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Manual
No. 1110-2-1619 1 August 1996

Engineering and Design
RISK-BASED ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES

1. Purpose. This manual describes and provides procedures for risk and uncertainty for Corps of Engineers flood damage reduction studies.

2. Applicability. The guidance presented and procedures described in this manual apply to all HQUSACE elements, major subordinate commands, districts, laboratories, and separate field operating activities having civil works responsibilities.

3. General. The procedures described herein lead to estimation of expected benefits of proposed flood damage reduction plans using risk and uncertainty analysis. Quantitative and qualitative methods of representing the likelihood and consequences of exceedance of the capacity of selected measures are also included. The procedures are generally an extension and expansion of the traditional plan formulation and evaluation regulations described in other Corps of Engineers guidance materials, in particular ER 1105-2-101 and ER 1105-2-100, and thus do not supersede guidance presented therein.

FOR THE COMMANDER:

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Table of Contents

Chapter 1
Introduction

1-1. Purpose of Document

a. Risk involves exposure to a chance of injury or loss. The fact that risk inherently involves chance leads directly to a need to describe and to deal with uncertainty. Corps policy has long been (1) to acknowledge risk and the uncertainty in predicting floods and flood impacts, and (2) to plan accordingly. Historically, that planning relied on analysis of the expected long-term performance of flood-damage-reduction measures, on application of safety factors and freeboard, on designing for worst-case scenarios, and on other indirect solutions to compensate for uncertainty. These indirect approaches were necessary because of the lack of technical knowledge of the complex interaction of uncertainties in predicting hydrologic, hydraulic, and economic functions and because of the complexities of the mathematics required to do otherwise.

b. With advances in statistical hydrology and the widespread availability of high-speed computerized analysis tools, it is possible now to describe the uncertainty in choice of the hyrologic, hydraulic, and economic functions, to describe the uncertainty in the parameters of the functions, and to describe explicitly the uncertainty in results when the functions are used. Through this risk and uncertainty analysis (also known as *uncertainty propagation*), and with careful communication of the results, the public can be informed better about what to expect from flood-damage-reduction projects and thus can make better-informed decisions.

c. This document describes and provides procedures for risk and uncertainty analysis for Corps flood-damage reduction studies. It presents templates for display of results. Finally, this document suggests how risk and uncertainty can be taken into account in plan selection.

1-2. Applicability

The guidance presented and procedures described in this manual apply to all Headquarters, U.S. Army Corps of Engineers (HQUSACE) elements, major subordinate commands, laboratories, and separate field operating activities having civil works responsibilities.

1-3. Summary of Procedures

a. The procedures described in this document lead to:

(1) Estimation of expected benefits and costs of proposed flood-damage-reduction plans.

(2) Description of the uncertainty in those estimates.

(3) Quantitative and qualitative representation of the likelihood and consequences of exceedance of the capacity of selected measures.

The procedures generally are an extension and expansion of the traditional plan formulation and evaluation procedures described in Engineer Regulations (ER) 1105-2-100 and ER 1105-2-101 and thus do not supersede guidance contained there.

b. The analyses proposed herein depend on:

(1) Quantitative description of errors or uncertainty in selecting the proper hydrologic, hydraulic, and economic functions to use when evaluating economic and engineering performance of flood-damage-reduction measures.

(2) Quantitative description of errors or uncertainty in selecting the parameters of those functions.

(3) Computational techniques that determine the combined impact on plan evaluation of errors in the functions and their parameters.

The results of plan evaluation following these guidelines are not the traditional statements of economic benefit and probability of exceedance of an alternative. Instead the results are descriptions of the likelihood that an alternative will deliver various magnitudes of economic benefit and the expected probability of exceedance, considering the uncertainty in all that goes into computation of that probability.

1-4. Definition of Terms

To describe effectively the concepts of flood risks and uncertainty, this document uses the terminology shown in Table 1-1.

Table 1-1
Terminology Used in this Manual

Term	Definition
Function uncertainty (also referred to as distribution uncertainty and model uncertainty)	Lack of complete knowledge regarding the form of a hydrologic, hydraulic, or economic function to use in a particular application. This uncertainty arises from incomplete scientific or technical understanding of the hydrologic, hydraulic, or economic process.
Parameter	A quantity in a function that determines the specific form of the relationship of known input and unknown output. An example is Manning's roughness coefficient in energy loss calculations. The value of this parameter determines the relationship between a specified discharge rate and the unknown energy loss in a specific channel reach.
Parameter uncertainty	Uncertainty in a parameter due to limited understanding of the relationship or due to lack of accuracy with which parameters can be estimated for a selected hydrologic, hydraulic, or economic function.
Sensitivity analysis	Computation of the effect on the output of changes in input values or assumption.
Exceedance probability	The probability that a specified magnitude will be exceeded. Unless otherwise noted, this term is used herein to denote annual exceedance probability: the likelihood of exceedance in any year.
Median exceedance probability	In a sample of estimates of exceedance probability of a specified magnitude, this is the value that is exceeded by 50 percent of the estimates.
Capacity exceedance	Capacity exceedance implies exceedance of the capacity of a water conveyance, storage facility, or damage-reduction measure. This includes levee or reservoir capacity exceeded before overtopping, channel capacity exceedance, or rise of water above the level of raised structures.
Conditional probability	The probability of capacity exceedance, given the occurrence of a specified event.
Long-term risk	The probability of capacity exceedance during a specified period. For example, 30-year risk refers to the probability of one or more exceedances of the capacity of a measure during a 30-year period.

1-5. Organization of Document

This document includes the following topics:

For	See
A summary of procedures presented in this document	Chapter 1
Brief definition of terms used	Chapter 1
An overview of Corps' plan formulation and economic evaluation procedures	Chapter 2
An overview of procedures for uncertainty analysis	Chapter 2
Procedures for evaluating engineering performance of damage-reduction measures	Chapter 3
Guidance on describing uncertainty of discharge and stage frequency functions	Chapter 4
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An example of plan formulation and evaluation in which uncertainty is considered	Chapter 9

Chapter 2
Plan Formulation and Economic Evaluation

2-1. Overview

A flood-damage-reduction plan includes measures that reduce damage by reducing discharge, reducing stage, or reducing damage susceptibility. For Federal projects, the objective of the plan is to solve the problem at hand in such a manner that the solution will "... contribute to national economic development (NED) consistent with protecting the Nation's environment, pursuant to national environmental statutes, applicable executive orders, and other Federal planning requirements (U.S. Water Resources Council (USWRC) 1983)." A planning study is conducted to determine (1) which measures to include in the plan, (2) where to locate the measures, (3) what size to make the measures, and (4) how to operate measures in order to satisfy the Federal objective and constraints. According to WRC guidelines, the study should lead decision makers to the optimal choice of which, where, what size, and how to operate by comparing "various alternative plans ...in a systematic manner." In Corps planning studies, this is accomplished by:

a. *Formulating* alternative plans that consist of combinations of measures, with various locations, sizes, and operating schemes. Engineer Manual (EM) 1110-2-1419 describes measures that might be included. ER 1105-2-100 provides guidance on formulating plans that are mixes of these measures. ER 1105-2-101 provides guidance on the use of risk-based analysis methods during the formulation process.

b. *Evaluating* the NED contribution and engineering performance of each plan. This document provides guidance on this evaluation.

c. *Comparing* the NED contribution, engineering performance, and satisfaction of environmental and policy requirements, thus leading to recommendation of a plan for implementation.

The search for the recommended plan is conducted in phases, as described in ER 1105-2-100. In the first phase, the *reconnaissance phase*, alternatives are formulated and evaluated in a preliminary manner to determine if at least one plan exists that (1) has positive net benefit, (2) is likely to satisfy the environmental-protection and performance standards, and (3) is acceptable to local interests. If such a plan can be identified, and if a local sponsor is willing to share the cost, the search for the recommended plan continues to the second phase, the *feasibility phase*. In that phase, the set of alternatives is refined and the search is narrowed. The evaluation is more rigorous, leading to identification of the recommended plan in sufficient detail that it can be implemented without significant change. In the third phase, the *pre-construction engineering and design study* (PED), design documents and plans and specifications necessary for implementation are prepared. Although applicable to some extent in all phases, the uncertainty analysis procedures described herein are intended for the feasibility phase. However, if plans change significantly between conduct of the feasibility and PED studies, reformulation is required. In that case, uncertainty analysis is required, consistent with requirements of a feasibility study.

2-2. Formulation

a. Plan formulation is the process of systematically reviewing the characteristics of the problem to identify promising candidate damage reduction measures or mixes of measures. The product of the formulation exercise is a set of alternative plans that are evaluated in progressively greater detail to identify a superior plan. This process is dynamic, as new alternatives may be revealed and added to the candidate list during the evaluation.

b. Corps planning, formulation, and the subsequent evaluation and selection take place in a public forum. The views and ideas of all stakeholders are solicited and incorporated in the plans formulated. To do so fairly and properly, Corps flood-damage reduction studies are conducted by multidisciplinary teams. Typically, such a team includes experts in planning, economics, hydrologic engineering, structural or geotechnical engineering, ecology, and public policy. Individually, these team members bring to bear their expertise in and knowledge of critical technical subjects. Jointly, the team members formulate candidate plans.

2-3. Traditional Economic Evaluation and Display

a. *NED contribution.*

(1) Once a set of candidate plans is formulated, each is evaluated using the NED objective and applicable environmental and policy constraints. In the case of flood-damage-reduction planning, the NED objective is measured by a plan's net benefit, NB, computed as

$$NB = (B_L + B_1 + B_{IR}) - C \qquad (2\text{-}1)$$

B_L is the *location benefit*, the value of making floodplain land available for new economic uses, such as shifting from agricultural to industrial use. B_I, the *intensification benefit*, is the value of intensifying use of the land, such as shifting from lower to higher-value or higher-yield crops. B_{IR}, the *inundation-reduction benefit*, is the value of reducing or modifying the flood losses to economic activity already using the floodplain land in the absence of any further action or plan. C is the total cost of implementing, operating, maintaining, repairing, replacing, and rehabilitating (OMRR&R) the plan. For comparison purposes, these benefits and costs are average values over the analysis period. This analysis period is the same for each alternative. The analysis period is the time over which any plan will have significant beneficial or adverse effects; or a period not to exceed 100 years (ER 1105-2-100).

(2) The basis for computation of the location, intensification, and inundation-reduction benefits is the *without-project* condition. This is defined as "...the land use and related conditions likely to occur under existing improvements, laws, and policies... (ER 1105-2-100)." The planning team must identify carefully this without-project baseline condition, and because of the need to account for both base and future benefits, it must be identified as a function of time. Identification for the base year condition is relatively straightforward: Basin attributes can be inventoried. For future year conditions, however, forecasts must be made. For example, to identify future without-project stage-damage functions, a study team might study zoning and floodplain development ordinances, land-use plans, and population projections. A most likely scenario is normally adopted for 20 to 30 years out.

(3) Once the without-project conditions are established, location benefit for a candidate plan is computed as the income of the newly available floodplain land with that plan (the *with-project* income) less the without-project income. Similarly, intensification benefit is with-project income from production on the same floodplain land less without-project production. The inundation-reduction benefit is

$$B_{IR} = (X_{without} - X_{with}) \qquad (2\text{-}2)$$

in which $X_{without}$ = without-project economic flood-inundation damage; and X_{with} = economic damage if the plan is implemented. For urban areas, this damage commonly is estimated with a stage-damage function that correlates damage and stage; the function is based on surveys of floodplain property. Stage, in turn, is related to discharge with a stage-discharge function (also known as a rating curve). This function is derived empirically from measurements or conceptually with a hydraulics model. Various damage-reduction measures alter either the discharge, the corresponding stage, or damage incurred. Thus, to find the inundation-reduction benefit of a plan, damage for the with-project case is found using the without-project discharge, stage-discharge, and stage-damage functions. This value is subtracted from damage found using the without-project discharge and functions.

b. Annual values. The random nature of flooding complicates determination of inundation damage: It raises a question about which flood (or floods) to consider in the evaluation. For example, the structural components of a plan that eliminates all inundation damage in an average year may be too small to eliminate all damage in an extremely wet year and much larger than required in an extremely dry year. WRC guidelines address this problem by specifying use of expected flood damage for computation of the inundation-reduction benefit. Thus the equation for computing a plan's NED contribution can be rewritten as

$$NB = B_L + B_I + (E\,[X_{without}] - E\,[X_{with}]) - C \qquad (2\text{-}3)$$

in which E [ ] denotes the expected value. This expected value considers the probability of occurrence of all floods, as described in further detail in Section 2.4.

c. Discounting and annualizing. WRC guidelines stipulate that benefits and costs "...are to be expressed in average annual equivalents by appropriate discounting and annualizing..." This computation is simple if conditions in the basin remain the same over the analysis period: In that case, the average annual benefits and costs will be the same each year. However, if conditions change with time, the benefits and cost will change. For example, if pumps for an interior-area protection component of a levee plan must be replaced every 10 years, the OMRR&R cost will not be uniform. In that case, a uniform annual cost must be computed. Procedures for computations in more complex cases are presented in James and Lee (1971) and other engineering economics texts.

d. Display. ER 1105-2-100 provides examples of tables for display of economic performance of alternative plans. The tables display benefits and cost by category for each alternative (Table 6-7 of the ER) and the temporal distribution of flood damage, for the without-project condition (Table 6-9), and with alternative plans (Table 6-8).

2-4. Inundation-Reduction Benefit Computation

a. Theoretical background.

(1) As noted earlier, the random nature of flood damage makes it impossible to predict the exact value of damage that would be incurred or prevented any year. Because of this, plan evaluation is based on large-sample or long-term statistical averages, also known as *expectations*. The expected value of inundation damage X can be computed as

$$E\ [X] = \int_{-\infty}^{\infty} x f_X\ (x)\ dx \tag{2-4}$$

in which $E[X]$ = expected value of damage; x = the random value of damage that occurs with probability $f_X(x)dx$. With this, all the information about the probability of occurrence of various magnitudes of damage is condensed into a single number by summing the products of all possible damage values and the likelihood of their occurrence.

(2) In the equation, $f_X(x)$ is referred to as the *probability density function* (PDF). In hydrologic engineering, an alternative representation of the same information, the so-called *cumulative distribution function* (CDF), is more commonly used. This is defined as

$$F_X\ [x] = \int_{-\infty}^{x} f_X\ (u)\ du \tag{2-5}$$

(3) This distribution function, also known as a *frequency or probability function*, defines the probability that annual maximum damage will not exceed a specified value X. Alternately, by exchanging the limits of integration, the CDF could define the probability that the damage will exceed a specified value. In either case, the CDF and PDF are related as

$$\frac{dF_X\ [X]}{dx} = f_X\ (x) \tag{2-6}$$

so the expected value can be computed as

$$E\ [X] = \int_{-\infty}^{\infty} x\ \frac{dF_X(x)}{dx}\ dx \tag{2-7}$$

$E[X]$ in the equation is the expected annual damage, commonly referred to as EAD.

b. Method of computation.

(1) Mechanically, then, finding the expected value of annual damage is equivalent to integrating the annual damage-cumulative probability function. The function can be integrated analytically if it is written as an equation, but this approach is of little value in a Corps study, as analytical forms are not available. In fact, the damage probability function required for expected-annual-damage computation is not available in any form. Theoretically, the function could be derived by collecting annual damage data over time and fitting a statistical model. In most cases, such damage data are not available or are very sparse.

(2) Alternatively, the damage-probability function can be derived via transformation of available hydrologic, hydraulic, and economic information, as illustrated by Figure 2-1. A discharge-probability function (Figure 2-1*a*) is developed. If stage and discharge are uniquely related, a rating function (Figure 2-1*b*) can be developed and the discharge-probability function can be transformed with this rating function to develop a stage-probability function. [This implies that the probability of exceeding the stage S that corresponds to discharge Q equals the probability of exceeding Q.] Similarly, if stage and damage are uniquely related, a stage-damage function (Figure 2-1*c*) can be developed, and the stage-probability function can be transformed with that function to yield the required damage-probability function. Finally, to compute the expected damage, the resulting damage-probability function is integrated. This can be accomplished using numerical techniques.

(3) As an alternative to transformation and integration, expected annual damage can be computed via sampling the functions shown in Figure 2-1. This procedure estimates expected annual damage by conducting a set of experiments. In each experiment, the distribution of annual maximum discharge is sampled randomly to generate an annual flood: the annual maximum discharge that occurred in an experimental "year." Then the annual damage is found via transformation with the stage-discharge and stage-damage functions. This is repeated until the running average of the annual damage values is

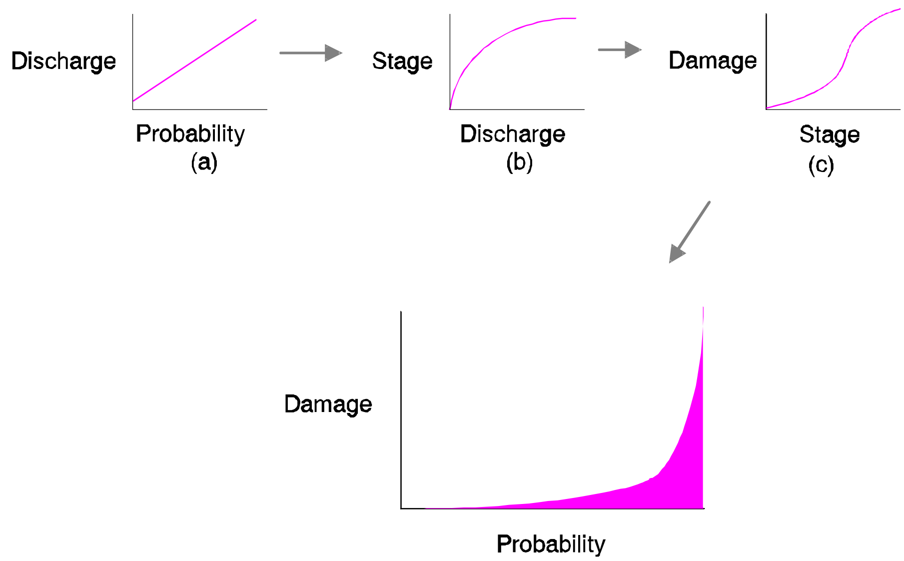

Figure 2-1. Illustration of transformation for traditional expected annual damage computation

not significantly changed (say by 1 percent) when more sample sets are taken. Finally, the average or expected value of all sampled annual damage values is computed. The procedure is illustrated in Figure 2-2.

2-5. Study Strategy

Proper administration of public funds requires that flood-damage-reduction studies be well planned and organized to ensure that the study will (a) provide the information required for decision making, (b) be completed on time, and (c) be completed within budget. To maximize the likelihood that this will happen, a study strategy should be developed before plan evaluation begins. At a minimum, this strategy must include:

(1) *Specification of a spatial referencing system.* Much of the data necessary for proper evaluation has a strong spatial characteristic. For efficiency, a common spatial referencing system should be specified and employed by all members of the multidisciplinary study team. This will ensure that, as necessary, it is possible to map, to cross-reference, and otherwise, to coordinate location of structures, bridges, and other critical floodplain elements.

(2) *Delineation of subbasins.* Hydrologic engineers will select subbasin boundaries based on location of stream gauges, changes in stream network density, changes in rainfall patterns, and for other scientific reasons. Based on this delineation, hydrologic engineering studies will yield discharge-probability and rating functions. This subbasin delineation, however, must also take into account the practical need to provide the information necessary for evaluation at locations consistent with alternatives formulated. For example, if a reservoir alternative is proposed, the subbasin delineation must be such that inflow and outflow probability functions can be developed at the proposed site of the reservoir.

(3) *Delineation of damage reaches for expected-annual-damage computation*. The damage potential for individual structures in a floodplain may be aggregated within spatially defined areas along the stream called damage reaches. Within each reach, an index location is identified at which exceedance probability is stage measured. Then flooding stage at the site of each structure is also related to stage at this index. Thus an aggregated function may be developed to relate all damage in the reach to stage at the single index. The boundaries of these damage reaches must be selected carefully to

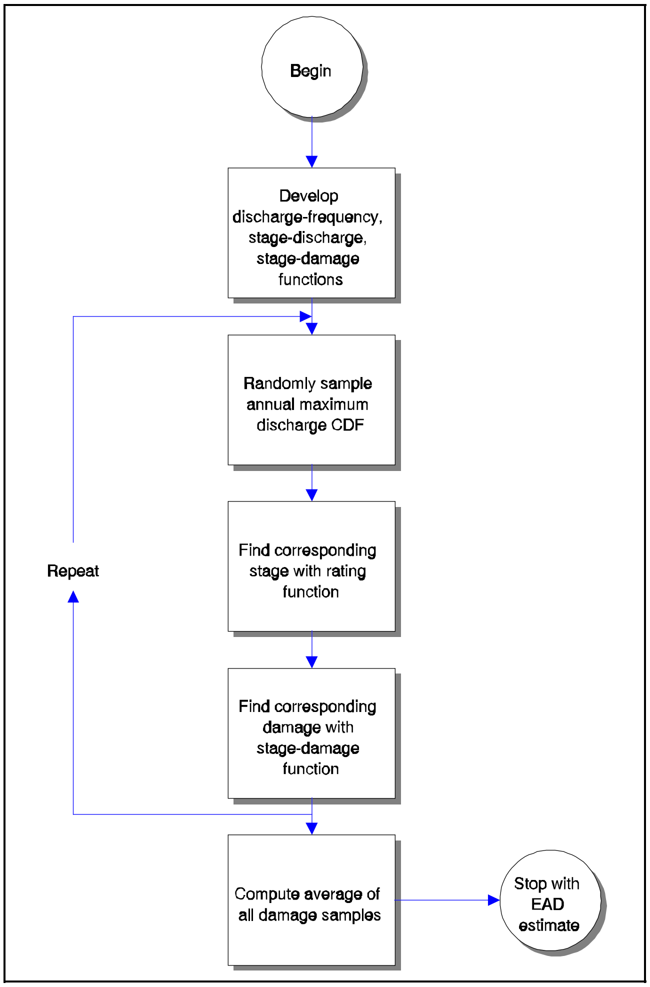

Figure 2-2. Flowchart for expected annual damage computation via annual-flood sampling (model and parameter uncertainty not considered)

ensure that information necessary for proper evaluation of plans proposed is available. For example, if a candidate plan includes channel modifications for a stream reach, evaluation of that plan will be most convenient if a damage reach has boundaries that correspond to the boundaries of the stream reach.

2-6. Uncertainty Description and Analysis

a. Sources of uncertainty. In planning, decisions are made with information that is uncertain. In flood-damage-reduction planning, these uncertainties include:

(1) Uncertainty about future hydrologic events, including future streamflow and rainfall. In the case of discharge-probability analysis, this includes uncertainty regarding the choice of a statistical distribution and uncertainty regarding values of parameters of the distribution.

(2) Uncertainty that arises from the use of simplified models to describe complex hydraulic phenomena, from the lack of detailed geometric data, from misalignment of a hydraulic structure, from material variability, and from errors in estimating slope and roughness factors.

(3) Economic and social uncertainty, including lack of information about the relationship between depth and inundation damage, lack of accuracy in estimating structure values and locations, and lack of ability to predict how the public will respond to a flood.

(4) Uncertainty about structural and geotechnical performance of water-control measures when these are subjected to rare stresses and loads caused by floods.

b. Describing uncertainty.

(1) Traditionally in Corps planning studies, uncertainties have not been considered explicitly in plan formulation and evaluation. Instead the uncertainties have been accounted for implicitly with arbitrarily selected factors of safety and for such features as levees with freeboard. Quantitative risk analysis describes the uncertainties, and permits evaluation of their impact. In simple terms, this description defines the true value of any quantity of interest in the functions shown in Figure 2-1 as the algebraic sum of the value predicted with the best models and parameters and the error introduced because these models and parameters are not perfect. When reasonable, a statistical distribution is developed to describe the error. Such a distribution might reveal that the probability is 0.10 that the error in stage predicted with a rating function is greater than 0.7 m or that the probability is 0.05 that the error in predicting the 0.01-probability discharge is greater that 500 m^3/s.

(2) Chapters 3, 4, and 5 provide guidance on describing uncertainty in functions necessary for flood-damage reduction plan evaluation. Once this uncertainty is described, the impact on evaluation of plan performance can be determined. Two broad categories of techniques are suggested for this uncertainty analysis, depending upon the nature of the uncertainties:

(a) *Simulation or sampling.* This includes (a) expansion of the annual-flood sampling technique to incorporate the descriptions of uncertainty, sampling from each; (b) modification of the sampling technique so that each sample is not a flood, but instead is an equally likely discharge-probability function, rating function, or stage-damage function with which expected annual damage can be computed, and (c) modification of annual-flood sampling technique to generate life-cycle sized samples that are evaluated.

(b) *Sensitivity analysis.* Here, the evaluation is based on specified alternative future conditions and evaluated with traditional procedures. These alternative futures include common and uncommon events, thus exposing the full range of performance of alternatives.

c. Uncertainty analysis via annual-flood sampling. This method computes expected annual damage as illustrated by Figure 2-2, except that an error component (ε) is added to the predicted discharge, stage, and damage at each step. The error cannot be predicted, it can only be described. To describe it, a random sample from the probability distribution of each error is drawn. This assumes that (1) the error in each function is random, and (2) the errors in predicting damage in successive floods are not correlated. Table 2-1 shows the steps of the computations.

d. Uncertainty analysis via function sampling. An alternative to the annual-flood sampling method is to compute expected annual damage by sampling randomly from amongst likely discharge-probability, rating, and stage-damage functions—functions that include explicitly the error components. Table 2-2 shows how this may be accomplished.

