

APPENDIX E

RISK ANALYSIS

INTRODUCTION

Risk describes the chance that some undesirable event will occur, resulting in exposure to injury or loss. Risk is typically associated with an acceptable standard or desired level of reliability. In flood damage reduction studies, the acceptable level of flood risk is often expressed as level of protection or performance. Uncertainty is an expression of doubt in the accuracy of knowledge or information. Flood damage reduction studies regularly use estimated information, such as stream flow records or stage predicted by hydraulic models, with varying degrees of accuracy or reliability. Risk and uncertainty are related in that flood damage reduction studies rely on an estimation of flood risk that is based on uncertain information. Uncertainty is also associated with environmental conditions and assumptions that could affect the success of ecosystem restoration efforts.

The Corps of Engineers historical approach to flood damage reduction planning has accounted for uncertainty by using safety factors, freeboard, worst-case scenarios, and other procedures that acknowledge uncertainty, but do not explicitly quantify it. This was necessary because of a lack in precision in predicting the complex interaction of hydrologic, hydraulic, and economic functions and because of the complexities of the required mathematics. An example of this traditional approach is the use of freeboard in projects that involved the construction of levees. Levees were designed based on a best estimate of the height required to contain a given flood; this height was then augmented by a standard increment of levee height, or freeboard, to account for uncertainty in hydrology and hydraulics. Unfortunately, the standard freeboard approach could not be tailored to localized conditions, did not consider the levee system as a whole, did not provide a consistent level of protection from project to project, and may have added unnecessary costs to some projects.

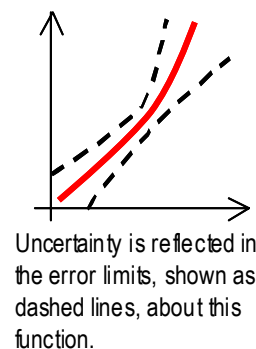
Today, advances in statistical hydrology and high-speed computerized analysis tools have made it possible to explicitly account for uncertainty. The Comprehensive Study has adopted a risk analysis approach that utilizes the Hydrologic Engineering Center's Flood Damage Assessment (HEC-FDA) computer model to analytically incorporate considerations of risk and uncertainty to express engineering and economic performance in terms of probability distributions. This appendix presents the risk analysis methodology used for this study to evaluate without-project (baseline) and with-project flood risk and economic damages.

TRADITIONAL RISK ANALYSIS APPROACH

Traditional risk analyses rely on information in the form of discharge-frequency, stage-frequency, and stage-damage functions identified at index points. The index points represent the link or interrelation between flood conditions and damages in an area or reach. They are the location where hydrology, hydraulics, geotechnical considerations, and types of damage

are equated to flood damages or flood risk. The discharge-frequency, stage-frequency, stage-damage functions, and geotechnical probability of failure curves describe the hydrologic, hydraulic, geotechnical, and economic conditions at each index point. A certain degree of uncertainty is inherent in these functions, ranging from deficiencies in hydrologic data records or the ability of a hydraulic model to accurately estimate stage in a complex river system.

For the purpose of flood damage analyses, uncertainty is the estimated amount or percentage by which an observed or calculated value may differ from the true value. Uncertainty distribution is the dispersion or variation of errors about the median or best estimate of values along a function. It is defined by error limits or a distribution of error associated with the key variables used in an analysis, illustrated at right. There are error limits around the discharge in the discharge-frequency relationship, around stage in the stage-discharge relationship, and damage in the stage-damage relationship.

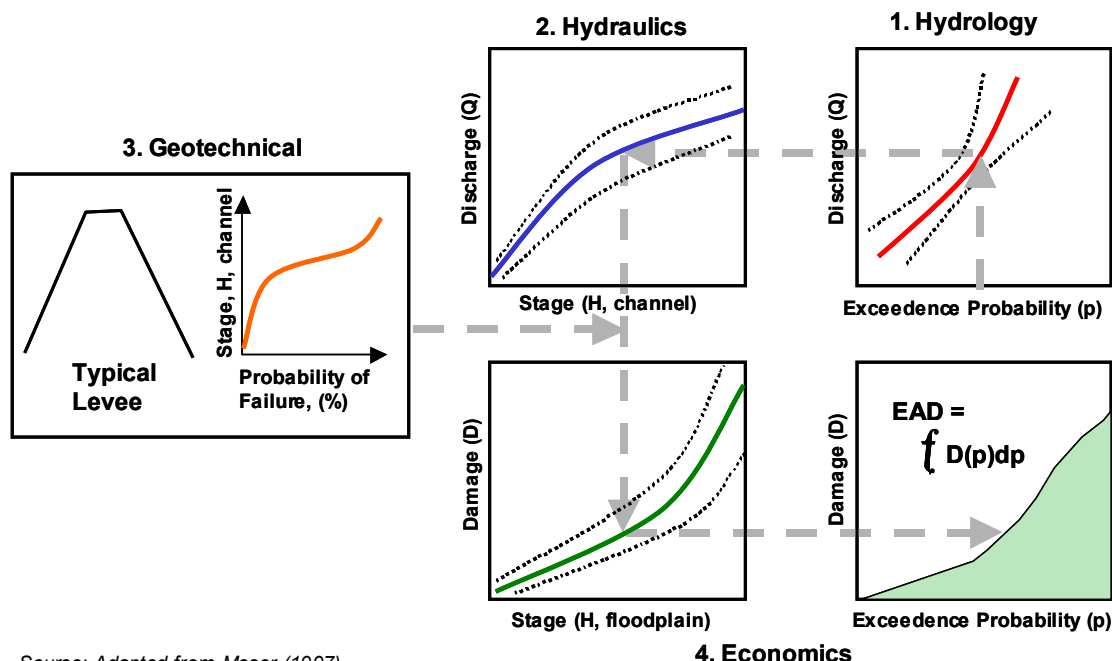


Rather than generating a series of random floods and estimating their consequences, a more sophisticated approach can be used to incorporate uncertainty in each of the key variables (hydrology, hydraulics, geotechnical performance, and economics). Monte Carlo simulation provides a way to estimate the statistical properties of outputs when the inputs are random variables. Traditional Monte Carlo simulation is a random number sampling of variables and the uncertainty distributions of these variables (also known as numerical integration). For flood damage reduction, Monte Carlo sampling of the stage-discharge, discharge-frequency, geotechnical probability of failure, and stage-damage relationships is repeated an indefinite number of times until the outputs, such as expected annual damages and annual exceedance probability, are statistically accurate.

Figure 1 illustrates the conceptual risk analysis approach for Corps' flood damage analyses. To find the damage for any given flood frequency, the discharge for that frequency is first located in the discharge-frequency panel (hydrology), then the river channel stage associated with that discharge value is determined in the stage-discharge panel (hydraulics). Most of the rivers being studied have levees that typically fail before the water reaches the top (geotechnical reliability). Once levees have failed and water enters the floodplain, then stages (water depths) in the floodplain cause damage to structures and crops (economics). This process is repeated thousand of times using Monte Carlo analysis and the results are plotted to form the damage-frequency curve (lower right).

COMPREHENSIVE STUDY METHODOLOGY

The Comprehensive Study utilizes the HEC-FDA computer model that analytically incorporates considerations of risk and uncertainty to express engineering and economic performance. This model works in conjunction with other hydrologic and hydraulic models and geotechnical evaluations developed by the Comprehensive Study. The risk analysis methodology is applied to without-project and with-project conditions.



Source: Adapted from Moser (1997)

FIGURE 1 –THE CONCEPTUAL RISK ANALYSIS MODEL

The risk analysis methodology used by the Comprehensive Study deviates slightly from the traditional methodology. The Monte Carlo simulation starts with a random number sampling of the stage-frequency, geotechnical probability of failure, and stage-damage relationships. However, there are no discharge-frequency relationships in the Monte Carlo simulations. The hydraulic model directly creates the stage-frequency relationships and uncertainty distributions at index points in the channel from five flood event hydrographs (events with a 10%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year) input into the hydraulic model. The exception is the Hamilton City Project, which uses the traditional methodology. Descriptions of the hydraulic models and other technical tools related to risk analysis are provided later in this document.

