ESTIMATING EXPECTED ANNUAL DAMAGE FOR LEVEE RETROFITS

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ABSTRACT: The U.S. Army Corps of Engineers (USACE) has instituted a new analysis methodology for estimating the expected annual damage (EAD) and resulting economic benefits accruing to proposed flood damage-reduction projects. Although the methodology is new, it still, in effect, uses expected probability to estimate the frequency of flooding and EAD. The National Research Council (NRC) in a review of USACE's study of the American River levees stated that the use of expected probability results in significantly biased estimates of EAD. An alternative damage model to that proposed by NRC is used to show that expected probability leads to an unbiased estimate of EAD. The damage model proposed requires that an unbiased estimate of damage results when applied to many projects. A simulation study demonstrates that EAD estimated with expected probability is unbiased, whereas the NRC's recommended estimator is biased.

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) participates with local communities in the development of flood damage-reduction projects. Evaluation of the benefits of a particular project depends on the estimation of proposed damage-reduction benefits. Net benefits are computed as the difference between the expected annual damage (EAD) with and without the proposed project minus the proposed project cost. The purpose of the present paper is twofold. First, this paper describes the USACE's methodology for estimating EAD. Second, this paper discusses the criticism that USACE's estimation technique has received from the National Research Council (NRC) (1995) in its application to a levee retrofit on the American River, Sacramento, Calif.

EXPECTED ANNUAL DAMAGE CALCULATION

The calculation of EAD involves the integration of a damage-probability distribution [see USACE (1996)]. The damage-probability distribution is usually estimated from a set of contributing variables, which, most typically, consist of a flow-probability distribution, a rating curve that relates river stage to flow, and a stage-damage relationship (see Fig. 1). In the past, single estimates of these relationships were used to derive the damage-probability distribution. The frequency curve was estimated using expected probability. The remaining contributing variables were estimated given the best field information and models available. More recently, USACE has chosen to incorporate estimates of uncertainty into the derivation of the damage-probability distribution and, ultimately, into the computation of EAD. USACE (1996) provides guidance for estimating the distribution of these errors.

The estimation of uncertainty depends on the contributing random variable. In the case of flow probability, the only contribution to estimation uncertainty considered is sampling error due to finite gauge record lengths. Typically, the flow probabilities are described by the log-Pearson type III distribution, and uncertainty about this distribution by the noncentral t, as recommended by the Interagency (IACWD) (1982). The application of the noncentral t involves approximations in that it is only appropriate for variates or logarithms of variates that are normally distributed, and a large sample approximation is used in its calculation. Estimating the uncertainty in the rating curve depends on the information available. If observed values are available, then deviations from the mean rating curve can be used to estimate an uncertainty distribution. If an open channel-flow model is used, then a sensitivity analysis on model parameters can be used to produce an error bound, which in turn could be used to approximate a distribution. The strategy for developing the distribution of uncertainty about a stage-damage relationship involves uncertain estimates of property and content values, and the first-floor elevation.

EAD is calculated by using the Monte Carlo simulation to integrate the contributing variables. The Monte Carlo procedure is implemented by obtaining a sample damage from a random sample of the contributing variables. The damage is averaged over a number of simulations to obtain EAD. A re-