Table 2-1
Annual-Flood Sampling Procedure

Step	Task
1	Sample the discharge-probability function to generate an annual flood. This amounts to drawing at random a number between 0.000000 and 1.000000 to represent the probability of exceedance of the annual maximum discharge and referring to the median probability function to find the corresponding annual maximum discharge.
2	Add a random component to represent uncertainty in the discharge-probability function; that is, the uncertainty in predicting discharge for the given exceedance probability from Step 1. This is accomplished by developing and sampling randomly from the probability function that describes the uncertainty. For example, as noted in Chapter 3, the uncertainty or error is described with a non-central *t* distribution for discharge-probability functions fitted with the log Pearson type III distribution.
3	Find the stage corresponding to the discharge plus error from Step 3.
4	Add a random component to represent the uncertainty in predicting stage for the given discharge. To do so, define the probability density function of stage error, as described in Chapter 4 and sample randomly from it.
5	Find the damage corresponding to the stage plus error from step 4.
6	Add a random component to represent uncertainty in predicting damage for the given stage. To do so, define the probability density function of damage error, generate a random number to represent the probability of damage error, refer to the error probability function to find the error magnitude, and add this to the result of Step 5.
7	Repeat Steps 1-6. The repetition should continue until the average of the damage estimates stabilizes.
8	Compute necessary statistics of the damage estimates, including the average. This average is the required expected annual damage.

Table 2-2
Function Sampling Procedure

Step	Task
1	Select, at random, a discharge-probability function from amongst those possible, given the uncertainty associated with definition of the probability function for a given sample. This selected probability function will be the median probability function plus an error component that represents uncertainty in the probability function.
2	Select, at random, a stage-discharge function from amongst those possible, given the uncertainty associated with definition of this rating function. Again, this will be the median stage-discharge function plus an error component.
3	Select, at random, a stage-damage function from amongst those possible, given the uncertainty associated with definition of the stage-damage function. This function will be the median stage-damage function plus an error component.
4	Use the results of Steps 2 and 3 to transform the discharge-probability function of Step 1, thus developing a damage probability function.
5	Integrate the damage probability function to estimate expected annual damage. Call this a *sample* of expected annual damage.
6	Repeat Steps 1-5 to expand the expected annual damage sample set.
7	Compute the average and other necessary statistics of the expected annual damage estimates.

Chapter 3
Engineering Performance of Flood-Damage Reduction Plans

3-1. Overview

Economic efficiency, as measured by a plan's contribution to national economic development, is not the sole criterion for flood-damage reduction plan selection. The Water Resources Development Act of 1986 provides that plans should be evaluated in terms of (1) contribution to national economic development; (2) impact on quality of the total environment; (3) impact on well-being of the people of the United States; (4) prevention of loss of life; and (5) preservation of cultural and historical values. This chapter describes indices of plan performance that provide information for making such an assessment. In particular, indices described herein represent some aspects of the non-economic performance of alternative plans; this performance is referred to herein as *engineering performance*. The indices include expected annual exceedance probability, long-term risk, consequences of capacity exceedance, and conditional probability.

3-2. Expected Annual Exceedance Probability

a. Expected annual exceedance probability (AEP) is a measure of the likelihood of exceeding a specified target in any year. For example, the annual exceedance probability of a 10-m levee might be 0.01. That implies that the annual maximum stage in any year has a 1-percent chance (0.01 probability) of exceeding the elevation of the top of the levee. In the absence of uncertainty in defining hydrologic, hydraulic, and economic functions, annual exceedance probability can be determined directly by referring to the discharge-probability function and stage-discharge functions, or to the stage probability function. For example, to find the annual exceedance probability of a levee with top elevation equal to 10 m, one would refer first to the rating function to determine the discharge corresponding to the top-of-levee stage. Given this discharge, the probability of exceedance would be found then by referring to the discharge-probability function: This probability is the desired annual exceedance probability. Conversely, to find the levee stage with specified annual exceedance probability, one would start with the discharge-probability function, determining discharge for the specified probability. Then from the rating function, the corresponding stage can be found.

b. If the discharge-probability function and rating function are not known with certainty, then the annual exceedance probability computation must include uncertainty analysis. Either annual-event sampling or function sampling can be used for this analysis; the choice should be consistent with the sampling used for expected-annual-damage computation. Figure 3-1 illustrates how the annual exceedance probability can be computed with event sampling, accounting for uncertainty in the discharge-probability function, rating function, and geotechnical performance of the levee.

3-3. Long-term Risk

a. Long-term risk, also referred to commonly as natural, or inherent, hydrologic risk (Chow, Maidment, and Mays 1988), characterizes the likelihood (probability) of one or more exceedances of a selected target or capacity in a specified duration. Commonly that duration is the anticipated lifetime of the project components, but it may be any duration that communicates to the public and decision makers the risk inherent in a damage-reduction plan.

Long-term risk is calculated as:

$$R = 1 - [1 - P\,(X \geq X_{Capacity})]^n \tag{3-1}$$

where $P(X \geq X_{Capacity})$ = the annual probability that X (the maximum stage or flow) exceeds a specified target or the capacity, $X_{Capacity}$; R = the probability that an event $X \geq X_{Capacity}$ will occur at least once in n years. This relationship is plotted in Figure 3-2 for selected values of duration n for annual exceedance probabilities P ($X \geq X_{Capacity}$) from 0.001 to 0.1.

b. Long-term risk is a useful index for communicating plan performance because it provides a measure of probability of exceedance with which the public can identify. For example, many home mortgages are 30 years in duration. With this index, it is possible to determine that within the mortgage life, the probability of overtopping a levee with annual exceedance probability of 0.01 is $1-(1-0.01)^{30}$, or 0.26. For illustration, such long-term risks can be compared conveniently with other similar long-term risks, such as the risk of a house fire during the mortgage period.

c. Likewise, the long-term risk index can help expose common misconceptions about flooding probability. For example, Figure 3-2 shows that the risk in 100 years of one or more floods with an annual

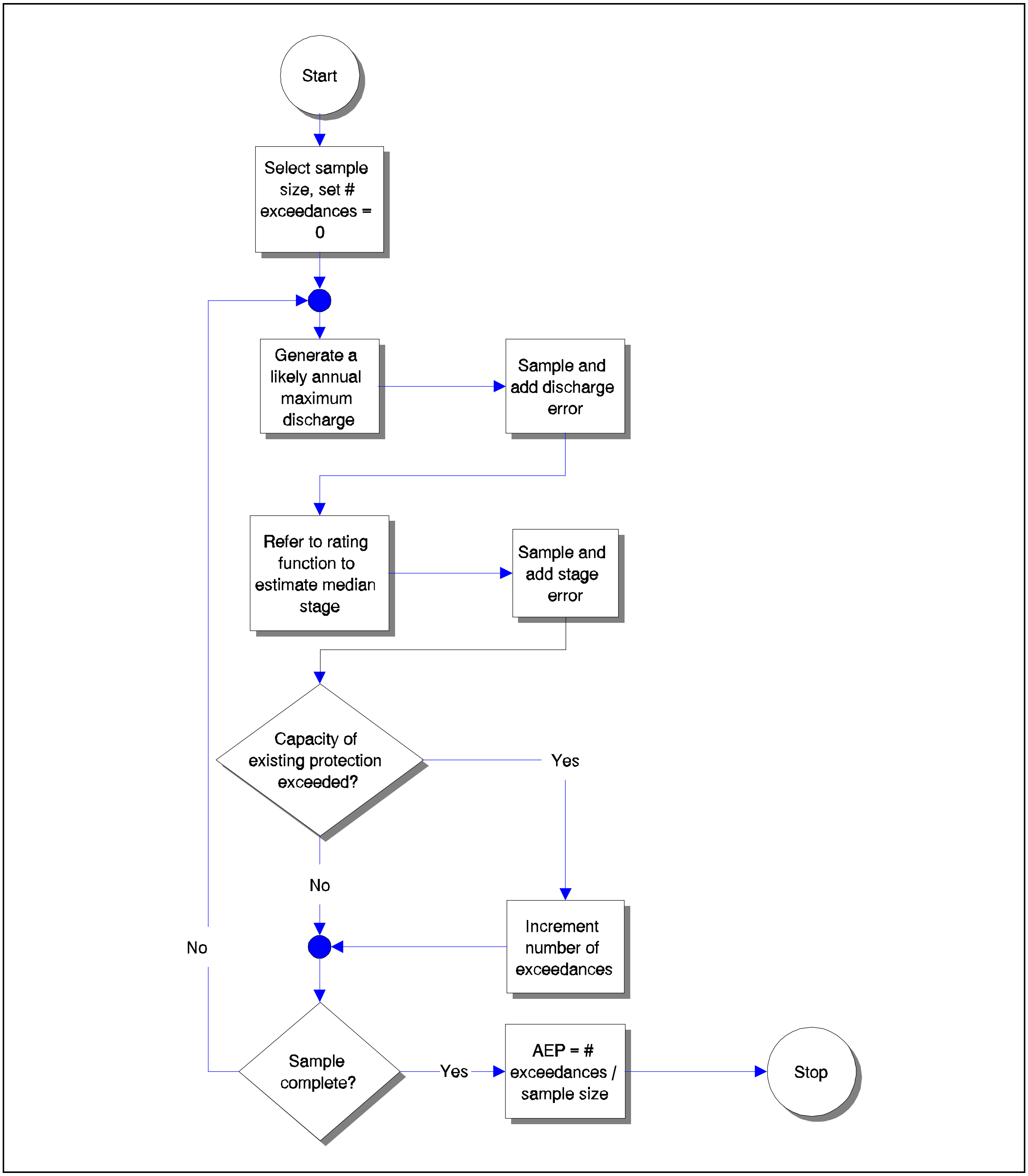

Figure 3-1. Annual exceedance probability estimation with event sampling

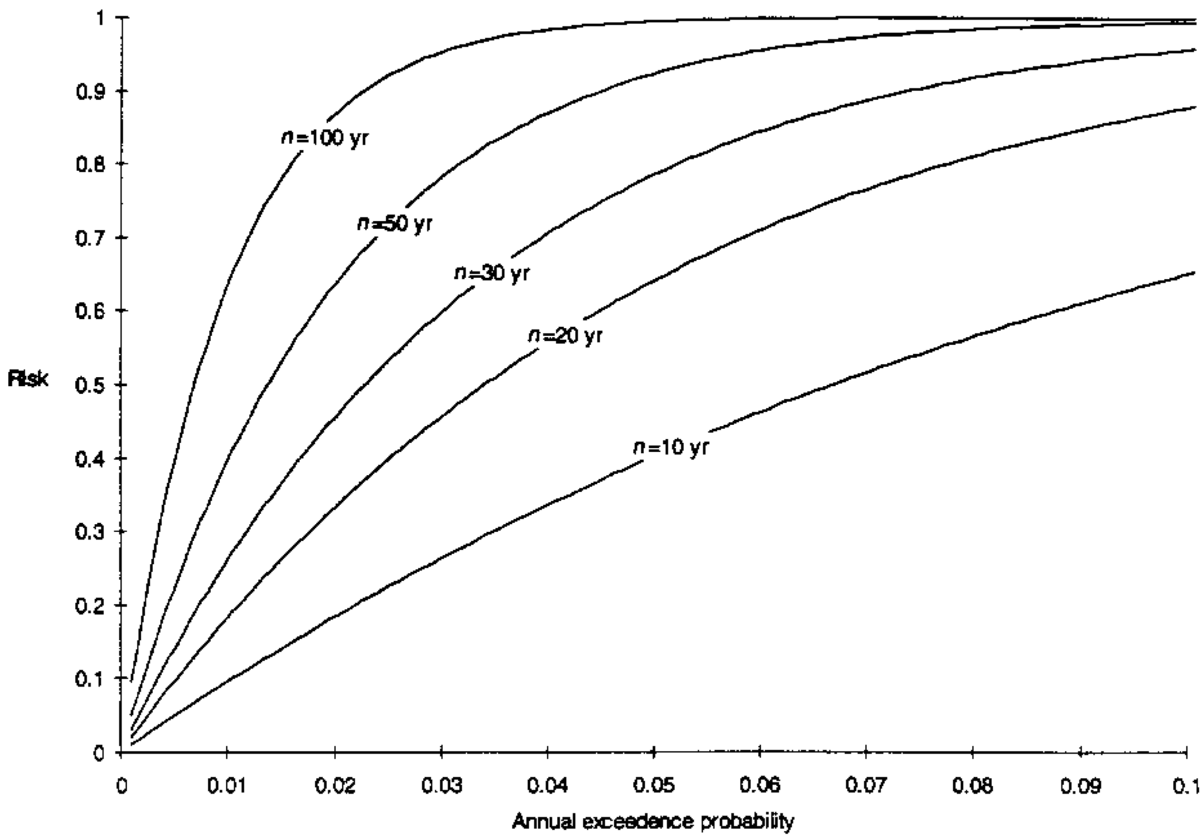

Figure 3-2. Long-term risk versus annual exceedance probability

exceedance probability of 0.01 is approximately 0.63. The complement is also true: The probability of *no* floods with annual exceedance probability of 0.01 is 1.00-0.63 = 0.37. That is, there is a 37 percent chance that no *floods* with a chance of exceedance of 1-percent or greater will occur within any 100-year period. Such information is useful to help the public understand the randomness of hydrologic events and to accept that it is not extraordinary that property in a regulatory floodplain has not flooded in several generations.

3-4. Conditional Annual Non-Exceedance Probability

a. Conditional annual non-exceedance probability (CNP) is an index of the likelihood that a specified target will not be exceeded, given the occurrence of a hydro-meteorological event. For example, the conditional non-exceedance probability of a proposed 5.00-m-high levee might be 0.75 for the 0.002-probability event. This means that if the plan is implemented, the probability is 0.75 that the stage will not exceed 5.00 m, given the occurrence of a 0.2-percent chance event. Conditional non-exceedance probability is a useful indicator of performance because of the uncertainty in discharge-probability and stage-discharge estimates. Evaluation of several events can provide insight as to how different measures perform. The assessment of a known historic event may assist local sponsors and the public in understanding how a project may perform.

b. Computation of conditional annual non-exceedance probability requires specification of:

(1) The performance target. This target commonly is specified as a stage, and it is commonly the maximum stage possible before any significant damage is incurred.

(2) One or more critical events. These should be selected to provide information for decision making, so the events chosen should be familiar to the public and to decision makers. These events can be specified in terms

of magnitude of stage, discharge, or annual exceedance probability. Reasonable choices include (1) the event with stage or discharge equal to the capacity of a flood-damage-reduction measure, such as the stage at the top of a proposed levee; (2) the stage or discharge associated with one or more historical events, and (3) events with familiar annual exceedance probabilities, such as the event with an annual exceedance probability of 0.01.

c. The method of computation of conditional non-exceedance probability depends on the form in which the target event is specified and the method of sampling used. In general, the computation requires repeated sampling of the critical event, comparison with the target, and determination of the frequency of non-exceedance. Figure 3-3 illustrates the computation for a levee alternative, using a critical event of specified annual exceedance probability. This figure assumes that the following are available: (1) discharge-probability function, with uncertainty described with a probability function; (2) rating function, with uncertainty described with probability function; and (3) geotechnical performance function. Conditional annual non-exceedance probability estimation with the critical event specified in terms of stage omits the discharge probability function uncertainties.

3-5. Consequences of Capacity Exceedance

a. EM 1110-2-1419 notes that "all plans should be evaluated for performance against a range of events." This includes events that exceed the capacity of the plan, for regardless of the capacity selected, the probability of capacity exceedance is never zero. No reasonable action can change that. A complete planning study will estimate and display the consequences of capacity exceedance so that the public and decision makers will be properly informed regarding the continuing threat of flooding.

b. The economic consequences of capacity exceedance are quantified in terms of residual event and expected annual damage. Residual expected annual damage is computed with the results of economic benefit computations; it is the with-project condition EAD (Equation 2-7).

c. Other consequences of the exceedance may be displayed through identification, evaluation, and description of likely exceedance *scenarios*. A scenario is a "particular situation, specified by a single value for each input variable" (Morgan and Henrion 1990). In the case of a capacity-exceedance scenario, specific characteristics of the exceedance are defined, the impact is estimated, and qualitative and quantitative results are reported. The scenarios considered may include a best case, worst case, and most-likely case, thus illustrating consequences for a range of conditions. For example, for a levee project, scenarios identified and evaluated may include:

(1) A most-likely case, defined by the planning team (including geotechnical engineers) to represent the most-likely mode of failure, given overtopping. The scenario should identify the characteristics of the failure, including the dimensions of a levee breach. Then a fluvial hydraulics model can be used to estimate depths of flooding in the interior area. With this information, the impact on infrastructure can be estimated explicitly. Flood damages can be estimated if assumptions are made regarding the timing of the exceedance and the warning time available. Review of historical levee overtopping elsewhere for similar facilities will provide the foundation for construction of such a scenario.

(2) A best case defined by the team to include minor overtopping without breaching. This scenario may assume that any damage to the levee is repaired quickly. Again, the impact will be evaluated with a hydraulics model. For evaluation of economic impact, loss of life, impact on transportation, etc., the timing of the exceedance may be specified as, say, 9 a.m.

(3) A worst case defined by the team to include overtopping followed by a levee breach that cannot be repaired. The breach occurs at 3 a.m., with little warning. Again, the same models will be used to evaluate the impact.

d. For each of the scenarios, the consequences should be reported in narrative that is included in the planning study report.

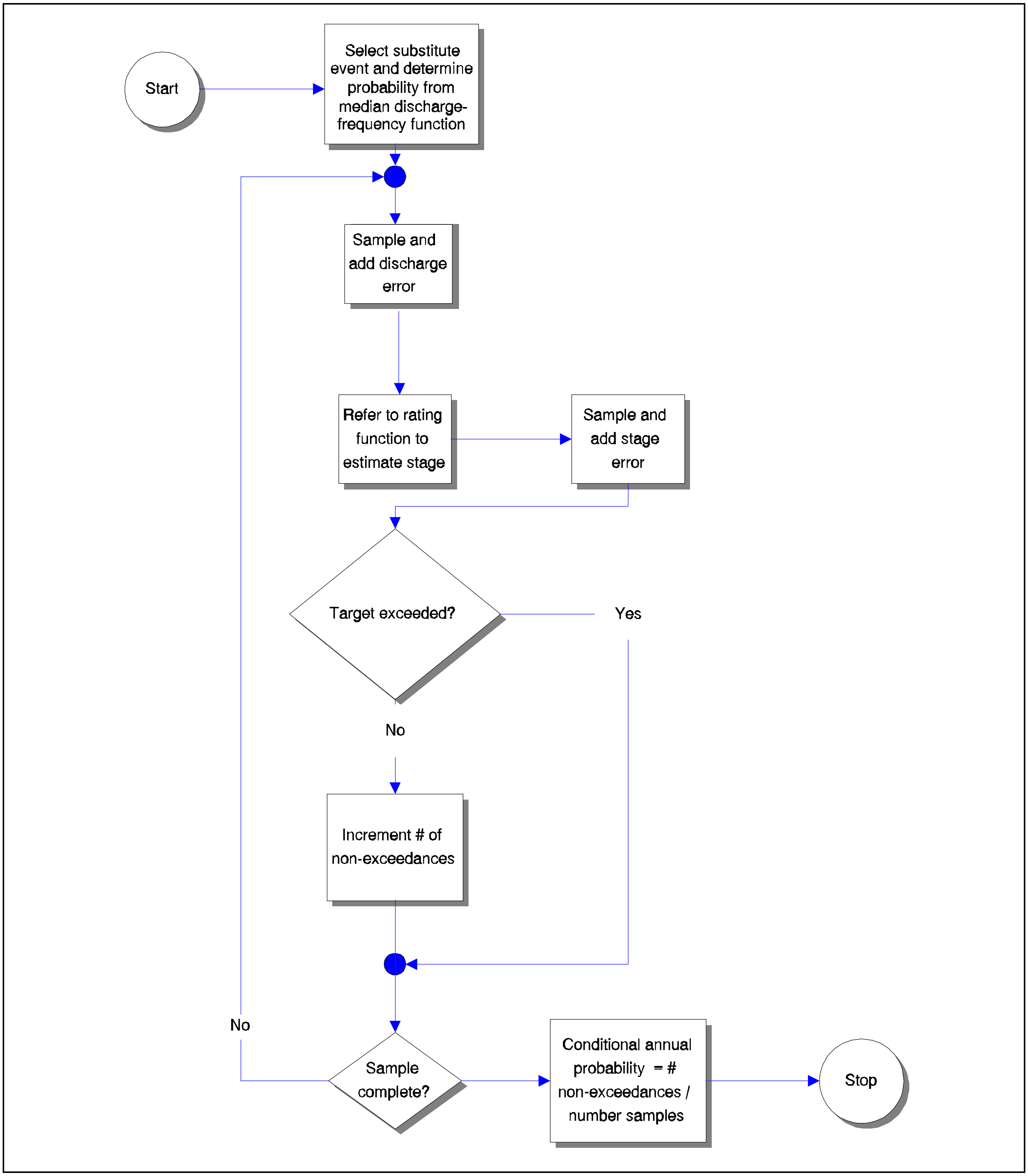

Figure 3-3. Conditional annual non-exceedance probability estimation with event sampling

Chapter 4
Uncertainty of Discharge-Probability Function

4-1. Function Development

a. A discharge or stage-probability function is critical to evaluation of flood damage reduction plans. The median function is used for the analytical method. The manner in which the function is defined depends on the nature of the available data. A direct analytical approach is used when a sample (such as stream gauge records of maximum annual discharges) is available and it fits a known statistical distribution such as log Pearson III. Other approaches are required if recorded data are not available or if the recorded data do not fit a known distribution. These approaches include using the analytical method after defining parameters of an adopted discharge-probability function generated by various means and the graphical or “eye fit” approach for fitting the function through plotting position points. The synthetic statistics approach is applied when the statistics for an adopted discharge-probability function are consistent with hydrologically and meteorologically similar basins in the region. The adopted function may be determined using one or more of the methods presented in Table 4-1. The graphical approach is commonly used for regulated and stage-probability functions whether or not they are based on stream gauge records or computed and stage-probability functions whether or not they are based on stream gauge records or computed from simulation analysis.

b. The without-project conditions discharge-probability functions for the base years are derived initially for most studies and become the basis of the analysis for alternative plans and future years. These functions may be the same as the without-project base year conditions or altered by flood damage reduction measures and future development assumptions. The uncertainty associated with these functions may be significantly different, in most instances greater.

c. Flood damage reduction measures that directly affect the discharge or stage-probability function include reservoirs, detention storage, and diversions. Other measures, if implemented on a large scale, may also affect the functions. Examples are channels (enhanced conveyance), levees (reduction in natural storage and enhanced conveyance), and relocation (enhanced conveyance).

4-2. Direct Analytical Approach

a. General. The direct analytical approach is used when a sample of stream gauge annual peak discharge values are available and the data can be fit with a statistical distribution. The median function is used in the risk-based analysis. The derived function may then be used to predict specified exceedance probabilities. The approach used for Corps studies follows the U.S. Water Resources Council's recommendations for Federal planning involving water resources presented in publication Bulletin 17B (Interagency Advisory Committee on Water Data 1982) and in EM 1110-2-1415 and ER 1110-2-1450.

Table 4-1
Procedures for Estimating Discharge-Probability Function Without Recorded Events (adapted from USWRC (1981))

Method	Summary of Procedure
Transfer	Discharge-probability function is derived from discharge sample at nearby stream. Each quantile (discharge value for specified probability) is extrapolated or interpolated for the location of interest.
Regional estimation of individual quantiles or of function parameters	Discharge-probability functions are derived from discharge samples at nearby gauged locations. Then the function parameters or individual quantiles are related to measurable catchment, channel, or climatic characteristics via regression analysis. The resulting predictive equations are used to estimate function parameters or quantiles for the location of interest.
Empirical equations	Quantile (flow or stage) is computed from precipitation with a simple empirical equation. Typically, the probability of discharge and precipitation are assumed equal.
Hypothetical frequency events	Unique discharge hydrographs due to storms of specified probabilities and temporal and areal distributions are computed with a rainfall-runoff model. Results are calibrated to observed events or discharge-probability relations at gauged locations so that probability of peak hydrograph equals storm probability.
Continuous simulation	Continuous record of discharge is computed from continuous record of precipitation with rainfall-runoff model, and annual discharge peaks are identified. The function is fitted to series of annual hydrograph peaks, using statistical analysis procedures.

b. Uncertainty of distribution parameters due to sampling error.

(1) Parameter uncertainty can be described probabilistically. Uncertainty in the predictions is attributed to lack of perfect knowledge regarding the distribution and parameters of the distribution. For example, the log Pearson type III distribution has three parameters: a location, a scale, and a shape parameter. According to the Bulletin 17B guidance, these are estimated with statistical moments (mean, standard deviation, and coefficient of skewness) of a sample. The assumption of this so-called method-of-moments parameter-estimation procedure is that the sample moments are good estimates of the moments of the population of all possible annual maximum discharge values. As time passes, new observations will be added to the sample, and with these new observations the estimates of the moments, and hence the distribution parameters, will change. But by analyzing statistically the sample moments, it is possible to draw conclusions regarding the likelihood of the true magnitude of the population moments. For example, the analysis might permit one to conclude that the probability is 0.90 that the parent population mean is between 10,000 m^3/s and 20,000 m^3/s. As the discharge-probability function parameters are a mathematical function of the moments, one can then draw conclusions about the parameters through mathematical manipulation. For example, one might conclude that the probability is 0.90 that the location parameter of the log Pearson type III model is between a specified lower limit and a specified upper limit. Carrying this one step further to include all three parameters permits development of a description of uncertainty in the frequency function itself. And from this, one might conclude that the probability is 0.90 that the 0.01-probability discharge is between 5,000 m^3/s and 5,600 m^3/s. With such a description, the sampling described in Chapter 2 can be conducted to describe the uncertainty in estimates of expected annual damage and annual exceedance probability.

(2) Appendix 9 of Bulletin 17B presents a procedure for approximately describing, with a statistical distribution, the uncertainty with a log-Pearson type III distribution with parameters estimated according to the Bulletin 17B guidelines. This procedure is summarized in Table 4-2; an example application is included in Tables 4-3 and 4-4.