There are numerous uncertainties associated with flood damage reduction studies related to both natural systems (variations in climate, stream flow, river stage, etc) and engineered systems (reliability of levees, flood gates, etc). These uncertainties are shown in **Figure 1** as “error bands” located above and below the hydrologic, hydraulic and economics curves.¹ Some of the important uncertainties specific to the Comprehensive Study include:

Hydrologic. Uncertainty factors include hydrologic data record lengths that are often short or do not exist, precipitation-runoff computational methods that are not precisely known, and imprecise knowledge of the effectiveness of flow regulation (reservoir operations). The hydrologic data record length, or period of record, is the number of years for which a systematic record of peak discharges is available at a given stream gage. This parameter directly influences the uncertainty associated with the frequency-discharge function and

¹ There are multiple uncertainties in the geotechnical probability of failure curves. The resultant curve used in this analysis reflects the uncertainty of whether a levee either has catastrophic failure or performs poorly during random periods of high flows.

consequently the project performance statistics discussed later in this report. Because hydrologic studies are most often based on statistical analyses of available gage data, a longer period of record implies less uncertainty associated with this function. For the Comprehensive Study, the hydrologic periods of record were identified for each economic impact area.

Hydraulics. Uncertainty arising from the use of simplified models to describe complex hydraulic phenomena, including the lack of detailed geometric data, potential misalignments or misrepresentations of hydraulic structures, channel bed material variability, and errors in estimating slope and roughness factors.

Geotechnical. Uncertainty in the geotechnical performance of flood control structures during loading from random events, such as flood flows and earthquakes, affect levee performance. Other uncertainties may include geotechnical parameters such as soil and permeability values used in the analysis, mathematical simplifications in the analysis models, frequency and magnitude of physical changes or failure events, and unseen features such as rodent burrows, cracks within the levee, or other localized defects.

Economics. Uncertainty concerning land uses, depth/damage relationships, structure/content values, structure locations, first floor elevations, floodwater velocity, the amount of debris and mud, flood duration, warning time, and response of floodplain inhabitants.

Impact Areas and Index Points

Because the Comprehensive Study floodplains cover over 2.2 million acres (about 3,400 square miles), the floodplains were divided into smaller impact areas to facilitate the analysis. These were delineated based primarily upon flooding characteristics (flood origination and flow patterns) and land uses within the 0.2% (1 in 500) floodplain. Within the Sacramento River Basin, 68 impact areas were identified covering just over 1.5 million acres. In the smaller San Joaquin Basin, 42 impact areas were identified covering about 654,000 acres. The impact areas are shown in **Figures 2 and 3** and summarized in **Tables 1 and 2**.

One index point was assigned to represent each impact area. Each index point is located along the river or waterway that has the greatest influence on flooding in a particular impact area. The index points are the location where data from the hydraulic models is passed to the risk analysis in order to calculate project performance and economic damages within each impact area.