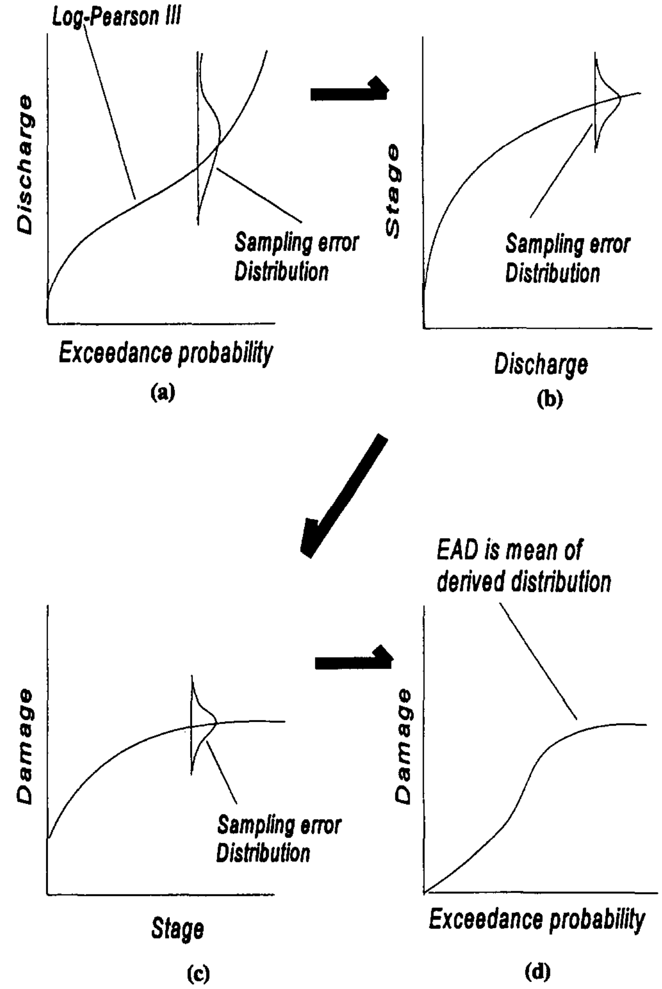

FIG. 1. Monte Carlo Computation of Expected Annual Damage Considering Risk and Uncertainty

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lationship between the accuracy of the integration and the number of simulations can be obtained by noting that EAD is a mean value and consequently is asymptotically normally distributed about an analytic value (a value that would be obtained from an infinite number of simulations). The normal distribution is used to construct a confidence interval that would contain the analytic value, which provide an accuracy estimate as a function of the number of simulations.

RELATIONSHIP WITH EXPECTED PROBABILITY

Prior to the consideration of uncertainty in the estimation methodology, USACE has used the expected or mean probability estimates of the flow-probability distribution to calculate EAD. The methodology described in the previous section, in effect, uses the expected probability estimate in deriving EAD by using the noncentral t-distribution to characterize uncertainty about the flow-probability distribution. Small differences exist between the expected probability and average probability distribution obtained as an intermediate product of the Monte Carlo integration because of both the large-sample approximation used for the noncentral t and the skewness of the estimated probability distribution.

OBJECTIONS TO USACE's METHODOLOGY BY NRC

In a review of the application of USACE's estimation methodology to a retrofit of levees on the American River near Sacramento, Calif., NRC (1995) objected to the preceding methodology because the use of expected probability provides upwardly biased estimates of EAD. NRC claims that expected probability results in a biased estimate of damages because it requires that the incipient level of significant damage is a function of exceedance probability. The following quote expands on this claim (NRC 1995): "Beard proposed another model for flood damages that would place the property at risk at a stage corresponding to a flow M + tS for some fixed scalar t (Beard 1990). Thus the location of valuable property would be determined completely by the sample mean M and the sample standard deviation S of the logarithms of the flood record that would be available when a study was performed . . ."

Note here that t is the standard normal deviate for the exceedance probability where significant damage occurs. NRC objects to this model for flood damage (continuing with the preceding quote). ". . .This is clearly an impossibility for older property and represents for newer property unusual social responsiveness to revealed flood hazard. In general, it is not a credible basis for a flood damage model."

NRC claims that a more appropriate model for arriving at an unbiased estimate of flood damage is to assume that the location of incipient damage is directly related to a fixed flow level. In this simplified model, EAD would be calculated as the product of the exceedance probability at the fixed flood level [see NRC (1995)] and incipient damage.