(3) The sampling methods described in Chapter 2 require a complete description of error or uncertainty about the median frequency function. To develop such a description, the procedure shown in Table 4-2 can be repeated for various values of *C*, the confidence level. Table 4-3, for example, is a tabulation of the statistical model that describes uncertainty of the 0.01-probability quantile for Chester Creek, PA.

c. Display of uncertainty. The probabilistic description of discharge-probability function uncertainty can be displayed with confidence limits on a plotted function, as shown in Figure 4-1. These limits are curves that interconnect discharge or stage values computed for each exceedance probability using the procedure shown in Table 4-2, with specified values of *C* in the equations. For example, to define a so-called *95-percent-confidence limit*, the equations in Table 4-2 are solved for values of *P* with *C* constant and equal to 0.95. The resulting discharge values are plotted and interconnected. Although such a plot is not required for the computations proposed herein, it does illustrate the uncertainty in estimates of quantiles.

4-3. Analytical Approach

The analytical approach for adopted discharge-probability functions, also referred to as the synthetic approach, is described in Bulletin 17B (Interagency Advisory Committee 1982). It is used for ungauged basins when the function is derived using the transfer, regression, empirical equations, and modeling simulation approaches presented in Table 4-1 and when it is not influenced by regulation, development, or other factors. The discharge-probability function used is the median function and is assumed to fit a log Pearson Type II distribution by deriving the mean, standard deviation, and generalized skew from the adopted function defined by the estimated 0.50-, 0.10-, and 0.01-exceedance probability events. Assurance that the adopted function is valid and is properly fitted by the statistics is required. If not, the graphical approach presented in the next section should be applied. The value of the function is expressed as the equivalent record length which may be equal to or less than the record of stream gauges used in the deviation of the function. Table 4-5 provides guidance for estimating equivalent record lengths. The estimated statistics and equivalent record length are used to calculate the confidence limits for the uncertainty analysis in a manner previously described under the analytical approach.

4-4. Graphical Functions

a. Overview. A graphical approach is used when the sample of stream gauge records is small, incomplete,

Table 4-2
Procedure for Confidence Limit Definition (from Appendix 9, Bulletin 17B)

The general form of the confidence limits is specified as:

$$U_{P,C}\ (X) = \bar{X} + S\ (K^{U}_{P,C})$$

$$L_{P,C}\ (X) = \bar{X} + S\ (K^{L}_{P,C})$$

in which X and S and are the logarithmic mean and standard deviation of the final estimated log Pearson Type III discharge-probability function, and $K^{U}{}_{P,C}$ and $K^{L}{}_{P,C}$ are upper and lower confidence coefficients. [Note: P is the exceedance probability of X, and C is the probability that $U_{P,C} > X$ and that $L_{P,C} < X$.]

"The confidence coefficients approximate the non-central t-distribution. The non-central-t variate can be obtained in tables (41,42), although the process is cumbersome when G_W is non-zero. More convenient is the use of the following approximate formulas (32, pp. 2-15) based on a large sample approximation to the non-central t-distribution (42).

$$K^{U}_{P,C} = \frac{K_{G_w,\,P} + \sqrt{K^2 G_w,\ P - ab}}{a}$$

$$K^{L}_{P,C} = \frac{K_{G_w,\,P} + \sqrt{K^2 G_w,\ P - ab}}{a}$$

in which:

$$a = 1 - \frac{Z_C^2}{2\ (N - 1)}$$

$$b = K^2_{G_{W},\ P} - \frac{Z_C^2}{N}$$

and Z_C is the standard normal deviate (zero-skew Pearson Type III deviate with cumulative probability, C (exceedance probability 1-C). The systematic record length N is deemed to control the statistical reliability of the estimated function and is to be used for calculating confidence limits even when historic information has been used to estimate the discharge-probability function.

Examples are regulated flows, mixed populations such as generalized rainfall and hurricane events, partial duration data, development impacts, and stage exceedance probability. The graphical method does not yield an analytical representation of the function, so the procedures described in Bulletin 17B cannot be applied to describe the uncertainty. The graphical approach uses plotting positions to define the relationship with the actual function fitted by "eye" through the plotting position points. The uncertainty relationships are derived using an approach referred to as order statistics (Morgan and Henrion 1990). The uncertainty probability function distributions are assumed normal, thus requiring the use of the Wiebull's plotting positions, representing the expected value definition of the function, in this instance.

b. Description with order statistics. The order statistics method is used for describing the uncertainty for frequency functions derived for the graphical approach. The method is limited to describing uncertainty in the estimated function for the range of any observed data, or if none were used, to a period of record that is equivalent in information content to the simulation method used to derive the frequency function. Beyond this period of record, the method extrapolates the uncertainty description using asymptotic approximations of error distributions. The procedure also uses the equivalent record length concepts described in Section 4-3 and presented in Table 4-5.

Table 4-3
Example of Confidence Limit Computation (from Appendix 9, Bulletin 17B)

The 0.01 exceedance probability discharge for Chester Creek at Dutton Mill gauge is 18,990 cfs. The discharge-probability curve there is based on a 65-year record length (N = 65), with mean of logs of annual peaks (X) equal to 3.507, standard deviation of logs (S) equal to 0.295, and adopted skew (G_w) equal to 0.4. Compute the 95-percent confidence limits for the 0.01 exceedance probability event.

Procedure: From a table of standard normal deviates, Z_c for the 95-percent confidence limit (C = 0.95) is found to be 1.645. For the 0.01 probability event with G_w = 0.4, the Pearson deviate, $K_{Gw,P} = K_{0.4,0.01}$ is found to be 2.6154. Thus a and b are computed as

$$a = 1 - \frac{(1.645)^2}{2\ (65 - 1)} = 0.9789$$

$$b = (2.6154)^2 - \frac{(1.645)^2}{65} = 6.7987$$

The Pearson deviate of the upper confidence limit for the 0.01-probability event is

$$K^U_{0.01,0.95} = \frac{2.6154 + \sqrt{(2.164)^2 - (6.7987)\ (0.9789)}}{0.9789} = 3.1112$$

and the Pearson deviate of the lower confidence limit for the 0.01-probability event is

$$K^L_{0.01,0.95} = \frac{2.6154 - \sqrt{(2.164)^2 - (6.7987)\ (0.9789)}}{0.9789} = 2.2323$$

Thus the upper confidence-limit quantile is

$$U_{0.01,0.95}\ (X) = 3.507 + 0.295\ (3.1112) = 4.4248$$

and the lower quantile is

$$L_{0.01,0.95}\ (X) = 3.507 + 0.295\ (2.2323) = 4.1655$$

The corresponding quantiles in natural units are 26,600 cfs and 14,650 cfs, respectively.

Table 4-4
Distribution of Estimates of Chester Creek 0.01-Probability Quantile

Exceedance Probability	Discharge, cms
0.9999	320
0.9900	382
0.9500	415
0.9000	437
0.7000	491
0.5000	538
0.3000	592
0.1000	694
0.0500	753
0.0100	895
0.0001	1,390

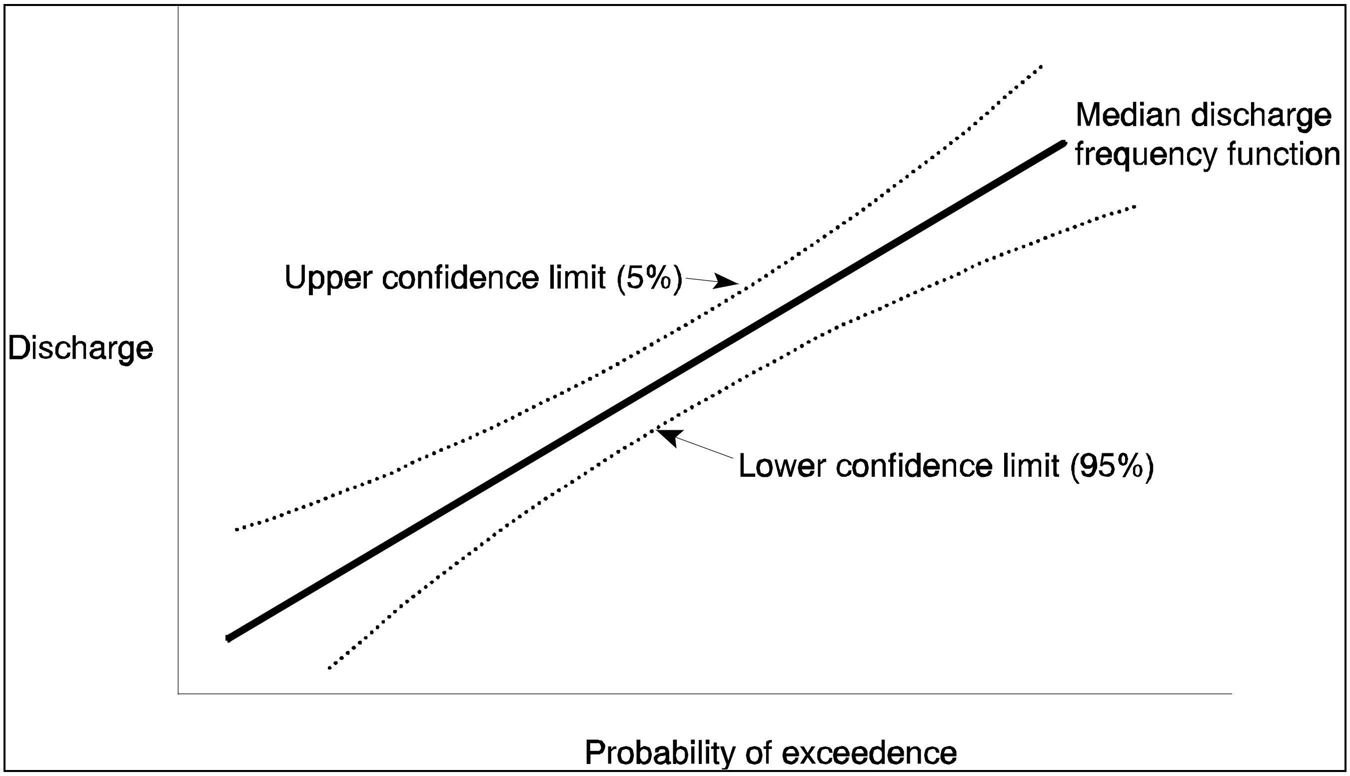

Figure 4-1. Confidence limits

Table 4-5
Equivalent Record Length Guidelines

Method of Frequency Function Estimation	Equivalent Record Length[1]
Analytical distribution fitted with long-period gauged record available at site	Systematic record length
Estimated from analytical distribution fitted for long-period gauge on the same stream, with upstream drainage area within 20% of that of point of interest	90% to 100% of record length of gauged location
Estimated from analytical distribution fitted for long-period gauge within same watershed	50% to 90% of record length
Estimated with regional discharge-probability function parameters	Average length of record used in regional study
Estimated with rainfall-runoff-routing model calibrated to several events recorded at short-interval event gauge in watershed	20 to 30 years
Estimated with rainfall-runoff-routing model with regional model parameters (no rainfall-runoff-routing model calibration)	10 to 30 years
Estimated with rainfall-runoff-routing model with handbook or textbook model parameters	10 to 15 years

[1] Based on judgment to account for the quality of any data used in the analysis, for the degree of confidence in models, and for previous experience with similar studies.

Chapter 5
Uncertainty of Stage-Discharge Function

5-1. Overview of Stage-Discharge Uncertainty

a. The determination of stage-discharge uncertainty requires accounting for the uncertainty associated with factors affecting the stage-discharge relationship. These factors include bed forms, water temperature, debris or other obstructions, unsteady flow effects, variation in hydraulic roughness with season, sediment transport, channel scour or deposition, changes in channel shape during or as a result of flood events, as well as other factors. In some instances, uncertainty might be introduced into the stage-discharge curve due to measurement errors from instrumentation or method of flow measurement, waves, and other factors in the actual measurement of stage and discharge.

b. Numerical models are commonly issued in project studies. While most studies use one-dimensional models, a number of studies now use multi-dimensional modeling to simulate flows in both the without- and with-project conditions. Models are limited by the inherent inability of the theory to model exactly the complex nature of the hydraulic processes. Data used in the models are also not exact, introducing errors in the model geometry and coefficients used to describe the physical setting. Many of the factors which determine stage-discharge uncertainty and which are estimated for modeling purposes are time-dependent, both seasonally as well as during a flow event. Many of the factors are also spatially variable both laterally and longitudinally in the channel and associated floodplain. In general, the more complex the flow conditions, the greater the need to use models that replicate the significant physical processes.

c. Several different methods can be used to estimate the stage-discharge uncertainty for a stream reach. Where possible, each should be applied to provide a check on uncertainty estimates derived from the other methods. The most applicable method will depend on the data available and the method used in project studies. Stage-discharge uncertainty can be evaluated for contributing factors, or for each factor individually. When the factors are analyzed separately, care must be taken to ensure that the resulting uncertainty from combining the factors is reasonable. An example would be a stream where floods always occur significantly after ice melt but where the ice creates significant stage increases when present. In this case the uncertainty for ice should not be imposed in addition to the uncertainty due to increased resistance from early summer vegetation. Any correlation of separate factors should also be considered in the analysis and accounted for in the combination of individual uncertainties.

5-2. Development of the Stage-Discharge Function

a. Stage-discharge rating curves are developed by several methods. The most common and precise practice is to measure stream flow and stage simultaneously and to plot discharge versus stage. U.S. Geological Survey (USGS) (1977) provides a technical procedure for measuring stage and velocity at a given channel section and the development of stage-discharge ratings curves. The stage-discharge function is developed as the best fit curve through the observed stage-discharge measurements. Where these gauge ratings are available, analysis of the measured data versus the rating curve can provide insight into the natural variability at the gauged location.

b. Gauged records may be used to directly estimate stage-discharge uncertainty. The gauged data are assembled, adjusted to remove non-stationary effects of datum changes, gauge location changes, and stream aggradation or degradation. Statistical outlier tests may be used to examine data anomalies. Engineering judgement is needed to identify and handle correctly occurrences of coincidental effects such as ice jams, debris blockages, etc.

c. Figure 5-1 is a plot of stage discharge data for a stream with more than 70 years of record where non-stationary effects have been removed from the record. The record is broken into sections to represent three zones of flow. The first zone is the within-bank flow zone; the second is measured-out-of-bank flow zone (or bank full to the highest measured flow), and the third the rare event zone where occasionally an event may have been measured. A minimum of 8 to 10 measurements out of banks is normally required for meaningful results. Unfortunately, it is not common to have measured events in the range of interest for flood damage reduction studies.

d. The method described in USGS (1977) uses an equation of the form:

$$Q = C\,(G - e)^b \tag{5-1}$$

to describe the stage discharge relationship where Q is discharge, G is the stage reading, and C, e, and b are coefficients used to match the curve to the data. It should

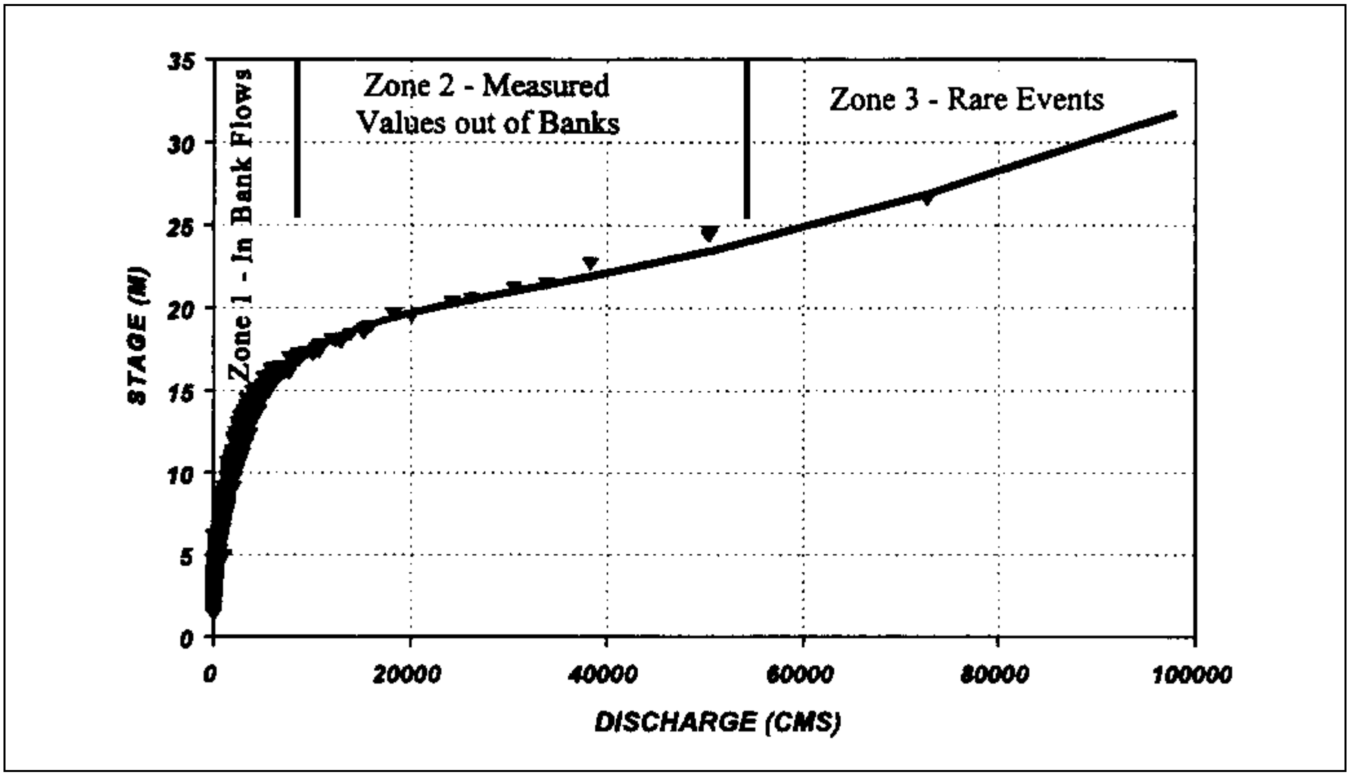

Figure 5-1. Stage-discharge plot showing uncertainty zones, observed data, and best-fit curve

be noted that the value of *b* is usually between 1.3 and 1.8.

e. An alternate equation reported by Freeman, Copeland, and Cowan (1996) is an exponential curve with decreasing exponents:

$$STAGE = a + bQ^{1/2} + cQ^{1/3} + dQ^{1/4} + eQ^{1/5} + fQ^{1/6} \quad (5\text{-}2)$$

where STAGE is in feet, Q is flow in cfs, and *a* through *f* are coefficients determined by a best fit algorithm to fit the equation to the data. This equation yielded an R^2 better than 0.80 for 115 rivers and streams out of 116 analyzed. Additionally, for 75 percent of the streams the R^2 was better than 0.97. Equation 5-2 does not accurately predict very low flows but these are not generally of concern in flood damage reduction studies.

5-3. Determination of Stage-Discharge Uncertainty for Gauged Reaches

a. The measure used to define the uncertainty of the stage-discharge relationship is the standard deviation. The stage residuals (difference between observed and rating function values) provide the data needed to compute uncertainty. It is recommended that only data values for flows above bank-full be used, since low flows are generally not of interest in flood studies. Note that the objective is to calculate uncertainty in stage, not discharge. These residuals characterize the uncertainty in the stage-discharge function and can be described with a probability distribution. The standard deviation of error (or square root of the variance) within a zone (or for the whole record) *S* can be estimated as:

$$S = \sqrt{\frac{\sum_{i=1}^{N} (X_i - M)^2}{N - 1}} \quad (5\text{-}3)$$

where X_i = stage for observation *I* which corresponds with discharge Q_i; *M* = best-fit curve estimation of stage corresponding with Q_i; and *N* = number of stage-discharge observations in the range being analyzed.

b. The distribution of error from the best-fit lines can vary significantly from stream to stream. The

Gaussian (normal) distribution can be used for the description of many rivers but not all. Freeman, Copeland, and Cowan (1996) found that for many streams, the data were much more concentrated near the mean value and the central portion of the distribution was much narrower than is the case for a normal distribution. On other streams, the distribution was markedly skewed. The gamma distribution can represent a wide range of stream conditions from normal to highly skewed and is suggested for use in describing stage uncertainty.

c. The gamma distribution is defined by a scale parameter and a shape parameter curve. Once the scale and shape parameters are known, the skew is fixed (McCuen and Snyder 1986). The values for the shape and scale parameters may be computed from the sample estimates of mean and variance.

d. For the gamma distribution, the standard deviation of the uncertainty is defined as:

$$S = \sqrt{\frac{\kappa}{\lambda^2}} \tag{5-4}$$

where κ = the shape parameter and λ = the scale parameter for the distribution and are simple functions of the sample parameters.

e. Where bank-full elevations and discharges are not available, 20 percent of the daily mean discharge exceedance value may be used instead. Leopold (1994) recommends the 1.5-year recurrence interval in the annual flood series for the approximate location of bank-full. For the streams reported by Freeman, Copeland, and Cowan (1996), there was at times a significant difference in uncertainty between the total record and the flows greater than the 20-percent exceedance flow, as shown in Figure 5-2.

f. If the gauging station is representative of the study reach, then the gauge results are representative. If the gauged results are not representative, other reaches must be analyzed separately.

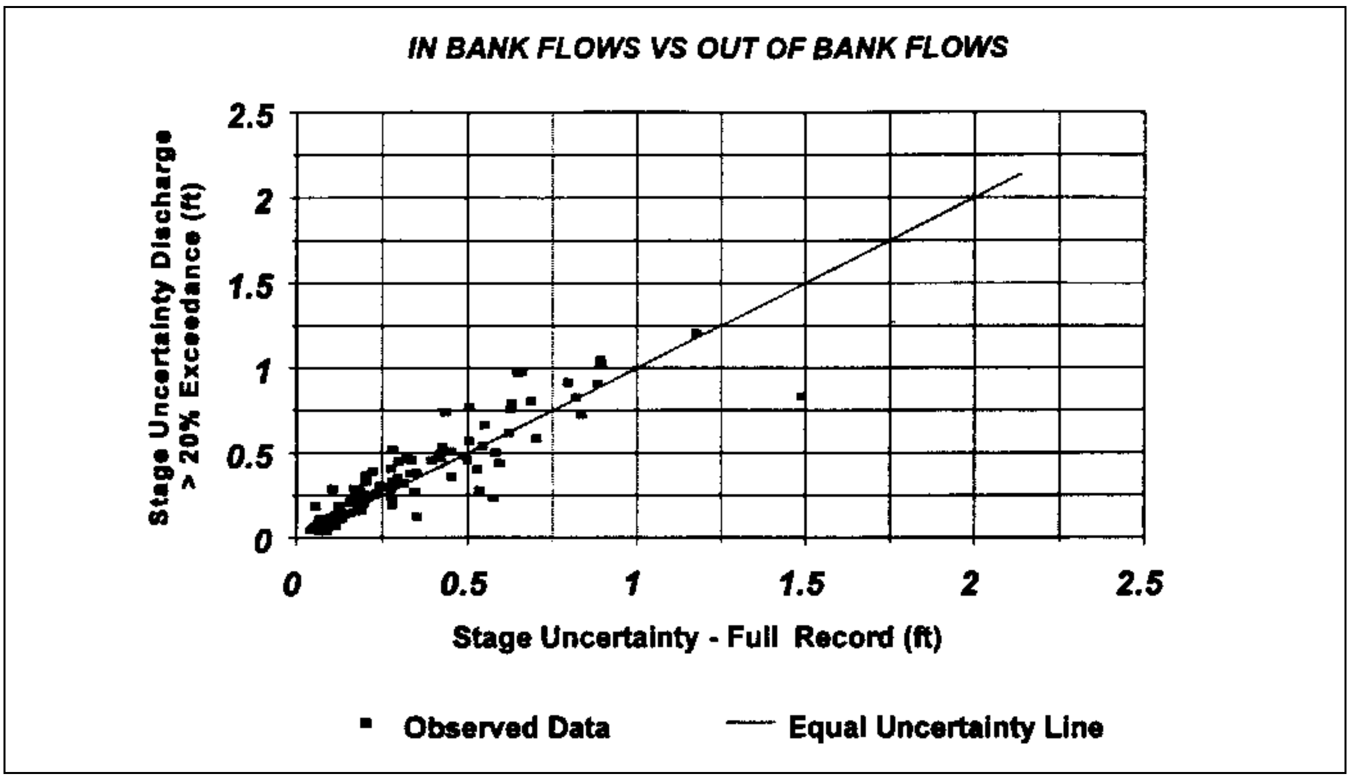

Figure 5-2. Stage-discharge uncertainty for flows greater than 20 percent exceedance compared with full record uncertainty

5-4. Uncertainty in Stage for Ungauged Stream Reaches

Efforts to develop correlations between stage uncertainty and measurable stream parameters have met with modest success (Freeman, Copeland, and Cowan 1996). The correlation between slope and uncertainty can be used as an upper bound estimate in the absence of other data. Figure 5-3 shows the standard deviation of uncertainty based on the Gamma distribution for U.S. streams studied. Using this same data, Equation 5-5 can predict the uncertainty in river stages with R^2 of 0.65.

$$\begin{aligned} S = [&0.07208 + 0.04936\ I_{Bed} \\ &- 2.2626x10^{-7} A_{Basin} \\ &+ 0.02164\ H_{Range} \\ &+ 1.4194 \times 10^{-5} Q_{100}]^2 \end{aligned} \tag{5-5}$$

where S = the standard deviation of uncertainty in meters, H_{Range} = the maximum expected or observed stage range, A_{Basin} = basin area in square kilometers, Q_{100} = 100-year estimated discharge in centimeters, and I_{Bed} is a stream bed identifier for the size bed material which controls flow in the reach of interest from Table 5-1. Equation 5-5 is not physically based but can give reasonable results for ungauged reaches using data that can be obtained from topographic maps at site reconnaissance, an estimate of the expected 100-year flow.

