Volume (Acre-Feet)

Spillway. The spillway for the dam is at an elevation of 976.5 feet. It has a length of 150 feet. The release from this overflow spillway is

Spillway-Outflow(h)	= 0,	$h \leq 976.5$ feet
	= $3.0(150)(h-976.5)^{1.5}$ cfs	$h > 976.5$ feet

Flow over the crest. Should the dam become so full that the elevation of the storage pool exceeds 995 feet, then water will begin to flow over the whole crest of the dam. The outflow over the dam's crest, which is not part of the 150 foot wide spillway, is

Crest-Outflow(h)	= 0	$h \leq 995$ feet
	= $3.0(5450)(h-995)^{1.5}$ cfs	$h > 995$ feet

Sluiceway Outlet Works Operating Policy

The previous section describes the potential release from the dam. The sluiceway outlet works can be controlled by the operator, and if used to discharge to the maximum rates, can cause significant damage downstream without any inflow. So as to model a reasonable operating policy, it was assumed that once the operators realized a major storm was coming, they would use the semicircular conduits to release 5,000 cfs, if possible, throughout the duration of the storm. The sluice gates will then be used to their capacity when water reaches that level. Thus, the controlled releases from the sluiceway outlet works as a function of reservoir elevation were:

$$\text{Sluice-Outflow}(h) \begin{cases} = 0, & h < 948 \text{ feet} \\ = 12{,}000(h-948)/(960-948) & 948 \le h < 953 \text{ feet} \\ = 5{,}000 & 953 \le h < 960 \text{ feet} \\ = 5{,}000+(21{,}000-12{,}000)(h-960)/(995-960) & h > 960 \text{ feet} \end{cases}$$

The resulting releases from the reservoir as a function of elevation are shown in Figure B-2 for all the discharge vehicles. Figure B-3 shows the total release as a function of elevation for a 450-foot wide spillway, which is one of the dam modifications considered in the text.

More complex operating policies could be employed that use inflow forecasts to determine appropriate sluiceway releases. The policy adopted is thought to be reasonable. If one always released from the sluiceway outlets at the maximum possible rate, then major downstream damages would result even when there was no rainfall.

With this operating policy, when the storage pool reaches 953 feet the release rate reaches 5,000 cfs at which it stays until elevation 960 when water begins to flow through the sluice gates. The total flow will then increase to 9,200 cfs at elevation 976.5 when the spillway begins to operate. The total rate of flow through the sluiceway and the spillway will reach 49,800 cfs when the storage level reaches elevation 995, the top of the embankment. Finally, with two feet of overtopping of the embankment, releases over the spillway and sluice gates, and 5,000 cfs through the conduits, the total release will equal 102,500 cfs. Should the dam fail at that point, the release rate would jump to 276,800 cfs.

Dam Failure

The analysis includes two vehicles for dam failure due to hydrologic events. One is a wash out of the spillway. The other is the overtopping of the dam and the subsequent washing out of the embankment.

The depths of water which can flow over the spillway or over the top of the dam before failure of the dam will occur are random variables. Both are modeled by Weibull variates. For the spillway, the mean depth at failure is 20 feet, corresponding to the reservoir being crest full plus 1.5 feet with a standard deviation of 2.0 feet. [These correspond to scale parameter $b = 0.0479$ per foot and shape parameter $k = 12.15$.] If the dam were raised ten feet to elevation 1,005, it was assumed that modification of the dam would also raise the mean depth at failure for the spillway to 30 feet with a standard deviation of 3.0 feet. [These correspond to scale parameter $b = 0.033$ per foot and shape parameter $k = 12.15$.]

For the dam crest, the mean depth at failure is 2.0 feet with a standard deviation of 0.33 feet. [These correspond to scale parameter $b = 0.468$ per foot and shape parameter $k = 7.06$.] This implies that the dam is most likely to fail from a spillway failure when the dam is already overtopped, but the embankment has not yet washed out. Failure due to an embankment failure due to overtopping is a close second.