NRC investigated the biasedness of both an approximately median estimator and expected probability estimator for application in their damage model via a Monte Carlo experiment. The median estimator is calculated from the sample statistics as

$$p_m = 1 - \Phi\left[\frac{\log(Q) - M}{S}\right] \quad (1)$$

where Q = discharge at the top of the levee; and Φ = normal cumulative distribution function. Value p_m is a good approximation to the median estimate for sample sizes greater than 10. The expected probability estimate is computed from an application of the student's t-distribution [see Proschan (1953); IACWD (1982)]

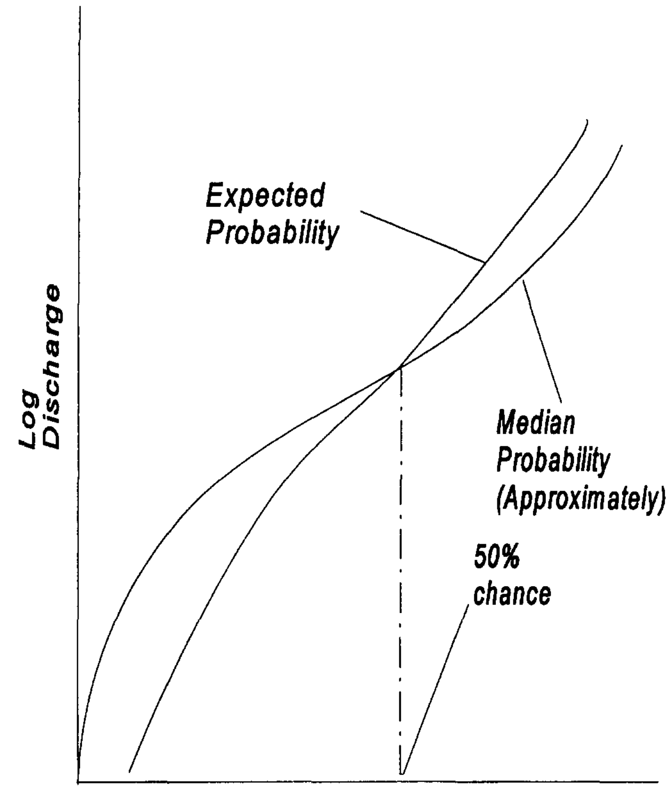

FIG. 2. Expected Probability versus Approximate Median Flow-Frequency Distributions

$$p_e = P\left[t_{N-1} > K_N\left(\frac{N}{N+1}\right)^{1/2}\right] \quad (2)$$

where $K_N = [\log(Q) - M]/S$; N = sample size; and t_{N-1} = deviate for Student's t-distribution. The qualitative relationship between these two estimators is shown in Fig. 2. The expected probability estimator is always greater than that of the approximated median estimate for exceedance probabilities greater than 50% chance. The practical implications of this difference is that EAD values obtained with expected probability will be greater than that obtained with the median.

The Monte Carlo experiment involved calculating the distribution statistics for numerous samples of a particular record length and averaging the exceedance probabilities over all samples. The experiment demonstrates results such as those originally arrived at by Arnell (1989). In these results, the average probability obtained using the approximately median estimator was significantly less biased than that obtained using the expected probability estimator [see Tables 4.1 and 4.2, NRC (1995)] for record lengths less than 50%. As the record length increases above 50%, the difference between the two estimators is relatively small.

EVALUATION OF EAD ESTIMATORS

The purpose of this section is to show that the use of expected probability is consistent with USACE's need to obtain both unbiased estimates of EAD and project benefits. The next subsection details the criteria appropriate for an estimator of EAD given USACE's need to estimate benefits. The second subsection outlines a procedure for evaluating the performance of NRC's and the expected probability estimators relative to these criteria. The third subsection provides the results of a Monte Carlo experiment that is used to evaluate the different estimators. The fourth subsection proposes a study of gauge records that could be used to evaluate the proposed estimators.

Criterion for Estimator

An important aspect of USACE project studies is to estimate benefits for proposed flood damage-reduction projects. Project benefits are computed as the difference between EAD estimates with and without project flood damage minus the cost of the project. A positive contribution results when the damage reduced, the difference between with and without project EAD, is greater than project costs. USACE policy requires that any recommended project results in positive benefits so as to contribute to National Economic Development (NED) (USACE 1990).