Table 5-1
Bed Identifiers

Material	Identifier
Rock/Resistant Clay	0
Boulders	1
Cobbles	2
Gravels	3
Sands	4

5-5. Uncertainty in Stages for Computed Water Surface Profiles

a. Computed water surface profiles provide the basis for nearly all stage-discharge ratings needed for the "with-project" conditions of Corps flood damage

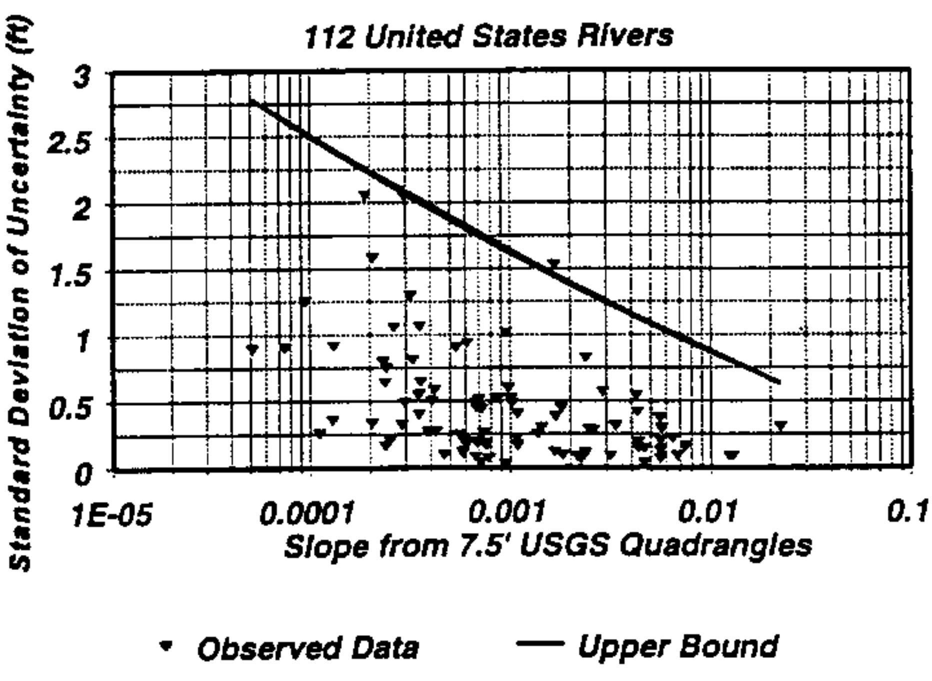

Figure 5-3. Stage-discharge uncertainty compared with channel slope from USGS 7.5-in. quadrangles, with upper bound for uncertainty

reduction studies. Published methods and guidelines for interpreting the accuracy, and thus uncertainty in computed stages, are few. For now, estimated uncertainties must be based on analytical studies of gauged ratings (where they are available), on methods described in Paragraph 5-4 for ungauged reaches, interpretation of the success (or lack thereof) of model adjustment/validation studies, and sensitivity studies designed to determine the stability/ robustness of computed profiles. Professional judgement is required to validate the reasonable limits for uncertainty. Uncertainty in stage-discharge ratings will be the synthesized result of several analyses.

b. The uncertainty in stage due to model and data limitations is best minimized by selecting the most appropriate model for the situation under study. Subsequent to model selection, model adjustment and calibration studies using observed flood data are performed to further minimize uncertainty in results from model applications for study conditions.

c. Research at the Hydrologic Engineering Center (HEC) and the U.S. Army Engineer Waterways Experiment Station (WES) (USACE 1986; Freeman, Copeland, and Cowan 1996) provides information for estimating uncertainty in water surface profiles obtained when using a gradually varied flow model. The standard deviation of the normally distributed errors in the estimated stages are based on topographic information and confidence in estimated Manning's *n* value as shown in Table 5-2.

d. Uncertainty due to natural variations as determined from gauged data, from Figure 5-3, or from Equation 5-5 should be combined with the values from Table 5-2 or values obtained from methods described later in this chapter to obtain an estimate of total uncertainty in a modeled reach of river as follows:

$$S_t = \sqrt{S_{natural}^2 + S_{model}^2 +} \tag{5-6}$$

where S_t is standard deviation of the total uncertainty, $S_{natural}$ is natural uncertainty, and S_{model} is modeling uncertainty. In general, the standard deviation of stage uncertainty could be expected to increase with decrease in data availability, accuracy, and model adjustment/ validation results. Stage uncertainty may also increase with increased complexity of analysis.

5-6. Analysis Complexity

While the majority of water surface profile analyses are within the capabilities of such programs as HEC-2 (USACE 1985), there is need, at times, for more complex analysis. For streams that have rapidly varying flows, or are subject to tides, an unsteady flow analysis may be needed. Sand bed streams may require mobile boundary modeling. Complex flow fields in unusual floodplains or estuaries may require multi-dimensional (and in a few cases, unsteady) flow analysis. In such cases a stage discharge rating for the highest stages commensurate with flow conditions of interest should be developed. The uncertainty associated with the rating is interpreted from the analysis results. Often, sensitivity analysis as discussed below is an appropriate approach to such determination. If it is not possible to develop a rating from the results, then analysis dealing directly with stage-frequency is likely to be necessary.

5-7. Sensitivity Analysis and Professional Judgement

a. One approach to estimating stage uncertainty that can always be used is to estimate the upper and lower bounds on stage for a given discharge and convert the

Table 5-2
***Minimum* Standard Deviation of Error in Stage**

Manning's n Value Reliability[1]	Standard Deviation (in feet): Cross Section Based on Field Survey or Aerial Spot Elevation	Standard Deviation (in feet): Cross Section Based on Topographic Map with 2-5' Contours
Good	0.3	0.6
Fair	0.7	0.9
Poor	1.3	1.5

[1] Where good reliability of Manning's *n* value equates to excellent to very good model adjustment/validation to a stream gauge, a set of high water marks in the project effective size range, and other data. Fair reliability relates to fair to good model adjustment/ validation for which some, but limited, high-water mark data are available. Poor reliability equates to poor model adjustment/validation or essentially no data for model adjustment/validation.

stage range to the needed uncertainty statistic. For example, 95 percent of the error range would be encompassed by stages two standard deviations above and below the mean. Professional judgement could thus be applied to estimate the "reasonable" upper and lower bounds of stage, and the standard deviation estimated as the total range divided by 4. Sensitivity analysis in which reasonable likely combinations of upper and lower bound estimates of model parameter values are used to obtain a range of predicted stages for a given discharge could augment or serve as an alternative to the range determined from professional judgement. Figure 5-4, derived by WES as an extension of the HEC analysis, can be used as a guide to estimating the reasonable bounds to the Manning's *n* value model parameter in sensitivity studies. Figure 5-5 is an example that shows high-water marks and upper and lower limits from sensitivity analysis.

b. The range between the upper and lower limit water stages is used to estimate the standard deviation of stage uncertainty. The mean reach profile differences may be estimated by inspection or determined from cross-sectional profile elevation differences, weighted by distances between cross sections, and averaged over the entire study reach. If the stage difference between the upper and lower limits is taken to be the "reasonable bounds," e.g., 95 percent of the stage uncertainty range, then the standard deviation may be estimated by the following equation:

$$S = \frac{E_{mean}}{4} \tag{5-7}$$

where E_{mean} = mean stage difference between upper and lower limit water surface profiles as shown in Figure 5-5.

c. It would be possible to sketch or estimate the profile range that encompasses the "majority" of the high water marks, compute the difference, and calculate the standard deviation using Equation 5-6. If the "majority" means accounting for two thirds of the marks, Equation 5-6 is used with a divisor of 2 instead of 4. The high-water marks should also be used as a check on the reasonableness of model parameters used in a sensitivity analysis.

5-8. Stage Uncertainty for With-Project Conditions

The discussion has focused on estimating stage uncertainty for the "without-project" condition. The stage

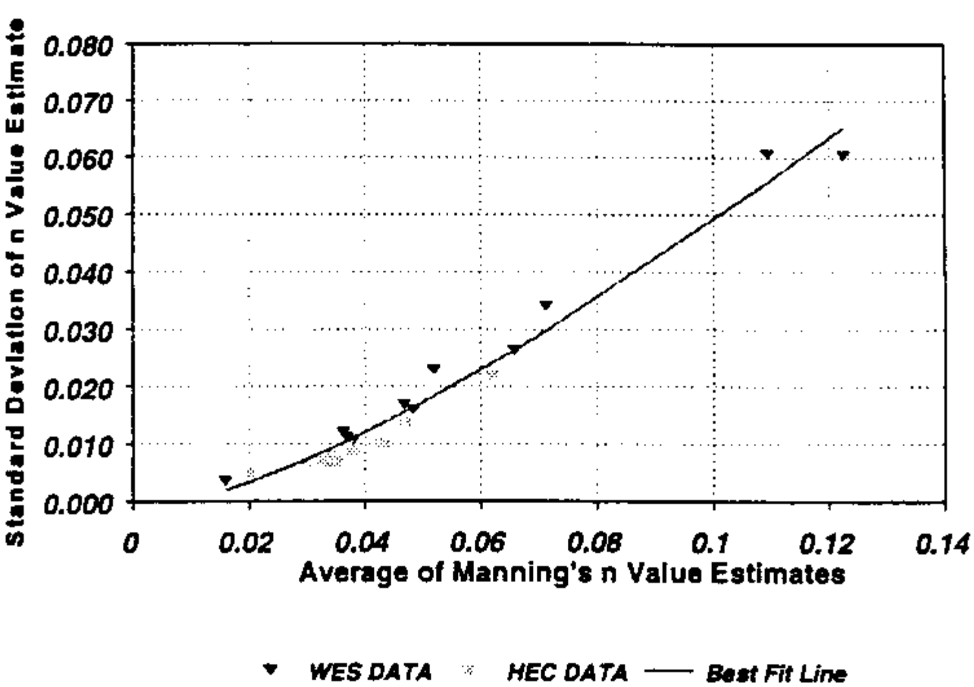

Figure 5-4. Uncertainty of Manning's *n* value estimates based on estimated mean values

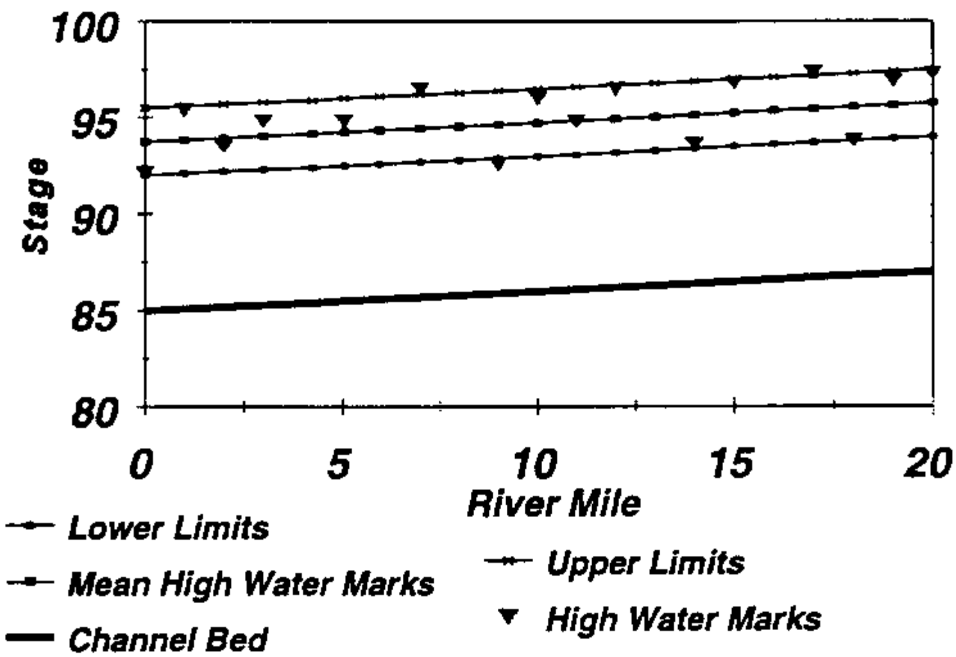

Figure 5-5. Water surface profiles from sensitivity analysis compared with high-water marks from field data

uncertainty for the with-project condition must also be estimated. If the flow conditions and conveyance are expected to be markedly different from the without-project condition, analysis as suggested previously in this chapter is appropriate to estimate stage uncertainty. If flow conditions and conveyance are expected to remain similar, then stage uncertainty may be taken to be the same or similar to the without-project condition.

Chapter 6
Uncertainty of Stage-Damage Function

6-1. Stage-Damage Function Development

a. Traditional method. A stage-damage function is a summary statement of the direct economic cost of floodwater inundation for a specified river reach. For residential structures, the function traditionally has been developed as shown in Table 6-1. Similar information on value, damage as a function of depth, and flood depth at a site is necessary to develop the stage-inundation damage functions for non-residential structures and for other property.

b. Function development accounting for uncertainty.

(1) In the procedure outlined in Table 6-1, much is uncertain. Table 6-2 identifies some of the sources of uncertainty. The remainder of this chapter presents methods for describing uncertainty of these individual components. With these descriptions, an aggregated description of uncertainty of the stage-damage function can be developed with the procedure shown in Figure 6-1. In this, probabilistic descriptions are developed to describe uncertainty or errors in estimating (a) the first-floor elevation of the structure; (b) the percent damage to a structure for a given water depth; (c) the structure value; (d) percent damage to the contents for a given water depth; and (e) the structure-to-content value ratio. Each is sampled to develop a description of the overall uncertainty or error. This uncertainty description then can be included in the sampling for expected annual damage and annual exceedance probability computations, as described in Chapter 2.

(2) This chapter addresses only description of uncertainty in inundation flood damage to residential structures.

Table 6-1
Traditional Procedure for Development of Stage-Damage Function

Step	Task
1	Identify and categorize each structure in the study area based upon its use and construction.
2	Establish the first-floor elevation of each structure using topographic maps, aerial photographs, surveys, and/or hand levels.
3	Estimate the value of each structure using real estate appraisals, recent sales prices, property tax assessments, replacement cost estimates, or surveys.
4	Estimate the value of the contents of each structure using an estimate of the ratio of contents value to structure value for each unique structure category.
5	Estimate damage to each structure due to flooding to various water depths at the structure's site using a depth-percent damage function for the structure's category along with the value from Step 3.
6	Estimate damage to the contents of each structure due to flooding to various water depths using a depth-percent damage function for contents for the structure category along with the value from Step 4.
7	Transform each structure's depth-damage function to a stage-damage function at an index location for the floodplain using computed water-surface profiles for reference floods.
8	Aggregate the estimated damages for all structures by category for common stages.

Table 6-2
Components and Sources of Uncertainty in Stage-Damage Function (USACE 1988)

Parameter/model	Source of uncertainty
Number of structures in each category	Errors in identifying structures; errors in classifying structures
First-floor elevation of structure	Survey errors; inaccuracies in topographic maps; errors in interpolation of contour lines
Depreciated replacement value of structure	Errors in real estate appraisal; errors in estimation of replacement cost estimation-effective age; errors in estimation of depreciation; errors in estimation of market value
Structure depth-damage function	Errors in post-flood damage survey; failure to account for other critical factors: flood water velocity, duration of flood; sediment load; building material; internal construction; condition; flood warning
Depreciated replacement value of contents	Errors in content-inventory survey; errors in estimates of ratio of content to structure value
Content depth-damage function	Errors in post-flood damage survey; failure to account for other critical factors: floodwater velocity, duration of flood; sediment load; content location, floodwarning

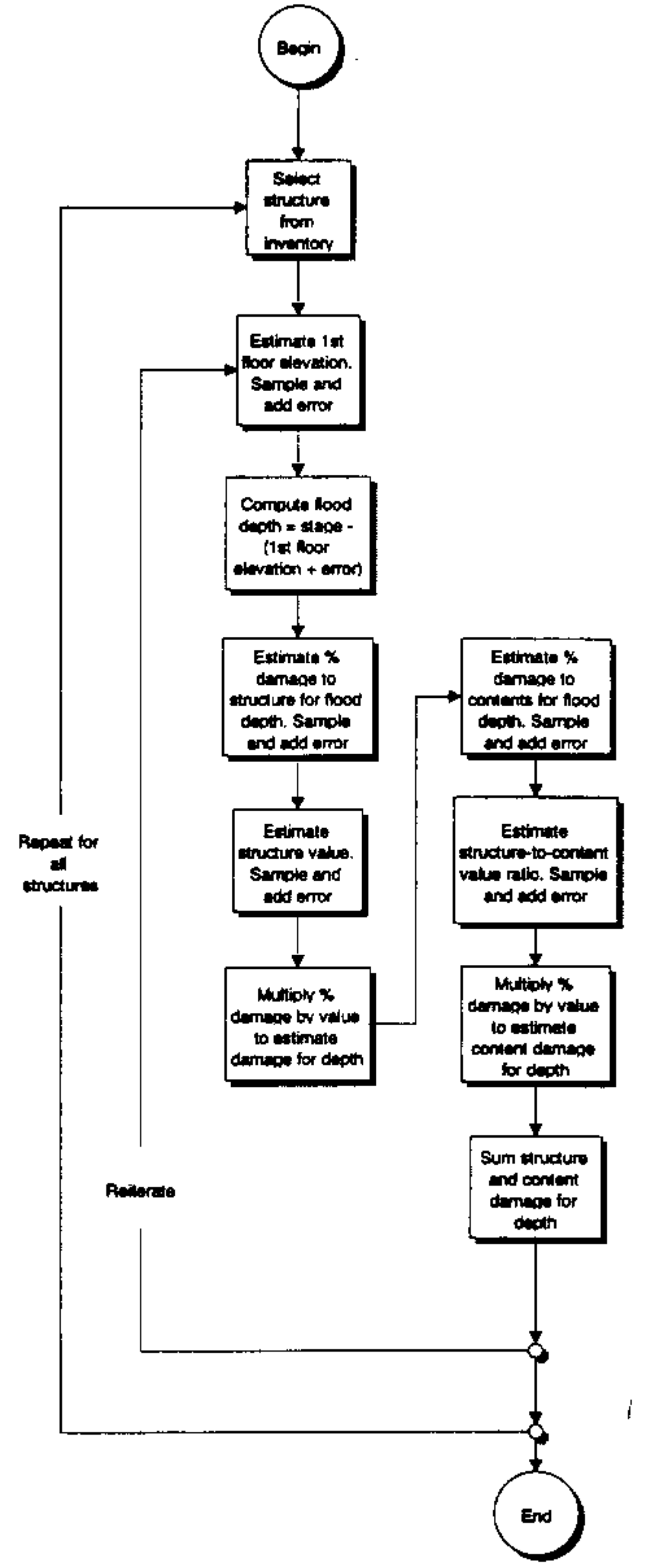

Figure 6-1. Development of stage-damage function with uncertainty description

However, the approach presented can be used to describe uncertainty of the stage-damage relationship for businesses, utilities, transportation and communication systems, and flood emergency costs.

6-2. Description of Parameter Uncertainty

a. Structure value.

(1) Structure value is a critical parameter of the stage-damage function, as it determines directly the structure damage and indirectly the content damage. Based upon the "rational planner" model and the willingness-to-pay principle, depreciated replacement value is used as the appropriate measure of this value for Corps studies. Acceptable methods for estimating depreciated replacement value are summarized in Table 6-3.

(2) To develop a description of error or uncertainty in structure value, one of the following may be used:

(a) *Professional judgment*. With this method, each structure's value is estimated by an expert in real-property valuation and is expressed as a range or as minimum and maximum values. From these, a uniform or triangular distribution can be fitted to describe the error. With a uniform distribution, all values between minimum and maximum are considered equally likely. With a triangular distribution, such as that shown in Figure 6-2, the best estimate is considered most likely. Alternatively, a normal distribution may be fitted. A common method for approximating the standard deviation in that case is to use the range of the variable. For instance, appraisers may attest that the depreciated replacement cost of a structure is between $60,000 and $70,000. Dividing this range by 4 provides an estimate of the standard deviation of $2,500. By implication, this method assumes that the error range is approximately equivalent to a 95-percent confidence interval. One caution in using this method, as with any method using "expert judgment," is that experts tend to be overly confident and provide an error range that is too narrow (Kahnemen, Slovic, and Tversky 1982).

(b) *Sampling to fit a distribution*. With this procedure, a sample of the structure values, stratified by structure category, is drawn from the real-estate

Table 6-3
Methods for Estimating Depreciated Replacement Value

Approach	Description	Comments
Replacement cost estimating using Marshall Valuation Service (both printed and computerized versions)	Develops a replacement construction cost estimate based on information on foundation, flooring, walls, roofing, heating system, plumbing, square footage, effective age, and built-in appliances. This estimate is then adjusted for depreciation.	No independent assessments of errors in resulting depreciated replacement value are available. Experienced building contractors and others may be useful in estimating error bounds.
Real estate assessment data	Involves adjusting real estate tax assessment values for deviations between assessed value and market value and subtracting land component of market value. Presumption is that remainder is depreciated replacement value of structure.	No general method for estimating error in resulting structure values. One approach is to compare results from a sample of individual structures to results using replacement cost estimating method. Random stratified sampling techniques should be used to assure that all structure categories and construction types are verified. Alternatively, verification should cover structure categories and construction types that are located in most flood-prone segment of study area. Sample size for verification should be sufficient to establish range of error, even if it is not large enough to develop empirically a frequency distribution of error in structure values. Easy, yet useful, approach to quantifying errors in structure values using real estate assessments is to query local real estate experts and appraisers.
Recent sales prices	Requires sufficient recent property sales in area for each of structure and construction types for which structure value is to be estimated. As with real estate assessment data, adjustments must be made to subtract land value to yield structure component.	Theoretically, sales prices should be a more accurate basis for estimating depreciated replacement value than real estate assessments. Obvious source of error is estimating and subtracting land portion of sales price to yield structure value estimate. Methods for estimating error when using recent sales prices to estimate structure values are same as those when using real-estate assessment data.

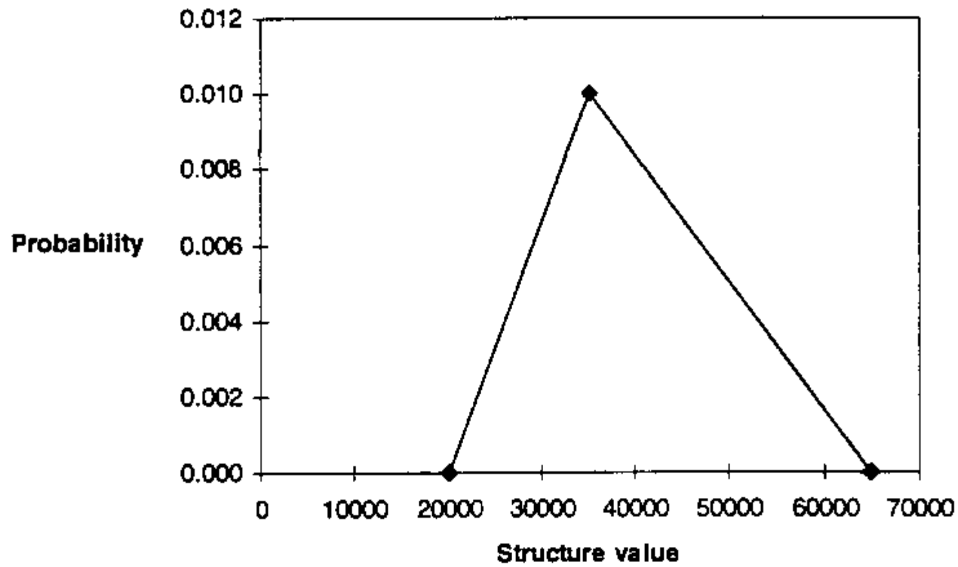

Figure 6-2. Example triangular distribution of structure value

assessments and is used to estimate statistics that describe errors in each category. From these statistics, the parameters of a probability function are estimated. For example, from the mean and standard deviation of logarithms of values in each category, parameters of a log normal distribution of values can be estimated.

b. Content-to-structure value ratio.

(1) A common approach to estimating residential content value is to estimate that value as a fraction of the structure value. This approach mimics that typically employed by residential casualty insurers in setting rates and content coverage for homeowners insurance. The value of contents found in any structure is highly variable, however. It may reflect the wealth and income of the occupants, their personal tastes and lifestyles, and a variety of other factors.

(2) Table 6-4 shows computed means and standard deviations of content-to-structure value ratios based on large samples of Flood Insurance Administration (FIA) claims records. These nationwide averages are not appropriate for all cases, but in lieu of better site-specific information, the values in this table can yield estimates of parameters of a probability distribution of errors.

(3) In some instances, content values may have been developed by using survey or inventory methods. It must be recognized that where content values are directly measured there will still be uncertainty in the actual content value due to errors in inventories, pricing, and age. It is difficult to judge the overall effect of these potential sources of uncertainty on content values. One easily implemented method is to request that the individual completing the survey or the inventory provide an estimate of the accuracy of the provided information.

c. First-floor elevation. Estimation of flood damage using depth-percent damage relationships requires specification of the first floor elevation of the structure. This elevation may be established via field or aerial surveys or by reference to topographic maps. Table 6-5 describes the elevation errors for each of these methods. This description of errors can be used to estimate parameters of a probability distribution of errors. If a Gaussian normal distribution is assumed to model the errors, the indicated standard deviation can be used, with mean error assumed equal to zero. Alternatively, professional judgment can be used to determine the most-likely, minimum, and maximum values, and a triangular distribution can be fitted.

6-3. Description of Uncertainty in Form of Depth-Damage Functions

a. The final elements required to develop the stage-damage function are the structure and content

Table 6-4
Content-to-Structure Value Ratios[1,2] (from FIA Claims Data)

Structure Category	Number of Cases	Mean	Standard Deviation	Minimum	Maximum
One story - no basement	71,629	0.434	0.250	0.100	2.497
One story - basement	8,094	0.435	0.217	0.100	2.457
Two story - no basement	16,056	0.402	0.259	0.100	2.492
Two story - basement	21,753	0.441	0.248	0.100	2.500
Split level - no basement	1,005	0.421	0.286	0.105	2.493
Split level - basement	1,807	0.435	0.230	0.102	2.463
Mobile home	2,283	0.636	0.378	0.102	2.474
All categories	122,597	0.435	0.253	0.100	2.500

[1] Note that these are less than ratios commonly used by casualty insurance companies, but those reflect replacement costs rather than depreciated replacement costs.
[2] Research by the Institute for Water Resources (IWR) suggests that errors may be described best with an asymmetrical distribution, such as a log-normal distribution. In that case, the parameters of the error distribution cannot be estimated simply from the values shown in this table.