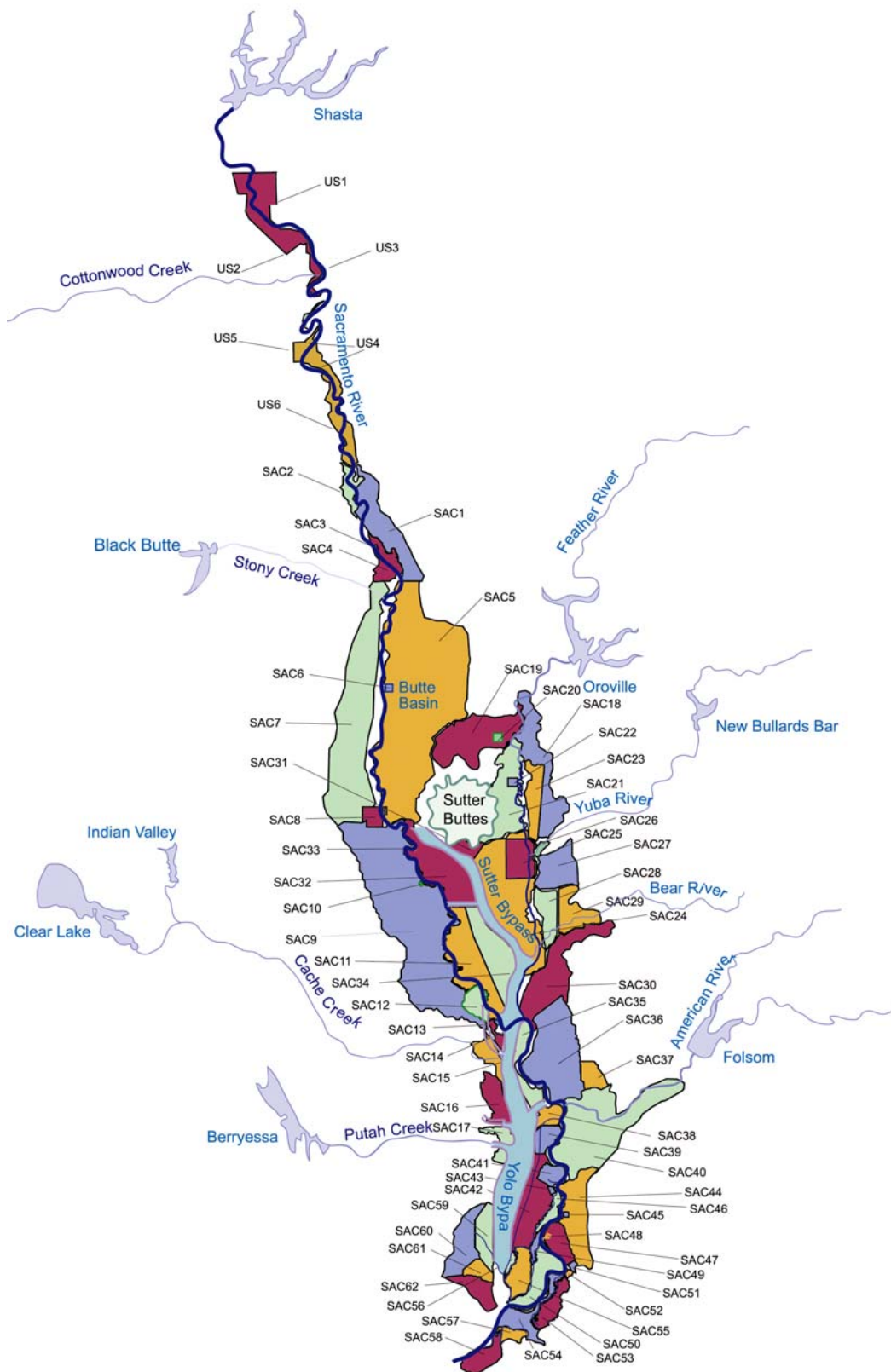


FIGURE 2 – SACRAMENTO RIVER BASIN ECONOMIC IMPACT AREAS

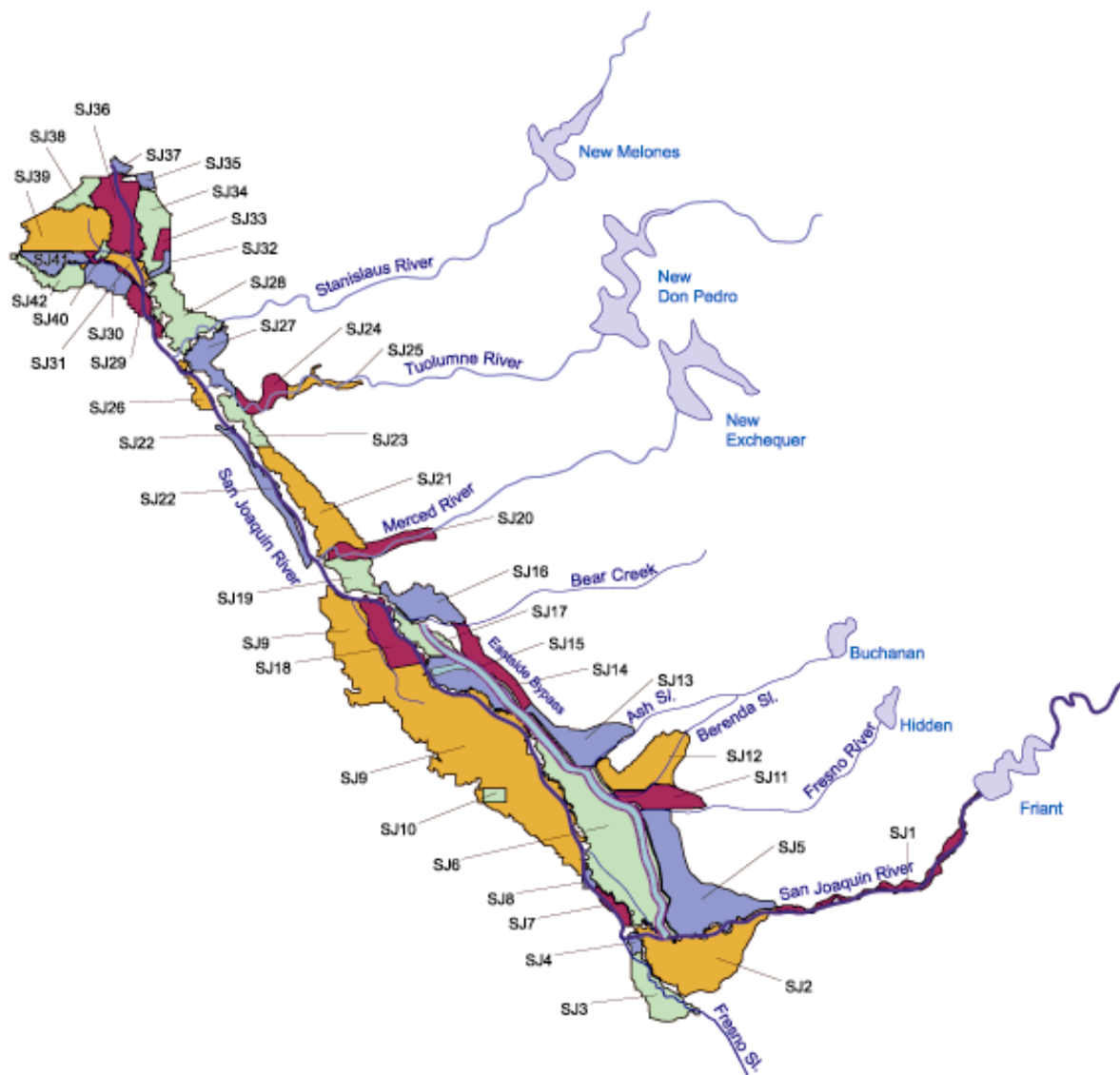


FIGURE 3 – SAN JOAQUIN RIVER BASIN ECONOMIC IMPACT AREAS

TABLE 1
SACRAMENTO RIVER BASIN IMPACT AREAS

| Impact Area No. | Impact Area Name | Area in Acres | Impact Area No. | Impact Area Name | Area in Acres | |
|-------------------------------|-------------------------|----------------------|------------------------|-------------------------|----------------------|-----------|
| Upper Sacramento Reach | | | | | | |
| US 1 | Redding | 3,358 | US 4 | Los Molinos | 28,162 | |
| US 2 | Anderson | 3,374 | US 5 | Red Bluff | 2,243 | |
| US 3 | Bend | 9,503 | US 6 | Tehama | 132 | |
| | | | | | <i>Subtotal</i> | 46,774 |
| Sacramento River Basin | | | | | | |
| 1 | Woodson Bridge East | 28,873 | 32 | Rec Dist 70-1660 | 66,658 | |
| 2 | Woodson Bridge West | 6,423 | 33 | Meridian | 235 | |
| 3 | Hamilton City | 434 | 34 | Rec Dist 1500 East | 66,351 | |
| 4 | Capay | 9,645 | 35 | Elkhorn | 13,287 | |
| 5 | Butte Basin | 182,862 | 36 | Natomas | 73,109 | |
| 6 | Butte City | 50 | 37 | Rio Linda | 10,457 | |
| 7 | Colusa Basin North | 87,530 | 38 | West Sacramento | 6,086 | |
| 8 | Colusa | 4,318 | 39 | Rec Dist 900 | 6,861 | |
| 9 | Colusa Basin South | 130,730 | 40 | Sacramento | 66,701 | |
| 10 | Grimes | 73 | 41 | Rec Dist 302 | 5,784 | |
| 11 | Rec Dist 1500 West | 65,401 | 42 | Rec Dist 999 | 29,913 | |
| 12 | Sycamore Slough | 7,905 | 43 | Clarksburg | 446 | |
| 13 | Knight's Landing | 745 | 44 | Stone Lake | 24,027 | |
| 14 | Ridge Cut (North) | 3,338 | 45 | Hood | 193 | |
| 15 | Ridge Cut (South) | 7,962 | 46 | Merritt Island | 4,475 | |
| 16 | Rec Dist 2035 | 13,069 | 47 | Rec Dist 551 | 9,136 | |
| 17 | East of Davis | 9,000 | 48 | Courtland | 346 | |
| 18 | Honcut | 29,667 | 49 | Sutter Island | 2,492 | |
| 19 | Sutter Buttes North | 38,873 | 50 | Grand Island | 16,161 | |
| 20 | Gridley | 1,120 | 51 | Locke | 692 | |
| 21 | Sutter Buttes East | 63,675 | 52 | Walnut Grove | 482 | |
| 22 | Live Oak | 2,030 | 53 | Tyler Island | 8,736 | |
| 23 | District 10 | 12,274 | 54 | Andrus Island | 14,829 | |
| 24 | Levee Dist. #1 | 148,893 | 55 | Ryer Island | 11,979 | |
| 25 | Yuba City | 24,392 | 56 | Prospect Island | 1,618 | |
| 26 | Marysville | 1,425 | 57 | Twitchell Island | 3,842 | |
| 27 | Linda-Olivehurst | 15,819 | 58 | Sherman Island | 10,226 | |
| 28 | Rec Dist 384 | 12,582 | 59 | Moore | 11,952 | |
| 29 | Best Slough | 12,265 | 60 | Cache Slough | 15,847 | |
| 30 | Rec Dist 1001 | 72,679 | 61 | Hastings | 4,591 | |
| 31 | Sutter Buttes South | 11,159 | 62 | Lindsey Slough | 7,493 | |
| | | | | | <i>Subtotal</i> | 1,500,226 |
| Total Acreage: | | | | | 1,547,000 | |

TABLE 2
SAN JOAQUIN RIVER BASIN IMPACT AREAS

| Impact Area No. | Impact Area Name | Area in Acres | Impact Area No. | Impact Area Name | Area in Acres |
|------------------------|-------------------------|----------------------|------------------------|-------------------------|----------------------|
| 1 | Fresno | 9,922 | 22 | Orestimba | 4,703 |
| 2 | Fresno Slough East | 43,928 | 23 | Tuolumne South | 7,198 |
| 3 | Fresno Slough West | 7,236 | 24 | Tuolumne River | 4,864 |
| 4 | Mendota | 1,506 | 25 | Modesto | 3,555 |
| 5 | Chowchilla Bypass | 48,982 | 26 | 3 Amigos | 3,649 |
| 6 | Lone Willow Slough | 74,608 | 27 | Stanislaus South | 9,517 |
| 7 | Mendota North | 3,050 | 28 | Stanislaus North | 17,390 |
| 8 | Firebaugh | 668 | 29 | Banta Carbona | 5,149 |
| 9 | Salt Slough | 142,265 | 30 | Paradise Cut | 7,751 |
| 10 | Dos Palos | 2,169 | 31 | Stewart Tract | 4,898 |
| 11 | Fresno River | 5,282 | 32 | East Lathrop | 1,546 |
| 12 | Berenda Slough | 33,194 | 33 | Lathrop/ Sharpe | 3,025 |
| 13 | Ash Slough | 16,784 | 34 | French Camp | 12,163 |
| 14 | Sandy Mush | 11,755 | 35 | Moss Tract | 2,059 |
| 15 | Turner Island | 15,310 | 36 | Roberts Island | 18,187 |
| 16 | Bear Creek | 16,626 | 37 | Rough and Ready Island | 1,360 |
| 17 | Deep Slough | 2,074 | 38 | Drexler Tract | 5,516 |
| 18 | West Bear Creek | 28,075 | 39 | Union Island | 23,865 |
| 19 | Fremont Ford | 8,008 | 40 | Southeast Union Island | 1,218 |
| 20 | Merced River | 7,308 | 41 | Fabian Tract | 6,556 |
| 21 | Merced River North | 23,659 | 42 | RD 1007 | 7,611 |
| Total Acreage: | | | | | 654,189 |