The estimated future damages and benefits for a particular project are not likely to be correct. After all, the estimated EAD is based on sample statistics that are not likely to correspond to future flood frequencies or damage. Consequently, the estimated EAD for a single application is almost assuredly to be in error. A reasonable requirement for an estimator is that it results in the population flood probabilities and EAD when predictions are averaged over many applications. An estimator that satisfies this requirement is said to be unbiased.

Unbiased estimation is in keeping with USACE policy of seeking projects with positive contributions to NED. The estimated benefits, and EAD, for a single project may not reflect the future reality. At least a positive benefit will be realized on the average if the appropriate estimator is used to estimate future flood frequencies and EAD.

Evaluation Methodology

An experiment needs to be devised that evaluates the EAD estimators for repeated application, i.e., the application of the estimator to the evaluation of USACE projects in the field. In the NRC experiment, EAD for a levee that protects a community at a particular critical discharge is estimated for repeated realizations of a period of flow record. In the field, this experiment could be conducted by finding sets of levees that are designed for approximately the same "critical" discharge. The probability with which flows exceed the top of the levee and the average damage that occurs since the levee has been constructed could be compared to the EAD values obtained from the NRC estimator. The difference between this field experiment and the NRC Monte Carlo experiment is that the set of levees does not correspond to a single population probability distribution. Obviously, the population probability distribution is never known in the field situation, and consequently the NRC experiment cannot correspond perfectly to the field situation. However, one could assume that the sample records are due to an equally likely set of populations, resulting in effectively the same experiment proposed by NRC.

The experiment proposed by Beard (1978) can also be used in field applications. Instead of aggregating based on discharge, the levees are aggregated based on the sample estimate of the flow-exceedance probability for the top of the levee.

Two different design criteria are being examined in the different ways the levees are being aggregated in the experiment. The aggregation by discharge reflects designs based on some historically large event. For example, the design of the previously mentioned American River levees was based on a historically large event observed in the region (USACE 1956). The aggregation based on exceedance probability reflects a typical requirement for design. For example, the national flood-insurance program uses the 1% chance exceedance probability flood as a basis for setting flood-insurance requirements.

In summary, an evaluation of the estimators will involve an aggregation of levee projects. In the case of NRC's estimator, the aggregation is based on a critical discharge, whereas for expected probability, levees are aggregated based on estimated exceedance probability at the top of the levee.

Monte Carlo Experiments

Monte Carlo experiments that attempt to simulate field conditions were devised to evaluate the estimators. The steps used in the experiment to evaluate the NRC estimator were performed as follows.

First, generate a "historic" flow record at the jth levee, $Q_{i,j}$, $i = 1, 2 \ldots N_h$, from an assumed lognormal population. The scheme used to obtain a random sample involved generating random uniformly distributed deviates using a linear congruential method (Press et al. 1989) and converting these deviates to normal variates using a transform presented by Box and Muller (1958).

Second, set the jth levee height based on the maximum flow in the sample record $(Q_m)_j = \max(Q_{i,j}, i = 1, 2 \ldots N_h)$.

Third, generate an additional record, $Q_{i,j}$, $i = (N_h + 1), (N_h + 2) \ldots N$, representing the years since the levee was built. Calculate sample statistics for the entire record, historic plus additional from the product moment relationships

$$M_j = \sum_{i=1}^{i=N} X_{i,j}/N; \quad S_j^2 = \sum_{i=1}^{i=N} (X_{i,j} - M_j)^2/N - 1 \qquad (3, 4)$$

where $X_{i,j}$ = logarithms of the flow, $\log(Q_{i,j})$; and M_j and S_j^2 = sample mean and variance for the jth levee.