Table 6-5
First-Floor Elevation Error and Standard Deviation Calculated from Results in *Accuracy of Computed Water Surface Profiles* (USACE 1986)

Method of Elevation Estimation	Error,[1] in ft	Standard Deviation,[2] in ft
Field survey, hand level	± 0.2 @ 50’	0.10
Field survey, stadia	± 0.4 @ 500’	0.20
Field survey, conventional level	± 0.05 @ 800’	0.03
Field survey, automatic level	± 0.03 @ 800’	0.02
Aerial survey, 2-ft contour interval	± 0.59	0.30
Aerial survey, 5-ft contour interval	± 1.18	0.60
Aerial survey, 10-ft contour interval	± 2.94	1.50
Topographic map, 2-ft contour interval	± 1.18	0.60
Topographic map, 5-ft contour interval	± 2.94	1.50
Topographic map, 10-ft contour interval	± 5.88	3.00

[1] Errors for aerial survey and topographic maps are calculated at the 99-percent confidence level, assuming the deviations from the true elevation are normally distributed with zero mean and indicated standard deviations.
[2] Standard deviation for field survey assumes that error represents a 99-percent confidence interval and assuming normal distribution.

depth-damage functions. These are models of the relationship of depth of flooding at a structure to the damage incurred. As with other models used in plan evaluation, these models are not known with certainty. For example, Table 6-6 shows factors that arguably should be included in, but that are commonly omitted from, a damage prediction model.

b. The impact of including or excluding these factors may be explored through sensitivity analysis, with the factors shown in Table 6-6 incorporated to develop a more complex relationship. For example, if duration is incorporated, a depth-duration-damage function might be developed. This function can be used in the expected annual damage and annual exceedance probability computations. In display of plan performance, the computed expected annual damage and annual exceedance probability values will then be identified as those computed with the alternative models.

c. An alternative approach suggested by the Institute for Water Resources is to treat model uncertainty directly as parameter uncertainty. In that case, the error in percent damage for each depth is described with a Gaussian normal probability distribution.

Table 6-6
Factors, Other than Depth, That Influence Damage (USACE 1988)

Factor	Effect
Velocity	Major factor aggravating structure and content damage. Limits time for emergency floodproofing and evacuation. Additional force creates greater danger of foundation collapse and forceful destruction of contents.
Duration	May be the most significant factor in the destruction of building fabric. Continued saturation will cause wood to warp and rot, tile to buckle, and metal objects and mechanical equipment to rust.
Sediment	Can be particularly damaging to the workings of mechanical equipment and can create cleanup problems.
Frequency	Repeated saturation can have a cumulative effect on the deterioration of building fabric and the working of mechanical equipment.
Building material	Steel frame and brick buildings tend to be more durable in withstanding inundation and less susceptible to collapse than other material.
Inside construction	Styrofoam and similar types of insulation are less susceptible to damage than fiberglass and wool fiber insulation. Most drywall and any plaster will crumble under prolonged inundation. Waterproof drywall will hold up for long periods of inundation. Paneling may be salvageable when other wall coverings are not.
Condition	Even the best building materials can collapse under stress if the construction is poor or is in deteriorated condition.
Age	May serve as an indicator of condition and building material.
Content location	Important factor, as small variations in interior location of contents can result in wide variation in damage.
Flood warning	Major reduction in both content and structural loss can be made through flood fighting and evacuation activities when there is adequate warning.

6-4. Stage-Damage Function Using the Opinions of Experts

a. The approach illustrated in Figure 6-1 does not reflect the methodology typically employed to estimate damages for non-residential property. For these unique properties, the stage-damage function may be developed as a consequence of post-flood surveys or through personal interviews with plant managers, plant engineers, or other experts. Then, instead of employing dimensionless depth-percent damage functions, damages incurred at various water-surface elevations are approximated directly.

b. To describe uncertainty in these cases, the experts should be asked to estimate the most-likely damage for a range of depths, to provide a range of damages for each depth, and their confidence that the range contains the actual damage value that would occur. These opinions on the range and confidence can be used to estimate the parameters of a probability distribution that describes error for each depth. If the respondent cannot or will not provide information other than an estimated range, the analyst can use the mid-point of the range as the mean and one-fourth of the range as the standard deviation; this assumes a normal distribution of errors and inclusion of 95 percent of all damages in the stated range.

6-5. Approach with Limited Data

In some flood damage-reduction planning studies, data in the detail or format for proper analysis of uncertainty is not available, and the cost to enhance existing data to conduct an uncertainty analysis is not justified. In those cases, the planning team must take care to acknowledge likely sources of uncertainty and their impact.

a. The mean stage-damage function is likely most sensitive to error in the first-floor elevation, other things being equal.

b. The error in damage at any stage is not symmetrically distributed around the mean damage. This is particularly true at the lower stages, because damage cannot be negative. Thus the probability of overestimating damage is greater.

c. Although the dispersion of damages about the mean, as measured by the standard deviation, increases with increasing stage, the coefficient of variation (standard deviation divided by mean) decreases with increases in stage. Thus, the error in damage, expressed as a fraction of the mean damage decreases as the stage (and hence, mean damage) increases. This is due, in part, to the truncation of damage at zero. It is also a consequence of lessening sensitivity of error to error in first-floor elevation as stage increases.

6-6. Intensification and Location Benefits

This chapter has not addressed estimation of intensification and location benefits or description of uncertainty in those estimates, even though these benefits may be significant. Their evaluation requires speculation on the response of floodplain occupants to a flood-damage reduction plan. In that case, sensitivity analysis or development and analysis of alternative future scenarios may provide a measure of the impact of the uncertainty.

Chapter 7
Uncertainty of Flood-Damage Plan Performance

7-1. Overview

Computation of expected annual damage and annual exceedance probability for comparison of plan performance requires definition of the with- and without-project conditions hydrologic, hydraulic, and economic functions for each plan. EM 1110-2-1419 identifies alternative damage reduction measures, the functions that are modified by each, and methods for evaluating these impacts. However, for every measure proposed, the damage reduction possible depends on performance as designed. Although such performance is likely in the case of well-planned, well-designed projects, it is never a certainty. Consequently, analysis of performance should acknowledge and account explicitly for this uncertainty. This chapter describes procedures for describing uncertainty of performance of reservoirs and diversions and of levees.

7-2. Performance of Reservoirs and Diversions

a. Discharge function modification. EM 1110-2-1417 notes that reservoirs, diversions, watershed management, channel alterations, and levees or floodwalls may alter the form of the discharge or stage-probability function for the with-project condition. EM 1110-2-1419 describes two methods to estimate the altered or regulated discharge-exceedance probability function.

(1) *Evaluate reservoir or diversion performance with a long continuous sequence of historical or hypothetical precipitation or inflow*. Continuous performance of the measure is modeled with a hydrometeorological sequence, computing modified-condition discharge (or stage) continuously. The discharge (or stage) sequence is examined to identify the annual peaks. Plotting positions are assigned, and a non-analytical frequency function is defined.

(2) *Evaluate performance for a limited sample of historical or hypothetical events*. A set of index events (hydrographs) are defined. These index events may be historical or hypothetical flood events. Each event is routed through the system without and with the project. The annual probability of exceedance of each peak is determined for the without-project condition by inspection of the annual maximum unregulated function. This same exceedance probability is assigned to the peak of the event routed with the with-project condition, thus defining the discharge or stage-exceedance probability relationship. This is illustrated in Figure 7-1. In the example illustrated by this figure, a discharge-probability function is available for without-project conditions downstream of a proposed reservoir. Hydrographs for three index events are defined and are routed for the without-project condition. The resulting without-project peaks are plotted; they are filled circles in the figure. The probabilities are estimated from the frequency function; here they are 0.50, 0.10, and 0.01. Next, the same hydrographs are routed through the proposed reservoir to determine outflow peak, given inflow peak; the asterisks in the figure represent these peaks. The exceedance probabilities found for the without-project peaks are assigned then to the with-project peaks, thus defining the regulated function.

b. Uncertainty description through order statistics. As with discharge or stage-probability functions defined via simulation, the order-statistics procedure provides a method for describing the uncertainty in with-project functions. The equivalent record length, based on consideration of the procedures, is used to estimate the function.

c. Distribution uncertainty. Description of uncertainty in the modified discharge or stage-probability function is made more complex by uncertainty surrounding performance. For example, to develop the modified frequency function that is shown in Figure 7-1, the analyst must decide how the reservoir will operate in order to determine the outflow peak for a given inflow peak. This operation depends on initial conditions, inflow temporal distribution, forecast availability, etc., but these cannot be defined with certainty.

(1) To permit development of a probabilistic description of the uncertainty, all the issues regarding performance may be converted to questions regarding parameters of the relationship of outflow to inflow, and the uncertainty of these parameters can be described. For example, for the reservoir, uncertainty might be described as follows:

(a) Identify critical, uncertain factors (model parameters) that would affect peak outflow, given peak inflow. These might include, for example, alternative initial storage conditions and alternative forecast lead times.

(b) Identify combinations of the factors that define the best-case, the most-likely case, and the worst-case operation scenario.

(c) Based on expert subjective judgment, select a probability distribution to represent the likelihood of the resulting scenarios. For example, a uniform distribution

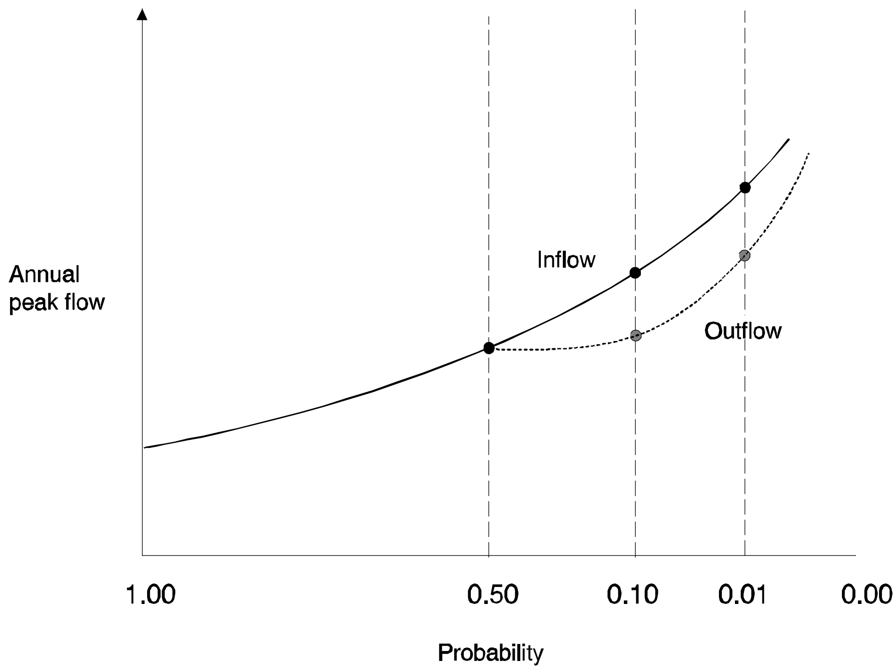

Figure 7-1. Illustration of index events for estimating with-project exceedance probability function

might be selected if all are considered equally likely, or a triangular distribution might be selected if outflow can never be greater than that predicted for the worst case or less than that predicted for the best case. [Use of expert judgment here introduces another element of uncertainty. However, such judgment may be a useful tool if decisions must be made before all necessary science is known (Morgan and Henrion 1990).]

(d) Compute outflow peak for a range of inflow peaks of known exceedance probabilities for all three cases. This computation provides the necessary probabilistic description of uncertainty. For display, confidence limits can be developed and shown on an inflow-outflow plot in the case of a single reservoir, as illustrated by Figure 7-2. In this plot, the probability is only 0.05 that the peak outflow will not exceed the upper limit, while the probability is 0.95 that outflow peak would exceed the lower limit. Equivalently, the probability is 0.90 that, given a peak inflow, the peak outflow would fall within the bands.

(2) The resulting probabilistic description of uncertainty can be included then in the sampling procedures described in Chapter 2. The sampled annual peak from the discharge-frequency function is the inflow to the reservoir. The inflow-outflow model is used to predict the outflow peak, to which a random component is added. This random component accounts for uncertainty in predicting the regulated discharge. Similar relationships can be developed for other damage-reduction measures. These would be used in a similar fashion for evaluation of expected annual damage and annual exceedance probability.

7-3. Uncertainty of Levee Performance

a. Overview of performance. With new or well-maintained federal project levees, analyses of damage traditionally have been based on the assumption that until water stage exceeds the top-of-levee elevation, all damage is eliminated; the levee blocks flow onto the floodplain. The without-project and with-project stage-damage functions thus are as shown in Figure 7-3. In this figure, the solid line represents the stage-damage function without the levee, and the dotted line represents the function with the levee in place. S_{TOL} is the stage that corresponds to

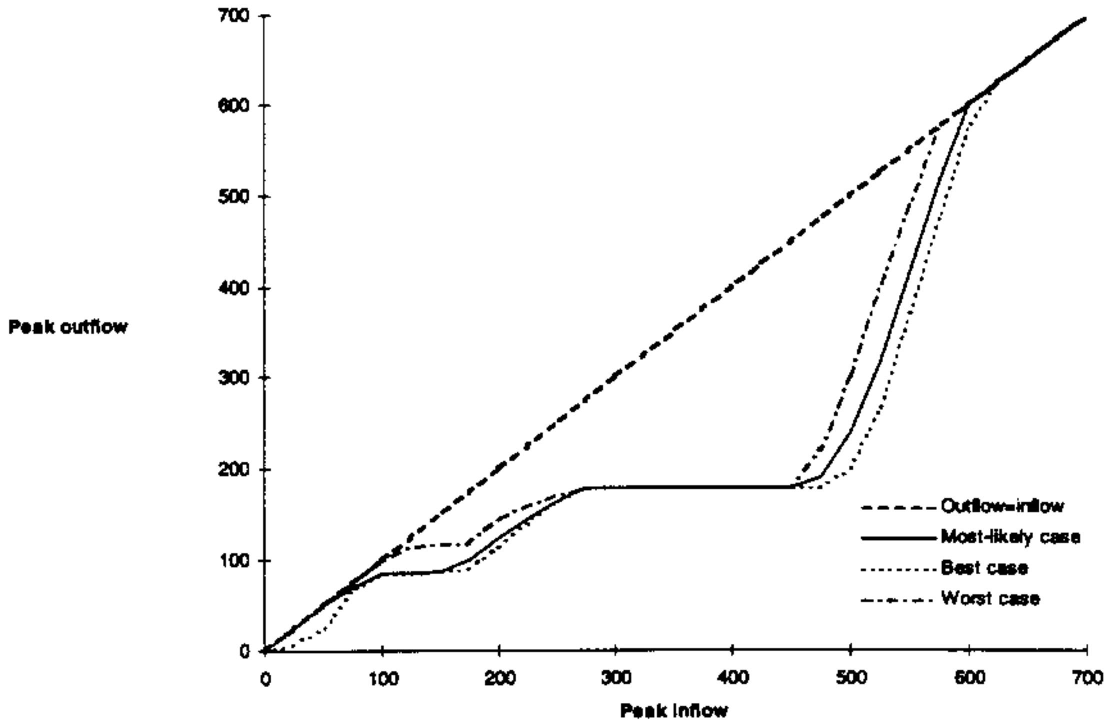

Figure 7-2. Example inflow-outflow function with confidence limits (based on function developed by U.S. Army Engineer District, Sacramento)

the top of the new levee. With the levee in place, no damage is incurred until the water stage rises to S_{TOL}. Then damage increases to a value equal to or greater than the without-project damage.

b. Sources of uncertainty about performance. The traditional analysis of damage reduction due to a levee does not account explicitly for uncertainty that arises as a consequence of:

(1) Imperfect knowledge of how an existing levee will perform from a geotechnical standpoint.

(2) Lack of ability to predict how interior water-control facilities will perform.

(3) Imperfect knowledge of the timeliness and thoroughness of closure of openings in an existing or new levee.

Each of these components should be described and included in assessment of levee performance for evaluation of the with-project condition, as each will have an impact on the stage-damage relationship.

c. Geotechnical performance.

(1) A procedure for describing the uncertainty of geotechnical performance follows. The procedure is applicable for existing and new levees not maintained or constructed to federal levee standards. This procedure defines two critical elevations for each levee reach: the probable failure point (PFP) and the probable nonfailure point (PNP). These elevations are shown in Figure 7-4. The PNP is defined as the water elevation below which it is highly likely that the levee would not fail. The highly likely condition is the probability of non-failure equal to 0.85. PFP is the water elevation above which it is highly likely that the levee would fail, and again this is interpreted as probability of failure equal to 0.85. The two elevations and the corresponding probabilities thus define a statistical distribution of levee failure, and this distribution, in turn, can be incorporated in development of the stage-damage function and description of the overall uncertainty of that function.

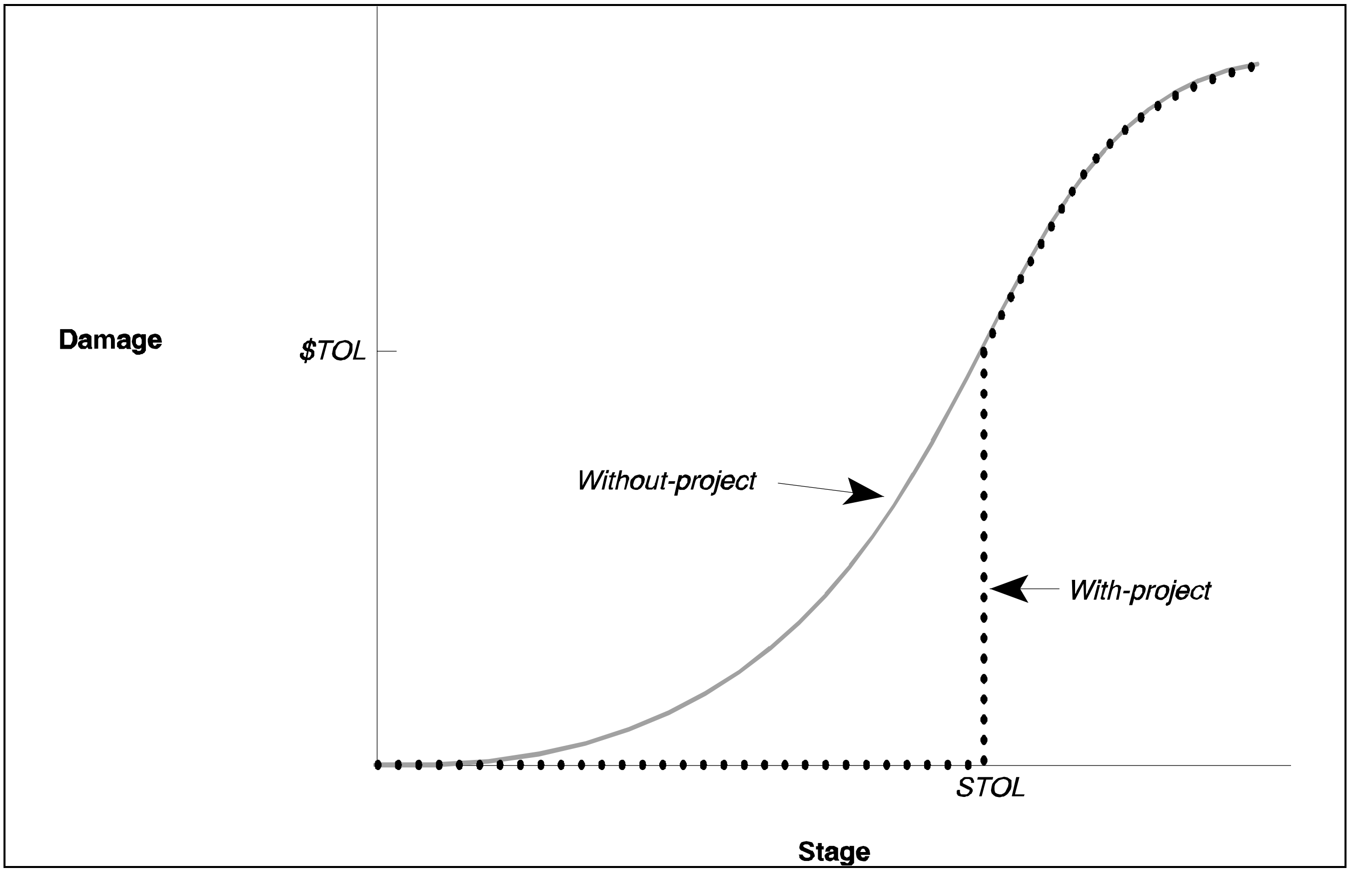

Figure 7-3. Stage-damage function modification due to levee

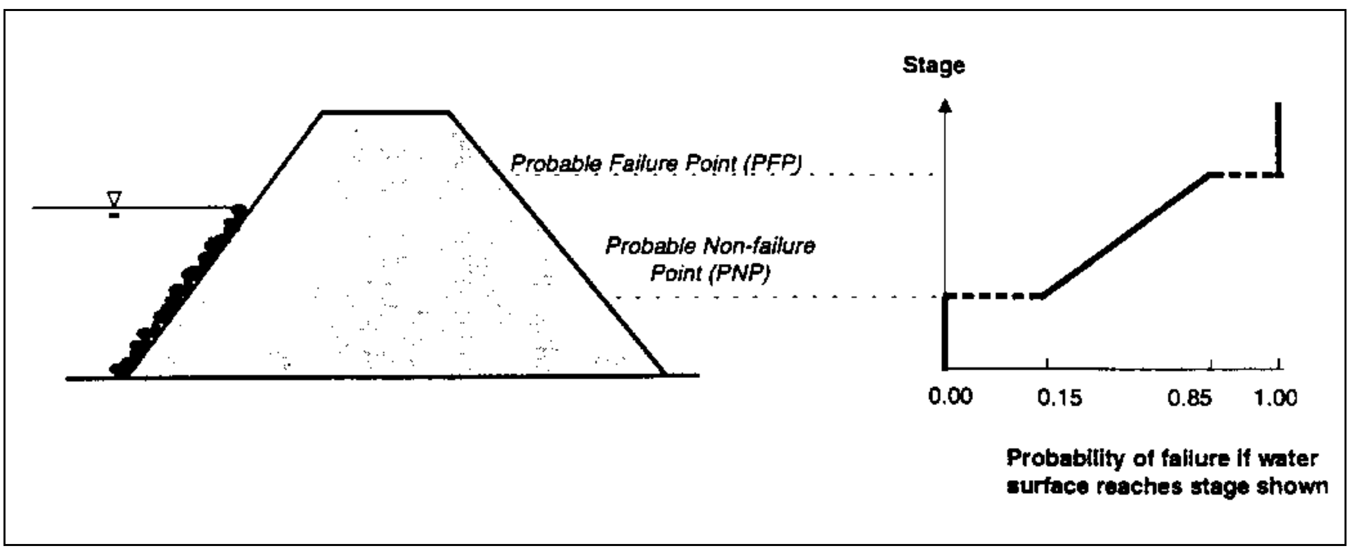

Figure 7-4. Existing levee failure-probability function

(2) The description of geotechnical uncertainty, once defined, is incorporated in development of the stage-damage function and description of the overall uncertainty of that function. To do so, the failure probability function shown in Figure 7-4 is sampled to simulate the uncertainty regarding geotechnical performance as water reaches a particular stage. If the sampling yields a "failure," then the damage incurred equals damage equivalent to without-project damage at that stage, regardless of whether or not the levee is overtopped. This damage and the corresponding count of failures are used as before for computation of expected annual damage and annual exceedance probability.

d. Interior facilities.

(1) The storm runoff from the watershed that drains to the interior of a levee must be passed through or over the levee. Interior flood damage reduction systems typically include gravity outlets, pumping stations, pump discharge outlets, collection facilities, pressurized storm sewers, and detention storage or ponding. The performance of the overall local protection project includes the proper functioning of these components. Interior flood damages naturally will occur during extreme events exceeding the capacity of the facilities. Uncertainties are also inherent in essentially all aspects of predicting the performance of system components for the full range of floods, including floods that exceed system capacity. These risks should be recognized and properly considered throughout the process of project planning, design, implementation, and operation.

(2) As with reservoirs and diversions, a probabilistic description of the uncertainty of the performance can be developed via analysis of likely scenarios of operation of the interior area facilities and assignment of probabilities to the results of the analysis. For example, the uncertainty can be described by:

(a) Identifying combinations of the critical factors that will define the best-case, the most-likely case, the worst-case, and a conservative case for interior-system operation, and selecting a probability distribution to represent the likelihood of these scenarios. The factors shown in Table 7-1 suggest using a probability density function such as that shown in Figure 7-5.

(b) Computing the interior stage for all four cases for a given exterior stage.

(c) With the results of step 2, defining the error probability function for use in subsequent estimation of expected annual damage or annual exceedance probability.

(d) Repeating steps 1, 2, and 3 for alternative exterior stages, thus developing an error probability function for the range of likely values of exterior stage that are relevant for computation of expected annual damage or annual exceedance probability. Figure 7-6 is an example of such a function; this shows the cumulative distribution function of interior stage (plus error) for a range of exterior stages.

(3) The resulting probabilistic description of uncertainty can be included then in the procedures described in Chapter 2. For example, with the event-sampling procedure, the exterior stage (with error) is found. Then a likely interior stage is found through sampling the error function for the given exterior stage. Damage (with error) is found for this interior stage, and the iteration and averaging continue as before.

Table 7-1
Factors That Influence Interior-Area Facility Performance

- Number of pumps or the proportion of the total pumping capacity that remains if one or two pumps are inoperative.
- Reliability of the electrical power supply.
- Type and design of pumps.
- Configuration and design of the pumping station.
- Configuration and capacity of the associated ponding area and gravity outlets.
- Hydrologic and hydraulic characteristics of both the major (exterior) river basin and the interior watershed.
- Adverse weather conditions that may occur during a flood such as high winds, intense precipitation, hurricanes, or ice.
- Effectiveness of flood monitoring, forecasting, and warning systems.
- Institutional, organizational, financial, and personnel capabilities for maintaining and operating the project.
- Perceived importance of the closure.