MODELING TOOLS

The Comprehensive Study has developed a suite of models and other technical tools that work together to evaluate ecosystem restoration and flood management conditions in the Sacramento and San Joaquin River basins. These tools include hydrologic data and models of reservoir operations, geotechnical failure models for levees, hydraulic models of river channels and floodplains, flood damage analysis models for economic and project performance evaluation, a geographic information system (GIS) for data management and evaluation, and an ecosystem function model. Detailed descriptions of these tools can be found in other appendices to the *Technical Support Document*. While no model is a perfect representation of actual conditions, the models developed for this study are of sufficient detail to provide appropriate results for a systematic flood damage analysis of the two basins. The models that are directly related to the risk analysis are described briefly below.

Hydraulic Models

The hydraulic models compute water surface elevation, delineate flooding extent, and track how flood volume changes as a flood moves through the river system. UNET and FLO-2D

hydraulic models were used to characterize baseline conditions, develop an understanding of how the overall flood management system functions, delineate flood inundation areas, and analyze the effects of various alternative scenarios and measures. The hydraulic models provide information to the flood damage analysis and ecosystem function models. A detailed description of the hydraulic models is included in *Appendix D – Hydraulic Technical Documentation*. A brief summary of the models is provided below.

UNET

This model is designed to simulate unsteady flow through a full network of open channels, weirs, bypasses and storage areas. The model's representation of channel geometry and alignment is based on topography from existing data, and bathymetric and aerial surveys performed by the Comprehensive Study between 1995 and 2000. Two models, one in the Sacramento River basin and one in the San Joaquin River basin, cover the main stem channels and their major tributaries, from their confluences upstream to either the major regulating reservoirs or where the channel becomes entrenched. The UNET models simulate the effects of weirs and overflows, bridges, and levees, including levee failure. Stage-frequency curves, the primary output related to risk analysis, are developed at index points by simulating multiple flood events in UNET and extracting peak river stages.

FLO-2D

FLO-2D was used to model overbank flows, which are comprised of flows that travel out of stream channels and across the topography of the floodplain. Out-of-bank flows are generated in UNET, either from overtopping or levee failure, and passed to the corresponding grid elements in FLO-2D to delineate the floodplain. FLO-2D has the capability of modeling both one-dimensional channel flow and two-dimensional overbank flow². In the Sacramento River system, FLO-2D was run in overbank areas only, exclusive of the channel. Channel areas in Sacramento River Basin are clearly defined; therefore, overbank flows occur less often. In the San Joaquin River Basin, channels are less well defined and have minimal capacity, making overbank flows more common. For this reason, FLO-2D was run over almost the entire San Joaquin River Basin, for both channel and overbanks. FLO-2D provides information on floodplain extent that is used to generate land use and structural inventories for the economic analysis. GIS was used in conjunction with FLO-2D to generate flood depths in the economic impact areas for the five modeled flood events.

Flood Damage Analysis Tools

HEC-FDA

HEC-FDA is the principal tool used by the Corps to calculate flood damage risks. The HEC-FDA model performs the Monte Carlo random sampling of the discharge-frequency, stage-discharge, geotechnical probability of failure, and damage-stage relationships and their

² The two-dimensional flow capability of FLO-2D allows it to track water that is moving in any of the eight compass directions (North, Northeast, East, Southeast, etc).

respective uncertainty distributions. This model is used to determine expected annual damages (EAD) and project performance statistics for proposed concepts and alternative plans, which are used in plan formulation. Project performance statistics include the annual exceedance probability (AEP), or the expected annual probability of flooding in any given year; the long-term risk of flooding over a 10-, 25-, or 50-year period; and the conditional non-exceedance (CNE) probability for specific events (the probability of passing specific flood events). Although HEC-FDA was designed to estimate urban flood damage, it was adapted to include agricultural analyses for the Comprehensive Study.

@RISK

Stage-damage curves were generated outside the HEC-FDA program using @RISK. Because flood flows can originate from outside an impact area (overland flow from an upstream levee break, for example), it was desirable to link flood damage to flood depths at parcels regardless of the source of flooding. A good example of this is in the Colusa Basin along the western portion of the Sacramento Valley. Floodwater can breakout along the right bank of the Sacramento River along the northern portion of the SAC 7 impact area, then flow south for 40 or 50 miles. As it flows south, it can influence flooding in the SAC 8 and SAC 9 impact areas. Thus, flood damage in SAC 8 and SAC 9 cannot be reliably linked to river stages within or adjacent to those impact areas, as HEC-FDA would do. @RISK was used to develop the stage-damage curves using parcel and depth information developed in GIS, and the completed curves were input into HEC-FDA. The @RISK model incorporated key economic uncertainty factors, including structural value, content value, foundation height number of stories, and depth-damage relationships that are described in more detail in *Appendix F – Economics Technical Documentation*.

Upper Sacramento Spreadsheet Analysis

A different methodology was used to estimate flood damages for the Upper Sacramento Reach. Hydraulic modeling in this reach was performed using HEC-RAS rather than UNET; thus, the stage-frequency curves required by HEC-FDA were not developed. In addition, only three flood events were modeled (events with a 2%, 1%, and 0.5% chance of occurring in any given year), rather than the eight events modeled in the remainder of the Sacramento River Basin. Estimated expected annual damage was based upon flood depths for these three events at the individual parcels, and the computations were performed using spreadsheets rather than within HEC-FDA. Consequently, project performance statistics were not developed for this reach. This approach was satisfactory for the purpose of preliminary basin-wide flood damage calculations, but future studies should employ more detailed hydraulic modeling and risk analysis techniques.

GIS

Although not an economics program, the use of geographic information system (GIS) software allowed efficient identification of thousands of structures within the floodplains where digitized parcel maps were available. Where possible, corresponding data required for flood damage analysis (frequencies and depths of events at specific parcels, improvement values, etc.) were also developed using GIS.

Ecosystem Function Model

The Ecosystem Function Model (EFM) was developed by the Comprehensive Study to predict changes in the quality and extent of riparian and aquatic habitats resulting from changes to the flood management system. These indicators include changes in the extent of suitable riparian and seasonally inundated aquatic habitats, key river channel conditions, and rates of ecosystem processes that may not be manifested for years to come. Currently, the EFM does not provide for risk analysis. For more information on the EFM, refer to *Appendix F – Ecosystem Functions Model*.

TECHNICAL CONSIDERATIONS AND ASSUMPTIONS

The results of the risk analysis are affected by technical considerations and assumptions regarding the input to HEC-FDA. For example, the geotechnical studies developed relationships that characterized the reliability of the levees, which were utilized to trigger levee failures in the hydraulic models, which ultimately affected the stage-frequency curves used in the risk analysis. The following section discusses the key technical evaluations and approaches that affected the risk analysis.