Rainfall Distribution

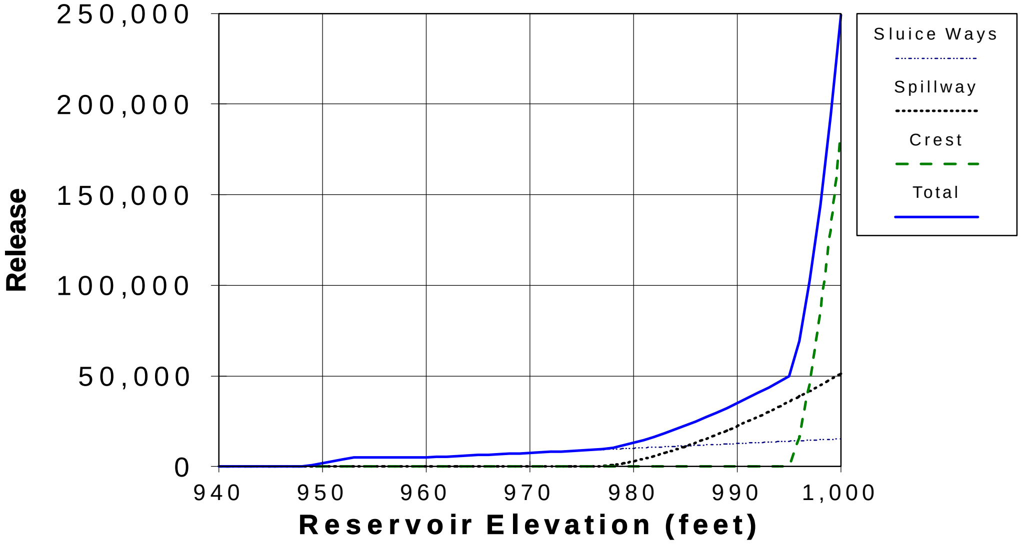

Figure B-2. - Reservoir Releases as Function of Elevation for 150-foot Spillway

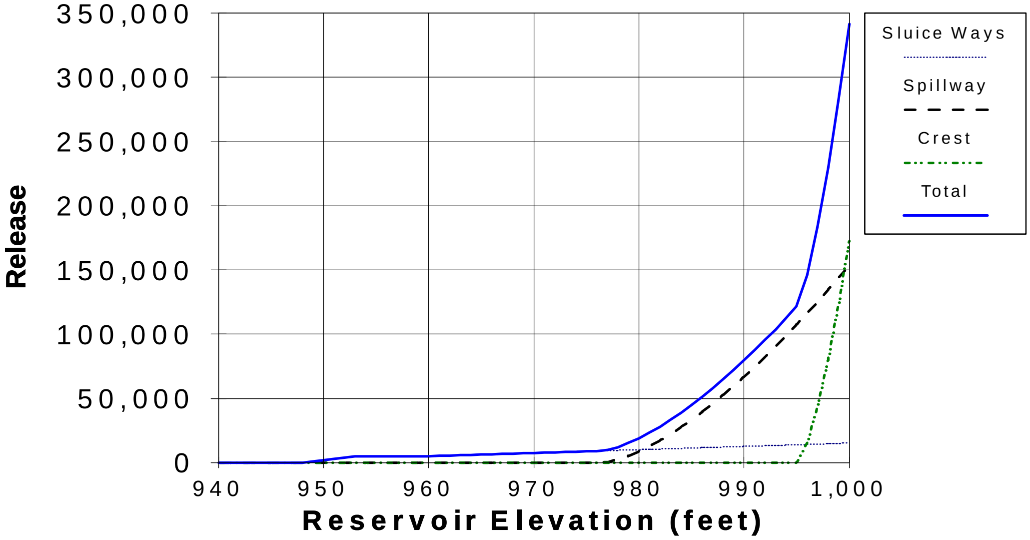

Figure B-3. - Reservoir Releases as Function of Elevation for 450-foot Spillway

Storm frequency and depth—A critical distribution is that selected to model the design rainfall. For a 24-hour period, the frequency distribution for the annual 24-hour maximum rainfall was assumed to have a Generalized Extreme Value (GEV) Distribution [Hosking et al., 1985].

The GEV distribution was transformed into a distribution for all peaks above a threshold of 0.9658 inches in 24 hours, so that the program could consider all damaging rainfall events and not just each year's largest. Potentially damaging storms are those of 0.966 inches or more, and such storms arrive at the rate of 3 per year. The distribution of the actual depth of such storms was

$$F(D \mid D > 0.9658 \text{ inches}) = 1 - [1 - k(D-0.9658)/a]^{1/k}$$

for $k = -0.10$ and $a = 0.6555$ in. This yields a 24-hour 100-year precipitation depth of 6 inches and a 2-year depth of 2 inches in 24 hours. A 23.5 inch rain has an exceedance probability of $1.0\text{x}10^{-6}$, and hence is a one in a million year event. See Figure 4, which also illustrates a thick-tailed alternative with $k = -0.25$, $a = 0.3689$, and a threshold of 1.3481 inches. For this alternative, the 2- and 100-year values are also 2 and 6 inches.