Fourth, estimate the exceedance probability for the maximum flow used to obtain the levee height in the second step using the sample statistics (the NRC approach) and the expected probability as follows:

$$K_N = \{\log[(Q_m)_j] - M_j\}/S_j; \quad (p_m)_j = 1 - \Phi(K_N) \qquad (5, 6)$$

$$(p_e)_j = P\left[t_{N-1} > K_N\left(\frac{N}{N+1}\right)^{1/2}\right] \qquad (7)$$

where K_N = estimated standard normal deviate for the maximum flow $(Q_m)_j$; and $(p_m)_j$ and $(p_e)_j$ = approximate median exceedance probability [see (1)] and the expected probability [see (2)] for the jth levee.

Fifth, compute the population exceedance probability at the top of the levee

$$K = \{\log[(Q_m)_j] - \mu\}/\sigma; \quad p_j = 1 - \Phi(K) \qquad (8, 9)$$

where μ and σ = population mean and standard deviation of the logarithms of flow values used to create a sample flow record in the first step; K = standard normal deviate; and p_j = population exceedance probability at the top of the levee.

Sixth, compute estimates and population values of EAD as

$$(\mathrm{EAD_{NRC}})_j = (p_m)_j D_j; \quad (\mathrm{EAD}_e)_j = (p_e)_j D_j; \quad (\mathrm{EAD}_p)_j = p_j D_j \qquad (10-12)$$

where D_j = damage occurring when the jth levee fails; $(\mathrm{EAD_{NRC}})_j$ and (EAD_e) = the EAD values obtained using NRC and expected probability estimators; and $(\mathrm{EAD}_p)_j$ = population EAD for the jth levee.

Seventh, repeat steps one through six for $j = 1$ to N_1 levees.

Eighth, aggregate the results by maximum discharge. This involves averaging exceedance probabilities and EAD within different discharge classes. For example, if $(Q_m)_j$ ranges between 0.0 and 10.0 units, then 10 class intervals of 1.0 might be used to average the EAD and exceedance probability values. This is done by distributing the EAD and exceedance probability values for each estimator and the population values among the classes for the N_1 levees, and computing the average for the total number of values within each class.

Finally ninth, assess the bias of each of the estimators by comparing the average population EAD values with the estimated values within each class.

In performing this experiment, a numerical integration is performed to obtain the expected value of EAD. The accuracy of the integration depends on the number of levees, N_1. As the number of levees examined becomes large, the estimated EAD values within each class will stabilize, providing the numerical integration accuracy desired.

The experiment assumes: (1) the sample flow records are from the same population and damage is a constant unit value; (2) the levee height is derived from the maximum flow on record; and (3) EAD is estimated at the end of a fixed additional flow period. The assumption of a single flow population and constant damage is used to simplify both the explanation and application of the experiment. The experiment could be modified to include random selection of damage about some mean value. However, the results would be the same with this additional randomization. The assumption of constant population values will be relaxed in a modification to the experiment to show that there is no effect on the results when population parameters are randomly selected from an equally likely set.

The assumption that EAD is estimated at a fixed period after the levee construction is somewhat more difficult to justify. The additional period is added to reflect the NRC concern about the responsiveness of communities to recent flooding events. In relating damage to flows exceeding the top of the levee, damage is effectively being related to an exceedance probability approximately equal to one divided by the number of years in a historic period. The additional period is added to reflect a community's desire to retrofit the levee due to a large event within the period or the fact that the levee failed within the period.

The experiment involving the aggregation with exceedance probability differed from the previous experiment only in that the exceedance probabilities based on sample statistics in the fourth step were used to group results. This grouping effectively reproduces the experiment used by Beard (1978) to show that the expected probability is an unbiased estimator of exceedance probability and EAD.

The aggregation by discharge results from the simulations for a population mean and standard deviation of 3.0, and 0.3; a historic period of 30 years; and an additional flow period of 20 years shown in Table 1 and by estimated probability shown in Table 2. It is interesting to view the aggregation by discharge results in terms of a population discharge of 3.55 corresponding to the exceedance probability equal to one over the historic record length (1/30). The results show that for a class of discharges less than this population discharge, the expected probability provides a better estimate of the population probability, whereas the NRC's approximate median estimator provides a better estimate of the population probability when the population discharge exceeds the class discharges.