Hydrologic Studies

The development of the without-project hydrology involved updating natural flow-frequency relationships in the river basins, historical storm analysis, modeling storm centerings in the basins to reflect the combination of several flood events that can shape a floodplain, and development of flood hydrographs for seven flood frequencies (10%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year) for input into the reservoir simulation and hydraulic models. A hypothetical storm centering method was developed to position an n-year flood event at a particular location in the river system. Uncertainty factors that may affect the hydrology are gage record lengths that may be short or not exist where needed, precipitation-runoff computation methods are inaccurate, and the effectiveness of flood flow regulation measures is not precisely known. Period of record is one of the inputs to HEC-FDA that accounts for uncertainty. A detailed description of the development of the synthetic hydrology, flood centerings, and reservoir operation models is included in *Appendix B – Synthetic Hydrology Documentation* and *Appendix C – Reservoir Operations Modeling*.

Geotechnical Evaluation

The potential for flooding along the Sacramento and San Joaquin Rivers and their main tributaries is highly dependent on the earthen structures, or levees, that protect much of the Central Valley. High levees essentially function as long dams, but they lack the inherent safety features that well-constructed dams possess, such as spillways, outlets, and internal drains. Levees may fail for geotechnical reasons before they are overtopped by flood flows. Floodwaters need only encounter one weak point in a particular reach to potentially cause a breach that could result in the loss of life or property.

There are various factors that can contribute to the geotechnical failure of levees. Floodwater velocities can be highly erosive as they move along levees, which are typically unprotected from scour. The interior soils and construction of levees can vary significantly and older

levees may not conform to modern design standards. High hydraulic gradients during floods can force seepage through levee foundation materials with high hydraulic conductivity (permeability), such as loose sand. Increased water flow through these materials can migrate, or erode, material from the levee or foundation, creating unstable conditions that can quickly lead to total or significant structural failure. These failure modes are exacerbated by extended periods of high flood flows.

Most of the levees of concern in the Sacramento and San Joaquin river systems are neither owned nor maintained by the Corps or other Federal agencies. The one exception is the right bank levee of the Sacramento Deep Water Ship Channel, which is maintained under a memorandum of understanding between the COE and the California State Department of Water Resources (DWR). All others are either privately owned and maintained or owned by the State, which typically delegates maintenance responsibilities to local levee and reclamation districts.

Risk analysis incorporates the chance of levee failure, typically expressed through a geotechnical reliability model, often expressed as a probability of failure curve. This model leads to a relationship between water elevation (stage) and the probability that the levee will fail, which is then applied to individual reaches of levees. This procedure assumes that damages can accrue in one of two ways: either the river stage becomes high enough to overtop the levee, or the stage rises high enough to cause geotechnical failure of the levee. The development of probability of failure curves is discussed in Attachment E.1 to this appendix, and summarized below.

Technical Approach

Levees can fail for many reasons and it is difficult to predict exactly where they will fail. Past flood events in the Central Valley have shown that levees often fail in the most unpredictable areas or at stages well below the design water surface. In other cases, stage has exceeded the design water surface without breaching or without significant damages. The geotechnical performance of a levee depends on local soil conditions and construction materials and methods. These conditions are generally not known in detail during the initial start of a planning study. The geotechnical reliability model is generally a good first step in fulfilling the practical needs of planning studies and risk analyses when detailed geotechnical information is not yet known.

The Corps traditional geotechnical reliability model defines a simple relationship between two stages on the levee: the probable failure point (PFP) and the probable non-failure point (PNP) (USACE, 1991b). By definition, the probable failure point is the stage or height associated with a high probability of levee failure, an 85 percent chance. Likewise, the probable non-failure point is the stage height associated with a low probability of levee failure, a 15 percent chance. These points are typically assessed for local conditions and change from reach to reach. However, in some instances these reaches can be many miles in length.

This simple model is still widely used by the Corps. However, the model was updated to reflect a broader understanding of geotechnical performance (USACE, 1999b). The updated model considers the risk of multiple modes of failures including underseepage, through-seepage, and strength instability. The results of a series of iterations comparing stage-

frequency functions with levee performance (derived from either PNP/PFP relationships or a composite probability of geotechnical levee reliability) are combined to form a risk-frequency curve. This curve shows the risk of levee failure as a function of stage.

Levee Evaluation

To assess the differences between an existing levee and a levee with proposed improvements, the engineering assessment of levee reliability must be quantified in a probabilistic form. However, geotechnical engineers are typically more knowledgeable of *deterministic* methods than *probabilistic* methods³. In addition, they are generally more experienced designing a structure within an appropriate factor of safety, rather than making numerical assessments of the condition of existing structures. For this study, the following key points provide a methodology for defining levee performance in probabilistic terms:

- Where possible, review the primary modes of failure, such as seepage or overtopping.
- Develop reliability curves for levees or geotechnical probability of failure functions that are simple and sufficient for use where data is limited, but reflect a geotechnical understanding of the underlying mechanics and uncertainty in the governing parameters
- Test and illustrate these procedures through comparison with existing or on-going study analyses.

Assumptions

Combined Probability Functions - Once a conditional probability of failure function has been obtained for each considered failure mode, they are combined to determine the total geotechnical conditional probability of failure of all modes as a function of floodwater elevation. As a first approximation, it may be assumed that each of the failure modes is independent: underseepage, slope stability, through-seepage and internal erosion. However, conditions that increase the probability of failure for one mode are likely to increase the probability of failure for another. Detailed research to better quantify such possible correlation is beyond the scope of the Comprehensive Study. Assuming independence simplifies the mathematics for geotechnical and economic analysis. For underseepage, the probability of levee failure at a specific water surface elevation is correlated to the probability of developing an upward gradient sufficient to cause heaving or boiling. For slope stability, the probability of failure is taken as the probability that the factor of safety is less than unity. For through-seepage and internal erosion, the probability of failure is based on past performance function.

Flood Duration - The probability of levee failure increases with the duration of flooding, as extended periods of high water increase pore pressures within the levee embankment and the likelihood of damaging erosion. For simplicity, the analysis methodology assumes that the

³ A deterministic analysis utilizes design equations with safety factors that have been calibrated (typically through past experience or experiment) to provide a target level of safety. The probabilistic approach to design also uses the basic deterministic equations but in a more-comprehensive analysis in which uncertainty is quantified by probability distributions. The probabilistic approach measures the variation of risks of failure with variations in design parameters and properties of materials, making it possible to determine the robustness or reliability of a design

flood has been of sufficient duration that steady-state seepage conditions have developed in pervious substratum materials and pervious embankment materials, but no pore pressure adjustment has occurred in impervious clayey foundation and embankment materials.

Judgmental Evaluation - Levees under evaluation are typically inspected in the field. During such inspections, it is likely that the inspection team will encounter other conditions or features in addition to the aforementioned failure modes that may compromise the reliability of the levee during a flood event. These might include animal burrows, cracks, roots, or poor maintenance practices that can impede detection of defects or execution of flood-fighting activities. To provide a mathematical means to quantify such information, one may develop a judgment-based conditional probability function by answering the following question:

Discounting the likelihood of failure accounted for in the quantitative analyses, but considering observed conditions, what would an experienced levee engineer consider the probability of failure of this levee for a range of water elevations?

While this may appear to be conjecture, leaving out such information may fail to account for the obvious.

Levee Reliability Evaluation

For the Comprehensive Study, the locations and likelihood of initial levee failure were based on an analysis of weak points in the levee system as determined by a reconnaissance-level geotechnical assessment of levee stability. To locate these weak points, the PNP and the PFP were defined for levees within each impact area. The PNP and PFP were based on the results of field investigations, past levee stability calculations, engineering judgment, and levee performance during the 1997 and 1998 flood events. To more clearly define the geotechnical conditional probability of failure curve for the 2,000 miles of levees evaluated in this study, additional probability of failure points were defined for the 3-, 50- and 100- percent probabilities of failure.