Were it necessary, the program converts a 24-hour precipitation depth to that of T hours, with the transformation $D_T = D_{24}(T/24)^{0.5}$. This means that the 12-hour precipitation quantiles are just 70.7% of the 24-hour values.

Distribution of rainfall within a storm—The fraction of the rainfall which falls within each of the twelve periods is generated randomly using a multinomial distribution. In particular, the total rainfall is divided into five equal packets which are distributed randomly among the twelve classes (corresponding to the twelve 2-hour periods).

Seasons—In future work, the distribution of rainfall should depend upon one or more seasons. Currently, the model includes two seasons, a wet season and a dry season. Given that a rainfall event has occurred, there is a 2/3 chance it has arrived in the wet season, and a 1/3 chance it is the dry season. Currently, season only affects the initial reservoir volume distribution and the runoff coefficient in the unit hydrograph calculation. Season is also a variable upon which the Monte Carlo simulation might profitably be stratified.

Damage and Loss-Of-Life Functions

Hypothetical damage functions were obtained using as a basis field data for an existing dam. However, the original data contained some inconsistencies and did not cover the entire range of interest. For the purposes of this example, for flow rate q at the dam, the following damage and loss-of-life functions were adopted:

$$\text{Dollar-Damage} \quad = 0. \qquad q \leq 6450 \text{ cfs}$$
$$= -1.044\text{x}10^{9} + 385q + 1.19\text{x}10^{8} \ln(q) \qquad q > 6450 \text{ cfs}$$

The third term involving ln(q) actually contributes very little. Possible damages range from zero to \$368 million at a discharge rate of 102,500 cfs. Should the dam fail at that point, losses increase to \$459 million. Dam failure causes an outflow downstream which is modeled as

$$q_{\text{failure}} = q_{\text{without-failure}} + 75(h_{\text{at-failure}} - 931)^{1.85}$$

where $q_{\text{without-failure}}$ is the discharge rate at the time of failure from the outlet works, spillway, and over the crest of the dam. For a failure when the embankment is overtopped by two feet, corresponding to an elevation h=997 feet, the release from the outlet works, spillway, and over the crest of the dam would total 102,500 cfs; were the dam to fail at that point, the total flow would jump to 277,000 cfs. The value of q_{failure} is used to determine the Dollar-Damage value using the equation above. The resultant damages are used as if they include both downstream damages from the flood and repair cost to fix the breach in the dam, or to rebuild the spillway should it have failed. If, for political or economic reasons, the dam would not be repaired, then the cost of any lost of service should be factored into the analysis at this point.

The loss-of-life model was also based upon that for a real dam, with a reasonable extension beyond the range for which data were available. The model is

$$\text{Loss-of-life} = 0 \qquad q \leq 6000 \text{ cfs}$$
$$= 10\,(q-6000)/(16{,}000) \qquad 6000 < q \leq 22{,}000 \text{ cfs}$$
$$= 0.517\, q^{0.2964} \qquad 22{,}000 < q$$

For a discharge rate of 102,5000 corresponding to 2 feet of overtopping, there would be 15.8 lives lost. If the dam failed at that point and no warning was given, the number of lives lost would increase to 21. If the dam fails and the warning system works, then loss-of-life is assumed to be that which occurred with the maximum release rate q at the dam before it failed. With the prescribed operating policy, some loss-of-life occurs whenever the storage elevation reaches 964 feet, corresponding to discharges in excess of 6000 cfs. Ten lives are lost when the discharge rate reaches 22,000 cfs, at a reservoir elevation a little less than 985 feet.

Figures B-4 and B-5 show the dollar damages and loss-of-life which result as a function of the release rate from the dam. Given the prescribed operating policy and the capacity and performance of the spillway and dam crest as outlet works, Figures B-6 and B-7 show the dollar damages and loss-of-life which occur as a function of reservoir elevation for the original 150-foot spillway and with a proposed 450-foot wide spillway. From Figures B-4 and B-5, one can see that for the damage and loss-of-life functions given for our dam, based on the data that was provided by the Corps, most of the damages and loss-of-life occur with relative smaller releases, particularly loss-of-life.

Failure of emergency evacuation procedures

It is assumed that evacuation procedures, if implemented, would eliminate incremental loss-of-life due to the failure of this dam. However, due to the confusion that is often associated with major storms, emergency evacuation procedures might not be executed in time. The probability the emergency evacuation-warning procedures fail was 50%.

Other Factors

The simulation analysis allows the stochastic modeling of a number of other factors that can affect the performance of the structure and the safety factor of the dam and the distribution of loss-of-life. These include the items discussed below.

