Chapter 2
Common Hydrologic Engineering Requirements

2-1. Summary

This and subsequent chapters define hydrologic engineering requirements for formulating and evaluating economically efficient flood damage reduction plans that will satisfy performance and environmental-protection standards. Some measures that may be included in a plan have unique requirements for formulation and evaluation. Others have some common requirements. These common requirements are described in this chapter and are summarized in Table 2-1.

2-2. Study Setup and Layout

Technical information is required to support the tasks of problem definition, plan formulation, and plan evaluation. The specific information needed and commensurate level of detail are dependent on the nature of the problem, the potential solutions, and the sensitivity of the findings to the basic information. Actions performed to set up and lay out the study are preliminary to the detail analysis. They include: defining the study scope and detail, field data collection and presence, review of previous studies and reports, and assembly of needed maps and surveys. Although this process involves more information gathering than analysis, it helps scope the study, lends credibility to the subsequent analysis, and provides insights as to potential solutions.

Table 2-1
Summary of Common Requirements

Objective or Standard	Requirement	Method/Model	Reference
Economic objective	Develop discharge-frequency function and uncertainty	Frequency analysis or ungauged catchment methods	EM 1110-2-1417 EM 1110-2-1415 ER 1110-2-1450
	Develop stage-discharge function and uncertainty	Observation or fluvial & alluvial process models	EM 1110-2-1416 EM 1110-2-1601 EM 1110-2-1612 EM 1110-2-4000
	Develop stage-frequency function and uncertainty	Statistical + system accomplishment models	EM 1110-2-1415
Performance standard	Determine expected annual exceedance probability	Risk-based analysis procedures	
	Determine expected lifetime exceedance probability	Hydrologic risk binomial distribution	EM 1110-2-1415
	Determine operation for range of events and assumptions	Hydrologic/ hydraulic models	ER 1110-2-1405 ER 1110-2-401
	Determine capacity exceedance consequences	Depends on measures	
	Perform reliability evaluation	Risk-based analysis procedures	
Environmental-protection standard	Assess impact	May require runoff, fluvial, alluvial, statistical-process models	ER 200-2-2

2-3. Requirements for Evaluating the NED Contribution

a. Benefit evaluation standard.

(1) As noted in paragraph 1-4, the economic efficiency of a proposed flood damage reduction alternative is defined as

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

in which NB = net benefit; B_L = location benefit; B_I = intensification benefit; B_{IR} = inundation-reduction benefit; and C = total cost of implementing, operating, maintaining, repairing, replacing, and rehabilitating the plan (the OMRR&R cost). The inundation-reduction benefit may be expressed as

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

in which $D_{without}$ = economic flood damage without the plan and D_{with} = economic flood damage if the plan is implemented.

(2) The random nature of flooding complicates determination of the inundation-reduction benefit. For example, a flood damage reduction plan that eliminates all inundation damage one 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 calling for use of expected annual flood damage. Expected damage accounts for the risk of various magnitudes of flood damage each year, weighing the damage caused by each flood by the probability of occurrence. Combining Equations 2-1 and 2-2, and rewriting them in terms of expected values, yields

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

in which E [ ] denotes the expected value. For urban flood damages, this generally is computed on an annual basis because significant levels of flood damage are limited to annual recurrence. For agricultural flood damages, it may be computed as the expected damage per flood, as more than one damaging flood may occur in a given year. The NED plan then is the alternative plan that yields maximum net benefit, accounting for the full range of likely hydrologic conditions that might occur.