For levees within the San Joaquin River basin, very little geotechnical information was available. Consequently, the State of California Department of Water Resources conducted an in-depth reconnaissance field inspection. The field survey delineated historic problem areas and potential problem areas through discussions with levee maintenance personnel, on-site evaluations, cross sectional data, remnants of sand bag rings constructed during floods to control boils and seepage, and engineering judgment. From this knowledge, conditional probabilities of failure curves were generated. Three levee curves characterize the reliability of the levees in the San Joaquin River basin; these curves typically depict the levees as behaving similar to sand levees.

For levees within the Sacramento River basin, geotechnical information was gathered from various system evaluation reports:

- Initial system evaluation reports submitted by the Mark Group in 1988 and 1989
- Flood Control System Evaluation reports of 1992, 1993, and 1994; and
- Supplemental evaluation reports from 1996, 2000, and 2001.

On-going flood management projects in construction, nearing construction, or recently completed were also referenced. Engineering judgment, based primarily on past-experience during the 1997 and 1998 flood events, contributed significantly to the development of the

levee curves. Since levees in the Sacramento River basin are constructed of a variety of levee material ranging in composition from loose sand to engineered pervious and impervious materials, geotechnical probability of failure curves were created to reflect a variety of levee materials. Three geotechnical probability of failure curves were generated representing strongly constructed levees, generally of clay or sandy clay, and four probability of failure curves were generated for poorer quality constructed levees and some non-project or privately maintained levees.

The probability of failure curves, illustrated in **Figures 4 and 5**, reflect both known and unknown inherent levee deficiencies in the San Joaquin and Sacramento River basins. The curves used in each basin reflect a range of levee performance conditions, from good (represented by curves indicating failure near the top of the levee) to poor (represented by curves indicating failure near the bottom of the levee). Development of the curves is further discussed in Attachment E1 to this appendix.

The geotechnical conditional probabilities of failure curves are based primarily on engineering judgment. These curves represent the results of a qualitative approach to evaluating the major aspects of levee integrity for very large flood control systems. A single conditional probability of failure curve was assigned to an entire reach of levee based on the weakest point in that reach. **Tables 3 and 4** summarize the geotechnical probability of failure curves applied to each reach of the Sacramento River and San Joaquin River basins.

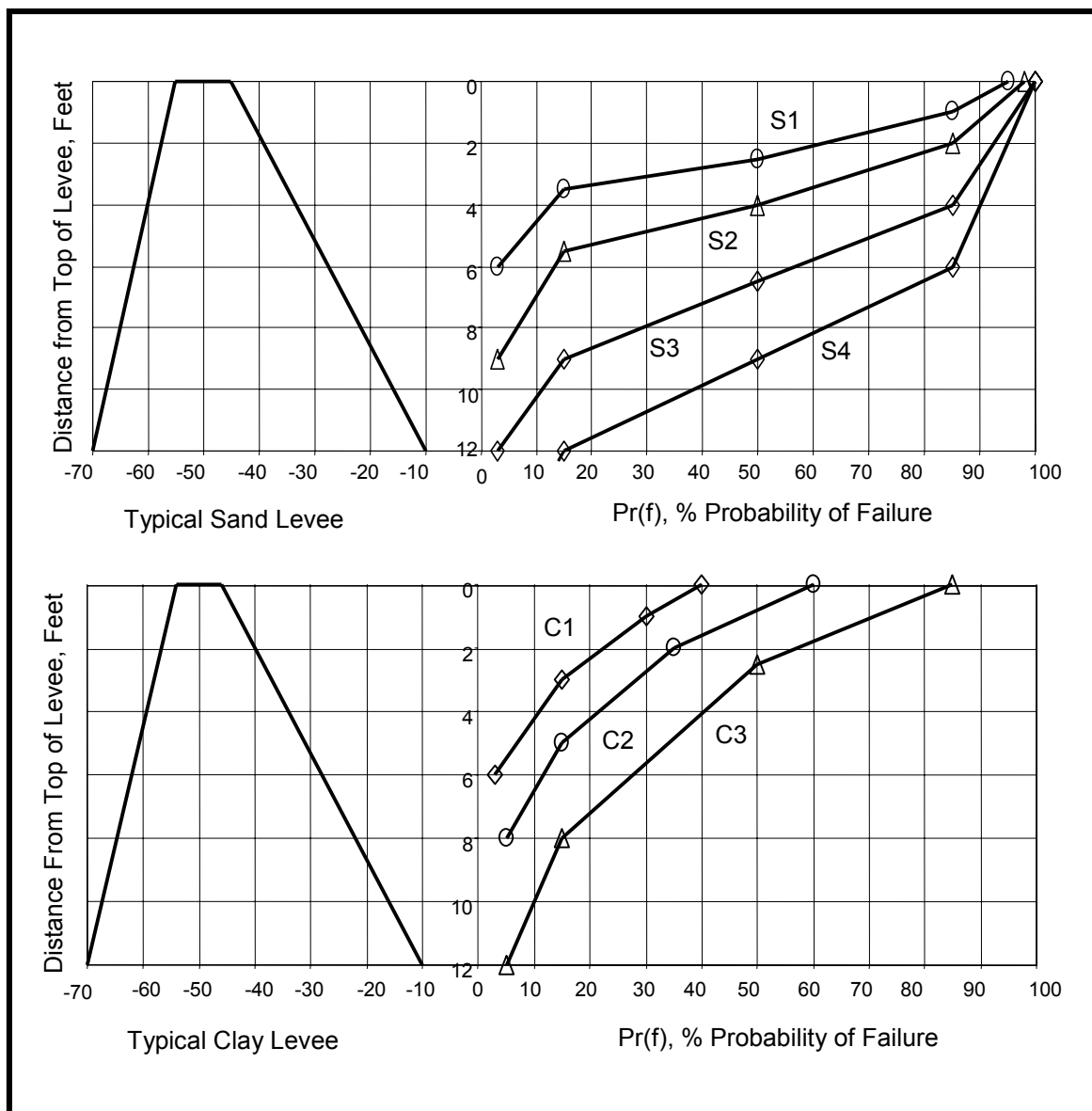


FIGURE 4 - CONDITIONAL GEOTECHNICAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SACRAMENTO RIVER BASIN PROJECT LEVEES

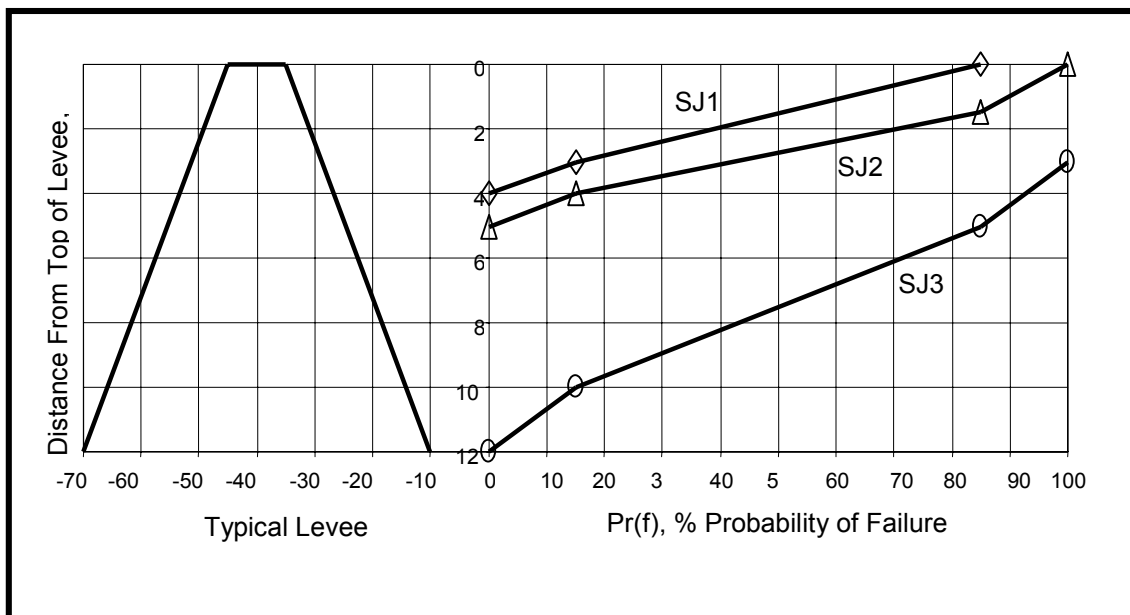


FIGURE 5 - CONDITIONAL GEOTECHNICAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SAN JOAQUIN RIVER BASIN PROJECT LEVEES

Once each reach was assigned a levee performance curve, this information was passed to the hydraulic models. For simplicity, the hydraulic analyses incorporated the probability of levee failure through the selection of a single, likely failure stage. The elevation corresponding to a 50 percent probability of failure according to the performance curves, termed the likely failure point (LFP), was used to trigger levee failures in the hydraulic models.