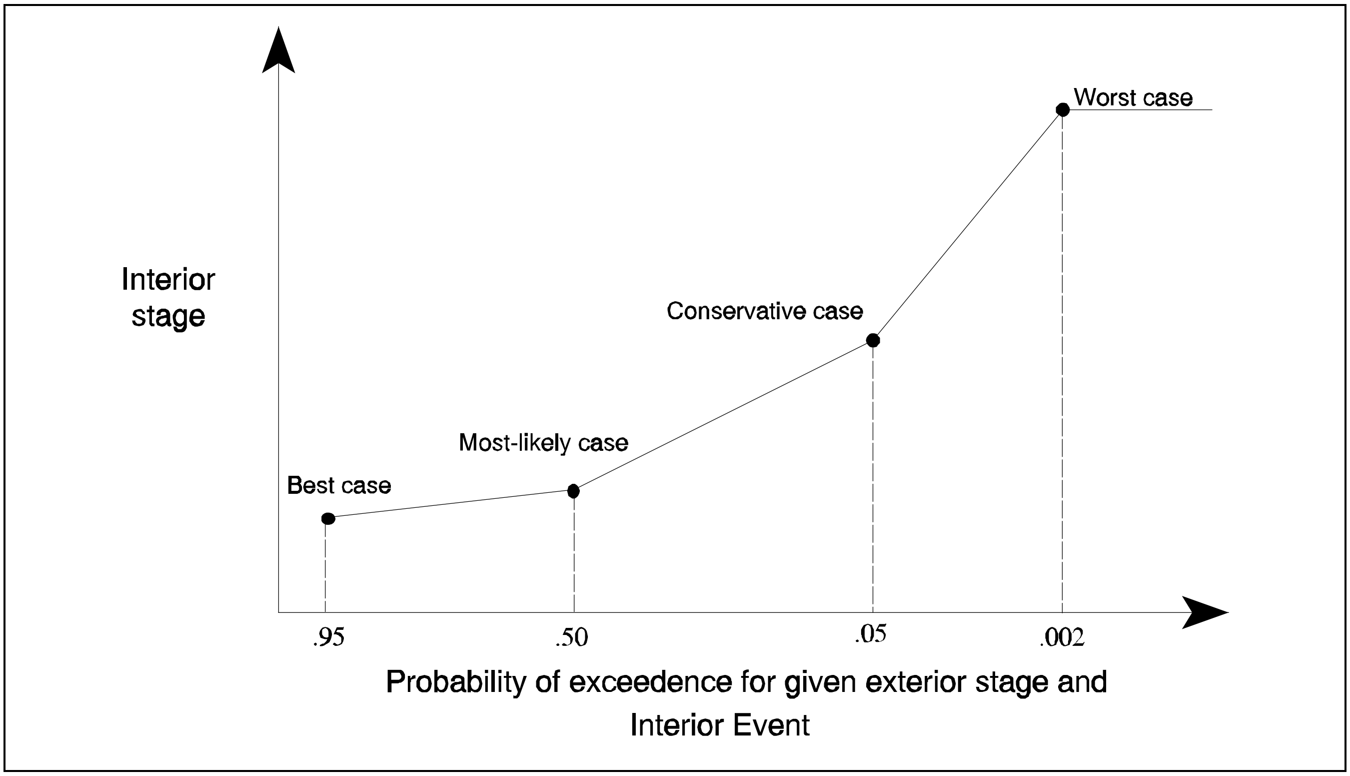

Figure 7-5. Probability function representing interior-stage uncertainty

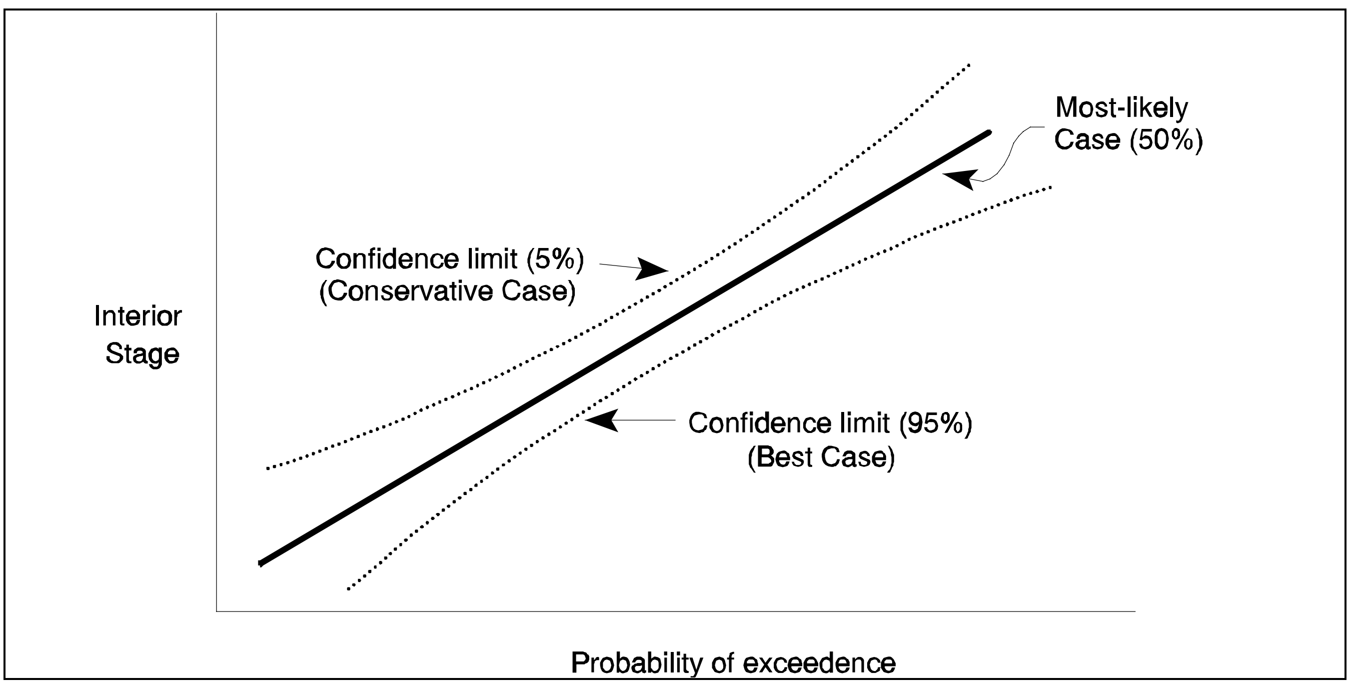

Figure 7-6. Example interior stage-exceedance probability function

e. Closures.

(1) Levee and floodwall closures are described as follows: providing openings in levees and floodwalls for highways, railroads, and pedestrian walkways is often much less expensive than ramping over or routing around the levee or floodwall. However, closure facilities are required to block the openings during floods. The risk that closures will not occur as planned, during a flood, is a disadvantage of this type of design that should be considered along with all other factors. Risk should be managed to the extent feasible, and its analysis should be included in plan formulation and evaluation.

(2) Again, the uncertainty may be described probabilistically via evaluation of alternative closure scenarios and assignment of probabilities to each. Two alternatives for doing so are described:

(a) A failure/nonfailure approach in which the closure is considered to be either a complete success or a complete failure. If the closure is a failure, interior stage is considered equal to exterior stage. The probability of failure is specified, and the failure/nonfailure function is sampled as expected annual damage and annual exceedance probability are estimated.

(b) A more detailed evaluation in which the best (no damage) case, the worst (complete failure) case, and a variety of partial failure cases are identified, simulated, and assigned a probability. These cases are identified by the analysts, considering likely combinations of factors that influence the success or failure of closures; Table 7-2 lists such factors.

(3) The resulting probabilistic description of uncertainty can be included then in the procedures described in Chapter 2. For example, with the event-sampling procedure, the exterior stage (with error) is found. Then a likely closure scenario is simulated and interior stage is found through sampling the error function for the given exterior stage. Damage (with error) is found for this interior stage, and the iteration and averaging continue as before.

7-4. Uncertainty of Channel-Project Performance

a. EM 1110-2-1417 notes that channel alterations and levees or floodwalls intentionally alter the stage-discharge relationship, and that other damage reductions may, as a secondary impact, alter the function. The modified functions must be defined, and uncertainty in the modified functions must be described. In general, procedures similar to those outlined for description of uncertainty in functions developed with simulation are to be used.

b. If channel alterations are a component of the damage-reduction plan, then the with-project condition stage-discharge function may be more certain than the with-project function. With an engineered channel project, the energy-loss model coefficients can be estimated with greater reliability because the channel roughness is, to a large extent, controlled. Likewise, the channel cross-section geometry and channel slope are controlled and are more uniform. Thus, following the argument presented in Chapter 5, errors in estimating stage that corresponds to a specific discharge are likely to be less.

Table 7-2
Factors That Influence Closures

- Hydrologic and hydraulic characteristics of the river basin and associated flood characteristics.
- Adverse weather conditions that may occur during a flood.
- Effectiveness of flood monitoring, forecasting, and warning systems.
- Configuration of the local flood protection project and number of closures.
- Configuration and design of individual closure structures.
- Traffic control operations that could affect timing of closures or the likelihood of accidents.
- Institutional, organizational, financial, and personnel capabilities for maintaining and operating the project.
- Perceived importance of the closure.

Chapter 8
Display and Comparison

8-1. Overview

Displays should be prepared (1) to facilitate comparison of the effectiveness of alternative plans in terms of solving the problem and of taking advantage of the opportunities identified, (2) to identify the monetary and non-monetary costs of the alternatives, and (3) to identify differences among the alternatives (ER 1105-2-100). This chapter provides guidance for such displays for flood-damage reduction plans. It includes templates that complement those included in ER 1105-2-100, with additions and modifications to describe property uncertainty and to display additional performance indices described in this manual.

8-2. Display of Uncertainty Description

Institute for Water Resources (IWR) Report 92-R-1 (USACE 1992b) notes that "Risk and uncertainty analysis in the current context does not require the analyst to do extra work. It does require the preservation of more of the information that is generated in an analysis." For example, a discharge-probability function may be included with plotted confidence intervals to illustrate the lack of knowledge about less frequent, higher discharge values. Such technical details of discharge-probability function uncertainty may truly be of little interest to the decision makers and public reviewers of the documents. However, the impact as this uncertainty propagates through computation of economic and engineering performance indices is important and, in some cases, can best be understood through reference to the source.

8-3. Display of Economic Benefits and Costs

a. The impact of uncertainty in evaluation of project benefits can be displayed as shown in Table 8-1. Such a table can be included for each alternative plan, and depending on the scale of the study, for each stream in the basin or for each damage reach of a stream. Table 8-1 also identifies various categories of benefits and costs. Entries in the inundation-reduction benefit category should include, as a minimum, subclassifications of residential property, commercial property, and industrial property. The annualized expected values of benefits and costs are shown. These values are computed with procedures described in Chapter 2 of this document. The difference in the expected value of total project benefit and the expected value of project costs is the expected net benefit. Uncertainty in various benefits and costs is presented, thus representing the net impact of all model and parameter uncertainties. Values shown for inundation-reduction benefits are computed via simple probability analysis of results of sampling procedures described earlier. For example, if 95 of 100 estimates of damages reduced for category 1 exceed $10,000, this implies that the probability is 0.95 that the inundation reduction benefit for category 1 exceeds $10,000. That benefit value is also entered. Similarly, when project costs are subtracted to compute net benefits, the net benefit estimate that is exceeded 95 percent of the time is computed and entered in the table.

b. Table 8-2 shows the time distribution of expected annual damage values computed, accounting for uncertainty. The values included here reflect changes in future conditions within the basin. For example, as land use changes, the discharge-probability function will change, and consequently, the expected annual damage will change. This table demonstrates that.

8-4. Display of Engineering Performance

a. Table 8-3 displays measures of engineering performance of proposed plans. The median estimate of annual exceedance probability is shown; this value is determined by inspection of the function derived without uncertainty analysis. The estimate with uncertainty analysis might be developed with the event sampling procedure illustrated in Chapter 2. Long-term risk is computed as described in Chapter 2. Again, depending on the scale of the study, this table may be repeated for each stream in the basin or for each damage reach of a stream.

b. Table 8-4 describes the performance of each plan for various flood events. It shows the probability that the target stage associated with each plan will not be exceeded, given the occurrence of an event of specified annual exceedance probability.

c. Table 8-5 describes, in quantitative terms, the impact of capacity exceedance. It shows (for a range of stages that exceed the capacity of the project) the damage that would be incurred, along with the probability that the stage will be exceeded.

Table 8-1
Summary of Annualized NED Benefits and Costs for Plan __ , Stream __ , Reach __

Project Benefit and Cost Categories		Expected Value	Probability That Benefit or Cost > Value Shown 0.95	0.75	0.50	0.25	0.05
Inundation-reduction benefit	Category 1						
	Category 2						
	Category 3						
	Category n						
Intensification benefit							
Location benefit	Floodplain						
	Off floodplain						
Benefits from other purposes							
Total project benefit							
Total project cost							
Net benefit							
Benefit/cost ratio							

Table 8-2
Expected Annual Damage by Decade

Plan	Time Period Year 0	Year 10	Year 20	Year n
1				
2				
3				

Table 8-3
Annual Exceedance Probability and Long-term Risk

Plan	Median Estimate of Annual Exceedance Probability	Annual Exceedance Probability with Uncertainty Analysis	Long-term Risk 10 yr	25 yr	50 yr
1					
2					
3					

Table 8-4
Conditional Non-Exceedance Probability

Plan	Probability of Annual Event 0.02	0.01	0.004
1			
2			
n			

Table 8-5
Summary of Residual Damage for Plan __ , Stream __ , Reach __

Stage	Annual Exceedance Probability	Damage with Project	Population Affected	Number of Structures Flooded

Chapter 9
Example: Chester Creek Flood-Damage-Reduction Plan Evaluation

9-1. Overview

This section provides a detailed example of the flood-damage plan evaluation procedures described in this document. It illustrates evaluation of economic efficiency and engineering performance accounting for uncertainty, using as an example the metropolitan Chester Creek, PA, basin. Floods have caused significant damage in this basin. The U.S. Army Engineer District, Philadelphia, addressed flooding problems in the basin in a water resources study completed in September 1978 (USACE 1977, 1978a, 1978b); data used herein are adapted from that study, with modifications and expansions to illustrate critical concepts.

9-2. Description of Problem

a. Setting. Chester Creek originates near West Chester, PA, and flows southeasterly for approximately 40 km to a confluence with the Delaware River at Chester, PA, as shown in Figure 9-1. Various tributaries intersect the Chester Creek main stem; the largest of these are the East Branch and West Branch. The 176.1-km^2 drainage basin is located within the Philadelphia Standard Metropolitan Statistical Area. Flow in Chester Creek is measured at a U.S. Geological Survey (USGS) gauge near

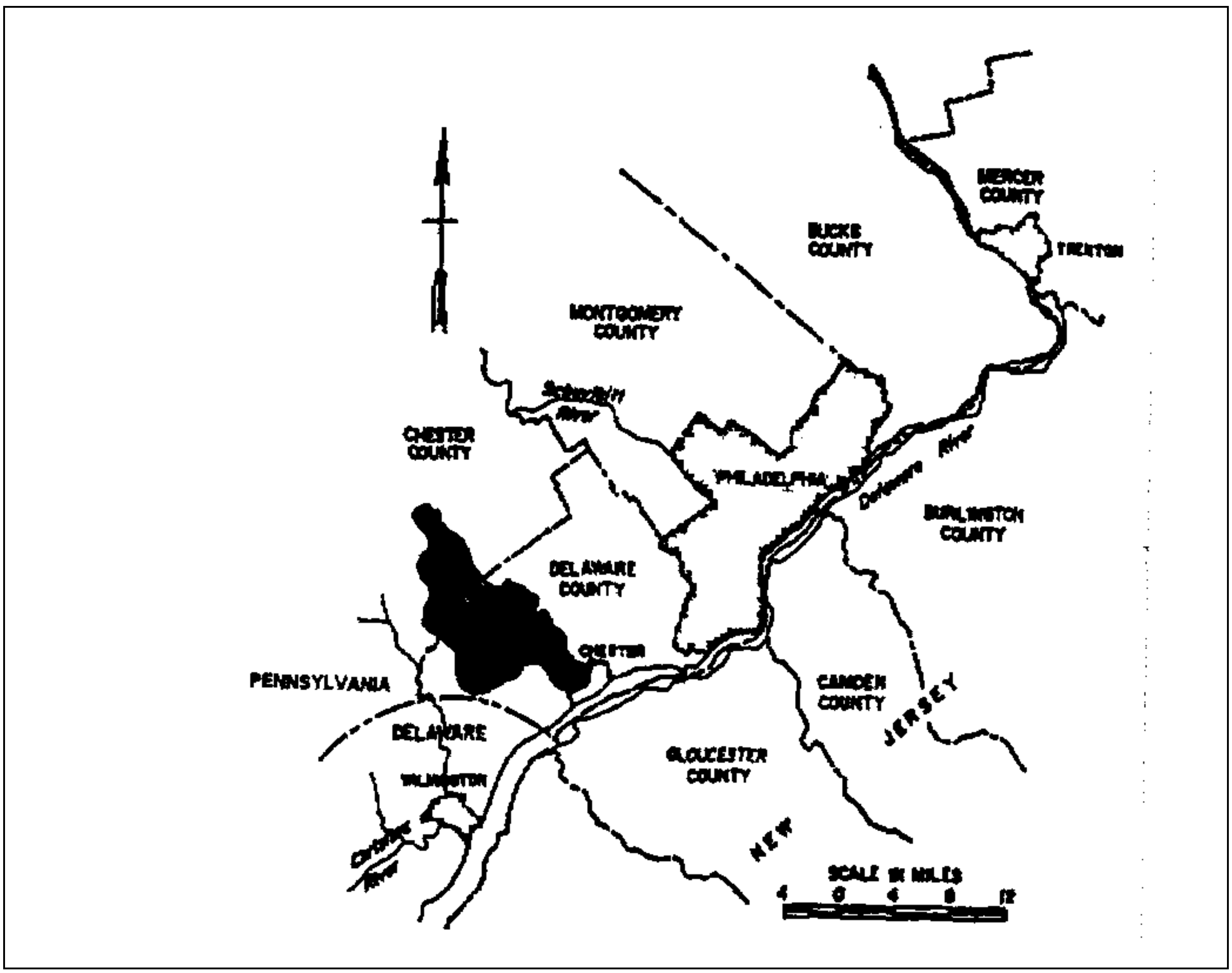

Figure 9-1. Chester Creek location map

Dutton Mill Road in Brookhaven, PA. The drainage area upstream of the gauge is 158.2 km^2, approximately 90 percent of the total basin area. The basin includes 21 municipalities, with an estimated 1990 population of 10,5400 within the basin boundary (USACE 1978b).

b. Flooding History. Developed communities in the basin have been flooded periodically, primarily due to high-intensity summer and fall thunderstorms falling on the relatively long, narrow, steep basin. The worst flooding occurs in the lower main stem reaches. Flooding there is aggravated by many channel constrictions and encroachments. Increased development in the upper portion of the basin promises to worsen the flood problem, as urbanization increases the volume and peak discharge. Table 9-1 shows the largest flood events recorded at the USGS gauge and estimates of the corresponding damage in the Chester Creek basin. The flood of record, in September 1971, was 594.7 m^3/s. This event inundated 130 businesses and 732 residences. Second-story flooding was common, and eight lives were lost.

Table 9-1
Historical Floods in the Chester Creek Basin (from USACE (1978a,b))

Date	Discharge at Dutton Mill Gauge, in m^3/s	Estimated Damage, in Millions of 1978 Dollars
13 Sep 1971	594.7	17.6
25 Nov 1950	407.8	4.6
12-13 Sep 1960	281.5	1.6
28 Jul 1969	270.7	1.4
18-19 Aug 1955	265.6	1.3
23-24 Aug 1933	177.0	0.5
22-23 Jun 1972	175.0	0.5
23 Jul 1938	145.0	0.2
09-10 Jan 1936	141.6	0.2
03 Aug 1950	141.6	0.2
15 Mar 1967	135.1	0.1
07 Mar 1967	133.6	0.1
01 Aug 1945	125.7	0.1

c. Previous studies. As noted, the Philadelphia District addressed flooding problems in the basin in a 1978 water resources study. Pennsylvania's State Water Plan presented an investigation of flooding problems and damage-reduction plans throughout the region. The Delaware Valley Regional Planning Commission developed drainage plans for southeastern Pennsylvania and reported these in the *1973 Drainage and Flood Control Work Program*.

9-3. Study Plan

a. The proper approach to finding a solution to the Chester Creek flood-damage problem is as follows: (1) analyze the flood problem to identify opportunities for damage reduction; (2) formulate a set of damage-reduction alternatives; (3) evaluate each alternative in terms of economic and engineering performance, accounting for the uncertainty in this evaluation, (4) display the results so that alternatives can be compared; and (5) identify and recommend a superior plan from amongst the alternatives.

b. For the example herein, a single damage reach is used for the formulation and evaluation, with all damage related to stage at the USGS stream gauge. Subbasins are defined as necessary to permit derivation of future and with-project discharge-exceedance probability relationships via application of catchment-runoff process models.

9-4. Present, Without-Project Condition

a. The standard for damage-reduction benefit computation and for engineering performance evaluation in Chester Creek is the without-project condition. Expected annual damage, annual exceedance probability, long-term risk, and conditional non-exceedance probability are computed for this standard for present and for future conditions. For the computation, discharge-frequency, stage-discharge, and stage-damage relationships were developed following standard Corps procedures described herein and in other pertinent documents. In each case, the characteristics of uncertainty in the relationships are described in terms of statistical models of errors.

b. The present, without-project condition for Chester Creek includes a variety of levee and floodwall projects that have been constructed in the basin to provide some relief from the flooding. Local governments built the Crozer Park Gardens, Crozer Park, and Toby Farms levees, and the Commonwealth of Pennsylvania has improved local drainage facilities, thereby reducing local flooding for frequent events. The Eyre Park levee project was constructed by the Corps and turned over to the City of Chester in June 1954. [The peak water-surface elevation during the 1971 flood exceeded the levee height by 2 to 3 m, causing a levee breach. For the example herein, however, this levee is assumed to be functional. The protection afforded is accounted for in computation of present, without-project expected annual damage and annual exceedance probability.]

(1) *Discharge-probability function*. The existing, without-project discharge-frequency relationship was developed from the sample of historical annual maximum discharge observed at the Dutton Mill gauge. The equivalent of 65 years of data are available. This is a random, unregulated, homogenous series of flow data which can be evaluated using the procedures outlined in EM 1110-2-1415 and Bulletin 17B (Interagency Advisory Committee 1982). Accordingly, a log-Pearson type III statistical model was fitted to the data, using the computer program HEC-FFA (USACE 1992a) to define the median exceedance probability function. The parameters of the present, without-project Chester Creek discharge-probability function are: mean of logs of annual maximum discharge = 1.959; standard deviation of logs = 0.295; and adopted skew of log = 0.4. With these parameters, the function shown in Table 9-2 was computed. Note that this is the median function; the expected-probability adjustment was not used, as this adjustment would duplicate the accounting for uncertainty that is accomplished with sampling procedures.

Table 9-2
Chester Creek Present, Without-Project Discharge-Probability Relationship

Probability of Exceedance	Discharge, in m^3/s
0.002	898.8
0.005	676.1
0.01	538.5
0.02	423.0
0.05	298.8
0.10	222.5
0.20	158.4
0.50	87.0
0.80	50.9
0.90	39.4
0.95	32.3
0.99	22.9

(2) *Uncertainty of discharge-exceedance probability function*. From a hydrologic engineering perspective, the sample at the Dutton Mill gauge is large, but from a statistical-analysis perspective, it is not. With a sample size of only 65 years, errors in the mean and standard deviation of the logarithms can lead to considerable errors in fitting the relationship, and hence in predicting quantiles. As recommended in Bulletin 17B, these errors were described with a non-central *t* probability model. Figure 9-2 illustrates the results: it is a probability relationship for the 0.01 event. The figure shows that, based on fitting the annual maximum discharge-probability function with 65 years of data at Dutton Mill, the probability is 0.05 that the true annual exceedance probability = 0.01 discharge is 413.5 m^3/s or less; it is 0.5 that the true discharge is 538.5 m^3/s or less; and it is 0.95 that the true value is 753.3 m^3/s or less. Similar relationships can be developed for any selected annual exceedance probability.

Another common interpretation of this description of uncertainty is that the probability is 0.90 (=0.95-0.05) that the true 0.01 probability discharge is between 413.5 m^3/s and 753.3 m^3/s. In that case, 413.5 m^3/s and 753.3 m^3/s are the so-called 90-percent confidence limits. These limits, along with the median probability function, are plotted in Figure 9-3. Note that the confidence limits are centered about the median estimate of the quantile: The probability is 0.50 that the true 0.01 probability discharge is greater than or less than the value predicted with the log Pearson type III parameters estimated with the sample.

(3) *Stage-discharge function.* The present, without-project stage-damage relationship at the Chester Creek index point was developed from water-surface profiles computed with computer program HEC-2 (USACE 1991) as follows:

(a) Field surveys were carried out to acquire the necessary geometric data; elevations were reported to the nearest foot (0.3 m), and distances were determined with stadia rod readings.

(b) Manning's *n* values were estimated by calibration, using high-water marks from the September 1971 flood; this event was approximately a 0.01 exceedance probability event, judging from values shown in Tables 9-1 and 9-2.

(c) Once calibrated, the HEC-2 model was exercised for a range of discharge values to compute the stage at the index location. The results are summarized in Table 9-3. Note that the computed relationship predicts stage for discharge values much greater than ever observed. This is necessary for proper evaluation of damage due to rare events.