(3) The so-called "without-project" condition in Equation 2-3 represents existing and future system conditions in the absence of a plan, "... accounting for the effect of existing and authorized plans, laws, policies and the flood hazard on the probable course of development" (EP 1165-2-1). It is the base "... upon which alternative plans are formulated; from which all benefits are measured; against which all impacts are assessed ..." (EP 1165-2-1).

b. EAD computation. Chapter 7 of EM 1110-2-1415 describes alternative approaches to computing the expected value of annual damage (EAD). The most widely used approach in the Corps is the frequency technique, which is illustrated in Figure 2-1. To compute

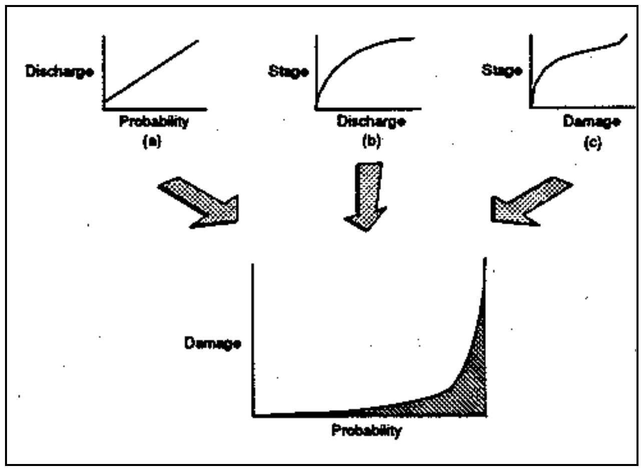

Figure 2-1. Derivation of damage frequency function from hydrologic, hydraulic, and economic information

EAD with this technique, the annual damage frequency function is derived and integrated. This damage frequency function commonly is derived from the annual maximum discharge frequency function (Figure 2-1*a*), transformed with a stage discharge (rating) function (Figure 2-1*b*), and a stage damage function (Figure 2-1*c*). This stage damage function may represent a single structure or it may be an aggregated function that represents many structures, their contents, and other damageable property. Dynamic catchment, channel, or economic conditions are accounted for by adjusting the appropriate functions and deriving and integrating the damage frequency function to compute EAD for the present and for each future year. The resulting EAD values can be averaged over project life, with discounting if appropriate. The transforming, integrating, and discounting computations can be performed by the Hydrologic Engineering Center's (HEC) EAD program (USACE 1989a), which is described in Appendix B. The task of the hydrologic engineer is to define the discharge frequency function and rating function for various alternatives, including the without-plan case, for existing and future system conditions. Procedures and analytical tools for doing so are described in various Corps publications and are summarized in paragraph 2-3(*d-f*) for convenience.

c. Risk-based analyses.

(1) The procedure illustrated in Figure 2-1 ignores uncertainty in the functions. Uncertainty is due to measurement errors and the inherent variability of complex physical, social, and economic situations. Traditionally, the Corps has accounted for this uncertainty by employing factors of safety, such as levee freeboard. However, the state of the art of risk analysis has advanced sufficiently as of the early 1990s to permit explicit accounting for uncertainty. Consequently, Corps policy is that all flood damage reduction studies will adopt risk-based analysis. Figure 2-2 illustrates the analysis strategy.

(2) The risk-based analysis procedure seeks to quantify the uncertainty in the discharge frequency function, stage discharge function, and stage damage function and to incorporate this analysis of the economic efficiency of alternatives. This is accomplished with Monte Carlo simulation, a numerical-analysis tool that yields the traditional estimate of the expected damage reduced, accounting explicitly for the errors in defining the discharge frequency function, rating function, and stage damage function. In addition, the Monte Carlo simulation procedure provides an assessment of the project performance

