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Evaluating Dam Safety Retrofits With Uncertain Benefits: The Case of Mohawk Dam (Walhonding River, Ohio)

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Mohawk Dam, part of the Muskingum basin flood control system, was built in 1938 and is operated by the U.S. Army Corps of Engineers (Corps). Since this high-hazard dam could not survive a probable maximum flood (PMF), the Corps conducted a study to determine the least expensive means of enabling the dam to survive a PMF. Applying a previously proposed framework to select the social cost minimizing capacity of a dam, we show that Mohawk Dam had sufficient capacity that any retrofit has a social cost larger than expected benefits. Sensitivity analyses were performed adjusting the peak flow distribution, the costs of modification, and downstream flood damage, as well as the possibility of loss of life. For any reasonable value of these variables the conclusion does not change that the structure already met so high a safety goal regarding extreme floods that no retrofit is needed. Using risk-based methods to perform reservoir safety evaluations, as recommended by a National Research Council committee in 1985, is indeed feasible. Furthermore, their use provides valuable insight and guidance into the selection of strategies to enhance the safety of dams.

We have previously proposed a framework to evaluate the implications of the current safety goal that high-hazard dams must survive a probable maximum flood (PMF) [*Resendiz-Carrillo and Lave*, 1987]. This paper applies the framework to a dam that has recently been retrofitted to survive a PMF. It uses readily available data and contrasts the resulting goal with the PMF. Retrofitting high-hazard dams to survive a PMF is the recommendation of the U.S. Government as well as of most major organizations associated with dam safety [*National Research Council*, 1985]. For Mohawk Dam a retrofit made no sense. More than eight million dollars were spent on a project that has extremely small social value.

Mohawk Dam, an earth structure, is part of the Muskingum basin flood control system. It was built in 1938 by, and is operated by, the U.S. Army Corps of Engineers (Corps). A decade ago this high-hazard dam was found to pose a safety hazard since it was not able to pass a PMF. This finding led to a study which concluded that the least expensive means of enabling the dam to survive a PMF was to raise the height of the dam at a total cost of approximately $2 million [*U.S. Army Corps of Engineers*, 1985]. However, the final decision consisted of raising the height of the dam and widening the spillway at a total cost of more than $8 million.

ESTIMATING THE PEAK FLOW DISTRIBUTION

Our framework suggests using at-site peak annual flows to estimate the extreme flow distribution. Available data for 65 years were used to fit four distributions that are commonly used to describe peak flows. The peak annual flows are shown in Figure 1. The best fitting distribution (as measured by the residual sum of squares) was the extreme value type 1 (EVT1). The estimated return periods for various peak flows (and the corresponding standard errors) for the four fitted distributions are shown in Table 1.

The four fitted distributions give extremely large return periods for the PMF of 380,000 cfs (10,800 m^3/s). The smallest return period for any distribution was two million years (see Table 2). The largest flow observed in 65 years is much larger than the second largest flow (see Figure 1); it is an outlier, as estimated by the other observed flows and the fitted distributions. Even so, the PMF is 4 times larger than the largest peak flow, making these extremely large return periods seem plausible.

The 65 years of peak annual flows might be too short a record to estimate the PMF with confidence. Conceivably, a massive hurricane that hovered over the watershed for a day might lead to the design event. Suppose that a large hurricane passes over this area with an annual frequency of 5×10^{-3}. Furthermore, suppose that the probability such a storm became stationary, given that it was over this area, is 10^{-3}. If so, the return period for a PMF would be 200,000 years. There are no tools available to estimate these probabilities with confidence given the scarcity of pertinent data.

A broader, more comprehensive data set is one approach for improving the estimation of the return period of extreme floods. The additional coverage is more likely to capture the underlying process that generates the large floods [*National Research Council*, 1988; *Hosking and Wallis*, 1986; *Stedinger and Cohn*, 1986; *Lettenmaier et al.*, 1987; *Lettenmaier and Potter*, 1985; *Hosking and Wood*, 1985].