(4) *Uncertainty of stage-discharge function.* The stage-discharge relationship is not known with certainty, due to uncertainty in estimating the *n* values, in defining

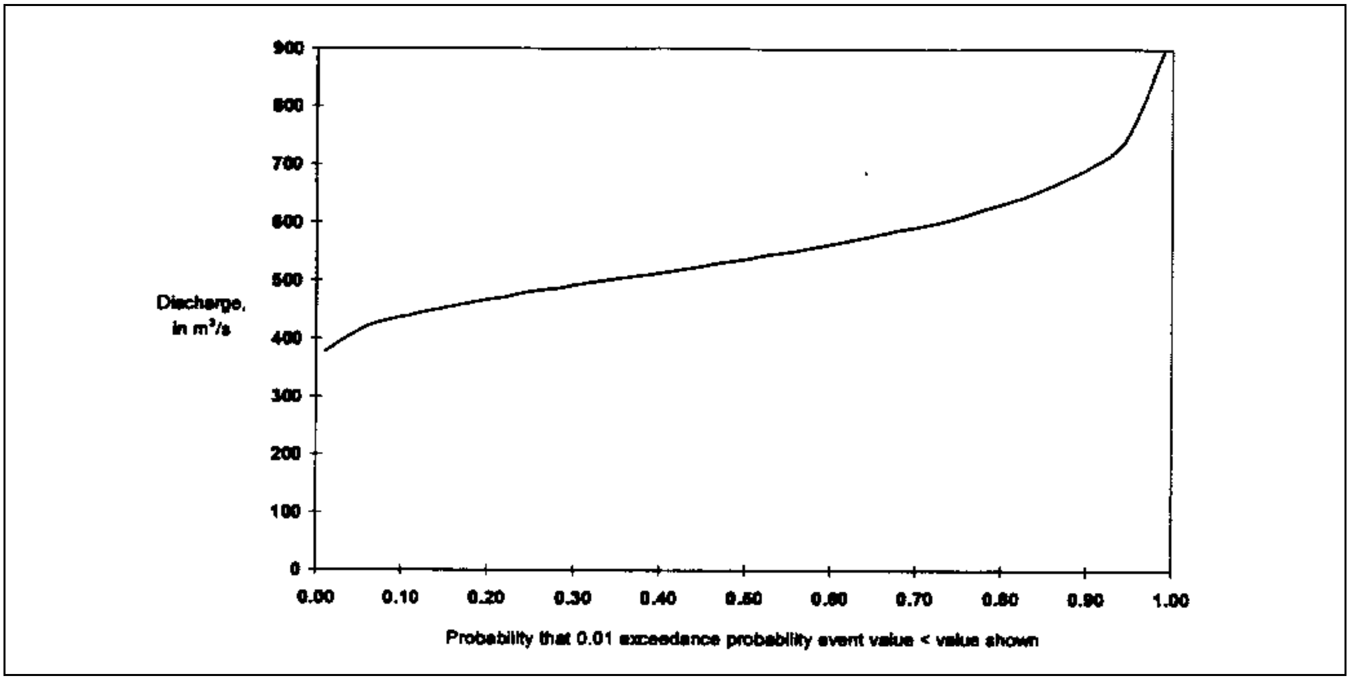

Figure 9-2.   Description of uncertainty in .01 exceedance probability discharge estimate

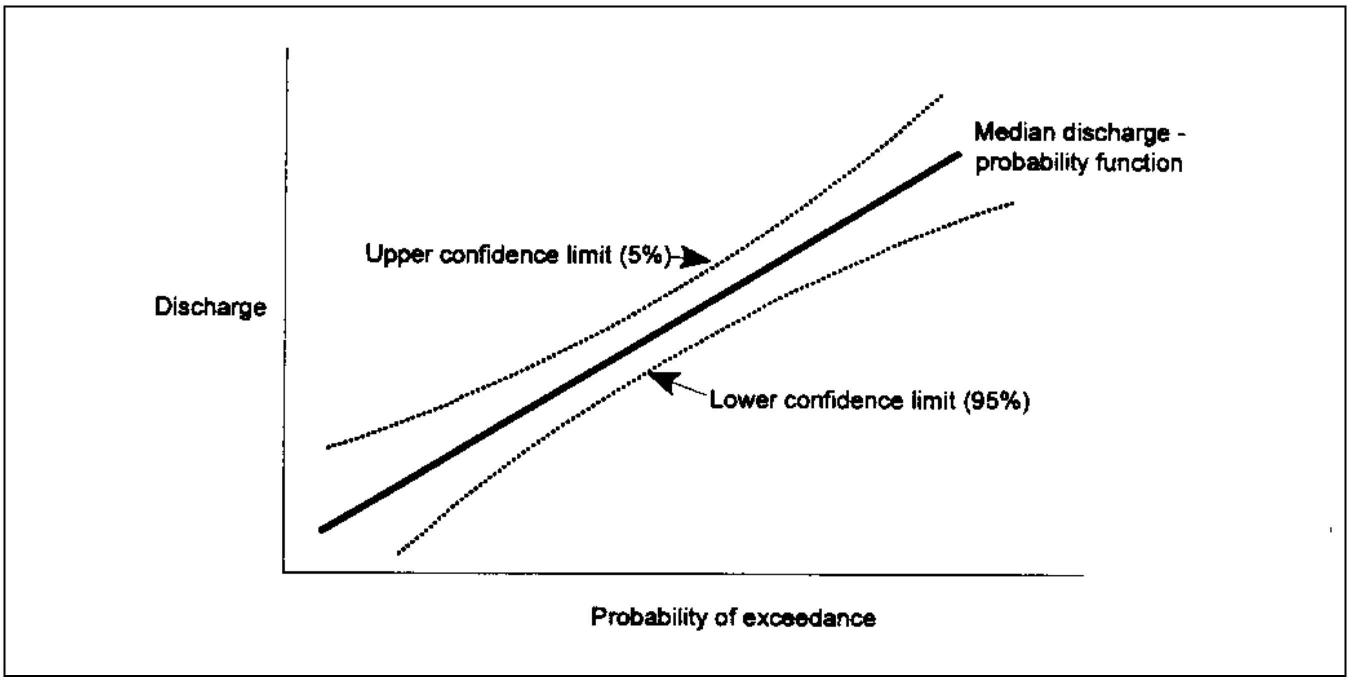

Figure 9-3. Chester Creek discharge-probability function

Table 9-3
Chester Creek Present, Without-Project Stage-Discharge Relationship

Stage, in m	Discharge, in m^3/s
1.97	084.4
2.39	100.4
3.39	168.2
4.07	228.4
4.58	277.5
5.50	383.7
6.70	538.5
7.13	605.8
7.47	651.5
7.75	721.7
8.10	838.2
8.79	1030.8
8.99	1159.1
9.57	1297.1

the exact cross-section geometry, in measuring distances, in estimating losses at expansions and contractions, etc. For Chester Creek, the relationship uncertainty is quantified following the procedure developed by HEC (USACE 1986), which is described in Chapter 5 of this document. This suggests that errors in predicting stage for a given discharge are normally distributed with mean equal zero and standard deviation related to the manner in which the stage-discharge relationship is established. For Chester Creek, the standard deviation for the 0.01 probability discharge was estimated to equal 0.3 m, as follows:

(a) The HEC-2 model calibration was reviewed. About two thirds of the computed elevations fell within ± 0.3 m of the observed high-water marks. In a normal distribution, approximately 63 perent of observations should fall within plus or minus one standard deviation, so it could be inferred that the standard deviation of error in stage is about 0.3 m.

(b) Based on comparison with the USGS rating, the estimated *n* values are graded "good." Guidance in Chapter 5 suggests that for good estimates of *n*, with channel geometry based on field surveys, the minimum standard deviation for the 0.01 probability exceedance event is 0.2 m.

(c) Finally, sensitivity of predicted stage to *n* values and other parameters was investigated. The analyses yielded upper and lower bounds on the stage associated with the 0.01 probability exceedance discharge. The difference in these stages averaged 1.2 m. Assuming that the distribution of errors about the best estimate is normal and that 95 percent of the values predicted would fall in this range, leads to the conclusion that four standard deviations encompass 1.2 m. Thus, each standard deviation is about 0.3 m.

The resulting statistical model that describes errors in predicting the stage associated with discharge of 538.5 m^3/s (the median estimate of the 0.01 exceedance probability discharge) is shown in Figure 9-4. For other values of discharge, a similar description is developed, with the standard deviation of error defined as follows:

(a) For discharge values greater than the 0.01 exceedance probability discharge, the standard deviation is assumed equal to the standard deviation for the 0.01 exceedance probability discharge.

(b) For discharge values smaller than the 0.01 exceedance probability discharge, the standard deviation is the standard deviation of error associated with the 0.01 exceedance probability discharge multiplied by the ratio of the given discharge to the 0.01 exceedance probability discharge. This multiplier will always be less than 1.

(5) *Stage-damage function.* The stage-damage relationship for Chester Creek was developed with the following procedure:

(a) All structures in the basin were categorized as either residential, commercial, industrial, or public facilities. Utilities, highways, and agricultural facilities that would be damaged were identified. Residential structures were further categorized as either one-story with no basement, one-story with basement, two-story with no basement, two-story with basement, split level with no basement, split level with basement, or mobile.

(b) Representative structures in each residential category were selected and assessed to define an average-case inundation depth-damage relationship for that category. Properties in other categories were assessed to establish a unique depth-damage relationship for each.

(c) The first-floor elevation of each structure was estimated. In the case of the assessed structures, these elevations were found to the nearest 0.3 m (1 ft), by surveying. For others, the elevation was estimated from maps with contours plotted at 0.6-m (2-ft) intervals.

(d) All inundation depth-damage relationships were converted to stage-damage relationships and aggregated at

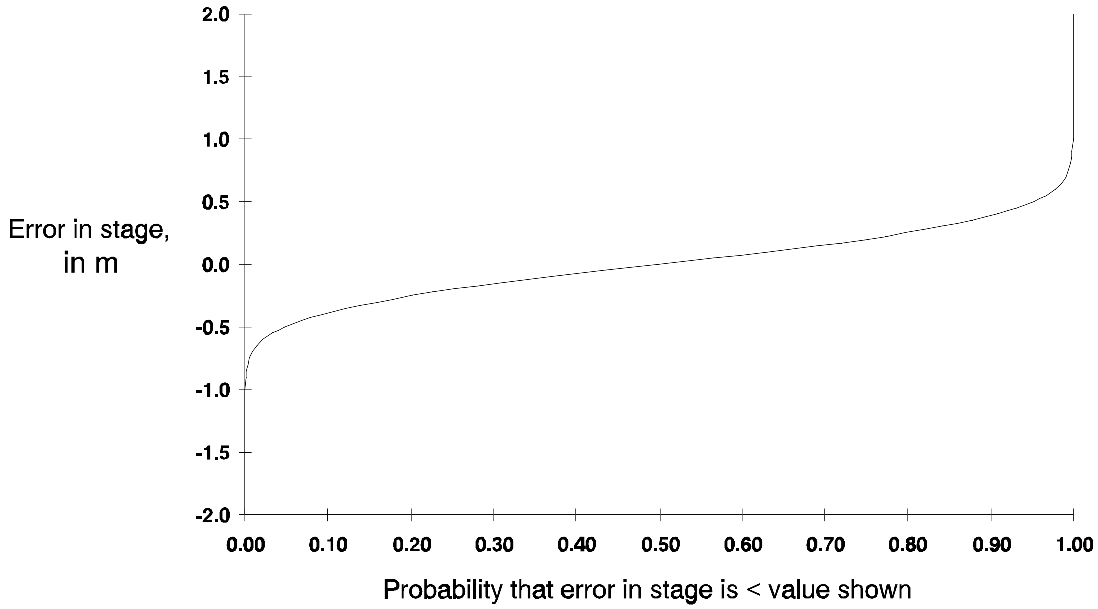

Figure 9-4. Stage uncertainty description for discharge = 538.5 m^3/s

the index point, using a reference flood to relate stage at the index point and stage at the individual structures.

(e) Flood emergency costs were estimated as a function of stage at the index point. These costs were added to the inundation damages to obtain an aggregated relationship.

Table 9-4 shows the aggregated stage-damage function. This function does not account for the existing Eyre Park levee project.

Table 9-4
Chester Creek Present, Without-Project Stage-Damage Relationship

Stage, in m	Inundation Damage, in $1000	Standard Deviation of Error in Damage, in $1000
3.35	0.0	0.0
4.27	25.7	13.6
4.57	88.6	28.6
5.18	339.3	55.7
5.49	525.1	77.5
6.10	1,100.0	114.1
6.71	2,150.6	182.9
8.23	5,132.8	333.5
8.53	5,654.2	365.9
9.14	6,416.5	403.6
9.45	6,592.2	410.8

(6) *Stage-damage function uncertainty.* Uncertainty in the stage-damage relationship is due to (a) errors in estimating structure elevations, (b) errors in assessing damage to structures, and (c) errors in assessing damage to contents. To describe this uncertainty in the Chester Creek study, a statistical distribution of error was defined for each of these three components, and the distribution of total error in predicting damage for each stage was developed by sampling. The resulting normal distribution of error has a mean error of zero, and standard deviations are shown in Table 9-4.

The Eyre Park levee project will reduce damage if it performs as designed. However, that performance is uncertain, as this levee is not a new levee. To account for this, the uncertainty is described with a statistical model that is sampled as the stage-damage function is sampled. For this model, the PNP is estimated by a geotechnical engineer as 5.78 m, and the probability of failure at that stage is 0.15. The PFP is estimated as 6.71 m, and the probability of failure at that stage is 0.85. For stages between the PNP and PFP, a linear relationship is assumed.

(7) *Economic analysis.* Expected annual damage for the present, without-project condition was estimated with annual-event sampling and averaging, accounting explicitly for uncertainty in all relationships. The estimate is $78,100; that is, without any action, over the long term, the average annual flood damage will be $78,100. In most years, the damage will be zero, but occasionally the damage is great, thus increasing the average.

(8) *Engineering performance.* Through annual flood sampling, the annual exceedance probability for the present, without-project condition is estimated as 1.7 percent. That is, the probability that the existing levee will fail is 0.017 percent. The conditional non-exceedance probability of the without-project system for the 0.01 exceedance probability event was estimated also via sampling, accounting for the uncertain performance of the levee. Figure 9-5 is the failure-frequency relationship for the levee for the 0.01 exceedance probability event. By sampling, the expected probability that the 0.01 exceedance probability event will not exceed the PNP is found to be 0.092. That is, there is a 9.2-percent chance that the stage will not exceed the PNP. Similarly, the expected probability that the 0.01 exceedance probability event will not exceed the PFP is 0.503. The probability of no structural failure is 0.85 at the PNP stage and 0.15 at the PFP stage. The expected value is the integral of the shaded area in the figure. In this case, that is 0.298. This is the conditional non-exceedance probability of the levee by the 0.01 exceedance probability event.

9-5. Future, Without-Project Condition

a. Description.

(1) Damage-reduction benefits and engineering performance must be evaluated over the project lifetime and compared to the without-project condition. Consequently, the without-project condition must be described as a function of time if conditions in the basin will change over time. In Chester Creek, as in most basins, development is anticipated. This development will alter the discharge-probability, stage-discharge, and stage-damage relationships. The modified relationships must be used, in turn, to evaluate future flood damage and system performance.

(2) The Chester Creek discharge-frequency relationship is expected to change as a consequence of changes in land use in the basin. The long-term plans for the upper basin anticipate development of urban neighborhoods on land that currently is either open space or is in agricultural use as the population spreads outward from the City of Chester. Such development will increase the volume of runoff, and local drainage improvements that accompany the development will speed the runoff into Chester Creek. While small detention basins planned for the urban areas may provide some relief from the volume increase for smaller, more-frequent events, the overall net impact will be an increase in discharge for any specified probability.

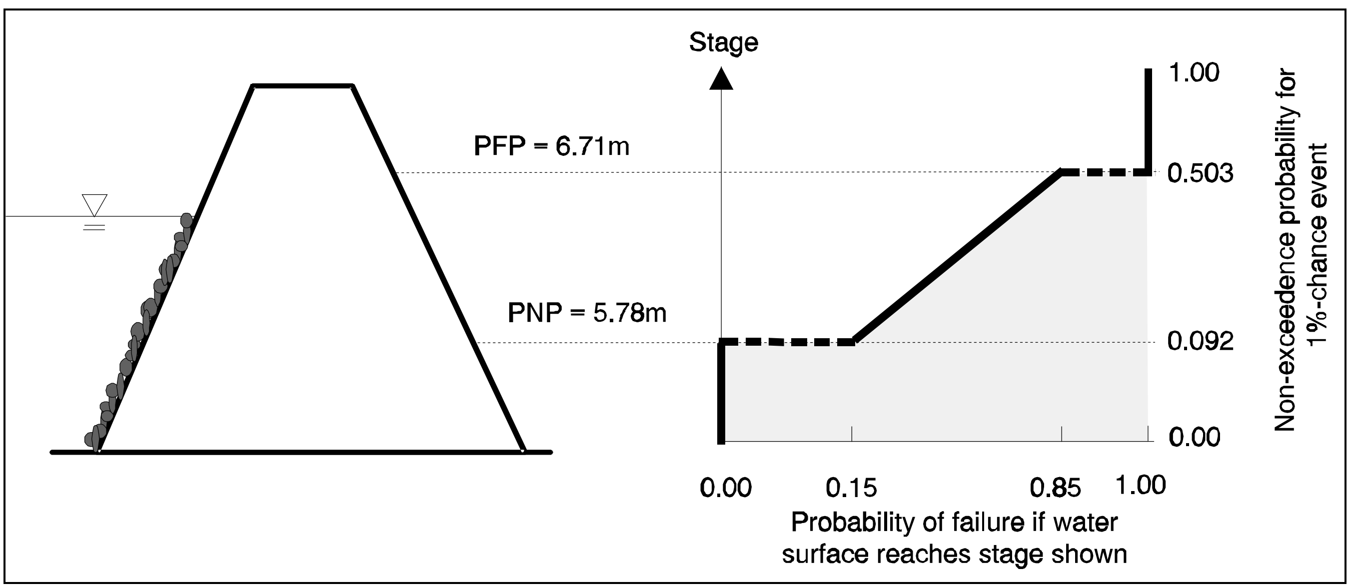

Figure 9-5. Conditional non-exceedance

(3) For economic and engineering performance analysis, a discharge-exceedance probability relationship should be estimated for each year in which significant changes are forecast. These relationships might be estimated with a rainfall-runoff-routing model, using procedures described in EM 1110-2-1417. Discharge-exceedance probability relationships for intermediate years may be estimated by interpolation if the changes are gradual.

(4) The Chester Creek stage-discharge relationship is expected to change over time as the channel is modified. Several communities have expressed a desire to bridge the channel to provide access to new development. The bridges are planned so that the low chord of each is above the current best estimate of the 0.01 exceedance probability stage. However, for larger events, the bridges will obstruct the flow, and thus may increase the stage for a given discharge. Further, a portion of the floodplain has been designated a riparian habitat, so channel maintenance will be restricted. This, in turn, will increase the roughness, impede flow, and lead to increases in stage.

(5) A stage-discharge relationship should be estimated for each year in which significant changes to the channel are forecast. These relationships might be estimated with a river hydraulics model, using procedures described in EM 1110-2-1416. Stage-discharge relationships for intermediate years may be estimated by interpolation if the changes are gradual.

(6) Increased development within the basin might be expected to lead to increases in damage. However, in the Chester Creek basin, all communities participate in the federal flood insurance program. These communities have ordinances that will limit any new construction within the 0.01 exceedance porbability floodplain. This will limit any increase in damage, even with the new development, and may, in fact, reduce damage as low-lying properties reach the end of their utility and are abandoned or razed. Furthermore, the Chester Redevelopment Authority intends to redevelop the Eyre Park area by purchasing and demolishing 216 homes there. This will lead to a decrease in damage for a given stage.

(7) As with the other relationships, a stage-damage relationship should be defined for each year in which significant changes occur, and relationships should be interpolated for intermediate years if the changes are gradual.

b. Economic and engineering performance. The same procedures used for evaluation of present, without-project expected annual damage and other indices are used to evaluate future, without-project economic and engineering performance. To account for uncertainty in the future-condition functions, the error distributions must be defined. In certain cases, estimating the form of these distributions may be easier for future conditions than for present. For example, in Chester Creek, a channel modification plan is authorized for a short reach of the main stem. Local authorities will remove a low bridge and modify the channel to yield a rock-lined trapezoidal cross section in the reach adjacent to the bridge location. In that case, the channel geometry, roughness value, and losses will be known reasonably well. Thus, the future condition standard deviation in stage prediction, in that reach, will be less than the 0.3 m used for the existing condition. Likewise, with structures removed from the floodplain, the likelihood of error in enumerating structures for the stage-damage relationship is reduced. On the other hand, the discharge-probability relationship is more uncertain. For the present, without-project condition, this relationship was developed via statistical analysis of the equivalent of 65 years of observed data. For the future condition, a rainfall-runoff-routing model must be used with handbook loss-model and unit hydrograph parameters to estimate the incremental runoff from portions of the catchment in which land use changes. The result may be a frequency curve that is approximately equivalent, in terms of uncertainty, to one based on statistical analysis of say 50 years of data. If that were the case, the error in predicting discharge for a specified event will increase.

9-6. Proposed Damage-Reduction Plans

a. The Chester Creek study team identified an initial set of 47 damage-reduction alternatives (USACE 1977). This set included various sizes of, locations for, and combinations of measures shown in Table 9-5.

b. Seventeen of the plans address flooding problems in the entire basin, 20 address flooding in Chester, and the remainder focused on flood-damage reduction in specific communities in the basin. The initial set of alternatives was screened to eliminate obviously inferior alternatives. Using economic criteria only, plans that could not meet the national objective were eliminated. To account implicitly for the uncertainty of this early screening, plans on the margin were retained. This screening yielded the smaller set of alternatives shown in Table 9-6. These are considered in more detail herein.

9-7. Levee Plans

a. General. The four levee alternatives entail construction of new levees that meet all Corps structural

Table 9-5
Measures in Initial Set of Chester Creek Alternatives

- Bridge modifications and replacements
- Bypass channels
- Channel modifications, including deepening, widening, realignment
- Dry detention reservoirs
- Levees and floodwalls
- Natural channel storage (natural impoundments)
- Multipurpose reservoirs
- Contingency floodproofing
- Flood insurance
- Regulatory measures, including floodplain zoning and floodway ordinances
- Flood warning and preparedness planning
- Land development regulations
- Permanent evacuation or relocation
- Pervious paving
- Temporary evacuation

Table 9-6
Flood-Reduction Alternatives for Chester Creek

- Levee alternatives: construct levees along the main stem. The following alternative heights are proposed: 6.68 m, 7.32 m, 7.77 m, 8.23 m.
- Channel-modification plan: straighten and enlarge the main stem in the vicinity of the City of Chester, increasing capacity from 170 m^3/s to approximately 255 m^3/s.
- Detention-storage plan: construct a dry, $5.55x10^6$-m^3 detention reservoir on the West Branch, at approximately the confluence with the main stem. Contributing area of the reservoir is 57.8 km^2.
- Mixed-measures plan. Straighten and enlarge the channel as above and construct the $5.55x10^6$-m^3 detention reservoir.

and geotechnical stability criteria. Thus for the proposed levees, the PNP and PFP correspond to the elevation of the top of the levee. The levees are located along Chester Creek in the lower portion of the basin and provide protection for the urbanized areas. Costs of the levees were estimated with standard Corps procedures, consistent with the accuracy necessary for a feasibility study; the annual equivalents are shown in Table 9-7.

b. Modification of functions. The levees proposed reduce damage in the basin by limiting out-of-bank flow onto protected area. This impact is represented with a modification to the stage-damage relationship. With a new Corps levee in place, the stage at which damage initially is incurred rises to an elevation equal to the elevation of the top of the levee. When the water-surface elevation exceeds the top-of-levee elevation, water flows onto the floodplain. Detailed analysis of overflow hydraulics will define the relationship between interior-area stage and stage in the channel. From this, appropriate damage in the interior or protected area can be determined. For Chester Creek, the interior-area and channel stage are assumed equal, so the damage incurred when the levee is overtopped is equal to that incurred without the levee. For example, with the 6.68-m levee in place, the without-project stage-damage relationship of Table 9-4 is modified to yield Table 9-8. Both relationships are plotted in Figure 9-6. If the stage in the protected or interior area would not reach the same stage as in the channel when the levee is overtopped, a relationship between interior and exterior (channel) stage can be developed and used in the analysis.

For the Chester Creek example, the stage-discharge function is not changed significantly by the levee. If the rating function did change, the modified rating would be used with the modified stage-damage relationship for each alternative.

c. Economic analysis. The economic efficiency of each levee plan is evaluated via sampling, using the

Table 9-7
Present Economic Benefits of Levee Alternatives

Plan	Annual With-project Residual Damage, in $1000	Annual Inundation Reduction Benefit, in $1000	Annual Cost, in $1000	Annual Net Benefit, in $1000
6.68-m levee	50.6	27.5	19.8	7.7
7.32-m levee	39.9	38.2	25.0	13.2
7.77-m levee	29.6	48.5	30.6	17.9
8.23-m levee	18.4	59.7	37.1	22.6

Table 9-8
Existing Conditions Stage-Damage Relationship with 6.68-m Levee

Stage, in m	Inundation damage, in $1000
3.35	0.0
4.27	0.0
4.57	0.0
5.18	0.0
5.49	0.0
6.10	0.0
6.68	0.0
6.71	2,150.6
8.23	5,132.8
8.53	5,654.2
9.14	6,416.5
9.45	6,592.3

modified stage-damage relationship appropriate for each alternative. The entire range of possible events is sampled, as is the range of uncertainty in the discharge-frequency, stage-discharge, and stage-damage relationships. (With new levees, geotechnical performance is assumed to be known with certainty. No uncertainty description is developed, and no sampling is conducted). The resulting expected annual damage estimates are shown in Table 9-7. The inundation-reduction benefit of each plan is shown; this is the difference in the with-project damage and the without-project damage ($78,100). The net benefit is computed as the cost less inundation-reduction benefit. Location and intensification benefits might increase this value.