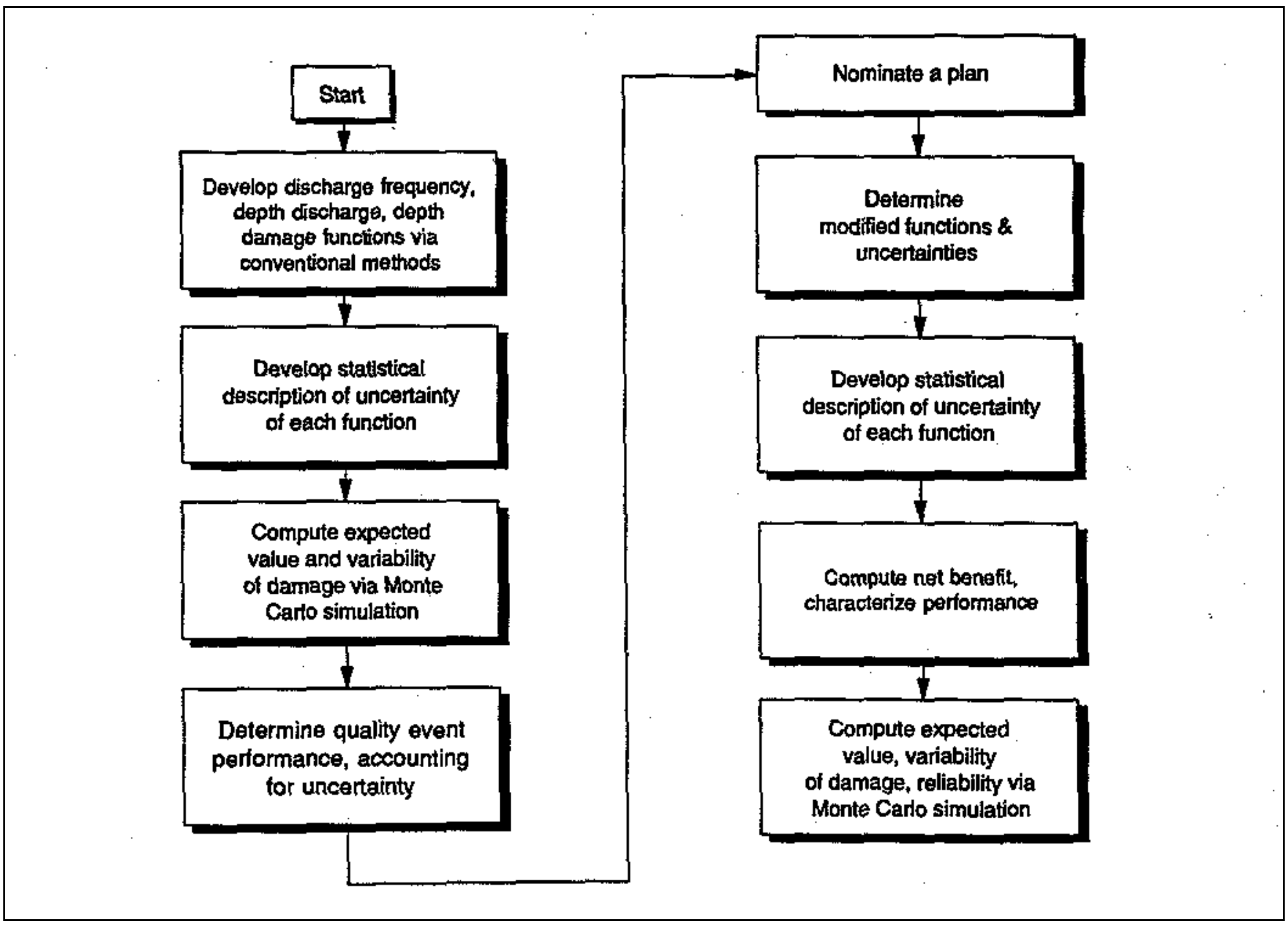

Figure 2-2. Risk-based analysis procedure

as described in paragraph 2-4. Performance indicators derived are the expected annual exceedance probability and reliability of a flood damage reduction plan. The expected annual exceedance probability is the chance of flooding in any given year. Respectively, this is an index of the frequency with which the plan performs as designed. For example, in analysis of a proposed levee sized to contain the 1 percent chance event, this procedure would estimate the probability that the levee would, in fact, contain the 1 percent chance and other events, should these occur.

d. Discharge frequency function definition.