ESTIMATED MODIFICATION COSTS

In its study for correction of deficiencies at Mohawk Dam, the *U.S. Army Corps of Engineers* [1985] evaluated raising the height of the dam and increasing the size of the spillway. The costs were estimated for increasing height enough to

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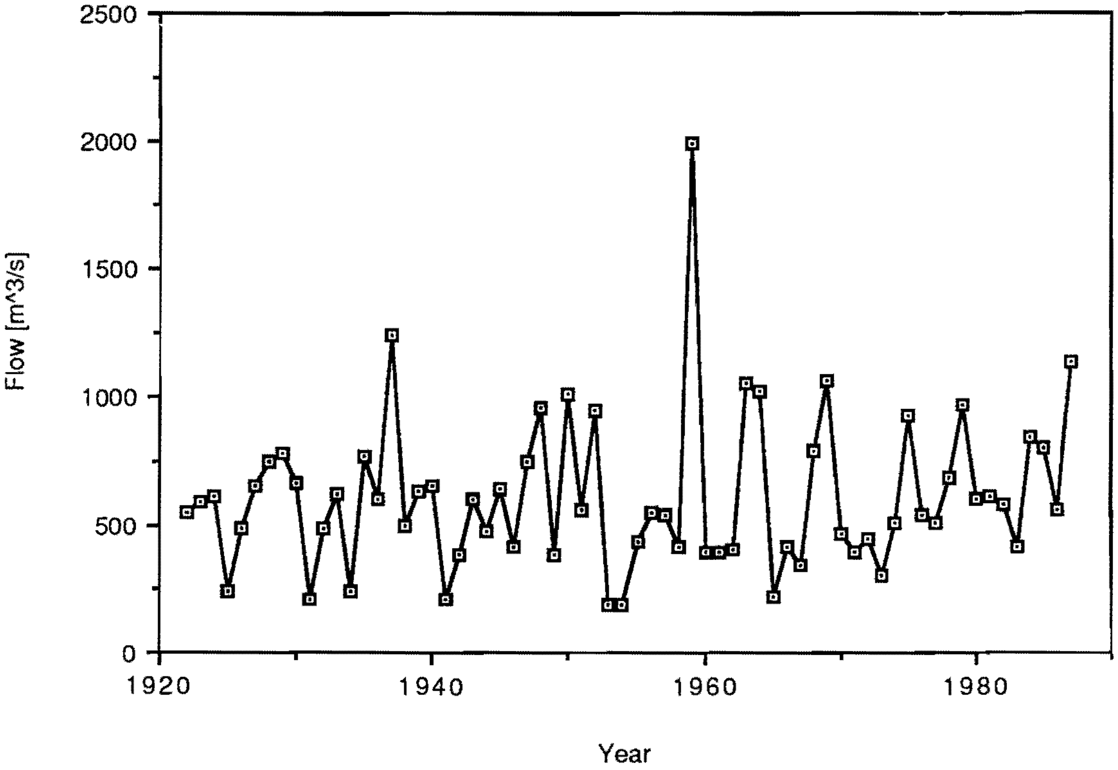

Fig. 1. Peak annual flows at Mohawk Dam, Walhonding River, Ohio, 1922–1987.

enable the dam to survive floods that were 80%, 88%, and 100% of the PMF. There is a zero cost of allowing the dam to pass 65% of a PMF, since this involves no modification. These four points were used to fit a quadratic function characterizing modification costs, as shown in Figure 2.

Increasing the height of the dam automatically increases the capacity of the structure. However, it does not decrease downstream flooding (water is spilling automatically over the same spillway as before). Since the increased height does reduce the likelihood of catastrophic dam failure due to overtopping, there is a modest reduction in the chance of extreme floods caused by dam failure.

Estimated Flood Damages

The *U.S. Army Corps of Engineers* [1985] also estimated the amount of downstream flooding that would be expected for three sizes of floods. For each of these inflow rates they estimated outflow rates and flood damage, both under the assumption that the spillway would be sufficient to pass the flood and then under the assumption that the spillway was insufficient so that the dam was overtopped and failed catastrophically.

We used these flood damage estimates to derive a quadratic flood damage function $d(f)$, with values for each peak flow. Flood damage below 102,000 cfs (2900 m^3/s) is zero since the current dam impounds these floods. A quadratic function was fitted to this zero damage point and the three damage points estimated by the Corps. Another quadratic function was fitted to the three damage estimates derived from assuming that the dam failed, $D(f)$. These two damage functions are shown in Figure 3. From our inspection of the site and of the Corps estimation procedure [*U.S. Army Corps of Engineers*, 1985] we believe that property damage is reasonably well characterized by these two functions.