Table 2 demonstrates the well-established result that expected probability provides an unbiased estimate of exceedance probability when projects are aggregated based on estimated exceedance probability, and that NRC's approximate median estimator is biased low. As can be seen from Table 3, the expected probability provides an unbiased estimate of es-

TABLE 1. Aggregation of Levee Exceedance by Critical Discharge (Based on Monte Carlo Simulations at 20,000 Stations)

Class[a] (1)	Fraction[b] (2)	Population[c] (3)	Median[d] (4)	Expected[e] (5)
3.39	0.05	0.1246	0.0834	0.0885
3.42	0.03	0.0891	0.0632	0.0682
3.44	0.03	0.0769	0.0565	0.0613
3.46	0.04	0.665	0.0528	0.0576
3.49	0.05	0.0567	0.0469	0.0515
3.51	0.06	0.0483	0.0418	0.0463
3.53	0.06	0.0411	0.0369	0.0412
3.56	0.07	0.0346	0.0320	0.0362
3.58	0.06	0.0290	0.0288	0.0329
3.60	0.06	0.0241	0.0248	0.0286
3.63	0.06	0.0201	0.0220	0.0256
3.65	0.06	0.0165	0.0191	0.0226
3.68	0.05	0.0136	0.0167	0.0200
3.70	0.05	0.0110	0.0148	0.0180
3.72	0.04	0.0090	0.0126	0.0155
3.75	0.04	0.0072	0.0107	0.0134
3.77	0.03	0.0058	0.0089	0.0114
3.79	0.03	0.0046	0.0084	0.0108
3.82	0.02	0.0037	0.0072	0.0095
>3.82	0.09	0.0016	0.0038	0.0053

[a]Lower bound for class of peak discharge determined from 30 years of simulated record at station.
[b]Fraction of 20,000 stations within class.
[c]Average population exceedance probability for class given population mean = 3.0 and standard deviation = 0.3 for normal distribution.
[d]Average estimate of exceedance probability using approximate median estimator of 50 years of record.
[e]Average estimate of exceedance probability using expected probability of 50 years of record.

TABLE 2. Aggregation of Levee Damage by Estimated Exceedance Probability (Based on Monte Carlo Simulations at 20,000 Stations)

Class[a] (1)	Fraction[b] (2)	Population[c] (3)	Median[d] (4)	Expected[e] (5)
0.0025	0.05	0.0024	0.0014	0.0023
0.0075	0.12	0.0068	0.0050	0.0069
0.0124	0.12	0.0126	0.0098	0.0126
0.0173	0.11	0.0181	0.0148	0.0180
0.0222	0.09	0.0233	0.0197	0.0234
0.0271	0.08	0.0291	0.0246	0.0286
0.0320	0.07	0.0350	0.0295	0.0338
0.0369	0.06	0.0393	0.0344	0.0389
0.0418	0.05	0.0446	0.0393	0.0439
0.0467	0.04	0.0498	0.0422	0.0490
0.0516	0.04	0.0543	0.0491	0.0540
0.0566	0.03	0.0590	0.0541	0.0590
0.0615	0.02	0.0639	0.0590	0.0640
0.0664	0.02	0.667	0.0638	0.0689
0.0713	0.02	0.0719	0.0687	0.0739
0.0762	0.01	0.0781	0.0736	0.0788
0.0811	0.01	0.0845	0.0786	0.0839
0.0860	0.01	0.0896	0.0833	0.0886
0.0909	0.01	0.0925	0.0884	0.0937
>0.0909	0.03	0.1177	0.1115	0.1167

[a]Lower bound of probability for class.
[b]Fraction of 20,000 stations within class.
[c]Average population exceedance probability for class given population mean = 3.0, standard deviation = 0.3 for normal distribution.
[d]Average estimate of exceedance probability using approximately median estimator of 50 years of record.
[e]Average estimate of exceedance probability using expected probability of 50 years of record.