(1) The manner in which the discharge frequency function is defined depends on the data available. For the existing, without-plan condition, if a sample of annual maximum discharge is available for the appropriate stream, the frequency function can be developed by fitting a statistical distribution with the sample. The procedures adopted by the Corps follow the guidelines proposed by the Water Resources Council (Interagency Advisory Committee 1982). These procedures are explained in detail in EM 1110-2-1415 and serve as the technical basis for the HEC-FFA computer program (USACE 1992a). That program is described in Appendix B.

(2) If a sample of annual discharge for existing condition is not available and for future and with-project conditions, the discharge frequency function must be developed with one of the procedures listed in Table 2-2. These procedures are described in detail in EM 1110-2-1417. For special cases, such as regulated flows, different methods are required and must normally be augmented with modeling studies.

(3) The uncertainty in the discharge frequency function varies depending on the physical characteristics of the stream, quality and nature of the available data, and other factors. With-project conditions uncertainty of the discharge frequency function may be less or greater than the without-project conditions. Future conditions functions are almost always less certain.

e. Stage discharge function definition. The stage discharge function, or rating curve, for the without-project, existing condition may be defined either by observations or with model studies. For cases that modify the function, the stage discharge function must be defined with model studies. With-project conditions uncertainty may be less (concrete channel) or greater (not maintained) than existing without-project conditions. Future conditions uncertainty will most likely be greater.

Table 2-2
Procedures for Estimating Annual Maximum Discharge Frequency Function Without Discharge Sample (adapted from USWRC 1981)

Method	Summary of Procedure
Transfer	Frequency function is derived form discharge sample at nearby stream. Quantiles are extrapolated or interpolated for the location of interest.
Regional estimation of quantiles or frequency-function parameters	Quantiles or frequency functions are derived from discharge samples at nearby gauged locations. Frequency function parameters are related to measurable catchment, channel, or climatic characteristics via regression analysis. The parameter-predictive equation is used for the location of interest.
Empirical equations	Peak discharge for specified probability event is computed from precipitation with a simple empirical equation. Typically, the probabilities 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 frequency 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. Frequency function is fitted to series of annual hydrograph peaks, using statistical analysis procedures.

Alluvial streams involving mobile boundaries, ice, debris, and flow bulking from land surface erosion can significantly add to the uncertainty of the stage discharge function estimates. Publications of the World Meteorological Organization (WMO 1980, 1981) describe procedures for measuring stage and discharge to establish empirically the stage discharge function for existing condition. In most cases, the Corps will rely on stage discharge relationships provided by the U.S. Geological Survey (USGS) for gauged sites or, in rare cases, will call on the USGS to establish relationships if these are deemed necessary but are not readily available.

(1) Gradually varied, steady-flow, rigid-boundary conditions. EM 1110-2-1416 describes use of physical and numerical models to establish stage discharge functions for existing, future, without-project, or with-project conditions. Commonly, a numerical model of gradually varied, steady-flow (GVSF), rigid-boundary in an open channel is used. Solution of the GVSF equations yields an estimate of stage at locations along a stream reach for a specified steady flow rate. To solve the equations, the channel geometry and hydraulic loss model parameters for the condition of interest must be defined. The geometry may be measured and parameters estimated for the existing channel condition or defined as part of the proposal for a flood-damage-reduction plan. One commonly used GVSF model, program HEC-2 (USACE 1982a), is described in Appendix B.

(2) Erosion and deposition.

(a) Channel bed, channel bank, and land surface erosion and deposition complicate evaluation of stage discharge function. Mobilization of bed and bank materials in alluvial channels alters the channel shape. If that happens, stage at a channel cross section is not a unique, time-invariant function of discharge, channel geometry, and energy losses. Instead, the stage depends on material properties and the time history of discharge, and a movable-boundary hydraulics model is required to define the relationship for EAD computation. Two such models, HEC-6 (USACE 1993a) and TABS-2 (Thomas and McAnally 1985), are described in Appendix B.