TABLE 1. *T*-Year Flood Magnitude and Standard Error Using Four Distributions

Distribution	Return Period *T*, Years 50	500	1,000	5,000	10,000
EVT1	1,300	1,900	2,000	2,400	2,500
	(100)	(160)	(170)	(210)	(220)
LN2	1,500	2,200	2,400	2,900	3,200
	(100)	(160)	(180)	(230)	(250)
LP3	1,600	2,600	3,600	4,100	4,700
	(180)	(390)	(470)	(690)	(800)
LN3	1,500	2,000	2,200	2,600	2,800
	(250)	(500)	(710)	(1,500)	(2,200)

Magnitudes are given in cubic meters per second, standard errors in parentheses. EVT1, Extreme value type 1; LN2, lognormal 2 parameters; LP3, log-Pearson; LN3, lognormal 3 parameters.

How Much Would Dam Failure Increase Drownings?

Dam failure induced deaths are unlikely. *Brown and Graham* [1988] present evidence supporting the intuitive

TABLE 2. Return Period for the Probable Maximum Flood

Distribution	Return Period *T*, years
EVT1	4.6×10^{15}
LN2	572,000,000
LP3	2,200,000
LN3	13,450,000,000

PMF = 380,000 CFS; EVT1 extreme value type 1; LN2, lognormal 2 parameters; LP3, log-pearson 3 parameters; LN3, lognormal 3 parameters.

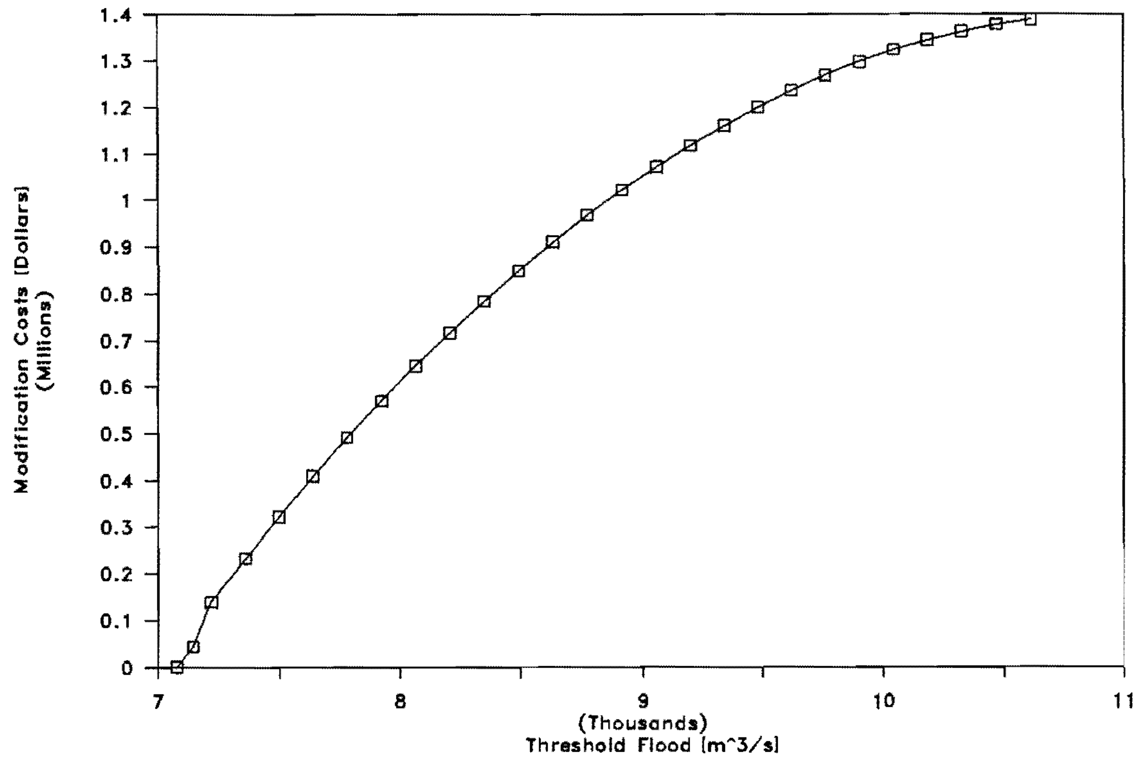

Fig. 2. Modification costs as a function of threshold flood.