TABLE 3
ASSIGNMENT BY REACH OF SACRAMENTO RIVER BASIN
CONDITIONAL PROBABILITY OF FAILURE CURVES

| Reach No. | Reach Description | River Miles | Design Capacity ^a (cfs) | Selected P(f) ^b Model | |
|--------------------|-------------------------------------|------------------|------------------------------------|----------------------------------|-----------------|
| | | | | LB ^c | RB ^c |
| 1 | Shasta Dam to Red Bluff | 315 -245 | No Levees | | |
| 2 | Red Bluff to Chico Landing | 245 - 194 | | | |
| | <i>Sacramento River</i> | | | | |
| | Red Bluff to Elder Creek | 245 - 230.5 | N/A | No levees | |
| | Elder Creek to Deer Creek | 230.5 - 220 | N/A | No levees | |
| | Deer Creek to Chico Landing | 220 - 194 | N/A | No levees | |
| | <i>Tributaries</i> | | | | |
| | Elder Creek | | N/A | C2 | C2 |
| Deer Creek | | N/A | C2 | C2 | |
| 3 | Chico Landing to Colusa | 194 - 146 | | | |
| | <i>Sacramento River</i> | | | | |
| | Chico Landing to head of east levee | 194 - 176 | N/A | No levee | S3 |
| | East Levee head to Moulton Weir | 176 - 158.5 | 150,000 | S2 | S2 |
| | Moulton Weir to Colusa Weir | 158.5 - 146 | 110,000 | S2 | S2 |
| | <i>Tributaries</i> | | | | |
| | Mud Creek | | N/A | C1 | C1 |
| | Butte Creek | | 3,000 | C1 | C1 |
| Cherokee Canal | | 12,500 | S3 | S3 | |
| 4 | Colusa to Verona | 146 - 80 | | | |
| | <i>Sacramento River</i> | | | | |
| | Colusa Weir to Butte Slough | 146 - 138 | 65,000 | S3 | S4 |
| | Butte Slough to Tisdale Weir | 138 - 119 | 66,000 | S3 | S4 |
| | Tisdale Weir to Knights Landing | 119 - 90 | 30,000 | S3 | S3 |
| | Knights Landing to Verona | 90 - 80 | 30,000 | S2 | S3 |
| | <i>Tributaries</i> | | | | |
| | Colusa Basin Drainage Canal | | 20,000 | | |
| | <i>Tisdale Bypass</i> | | 38,000 | S3 | S3 |
| | <i>Sutter Bypass</i> | | | | |
| | Butte Slough to Wadsworth Canal | | 150,000 | C3 | C3 |
| | Wadsworth Canal to Tisdale Bypass | | 155,000 | C2 | C2 |
| | Tisdale Bypass to Feather River | | 180,000 | C2 | C2 |
| | Feather River to Verona | | 380,000 | S3 | C2 |
| | <i>Feather River</i> | | | | |
| | Oroville to Mouth of Yuba River | | 210,000 | S2 | S2 |
| | Mouth of Yuba River to Bear River | | 300,000 | S2 | S2 |
| | Bear River to Yolo Bypass | | 320,000 | S3 | S2 |
| <i>Tributaries</i> | | | | | |
| Yuba River | 0-5 | 120,000 | S2 | S3 | |
| Bear River | 0-3 | 40,000 | S2 | S2 | |

TABLE 3 (CONT.)

| Reach No. | Measure Reach Description | River Miles | Design Capacity, Q ^a | Selected P(f) ^b Model | |
|------------------|---|------------------|---------------------------------|----------------------------------|-----------------|
| | | | | LB ^a | RB ^a |
| 5 | Verona To Steamboat Slough | 80 - 32.3 | | | |
| | <i>Sacramento River</i> | | | | |
| | Verona to Sacramento Weir | 80 - 63 | 107,000 | S2 | S4 |
| | Sacramento Weir to American River | 63 - 60 | 107,000 - 108,000 | S2 | S2 |
| | American River to Elk Slough | 60 - 42 | 107,000 - 110,000 | S2 | S2 |
| | Elk Slough to Sutter Slough | 42 - 34 | 110,000 | S3 | S3 |
| | Head of Sutter Sl. to Steamboat Sl. | 34 - 32.3 | 84,500 | S3 | S3 |
| | <i>Tributaries</i> | | | | |
| | Natomas Cross Canal | 0 - 5 | 22,000 | C2 | C3 |
| | American River | | 115,000 | S3 | S2 |
| | <i>Yolo Bypass</i> | | | | |
| | Verona to Knight's Landing Ridge Cut | | 343,000 | S4 | S3 |
| | Knight's Landing Ridge Cut to Cache Ck | | 362,000 | S3 | S3 |
| | Cache Creek to Sacramento Weir | | 377,000 | C3 | C3 |
| | Sacramento Weir to Putah Creek | | 480,000 | C3 | C3 |
| | Putah Creek to Miner Slough | | 490,000 | C3 | C3 |
| | Miner Slough to Cache Slough | | 579,000 | C3 | C3 |
| | Cache Creek to Mouth Old River | | N/A | C3 | C3 |
| | <i>Tributaries</i> | | | | |
| | Knight's Landing Ridge Cut | 0 - 6 | 20,000 | S3 | S3 |
| | Cache Creek | | N/A | S-3 | S-3 |
| | Willow Slough | 0 - 7 | 6,000 | C3 | C3 |
| | Putah Creek | 2 - 7 | 62,000 | C3 | C3 |
| Miner Slough | 0 - 2 | 10,000 | S4 | S4 | |
| Cache Slough | 0 - 5 | N/A | S4 | S4 | |
| 6 | Steamboat Slough To Collinsville | 32.3 - 0 | | | |
| | <i>Sacramento River</i> | | | | |
| | Steamboat Sl. to head of Georgiana Sl. | 26.5 - 32.3 | 56,500 | S3 | S3 |
| | Georgiana Sl. to Cache Sl. - Junction Pt | 14 - 26.5 | 35,900 | S3 | S3 |
| | Cache Sl. to 3-mile Sl. | 9 - 14 | N/A | S4 | N/A |
| | 3-Mile Slough to Collinsville | 0 - 9 | N/A | S4 | N/A |
| | <i>Tributaries</i> | | | | |
| | Elk Slough | 0 - 9 | 25,500 | S3 | S3 |
| | 3-Mile Slough | 0 - 3 | 65,000 | S4 | S4 |
| | Steamboat Slough | 0 - 6.5 | 43,500 | S2 | S3 |
| | Sutter Slough - Steamboat to Miner | 0 - 2.5 | 15,500 | S3 | S3 |
| | Sutter Slough - Miner to Sacramento River | 2.5 - 7 | 25,500 | S4 | S3 |
| Georgiana Slough | 0 - 10 | 20,600 | S4 | S4 | |

Notes

- a) Estimated design flow capacity per DWR (May 1985)
- b) P(f) = Conditional Probability of Failure
- c) LB = Left Bank, RB = Right Bank