(b) Mobilization and subsequent deposition of the sediment may cause other complications if not anticipated. For example, construction of a reservoir will alter a stream's natural gradient, but the flow and sediment load moving in the channel upstream of the reservoir are not changed. As the stream reaches the reservoir, velocity decreases significantly. The response of the stream is to deposit the bed load and decrease the gradient immediately upstream of the reservoir. This effect moves upstream as more sediment is deposited. This can induce flood damages upstream of the reservoir. Downstream, the effect is to scour the channel and erode the banks due to the relatively clear releases of the reservoir. Continuous downstream migration of the instability problem is likely over time.

(c) Similarly, a channel straightening can alter the natural alluvial processes. Straightening increases the energy gradient while other conditions remain unchanged. This change can lead to increased erosion upstream of the realignment and increased deposition downstream. After some time, erosion of the channel banks and bed may occur.

(d) Likewise, land-surface erosion increases the sediment load on the stream resulting in bulking of the flows. Also, if significant watershed construction accompanied by removal of vegetation occurs, the sediment runoff will increase during the construction period. Unless proper precautions are taken for these conditions, this sediment may move into adjacent channels, where it will be deposited. This, in turn, reduces the channel cross-section area, increases the stage for a given discharge, and induces damage.

(e) EM 1110-2-4000 provides guidance on analysis of erosion and deposition impacts. It identifies locations at which sedimentation problems are likely to occur and suggests design or maintenance solutions to those problems.

(3) Ice impacts. Ice accumulations alter adversely accomplishments of flood damage reduction measures by restricting the flow in channels and conduits and by increasing pressure or forces on the measures. In cold regions, ice formation buildup and breakup must be anticipated, the impact must be evaluated, and project features must be adjusted to ensure proper performance. With some measures, such as channel-lining improvements, this translates to an increase in project dimensions so the measures can withstand impacts of floating ice. Likewise, if ice is likely to form on a reservoir surface, the dam design must be altered to withstand the increased overturning moment due to the added force on the dam. EM 1110-2-1612 and the Cold Regions Research Engineering Laboratory can provide guidance.

(4) Debris impacts. The effect of debris is similar to that of ice; it can significantly reduce channel conveyance

and constrict flows at obstacles. Examples are more volume associated with runoff, constrictions at bridges, and accumulation of urban trash and waste in channels. If debris is mobilized and subsequently redeposited, it may adversely affect performance of pumps, gates, and other plan features. Proper maintenance measures should be included as a component of any plan to avoid these problems.

f. Stage-frequency definition. If flood inundation results from a flooding river, storm surges along a lake or ocean, wind-driven waves (runup), a filling reservoir, or combinations of these events, a stage-frequency function is more appropriate for derivation of the damage-frequency function. EM 1110-2-1415 describes statistical-analysis procedures for fitting a frequency function with observations for a current, existing condition. The procedures are similar to those used for fitting a frequency function with a discharge sample. For future condition and other cases, the function must be defined with model studies. The model used depends on the condition to be analyzed. For example, if reservoir operation changes are proposed to reduce flood damage due to reservoir pool elevation rise, a reservoir-operation simulation model might be used to estimate the modified time series of lake levels. The stage-frequency function then could be fitted to this series with the methods of EM 1110-2-1415.

2-4. Requirements for Satisfying Performance Standard

Selecting the alternative that maximizes NED contribution provides for efficient investment of public funds, but it does not guarantee that a plan will perform as effectively as the public has a right to expect. Two plans may yield the same net benefit, but one may be less vulnerable and thus more desirable. For example, consider two hypothetical alternatives: a levee plan and a channel improvement plan, both sized and located to protect a floodplain from events less than the best-estimate of the 1 percent chance event. When a slightly larger event occurs, the levee will be overtopped and may be breached, causing significant losses. If this same event occurs with the channel plan, flow will be out-of-bank. However, the consequences of out-of-bank flow likely will be less significant than those associated with a levee breach. The channel project is less vulnerable. Performance indicators are used in determining the validity of the project and for comparing alternatives based on long-term project operational stability and public safety, and in determining potential significant damage locations. They include defining the flood risk for the project life, determining the expected annual exceedance probability, estimating the project reliability, describing the operation for a range of events and key assumptions, and defining the consequences of capacity exceedance events of each plan. Hydrologic engineering analyses are critical in the plan formulation phase to ensure that flood damage reduction plans satisfy the performance standard, functioning as anticipated. The performance indicators are described in more detail in subsequent paragraphs. EP 1110-2-8 may be used as a guide for explaining flood risk.