hypothesis that, given enough warning time (usually as little as 1.5 hours), fatalities can be averted or reduced to a minimum. After having inspected Mohawk dam and toured adjacent communities, we feel confident sufficient time would be available for successful evacuation if the dam is overtopped. In more than 50 years since the dam was built, the spillway has never been used and the river has never been out of its channel. Since severe flooding would begin

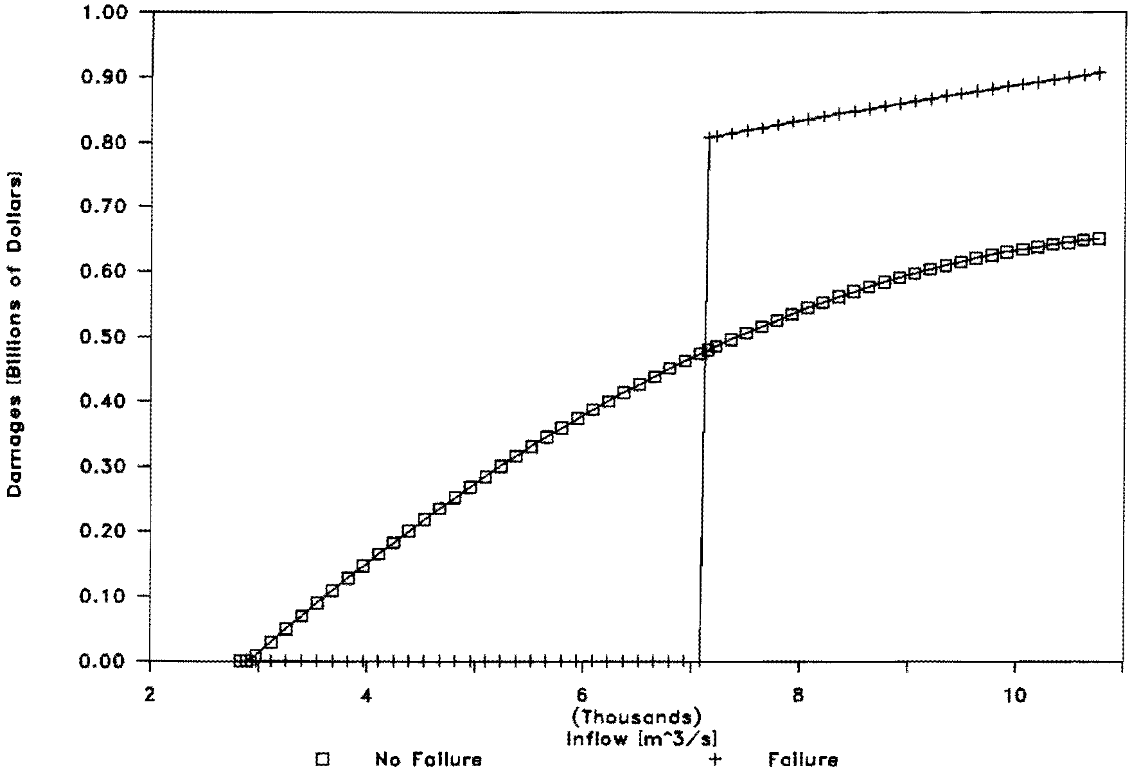

Fig. 3. Downstream flood damages as a function of peak inflow.