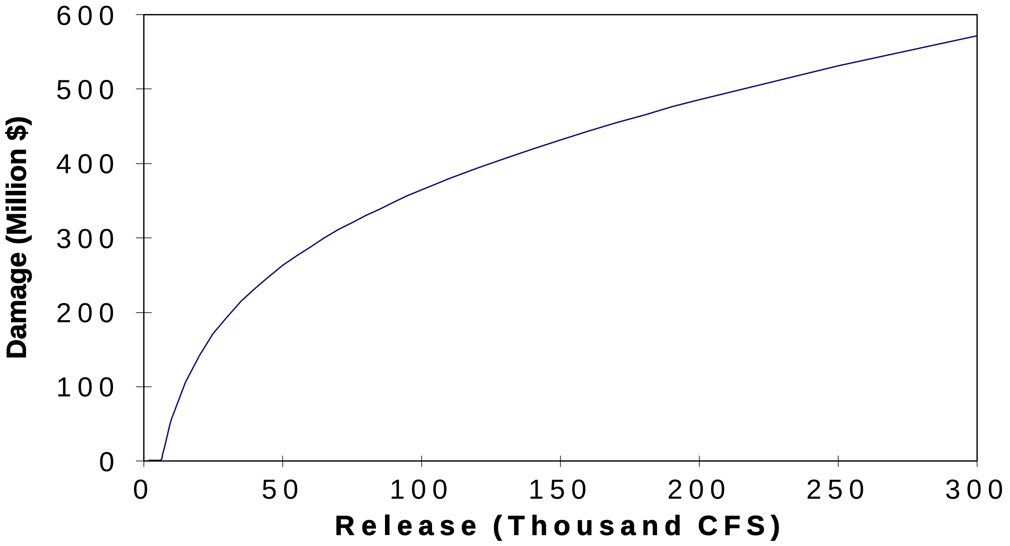

Figure B-4. - Damages in Million $

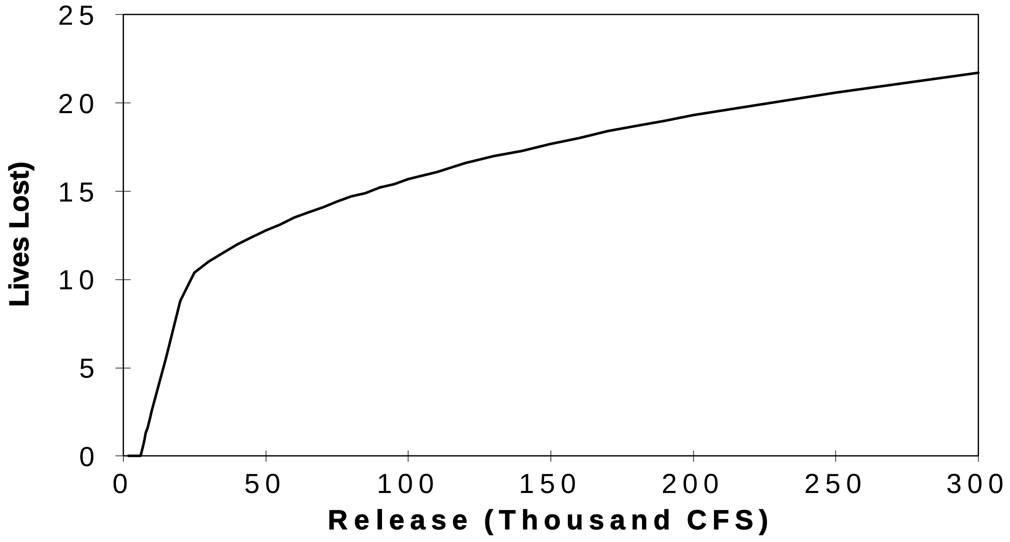

Figure B-5. - Lives Lost as Function of Release

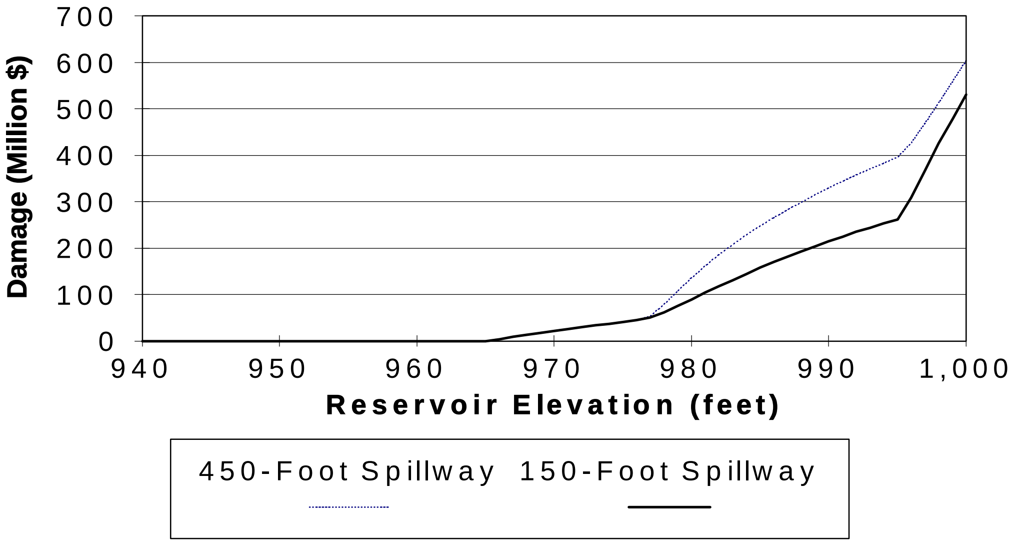

Figure B-6. - Dollar Damage in Million $

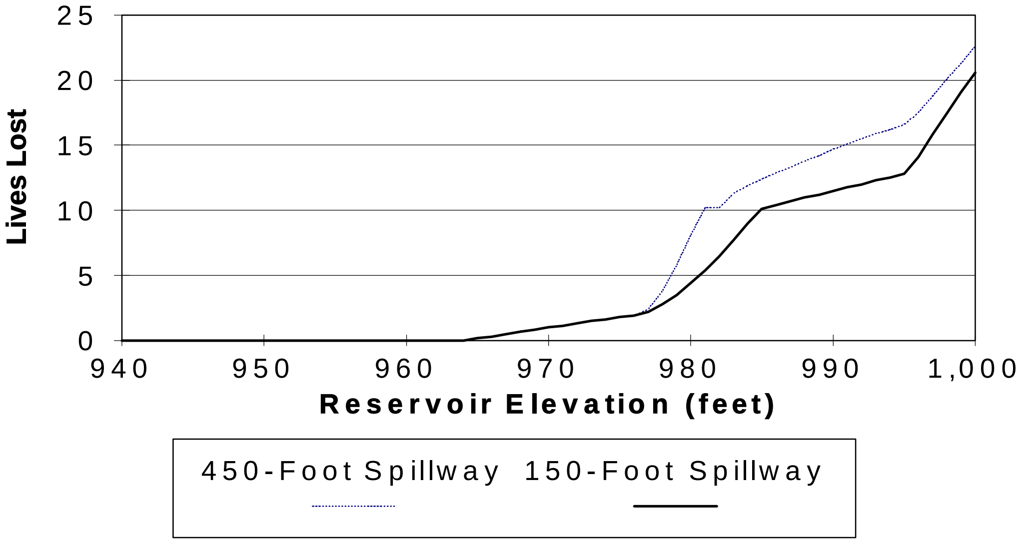

Figure B-7. - Loss-of-Life as Function of Elevation

1. *Wind Runup*—Wind across the lake behind the dam can effectively increase the elevation of the water at the dam. To model this effect in practice, one would need to consider the wind directions associated with the storm being modeled and in what direction the wind could be blowing at the point in time the elevation of the storage pool would be at its maximum elevation. In this simple analysis, the effect of wind on the elevation of the storage pool at the dam was modeled as a normal random variable with a mean of 1 foot and a standard deviation of 0.5 feet.

In practice, one might also consider wave runup on the dam and the possibility of overtopping of the dam crest due to wind-driven wave action. That phenomenon is ignored in this analysis.

2. *Sluice Gate Failure*—The number of sluiceway gates actually functioning can vary. It is assumed that from one to six gates can function with various probabilities as given below

Gates Functioning:	6	5	4	3	2	1
Probability:	0.80	0.15	0.05	0	0	0

Other probabilities could be adopted. If only m sluice gates are working, then the maximum release capacity at h=995 feet is reduced to 12,000 + (21,000-12,000)(m/6) cfs. Below h=960 feet elevation, the release capacity of the conduits is unaffected. Failure of one or more of the sluice gates would decrease the maximum flow associated with two feet of overtopping. In that case, instead of a release of 107,000 cfs with all six gates functioning, the release rate would drop to 104,000 cfs.

Stratification

To try to make the Monte Carlo analysis program as efficient as possible, the contribution of the rain distribution is evaluated analytically. Other variables, such as spillway overtopping depth, to cause failure are treated as random variables. Stratified variables are:

1) the number of sluiceway gates working, and
2) whether the warning system works.