a. Expected annual exceedance probability. The expected annual exceedance probability is a key element of defining the performance of a given plan. It is the probability that the specified capacity or target stage will be exceeded in any given year. The value is determined from the risk-based analysis study that includes the uncertainties of the various functions. The target stage is normally that associated with the start of significant damage. For a levee or floodwall, the stage may be the stage where overtopping occurs. For a channel or nonstructural measures, the target stage may be that where flooding of the structures begins. Although variable for plans that modify the stage-damage function, the target stage should be consistent among plans that don't modify the stage-damage functions.

b. Expected lifetime exceedance probability. The probability that one or more flood events will occur within a specified time period, normally the project life, is a means of indicating performance. The calculations may be made directly using the binomial distribution as described in EM 1110-2-1415. Figure 2-3 graphically shows the relationships. The threat may be similar for all structures, such as behind a levee or floodwall, or

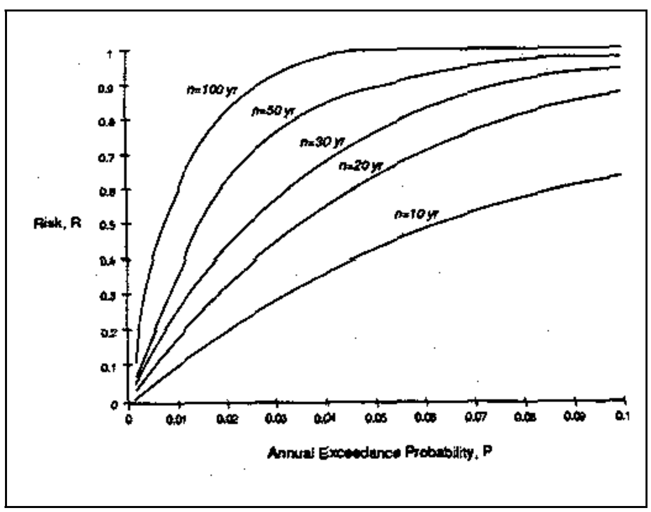

Figure 2-3. Probability of capacity exceedance during project life

variable depending on the elevation of individual structures, such as for a channel. For a channel example, a house located with the ground floor at the 1 percent chance flood level (the so-called 100-year flood level), the probability of one or more exceedances is approximately 0.40, or about one chance in 2.5 over a 50-year project life. If the house is located with the ground floor at the 0.5 percent chance level (the 200-year flood), the probability of one or more exceedances is 0.22. For a levee with an expected stage exceedance probability of 1 percent there is a 0.40 probability of one or more event exceedances during the 50-year project life for all the protected structures.

c. Operation for range of events and key assumptions.

(1) Each plan should be evaluated for performance against a range of events and key assumptions. Evaluation based solely on a specific design event is not a valid performance indicator by itself. For example, a pumping station must be configured to operate satisfactorily for a range of events, not simply designed for the 4 percent chance event. The analysis should be for a range of frequent and rare events including those that exceed the project capacity.

(2) Analysis of the sensitivity of the operation of the project to critical assumptions is required to assist in determining the stability of the project over its project life. An example is that there is a somewhat high likelihood of future encroachment of the natural storage associated with an interior system although it was not assumed as part of the plan assumptions. The sensitivity of the encroachment on the project performance should be evaluated. Similarly, the sensitivity of future development scenarios, erosion, debris, sediment, O&M, and other assumptions that are critical to having the project performed as planned and designed must be evaluated.