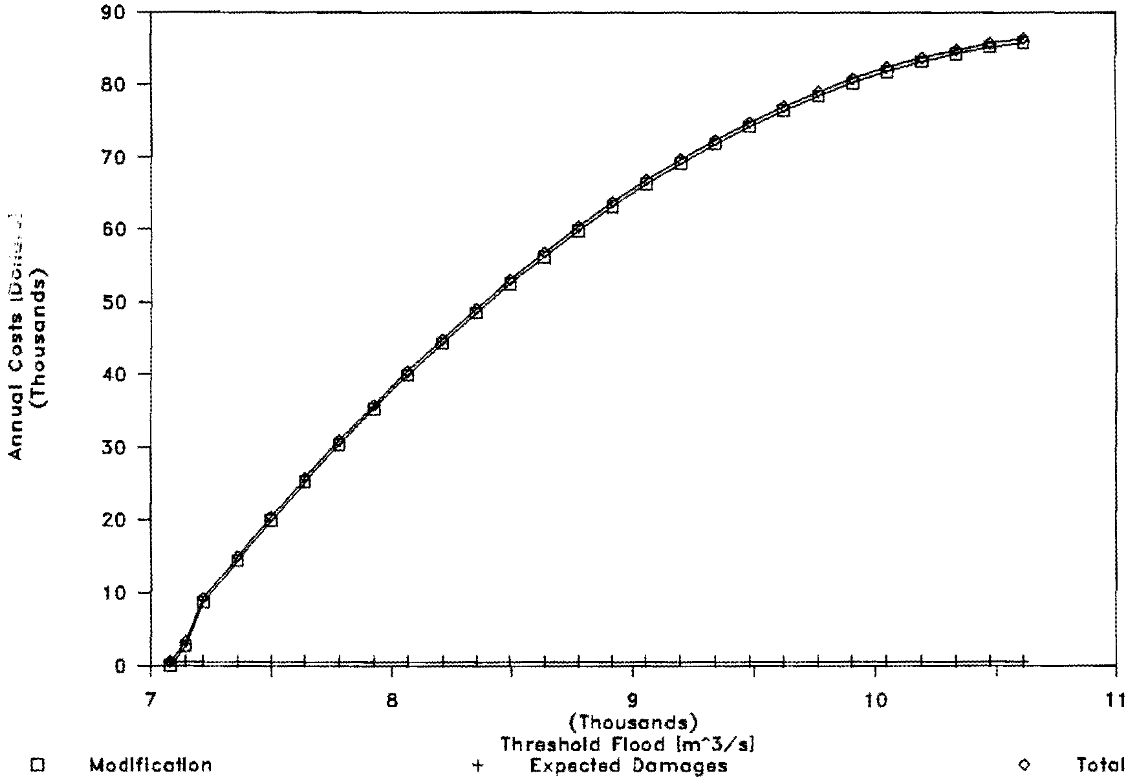

Fig. 4. Annual costs as a function of threshold flood.

long before dam failure, even skeptical individuals would see ample signs of extreme danger with enough lead time to evacuate.

Expected Annual Flood Damages and Annual Retrofit Costs

With the probability distribution for peak flows (EVT1) reported in Table 1 and the flood damage function shown in Figure 3, we can calculate the expected downstream damage from flooding: $p(f)d(f)$, where $p(f)$ is the probability density function of a peak inflow of size f, and $d(f)$ is the damage associated with a peak inflow of size f under the no-failure scenario. This formulation holds for floods up to the capacity of the structure (design or threshold flood), TF. For larger floods the dam fails and there is a larger flood leading to damages $D(TF)$. Although the flood damage from dam failure changes with the level of the design flood (the larger the design flood, the more water is impounded at the time of failure), we assume that the flow from catastrophic failure due to an extreme flood is much larger than the flow from the storm itself. Thus, for Mohawk dam, expected flood damage can be expressed as the sum of two terms: flood damage from (1) the deliberate spilling of water beginning at 102,000 cfs (2900 m^3/s) and continuing to the threshold flood and (2) catastrophic failure due to a flood above the threshold level. Letting $P(f)$ be the cumulative density function, the expected damage function is

$$\int_{102,000}^{TF} p(f)d(f)\, df + [1 - P(TF)]D(TF) \quad (1)$$

The larger the threshold flood (the capacity of the spillway and thus of the structure to survive a large flood), the lower the expected flood damage. As shown in Figure 4, expected damages decline only slightly for threshold floods larger than the current capacity of the spillway. Floods greater than 252,000 cfs (7100 m^3/s) are so improbable that the area in the right-hand tail of the expected damage distribution is essentially zero. Increasing the capacity of the structure beyond that needed to survive a flood of 252,000 cfs (which characterized Mohawk dam before the retrofit) is estimated to reduce expected annual flood damage by only about $50 per year or less than $1000 in present discounted value (assuming an interest rate of 6% and an useful life of 60 years) if the threshold flood after modification equals the PMF.

A Benefit-Cost Analysis of Retrofitting Mohawk Dam

The present value of preventing future flood damage amounts to less than $1000. This number is the benefit of retrofit and should be compared to the $2 million cost of retrofit. Alternatively, both flood damages and modification costs can be expressed in annual terms [*Resendiz-Carrillo and Lave*, 1987]. Total annual costs (annualized modification costs plus annual expected damages) are presented in Figure 4. Since expected annual flood damage is so small, the annualized modification costs and the total annual costs curves are essentially indistinguishable in this scale. Total annual costs increase for design floods larger than the status quo. Clearly, the costs of modification are much greater than the benefits of flood damage reduction.

