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

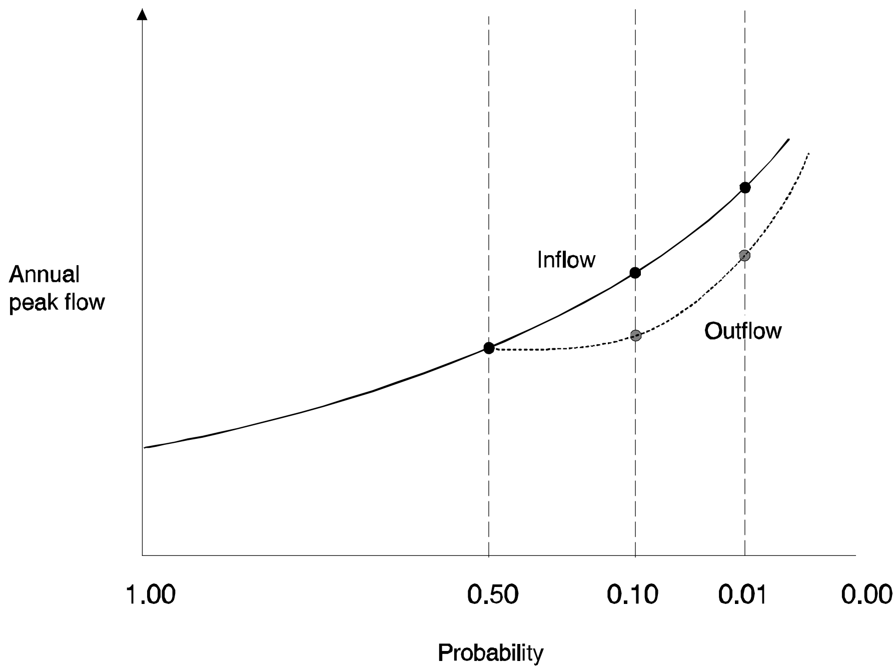

Figure 7-1. Illustration of index events for estimating with-project exceedance probability function

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

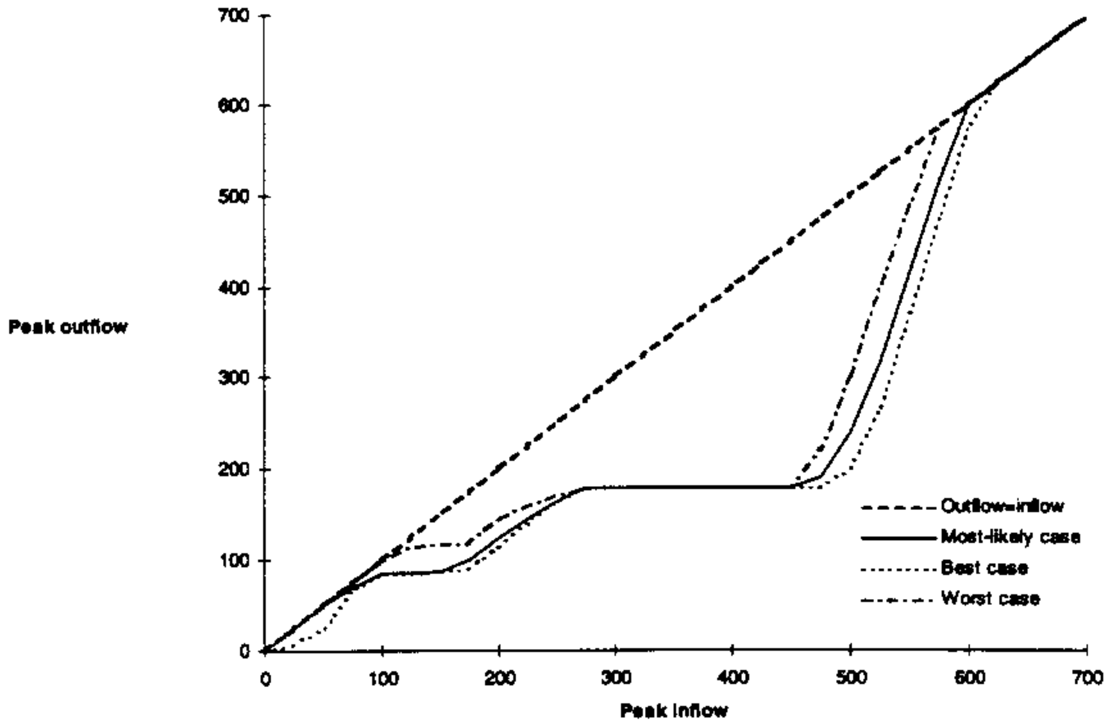

Figure 7-2. Example inflow-outflow function with confidence limits (based on function developed by U.S. Army Engineer District, Sacramento)

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.