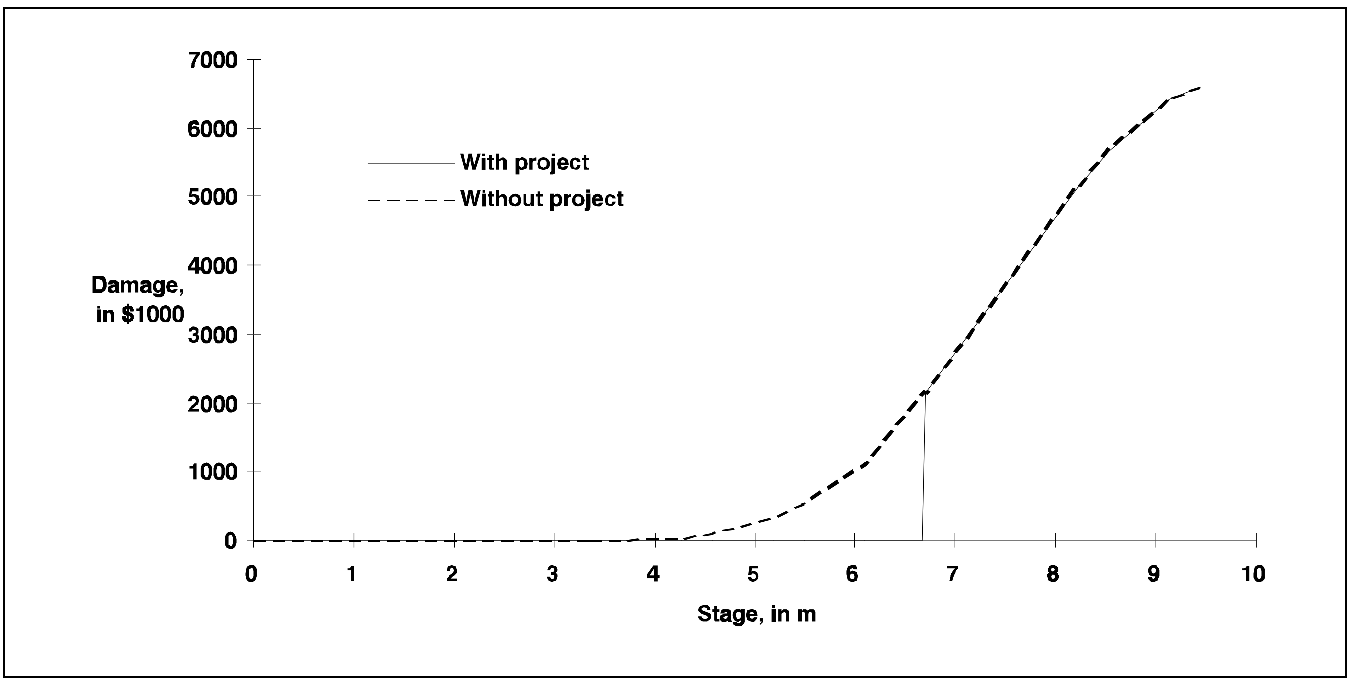

Figure 9-6. Present-condition stage-damage functions without and with 6.68-m levee

d. Engineering performance.

(1) Table 9-9 reports indices of engineering performance of the levee plans. For reference, the median annual exceedance probability that corresponds to the top-of-levee stage is determined by direct reference to the stage-discharge and discharge-frequency relationships shown in Table 9-3 and Table 9-2, respectively. The annual exceedance probability with uncertainty analysis values equals the annual exceedance probability with uncertainty included. These represent the protection provided, incorporating explicitly the uncertainty in predicting discharge associated with a specified probability and in predicting stage associated with discharge. In each case, the value is the probability with which the stage, with error included, exceeds the specified top-of-levee in the simulation for economic evaluation. For example, with the 6.68-m levee, the simulated water-surface elevation with errors included exceeded the top-of-levee elevation 61 times in 5,000 iterations. Therefore, the annual exceedance probability is 61/5,000 = 0.0122. This differs from the median exceedance probability in column 2 because of the interaction of errors in discharge and stage.

(2) The long-term risk shows the probability that each levee would be overtopped at least once during the 10, 25, or 50-year time period. These values are computed using the annual exceedance probability values. For the 8.23-m levee, the odds of exceedance are about 1-in-7, while for the 6.68-m levee, the odds approach 1-in-2.

(3) Table 9-10 shows the conditional non-exceedance probability of the levee plans for six benchmark events. The values shown are frequencies of *not* exceeding the levee capacity, given occurrence of the events shown. For example, for the 8.23-m levee, the conditional non-exceedance probability for the 0.02 exceedance probability event is 0.997. That means that should a 0.02 exceedance probability event occur, the probability is 0.997 that it would not exceed the capacity of the levee. This is estimated via simulation in which only 0.02 exceedance probability events are sampled. For each sample, error in discharge and stage is included.

(4) The probability with which the result does not exceed the top-of-levee elevation is determined. Here, with 5,000 iterations of the 0.02 exceedance probability event, the 8.23-m levee was not overtopped in 4,985, or 99.7 percent, of the iterations.

(5) Table 9-10 shows that the conditional non-exceedance probability is about 0.50 for events that yield stages equal to the proposed top-of-levee stages. For example, the median exceedance probability corresponding to 6.68 m is 0.01. However, the conditional non-exceedance probability of the 6.68-m levee plan for the 0.01-probability event is only 0.483. Similarly, the conditional non-exceedance probability of the 7.77-m levee, which has top of levee at stage corresponding to the 0.4-percent-chance event, has conditional non-exceedance probability equal to 0.489 for the 0.4-percent-chance event.

Table 9-9
Annual Exceedance Probability and Long-term Risk

			Long-term risk		
Plan	**Median Estimate of Annnual Exceedance Probability**	**Annual Exceedance Probability with Uncertainty Analysis**	**10 yr**	**25 yr**	**50 yr**
6.68-m levee	0.010	0.0122	0.12	0.26	0.46
7.32-m levee	0.007	0.0082	0.08	0.19	0.34
7.77-m levee	0.004	0.0056	0.05	0.13	0.25
8.23-m levee	0.002	0.0031	0.03	0.08	0.14

Table 9-10
Conditional Non-Exceedance Probability

	Probability of Annual Event		
Plan	**0.02**	**0.01**	**0.004**
6.68-m levee	0.882	0.483	0.066
7.32-m levee	0.970	0.750	0.240
7.77-m levee	0.990	0.896	0.489
8.23-m levee	0.997	0.975	0.763

9-8. Channel-Modification Plans

a. General. The channel-modification plan reduces damage in Chester Creek by making the channel "more efficient." That is, the improved channel will carry greater discharge within its banks, without overflowing onto the surrounding floodplain. To achieve this, 730 m of the channel will be realigned, and the cross section will be reshaped to provide a 15-m bottom width and 43-m top width. The channel will be lined with riprap. The equivalent annual cost of this plan is $36,400.

b. Modification of functions.

(1) The proposed channel modifications will alter the stage-discharge relationship. The form of the modified relationship was determined with computer program HEC-2. To do this, the calibrated without-project model was altered to describe the modified channel, and the model was executed for a range of steady flows. From the computed water-surface elevations at the Chester Creek index point, the modified stage-discharge relationship shown in Table 9-11 was developed. Both this modified relationship and the existing-condition relationship are shown in Figure 9-7. (Only one channel plan is shown here. For completeness, a set of sizes and configurations should be evaluated).

Table 9-11
Modified Stage-Discharge Relationship

Stage, in m	Discharge, in m^3/s
0.76	56.6
1.71	113.3
2.47	169.9
3.20	226.6
3.78	283.2
4.72	396.5
5.67	509.8
6.40	623.0
7.07	736.3
7.65	849.6
8.23	962.9
8.60	1,076.2
9.08	1,189.4
9.20	1,246.1
9.60	1,302.7

(2) As was the case with the without-project stage-discharge relationship, the with-project rating function is not known with certainty because the model parameters and boundary conditions are not known with certainty. Sensitivity analyses with the HEC-2 model show a 0.9-m difference between the upper and lower bounds on the 0.01 exceedance probability water-surface elevation. As before, the stage-prediction errors are assumed to be normally distributed. If 95 percent of stages predicted for the 0.01 exceedance probability event should fall between the bounds, the standard deviation is 0.23 m. Note that for this modified condition, the geometry and *n* values are better known, as the shape and material are "engineered." Thus the computed with-project stage-discharge relationship is more certain than the without-project relationship.

c. Economic analysis. To compute the benefit of the proposed channel plan, the entire range of possible events is sampled, along with the range of uncertainty in the discharge-frequency, stage-discharge, and stage-damage relationships. The expected annual damage is $41,200, and the inundation-reduction benefit is $36,900. The latter is the difference in the with-project damage and the without-project damage. The net benefit, computed as the cost ($25,000) less inundation-reduction benefit, is $11,900. In this case, inundation-reduction benefit exceeds cost, so the plan is feasible. Other benefits, such as location and intensification benefits, would affect the net benefit, and might alter this.

d. Engineering performance. For analysis of engineering performance, conditional non-exceedance probability of the 0.02-, 0.01-, and 0.004-exceedance probability events is determined. In order to define this conditional probability, a target stage of 4.58 m is selected, and the frequency of non- exceedance is computed. This stage was identified as the stage at which significant damage begins in the floodplain. The median probability associated with this stage is 0.027; this was determined by estimating first the discharge corresponding to 4.58 m (378.2 m^3/s) and then estimating the probability of exceeding that discharge. This does not account for errors in predicting discharge or stage. The annual exceedance probability, however, does. With 4,500 samples, the annual exceedance probability, the frequency with which stage exceeded 4.58 m, is 0.031. The long-term risk, in this case the probability that the 4.58-m target will be exceeded at least once in the 50-year project life, is 0.79. This value is quite large, but it does not indicate the consequence of capacity exceedance. In fact, with this channel modification, the impact of exceedance might be less than a meter near the channel, or it could be a very large flood with significant depths of flooding. The conditional probability for the 0.02-, 0.01-, and

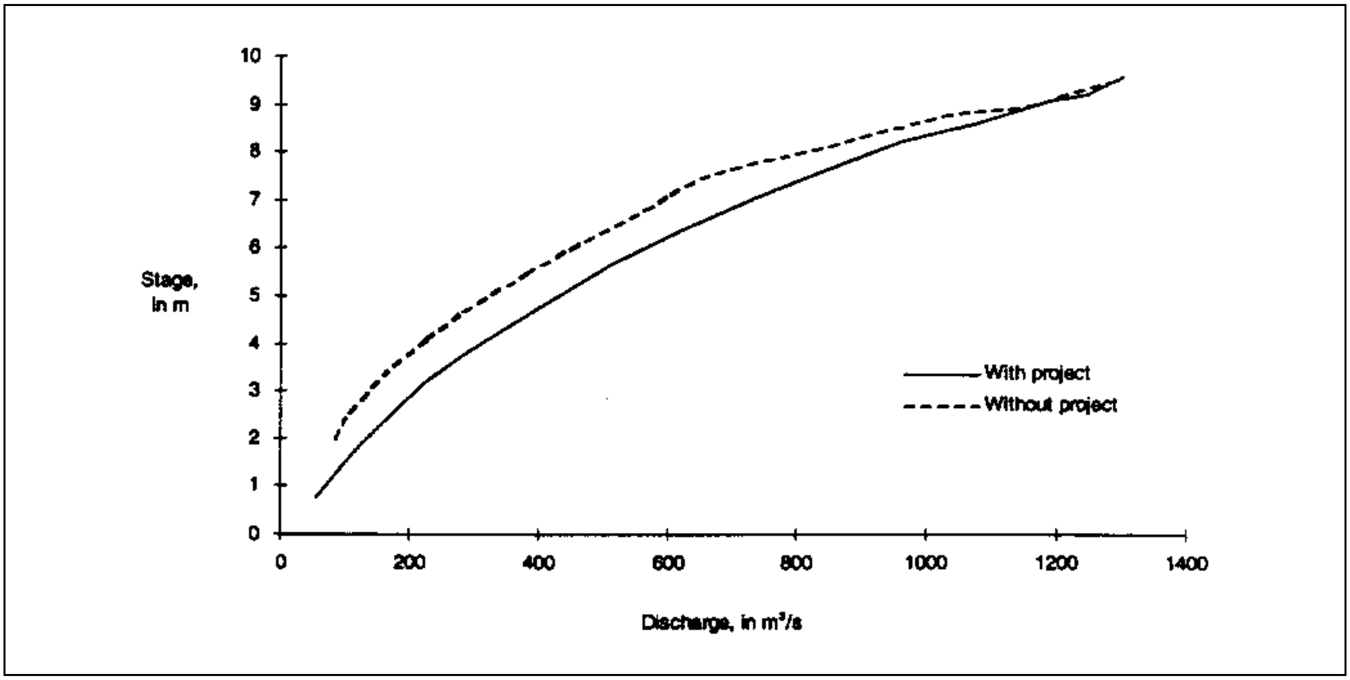

Figure 9-7. Stage-discharge functions without and with channel modification

0.004-exceedance probability events is 0.25, 0.02, and 0.00, respectively. These values indicate that with the channel modification, it is very likely that a 0.01 exceedance probability or greater flood will cause stage to exceed the 4.58-m target.

9-9. Detention Plan

a. General. The proposed detention basin is on the West Branch of Chester Creek. Runoff from 57.8 km^2 will be regulated by a 305-m-long structure, which impounds 5.55 million m^3 at full pool. However, to maintain the riverine recreation opportunities, the detention is designed to have no permanent storage: all flood waters will drain through an uncontrolled outlet after every event. The annual equivalent cost of this plan is $17,500. As with the levee plans, a variety of detention basin sizes and locations should be evaluated, but for illustration only, one is considered herein.

b. Modification of functions. The primary impact of storage is reduction of downstream discharge, and hence modification of the downstream discharge-frequency relationship. This reduction can be modeled for individual runoff events with routing models described in EM 1110-2-1417, and from this, the regulated frequency relationship can be defined. For Chester Creek, computer program HEC-1 was used for the routing. A set of historical and hypothetical events was routed through the stream system to Dutton Mill. From the without-project median discharge-frequency relationship there, the exceedance probability of each unregulated peak was found. Then the same events were routed through the system with the detention included in the model. Each regulated peak was assigned the same probability as the corresponding unregulated peak. Selected quantiles of the resulting regulated discharge-frequency relationship are shown in Table 9-12. Quantiles are approximately the same as those of the without-project relationship (Table 9-2) for frequent, smaller events. For larger events, the detention basin reduces the peak.

Uncertainty in the Chester Creek regulated discharge-frequency was determined with the LIMIT computer program. This program uses order statistics to establish the error in predicting the regulated quantile. For this application of LIMIT, the equivalent length of record was 65 years, and log transforms of the data are used.

c. Economic analysis. The expected annual damage with the proposed detention plan is $44,100. To determine this, the entire range of possible events is sampled, as are the distributions of error in discharge, stage, and damage. Damage reduction possible with the

Table 9-12
Chester Creek Regulated Discharge-Frequency Relationship

Probability of Exceedance	Discharge, in m^3/s
0.002	821.3
0.005	560.7
0.01	424.8
0.02	331.3
0.05	243.6
0.10	192.6
0.20	153.6
0.50	87.0
0.80	50.9
0.90	39.4
0.95	32.3
0.99	22.9

detention plan then is $34,000. With the total annual cost of the plan equal to $35,800, the resulting annualized net benefit is -$1,800, so the plan is not feasible. However, other benefits could affect the total, and thus may make the plan feasible.

d. Engineering performance. To define indices that describe the performance of the detention plan, the target stage is set at 4.58 m. The median exceedance probability of this stage is 0.033, and the annual exceedance probability, accounting for uncertainty, is 0.035. The probability of one or more exceedances in a 50-year project life is 0.83. The conditional non-exceedance probability of the plan for the 0.02-, 0.01-, and 0.004-exceedance probability events are 0.21, 0.04, and 0.003, respectively.

9-10. Mixed-Measure Plan

a. Modification of functions. The final plan proposed for Chester Creek is a mixed-measure plan that includes both the proposed channel straightening and enlarging and the 5.55-million-m^3 detention. Consequently, both the discharge-frequency relationship and the stage-discharge relationship will be modified. The annual equivalent cost of this plan is $45,600. This is less than the sum of the cost of the individual plans, due to some economy of scale achieved in mobilization and demobilization of construction equipment and significant reduction in cost of haul of fill material.

b. Economic analysis. Expected annual damage with the mixed-measure plan is $24,500, so the annual damage reduction is $53,600. This is less than the sum of the inundation-reduction benefit of the individual measures. Much of the damage reduced is damage incurred by events less than or equal to the 1-percent-chance event. Either the channel modification or the detention will eliminate most of the damage, and the second measure can only reduce the remaining damage. That remaining damage is due to rarer events, and so contributes little to the average annual damage. The net benefit of the plan is $8,000 ($53,600 - $45,600).

c. Engineering performance. For comparison, a 4.58-m target stage is used. The annual exceedance probability is 0.016, while the estimated median probability is 0.014. The difference is due to uncertainty in estimating discharge corresponding to the stage and probability corresponding to the discharge. The risk of exceeding the target stage at least once during the 50-year project life is 0.55. The conditional non-exceedance probability for the 0.02-, 0.01-, and 0.004-exceedance probability events are 0.74, 031, and 0.04, respectively.

9-11. Comparison of Plans

a. Table 9-13 summarizes the without-project condition and the economic accomplishments of each of the proposed plans. All plans proposed significantly reduce the $78,100 expected annual damage. The 6.68-m levee, which provides the least reduction, still eliminates about one-third of the average damage. The 8.23-m levee and the mixed measure plan eliminate about two-thirds of the average damage. The detention basin plan eliminates about half the average damage, but the cost of that plan exceeds the damage reduced. Unless the associated location and intensification benefits exceed $1,800/yr, the detention plan should be eliminated from further consideration. The net benefit of the 8.23-m levee exceeds all others, so from a narrow economic point of view, it would be recommended. The next-best plan economically is the 7.77-m levee, followed in order by the 7.32-m levee, the channel-modification plan, the mixed measure plan, and the 6.68-m levee.

b. Table 9-14 summarizes engineering performance indices for the proposed plans. With the detention basin plan, the target stage downstream will be exceeded, on the average, about 38 times in 1,000 years. However, this exceedance likely can be forecast with some certainty, so will not be sudden and catastrophic. Thus, the consequences may be acceptable. The same is true of the channel modification: the capacity is exceeded frequently, but this likely will not imperil the public due to sudden failure. On the other hand, the consequences of

Table 9-13
Present Economic Benefits of Alternatives

Plan	Annual With-Project Residual Damage, $1000's	Annual Inundation Reduction Benefit, $1000's	Annual Cost, $1000's	Annual Net Benefit, $1000's
Without project	78.1	0.0	0.0	0.0
6.68-m levee	50.6	27.5	19.8	7.7
7.32-m levee	39.9	38.2	25.0	13.2
7.77-m levee	29.6	48.5	30.6	17.9
8.23-m levee	18.4	59.7	37.1	22.6
Channel modification	41.2	36.9	25.0	11.9
Detention basin	44.1	34.0	35.8	-1.8
Mixed measure	24.5	53.6	45.6	8.0

Table 9-14
Annual Exceedance Probability and Long-term Risk

			Long-term Risk		
Plan	Median Estimate of Annual Exceedance Probability	Annual Exceedance Probability with Uncertainty Analysis	10 yr	25 yr	50 yr
6.68-m levee	0.010	0.0122	0.12	0.26	0.46
7.32-m levee	0.007	0.0082	0.08	0.19	0.34
7.77-m levee	0.004	0.0056	0.05	0.13	0.25
8.23-m levee	0.002	0.0031	0.03	0.08	0.14
Channel modification	0.027	0.031	0.27	0.55	0.79
Detention basin	0.033	0.038	0.32	0.62	0.86
Mixed measure	0.014	0.016	0.15	0.33	0.55

exceeding the top-of-levee stages are significant. Fortunately, according to the values shown in column 3, the probability of exceeding this target stage is relatively low for all proposed configurations. The 6.68-m levee will be overtopped on the average about 12 times in 1,000 years, while the 8.23-m levee will be overtopped on the average only three times in the same period.

c. Table 9-15 shows that the conditional non-exceedance probability for the levee plans are significantly greater that those of the other plans. This can be seen clearly if the conditional non-exceedance probability values are plotted, as in Figure 9-8. The conditional non-exceedance probability for the channel modification and detention plans are only about 0.20-0.25 for the 0.02 exceedance probability event. That is, if a 0.02 exceedance probability event occurs (and the probability is 0.63 that it will at least once in the 50-year lifetime), the probability of some flooding is about 0.75-0.80 with either of these. The conditional non-exceedance probability improves when the detention and channel modification are combined. In that case, the probability of target exceedance is reduced to about 0.30 for the 0.02 exceedance probability event. The levee plans, though, appear to be far superior in performance. The 8.23-m levee is almost sure to contain the 0.02 exceedance probability event, and the probability is about 0.75 that it will contain the 0.004-exceedance probability event. However, this performance index is a bit misleading: with the higher levees, the target has shifted from 4.58 m to 8.23 m. Nevertheless, the levee plans provide more reliable damage reduction. If the 8.23-m levee plan is acceptable to local sponsors, if the consequences of overtopping can be managed to within reasonable limits, and if it does not adversely impact the environment, it would likely be recommended.

Table 9-15
Conditional Non-Exceedance Probability

	Probability of Annual Event		
Plan	**0.02**	**0.01**	**0.004**
6.68-m levee	0.882	0.483	0.066
7.32-m levee	0.970	0.750	0.240
7.77-m levee	0.990	0.896	0.489
8.23-m levee	0.997	0.975	0.763
Channel modification	0.248	0.019	0.000
Detention basin	0.205	0.040	0.003
Mixed measure	0.738	0.312	0.038

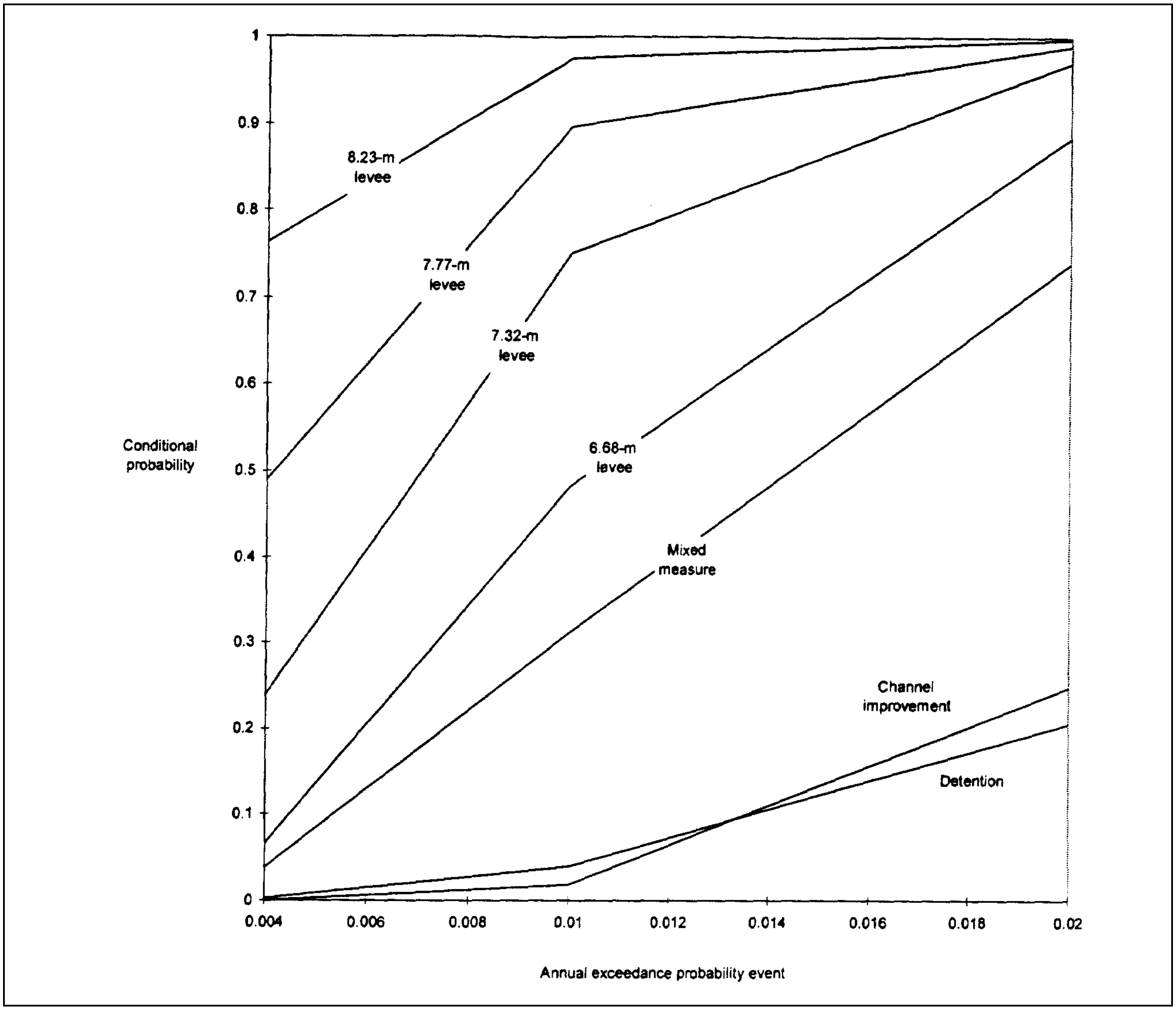

Figure 9-8. Conditional exceedance probability of proposed plans

Appendix A
References

A-1. Required Publications

These documents define policy and basic methods directly related to hydrologic engineering for flood-damage reduction planning by the Corps of Engineers. They are cited in the text and in this list by number only. All are promulgated by the Headquarters, U.S. Army Corps of Engineers (HQUASCE), Washington, DC.

ER 1105-2-100
Guidance for Conducting Civil Works Planning Studies

ER 1105-2-101
Risk-Based Analysis for Evaluation of Hydrology/ Hydraulics, Geotechnical Stability, and Economics in Flood Damage Reduction Studies

ER 1110-2-1450
Hydrologic Frequency Estimates

EM 1110-2-1415
Engineering and Design: Hydrologic Frequency Analysis

EM 1110-2-1416
River Hydraulics

EM 1110-2-1417
Engineering and Design: Flood-runoff Analysis

EM 1110-2-1419
Hydrologic Engineering Requirements for Flood Damage Reduction Studies

A-2. Other Publications

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