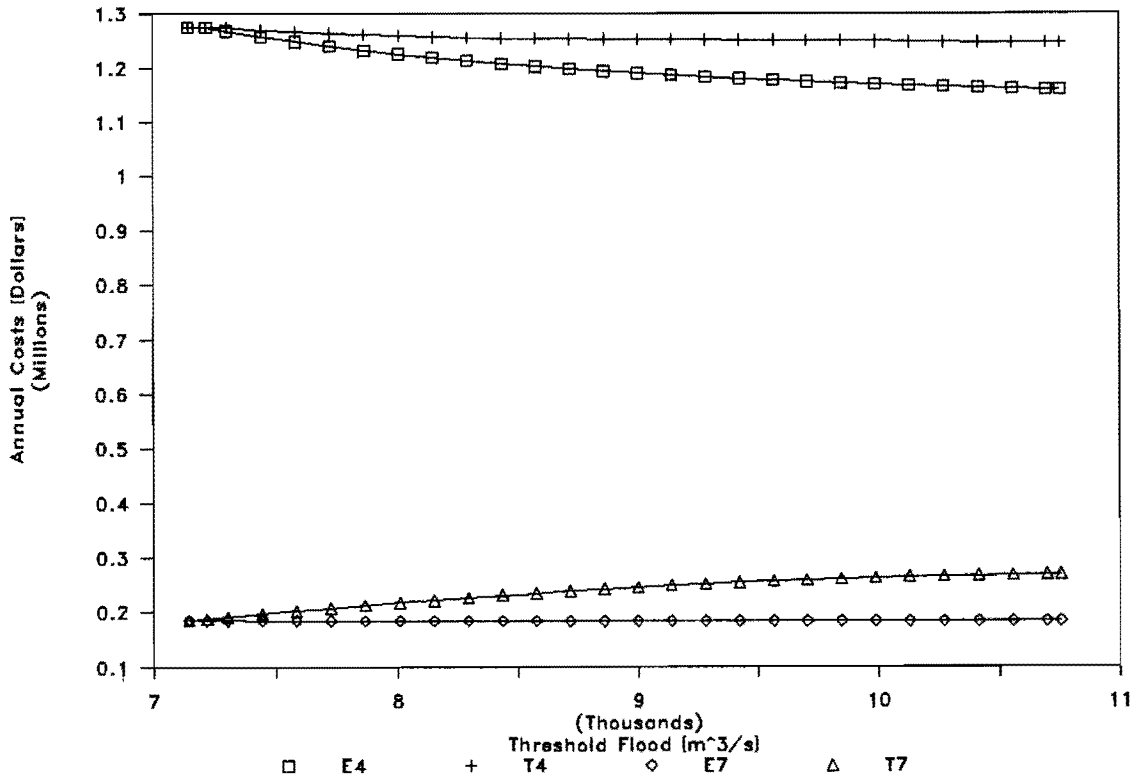

Fig. 5. Annual costs when interpolating between the 100-year flood and the PMF. E4; expected damages, $T = 10^4$; T4, total annual costs, $T = 10^4$; E7, expected damages, $T = 10^7$; T7, total annual costs, $T = 10^7$.

Suppose, despite the ample warnings, some deaths occur. If these drownings were assigned the upper level dollar value from the values implicit in current government decisions, $5 million [*Graham and Vaupel*, 1981], more than 310,000 deaths would have to occur before retrofit to PMF levels would make sense.

Sensitivity Analysis: Distribution of Floods

The estimated benefits and costs displayed in Figure 4 leave no doubt about whether Mohawk Dam should be retrofitted. However, these figures assume the correctness of (1) an analysis based on taking expected values of the probability distributions, (2) the frequency distribution for floods, (3) the estimated flood damage function, and (4) the estimates of retrofit cost. If any of these assumptions is incorrect, Figure 4 might be misleading. Since before modification the dam could survive 65% of a PMF, the analysis is already focusing on the extreme right-hand tail of the flood distribution. In this case there is little to be gained by using the *Karlsson and Haimes* [1988, 1989] method of focusing on extreme events. To evaluate the other three possibilities we did a sensitivity analysis.