(3) The hydrologic engineering study is critical to development of the operation and maintenance plan as required by provisions of Federal Code 208.10, Title 33. It forms much of the basis for more detailed information included in the Operation and Maintenance Manual furnished local interests as provided for in the Federal Code. (ER 1110-2-1405 and ER 1110-2-401).

d. Consequences of capacity exceedance events. The project performance for one or more capacity exceedance events is required. Analyses to determine the extent, depth, and velocities of flooding and warning times for each event are conducted as part of the hydrologic engineering studies. Additional hydrologic engineering data to support definition of the population at risk, warning dissemination, and emergency response actions from the technical, social, and institutional perspectives for various times-of-the-day are also required. The hydrologic engineering studies to determine the consequences of the capacity exceedance events may vary significantly depending on the plan. Plans, such as levees and floodwalls, normally require the most detail because of the potential high loss potential. Flood-fighting efforts may be assumed as those necessary to preserve the integrity of the facility/system to pass the capacity exceedance event, no more-no less.

e. Event performance. This is the conditional probability associated with the chance of the project containing a specific event should it occur. The analysis is based on consideration of the uncertainties of the discharge-frequency and stage-discharge relationships. An example of this performance indicator is that the proposed levee would have a 75 percent chance of containing the 1 percent chance exceedance frequency event should it occur.

2-5. Requirements for Satisfying Environmental-Protection Standard

a. Policy. The policy of the Corps of Engineers is to develop, control, maintain, and conserve the Nation's water resources in accordance with the laws and policies established by Congress and the Administration, including those laws designed to protect the environment. The National Environmental Policy Act (NEPA) is the Nation's broadest environmental law. It requires that every Federal agency prepare an environmental impact statement (EIS) for proposed legislation or other major actions that would affect the environment significantly.

b. Corps procedure.

(1) For all Corps actions, except those categorically excluded from NEPA requirements, the Corps conducts an environmental assessment (EA) to determine if the action will have a significant impact on environmental quality. The EA presents the alternatives and defines the environmental impacts of each. In the event of a finding of no significant impact, no further action is necessary. Otherwise, an EIS will be prepared. The Corps normally prepares an EIS "... for feasibility reports for authorization and construction of major projects, for changes in projects which increase size substantially or incorporate additional

purposes, and for major changes in the operation and/or maintenance of completed projects (EP 1165-2-1)."

(2) NEPA requires that an EIS include the components shown in Table 2-3. Much of the scientific and engineering information required to develop these components is identical to or an expansion or extension of information otherwise required for economic and performance assessment. Hydrologic engineering studies are key providers of information for the EIS. For example, assessment of a proposed channel improvement may require erosion analysis. This same analysis may provide information required to assess the impact of the channel improvement on wildlife habitat along the channel banks. Coordination is required with environmental specialists to define such needs and to explore opportunities to expand the economic and performance analyses to provide the information. These resource requirements should be accounted for in the HEMP.

Table 2-3
Technical Components of EIS

1. Description of the alternatives considered, including at least the "no-action" alternative, the Corps' preferred alternative, and the "environmentally preferable" alternative;

2. Presentation of the environmental impacts of each alternative;

3. Explanation of why any alternatives were eliminated from further consideration;

4. Delineation of the affected environment;

5. Assessment of the environmental consequences of each alternative, including (a) direct effects; (b) foreseeable indirect effects; (c) cumulative effects from the incremental impact of the alternative plus other past, present, and foreseeable future actions; and (d) other effects, including unavoidable effects, irreversible or irretrievable commitments of resources, effect on urban quality, effect on historical and cultural quality; and

6. Actions that may be taken to mitigate adverse impacts, including (a) avoiding the impact by not implementing the plan; (b) minimizing the impact by limiting the plan; (c) rectifying the impact by repair, rehabilitation, or restoration; (d) reducing or eliminating the impact over time by preservation or maintenance; or (e) compensating by replacement or substitution of resources.