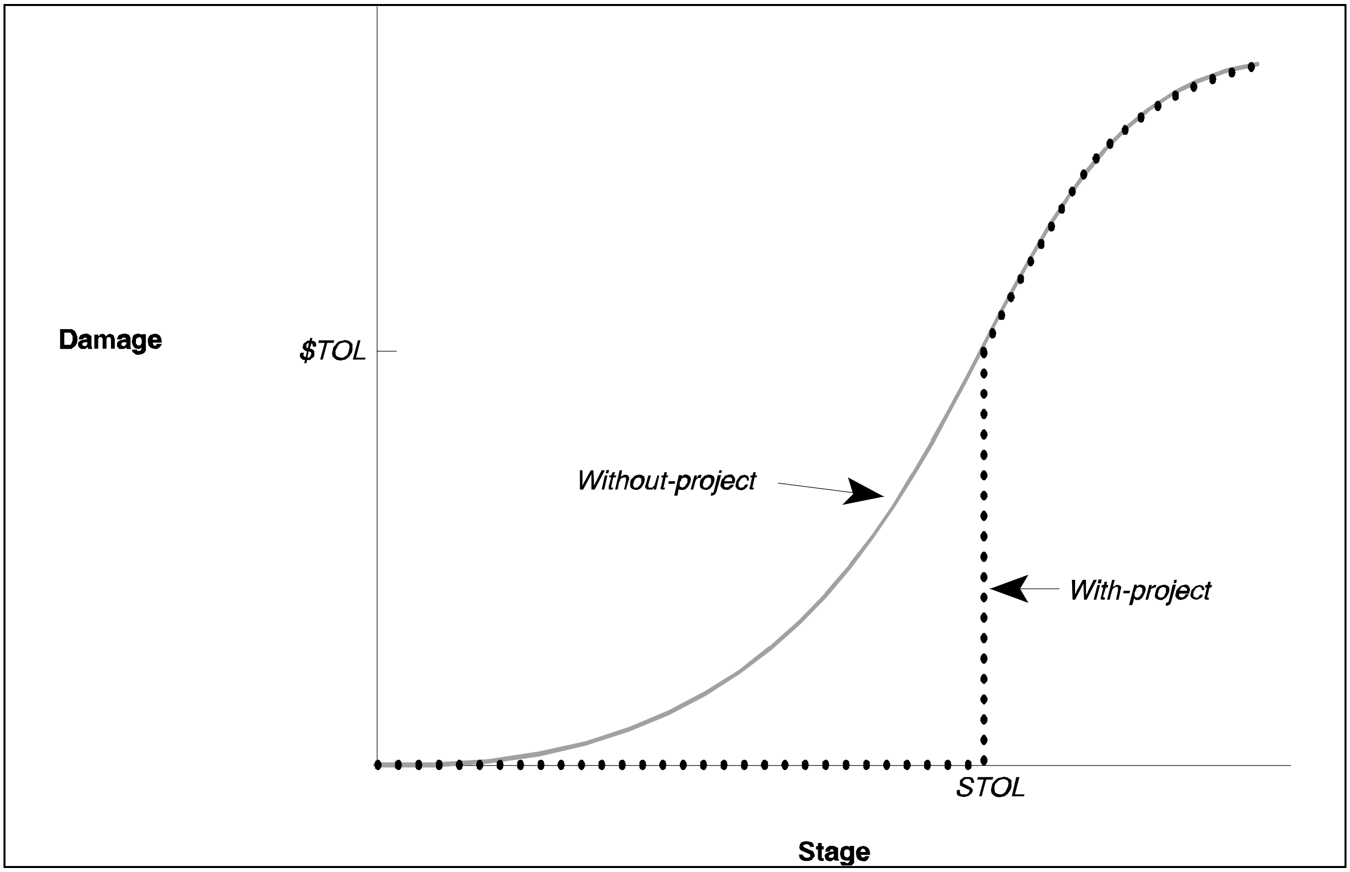

Figure 7-3. Stage-damage function modification due to levee

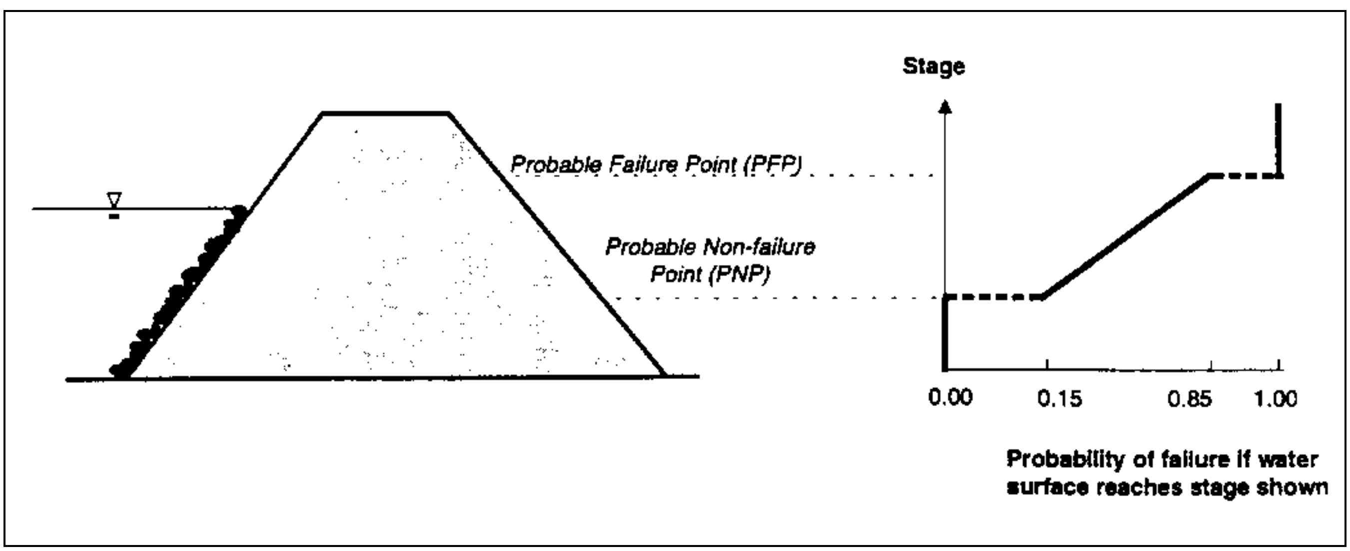

Figure 7-4. Existing levee failure-probability function

(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.