TABLE 3. Expected Annual Exceedances Averaged for All Levees (Based on 20,000 Levees)

Historic period (1)	Population (2)	Median (3)	Expected (4)
10	0.0911	0.0865	0.0911
20	0.0480	0.0428	0.0480
30	0.0324	0.0286	0.0324
30[a]	0.0328	0.0290	0.0327

[a]Results for population parameter randomly selected from a uniform distribution, the mean ranged between 2.5 and 3.5, and the standard deviation ranged between 0.25 and 0.35.

TABLE 4. Aggregation of Levee Exceedances by Discharge for Equally Likely Populations (Based on Monte Carlo Simulations at 20,000 Stations)

Class[a] (1)	Fraction[b] (2)	Population[c] (3)	Median[d] (4)	Expected[e] (5)
2.93	0.001	0.1226	0.0877	0.0927
3.07	0.037	0.0701	0.0532	0.0579
3.22	0.091	0.0483	0.0393	0.0435
3.36	0.124	0.0367	0.0326	0.0366
3.51	0.142	0.0338	0.0301	0.0338
3.66	0.148	0.0334	0.0294	0.0331
3.80	0.146	0.0319	0.0286	0.0322
3.95	0.134	0.0278	0.0259	0.0295
4.09	0.097	0.0176	0.0187	0.0219
>4.09	0.074	0.0069	0.0096	0.0119

[a]Lower bound for class for peak discharge determined from 30 years of simulated record at station.
[b]Fraction of 20,000 stations within class.
[c]Average population exceedance probability for class, given population mean randomly selected from the uniform distribution, range 2.5–3.5, and the standard deviation, 0.25–0.35.
[d]Average estimate of exceedance probability using approximate median estimator of 50 years of record.
[e]Average estimate of exceedance probability using expected 50 years of record.

timated exceedance probability, and consequently damage, when estimates are averaged over all the levees considered.

Additional experiments were conducted to determine the impact of parameter assumptions on the conclusion concerning aggregation by discharge. This was accomplished by varying the class interval size and number of levees, the historic record length, and population parameters. The numerical integration error resulting from the experiment was investigated by doubling the number of levees from 20,000 to 40,000 and choosing the number of class intervals as 10, 20, and 40. Doubling the number of levees had no effect indicating minimal numerical integration error, and the different number of class intervals had no impact on the conclusions already discussed.

The impact of record length was investigated by performing simulations for additional historic periods of 10 and 20 years. Examination of the results demonstrated that record length had no effect on the conclusions. Table 3 provides a summary of the variation in expected damages obtained using the various historic periods. In examining this table, notice that the population exceedances correspond to the period used to choose the maximum levee height. For example, if the historic period chosen is 10 years, then an unbiased estimate of future exceedance is given by the Weibull Plotting position of 1/11 or 0.91. The Weibull plotting position is unbiased with regard to estimated exceedance and consequently corresponds to both the population value and expected probability estimates [see Mood et al. (1963)].

The sensitivity of results to assumed population parameters was investigated by considering a range of equally likely population parameters in a modified Monte Carlo experiment. As might be expected, the random variation had no impact on evaluation of the estimators, as can be seen from Tables 3 and 4.

Consequently, the expected probability estimator should be preferred to the NRC's estimator since it alone provides unbiased estimates of EAD over all projects considered. The NRC estimator demonstrates superior performance in the discharge aggregation when the discharge corresponding to the top of the levee is larger than a population discharge determined from a probability equal to one over the historic record length. Practically speaking this is of limited use in field applications since the population discharges are never known.

A Regional Experiment

Regional information has been used in the past to select an appropriate model for application to water-resources problems. For example, the Water Resource Council used observed streamflows at gauge locations to select the log-Pearson type III distribution (Thomas 1985). Similarly, regionally observed data could be used to select an estimator for EAD.