The greatest source of uncertainty is the estimated peak flow distribution. For any of the four distributions estimated from available data the PMF is extremely unlikely to occur. *Stedinger and Grygier* [1985] estimated the parameters of a flood distribution using peak flow data and then interpolated between the 100-year flood and the PMF; they assumed different return periods for the PMF. We adopt their method, utilizing the 500- (and 100-) year flood as a departure point for the interpolation and return periods for the PMF of 10,000, 100,000, 1,000,000, and 10,000,000 years, which are likely to encompass the range of feasible return periods for a PMF [*Newton*, 1983; *National Research Council*, 1985].

The resulting expected downstream damages for interpolating from the 100-year flood are shown in Figure 5 for two different return periods for the PMF, $T = 10{,}000$ and $T = 100{,}000$ years. Expected damages decline slightly as the size of the threshold flood is increased; the decline is greater for the assumption that the PMF has a return period of only 10,000 years. Also shown is the result of adding the annualized modification costs to the expected flood damages. Total annual costs decrease only if the PMF has a return period as short as 10,000 years. For larger, more realistic return periods, total annual costs increase to the right of the "do-nothing" alternative. Interpolating between the 500-year flood and the PMF gives similar results, which are not presented.

Sensitivity Analysis: Flood Damage Estimates

The second source of uncertainty is the accuracy of the downstream flood damage estimates. The estimates are based on surveys and Census data rather than inspection of each building [*U.S. Army Corps of Engineers*, 1985]. To explore sensitivity we assumed downstream flood damages had been overestimated; thus the damage estimate at each threshold flood was multiplied by 0.5. Alternatively, we assumed that downstream damages had been underestimated and so multiplied each damage estimate by 1.5. Underestimation seems unlikely given the conservative nature of the estimation process. Total annual costs rise with the size of the threshold flood even assuming underestimation. Thus the conclusions are not sensitive to a halving or 50% increase in flood damages. Even assuming that underestimation occurred, annual net costs decline only if the PMF has a return period as short as 10,000 years.

SENSITIVITY ANALYSIS: DAM MODIFICATION COSTS

If the modification costs are underestimated, the qualitative conclusion is strengthened: it makes no sense to retrofit the dam. Only if the modification costs are overestimated by a large amount would the conclusions be changed. We consider it unlikely that the Corps report overestimated the cost of modification significantly.

CONCLUSIONS

We have developed our framework for estimating the safety goal for high-hazard dams and applied it to the Mohawk Dam. Although the dam was unable to pass a PMF, we concluded there was only a trivial social benefit ($50 per year) associated with modifying the dam to handle a PMF. At the same time the costs of modification are extensive. Thus both a benefit-cost analysis and good sense show that modification makes no sense. If society were extremely risk averse about the possibility of catastrophic damage failure, values could be chosen to reverse this conclusion.

An extensive sensitivity analysis for the probability distribution of extreme floods, the flood damage function, and the cost of modification shows that no reasonable changes in these functions would serve to justify dam retrofit. Thus we conclude that retrofitting Mohawk Dam to survive a PMF made no sense. In at least one case the safety goal of having a high-hazard dam survive a PMF makes no sense. In an associated analysis we conclude that this safety goal is flawed more generally [*Lave et al.*, 1990].

While the modification of Mohawk Dam has been completed, many other Federal and private dams, considered to represent unacceptable hazards, await modification. A *National Research Council* [1985] committee strongly recommended the use of risk-based frameworks to perform these kind of reservoir safety evaluations where billions of dollars are at stake [*Dawdy and Lettenmaier*, 1987]. We have shown here that the explicit balancing of risks and benefits can be accomplished in a sensible manner despite the pervasive uncertainty. Careful risk analyses performed by or in collaboration with the federal agencies responsible for the safety of dams in this country should produce valuable insight and guidance into the selection of efficient, sensible strategies to enhance the safety of dams.

NOTATION

- f peak inflow in cubic feet per second (cfs).
- $d(f)$ downstream flood damage as a function of peak inflow f under the no-failure scenario.
- $D(f)$ downstream flood damages as a function of peak inflow f under the failure scenario.
- $D(TF)$ downstream flood damages from dam failure during an extreme flood when the threshold flood is TF.
- $p(f)$ probability density function of peak inflow f.
- $P(f)$ cumulative density function of peak inflow f.
- TF threshold or design flood.

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