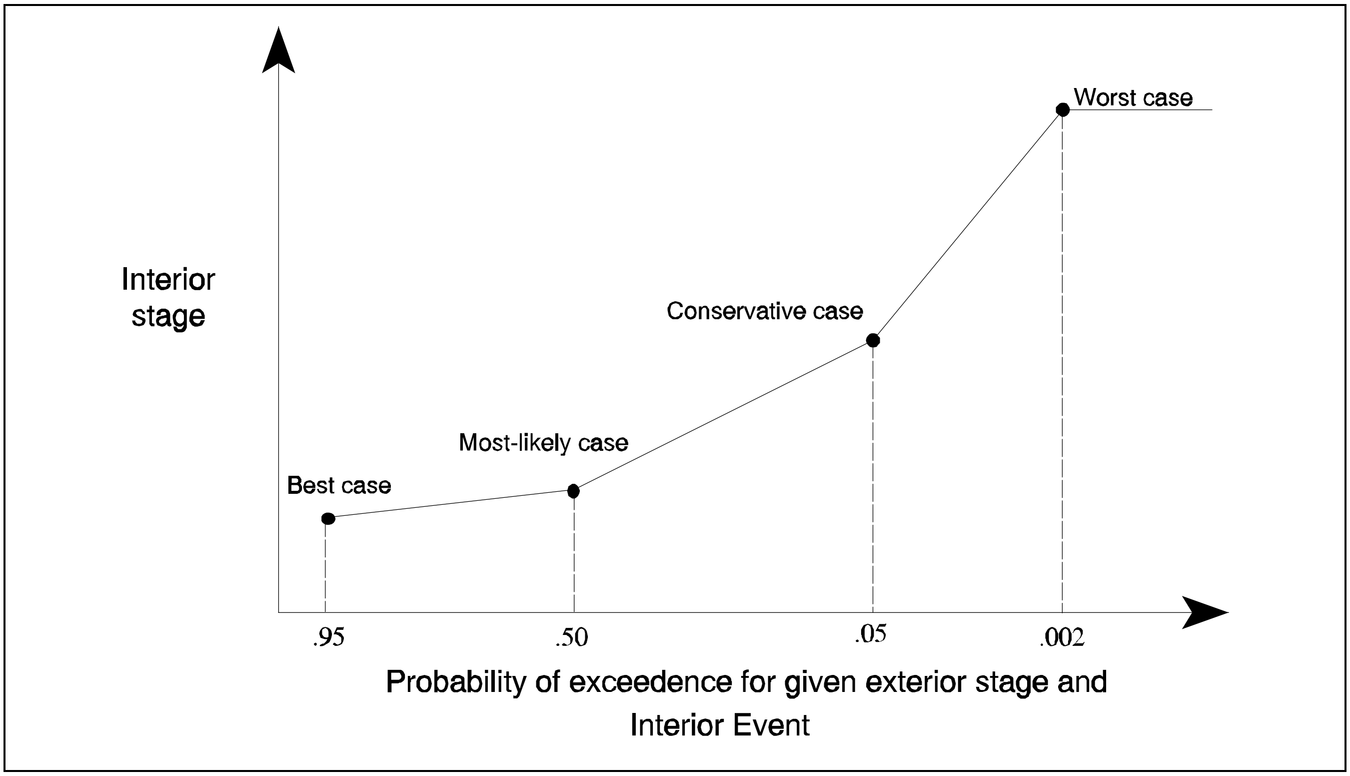

Figure 7-5. Probability function representing interior-stage uncertainty

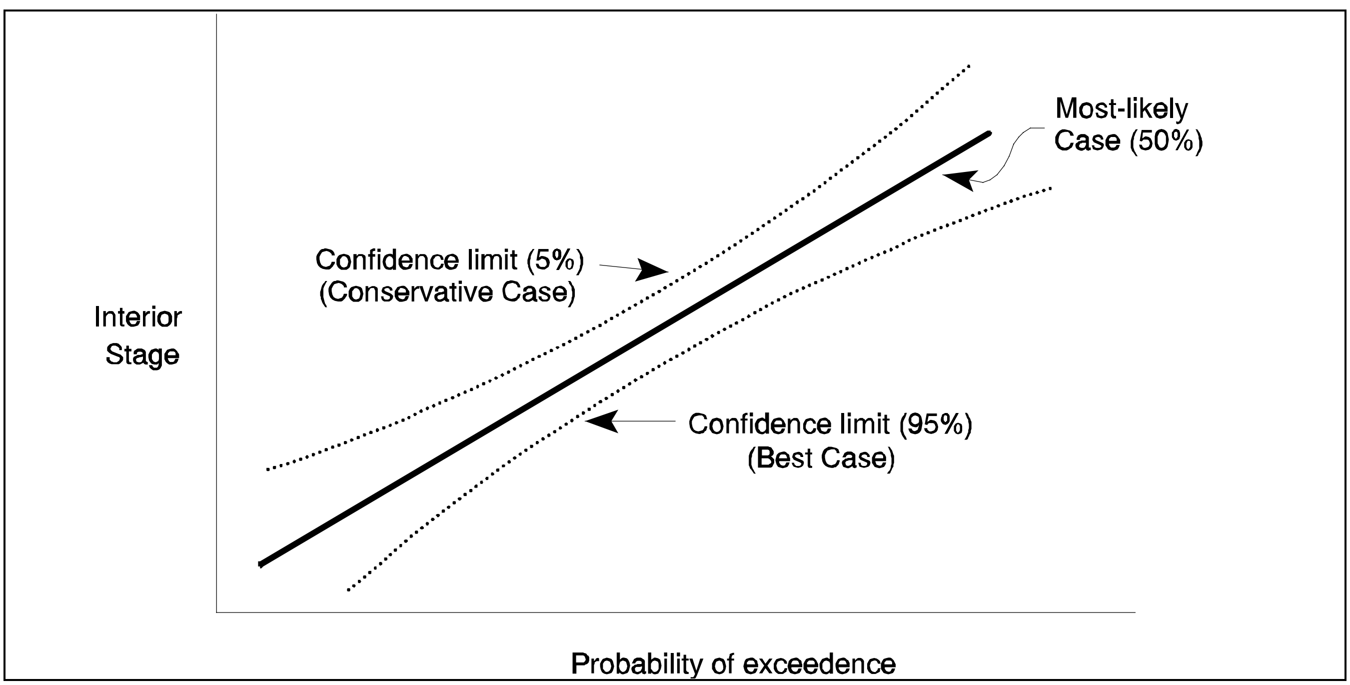

Figure 7-6. Example interior stage-exceedance probability function

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.