Direct averaging or split-sample testing probably could be applied to the gauge information to select either the expected or the NRC recommended estimators. In the direct averaging approach, the average annual damage that occurred over all levee sites during the period of record would be compared to the estimate of EAD averaged over all sites, as predicted by either estimator. Presuming that enough sites are involved, an estimator is selected depending on the closest correspondence between the predicted average EAD estimate and the averge annual damage. This test presumes, of course, that the sample observations result from a random population of probability distributions and that the average annual damage is approximately equal to the population estimate of regional EAD.

A split-sampling test would involve selected locations that have a significant flow record. The exceedance probability and discharge at the top of the levee would be determined from a portion of the record. Estimated damages would be aggregated as discussed for the Monte Carlo experiments mentioned previously. The average annual damage for the remaining portion of the record would be used to select from the competing estimator based on comparative performance.

CONCLUSIONS

A discussion has been provided of USACE's EAD estimation method and the NRC (1995) objection to its application to the American River. The NRC objection results from their assertion that expected probability results in an upwardly biased estimate of EAD. The claim made herein is that this objection results from an incorrect perspective of USACE's need in evaluating flood damage-reduction projects. The estimator proposed by NRC and the Monte Carlo experiment used to recommend this estimator over the application of expected probability results from this incorrect perspective.

USACE's focus is in providing unbiased estimation of future damage over repeated application of an estimation procedure. Repeated applications result from the analysis of flood-damage problems at numerous projects across the United States.

A Monte Carlo experiment, which reflects USACE's estimation problem for levees, was performed to evaluate the NRC and expected probability estimators of EAD. In the experiment, levee heights were chosen as the maximum value in a historic period. An additional period was then simulated to reflect a period between the construction of the levee and the time when a community would evaluate expected damages at the levee location. The results of the experiment were aggregated by levee design discharge to satisfy the assumptions made in the application of the NRC's approximate median estimator and by estimated exceedance probability at the top of the levee for application of the expected probability estimator. The aggregation corresponding to discharge demonstrated that the advantage of one estimator over the other depended on knowledge of the population. However, this result is of limited use since the actual population statistics are never known in a field experiment. The aggregation corresponding to sample exceedance probability demonstrated the well-known unbiasedness of the expected probability estimator. More importantly, the experiment demonstrated that expected probability is an unbiased estimator of EAD and that the estimator proposed by NRC is biased when considering damage at all the levees. Consequently, expected probability is commensurate with USACE's policy of assessing flood-control benefits. Expected probability provides an unbiased estimate of EAD over many applications and thus, an unbiased estimate of benefits. Finally, a regional experiment was proposed to choose between the estimators based on observations at gauge locations.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

(EAD_{NRC}) = approximate median estimate of expected annual damage for jth levee;
$(EAD_e)_j$ = expected probability estimate of expected annual damage for jth levee;
$(EAD_p)_j$ = population expected annual damage for jth levee;
M = sample estimate of mean peak annual flow logarithms;
M_j = sample estimate of mean peak annual flow logarithms for jth station;
N = total number of years of flow record;
N_H = number of years of record to determined maximum flow for levee design;
N_l = number of levees simulated;
p_e = expected probability of peak annual flow exceeding given magnitude;
$(p_e)_j$ = expected probability of peak annual flow exceeding top of jth levee;
p_j = population probability of peak annual flow exceeding the top of jth levee;
p_m = approximate median estimate of peak annual flow exceeding given magnitude;
$Q_{i,j}$ = annual peak flow in ith year for jth station;
S = sample estimate of standard deviation of logarithms of peak annual flood;
S_j = sample estimate of standard deviation of logarithms of peak annual flood for jth station;
S_j^2 = variance of standard deviation of logarithms of peak annual flood for jth station;
t_{N-1} = Student's t-distribution variate for $N - 1$ degrees of freedom;
$X_{i,j}$ = logarithms of annual peak flow in ith year for jth station;
μ = normal distribution population mean of peak annual flow logarithms;
σ = normal distribution population standard deviation of peak annual flow logarithms; and
$\Phi(\ )$ = normal cumulative distribution function.