TABLE 4
ASSIGNMENT BY REACH OF SAN JOAQUIN RIVER BASIN
CONDITIONAL PROBABILITY OF FAILURE CURVES

| Reach No. | Reach Description | River Miles | Design Capacity ^a (cfs) | Selected P(f) ^b Model |
|--|--|-------------------|------------------------------------|----------------------------------|
| A | Mendota Dam to Friant Dam | 205 To 286 | | |
| | <i>San Joaquin River</i> | | 2,500 – 8,000 | SJ1 |
| | <i>Fresno Slough & James Bypass</i> | | 4,750 | SJ1 |
| B | Sand Slough Control Structure to Mendota Dam | 168 to 205 | | |
| | <i>San Joaquin River</i> | | 4,500 | SJ2 |
| | <i>Chowchilla Bypass / Eastside Bypass</i> | | 5,500 – 17,000 | SJ2 |
| | <i>Tributaries</i> | | | |
| | Fresno River – San Joaquin to Road 18 | | 5,000 | SJ2 |
| | Berenda Slough - San Joaquin to Route 152 | | 2,000 | SJ2 |
| | Ash Slough - San Joaquin to Route 152 | | 5,000 | SJ2 |
| C | Merced River to Sand Slough Control Structure | 118 to 168 | | |
| | <i>San Joaquin River</i> | | | |
| | Merced River to Eastside Bypass | | 26,000 | SJ2 |
| | Eastside Bypass to Control Structure | | 1,500-10,000 | SJ2 |
| | <i>Eastside Bypass</i> | | 13,500 – 16,500 | SJ2 |
| | <i>Deep Slough</i> | | 18,500 | SJ2 |
| | <i>Bear Creek</i> | | 7,000 | SJ2 |
| <i>Mariposa Bypass</i> | | 8,500 | SJ2 | |
| D | Stanislaus River to Merced River | 75 to 118 | | |
| | <i>San Joaquin River</i> | | 45,000 – 46,000 | SJ3 |
| | <i>Merced River</i> | | 6,000 | SJ2 |
| | <i>Tuolumne River</i> | | 15,000 | SJ3 |
| | Dry Creek | | N/A | SJ3 |
| | <i>Stanislaus River</i> | | 8,000 | SJ3 |
| E | Deep Ship Channel to Stanislaus River | 40 to 75 | | |
| | <i>San Joaquin River</i> | | 37,000 – 52,000 | SJ3 |
| | <i>Tributaries</i> | | | |
| | Paradise Cut – Old River to San Joaquin River | | 15,000 | SJ3 |
| | Old River - Tracy Boulevard to San Joaquin River | | - | SJ3 |
| | Grant Line Canal - Tracy Blvd to Doughty Cut | | - | SJ3 |
| | Doughty Cut - Grant Line Canal to Old River | | - | SJ3 |
| Middle River - Victoria Canal to Old River | | - | SJ3 | |

Notes:

a) Estimated design flow capacity per DWR (May 1985)

b) P(f) = Conditional Probability of Failure (applies to both left and right bank levees) .

Key Findings and Considerations

It should be noted that the geotechnical probability of failure curves should only be used for comparative economic and project performance analyses of the flood control systems. They do not necessarily represent actual deterministic conditional probability of failure functions, which are only achieved through extensive evaluations of site-specific conditions, past performance, and analytical modeling in accordance with acceptable engineering manuals and regulations. Wherever possible, geotechnical information from more detailed studies was used in estimating levee performance. For example, the probability of levee failure curves for the American River were derived from the Corps' American River Study and approximate the levee performance resulting from that study. Other examples where existing information greatly influenced the probability of failure curves that were used in this study include the Corps' Marysville / Yuba City study and on-going levee reconstruction work either in-progress or authorized for construction.

The frequency of flood events and other physical stressors can also affect levee integrity. Physical conditions will naturally change over time and may lead to unsatisfactory performance. Hence, the geotechnical probability of failure function for any of the levees within the study area is time-dependent and subject to change.

Use of the LFP to trigger levee failures does not account for flood fighting and other emergency work that occurs during actual flood events. Flood fighting efforts can, and have, significantly reduced flood damages in some areas. However, these efforts often induce higher stages and pass higher flows to downstream reaches, resulting in subsequent levee failures. This is especially true for more frequent flood events. Very large flood events, on the other hand, generate flows that overwhelm the flood system to such an extent that flood fighting becomes ineffective. Alternative formulation generally does not assume flood fighting as part of a plan because there is no guarantee that it would occur at the right locations or be effective in contributing to the success of a Federal flood management project. In summary, for plan formulation purposes, it is important to recognize that flood fighting occurs and can be effective; however, it is not considered in the Comprehensive Study geotechnical evaluation and, therefore, should not be included in comparison of existing and with-project damages and resulting benefits. Furthermore, geotechnical conditions are not static, and the geotechnical data used in developing projects should be re-evaluated and updated whenever information becomes available. It is anticipated that the geotechnical levee performance curves and their application in the basins will change as additional technical evaluations are performed.

Hydraulic Studies

As described previously, two hydraulic models were used jointly to simulate the hydraulics of the river basins. UNET was used to simulate in-channel flows, flows leaving the river channels through failure points in the levees or overtopping, and routing of the flows through the overbanks. FLO-2D was used to simulate overbank and floodplain flows in order to delineate floodplains for various frequency events.

Flood discharge hydrographs for a range of possible storm centerings, with 10%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year, were explicitly modeled. Flows with less than a 10% chance of occurring in any year were not modeled because they typically remain

in the banks and do not cause serious economic damage on a system-wide basis. UNET was used to develop flow-frequency and stage-frequency relationships within the damage reaches at breakout points in the river channel, but not in the floodplain.

River System Modeling

A series of hydrographs representing a range of frequencies and a suite of storm centerings were used as input to the UNET model. As described previously, the LFP profile was developed for levees in the Sacramento and San Joaquin River Basins on a reach-by-reach basis. Levee failure was simulated in UNET when the water surface elevation reached the LFP for a given levee. Levee failure is simulated by UNET as a levee breach. This failure method was adopted for UNET because levees tend to fail before they overtop, and flood-fight efforts and intentional breaching often prevent catastrophic failures of long sections of levee. Flow through a levee breach is then routed into floodplain storage areas by UNET.

Within any given impact area, there could be multiple failure points or breakout points. The number and location of breakout points can vary depending upon the frequency of the flood and the storm runoff centering. As would be expected, the more frequent events generally had fewer breakout points. Stage-frequency and discharge-frequency relationships, including error distributions, are developed at the 104 index points based on UNET output. Rating tables relating frequency, discharge, and stage at the index points are included in *Appendix D – Hydraulic Technical Documentation*.

Composite Flood Plain – Composite floodplains were developed for floods with a 10%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year in the Sacramento and San Joaquin River Basins. The composite floodplains developed for the purpose of this study are not traditional design-event floodplains, but represent combined floodplains from the regional storm runoff centerings developed by the Comprehensive Study. FLO-2D was used to delineate flood flows into overbank and floodplain areas for the purpose of delineating floodplains for each of the 5 flood frequencies. Stage-damage relationships in the floodplain were linked to stage-frequency relationships in the channel through frequency.

In many reaches, simulated stages were substantially below the LFP, especially in downstream reaches. This was due to the progressive loss of floodwater through multiple breaches, a result of the LFP failure methodology. After failure, the water surface elevation remains relatively constant for all higher flood frequencies because flows are escaping into the floodplain through the levee break, causing the stage-frequency curves to tail over or flatten at the LFP elevation. Monte Carlo sampling in HEC-FDA requires a stage-frequency curve that covers a full range of potential flood frequencies. Consequently, two sets of simulations were required to construct the stage-frequency curves in reaches with levees: one that assumes levee failures occur and one that assumes all flow is contained within the channel (termed infinite channel). The portion of the curve below the LFP is developed using the LFP-failure simulations and the upper portion of the curve above the frequency of levee failure is formed using the infinite channel simulation. HEC-FDA samples the resulting hybrid stage-frequency curve, shown in **Figure 6**, in reaches that have levees.

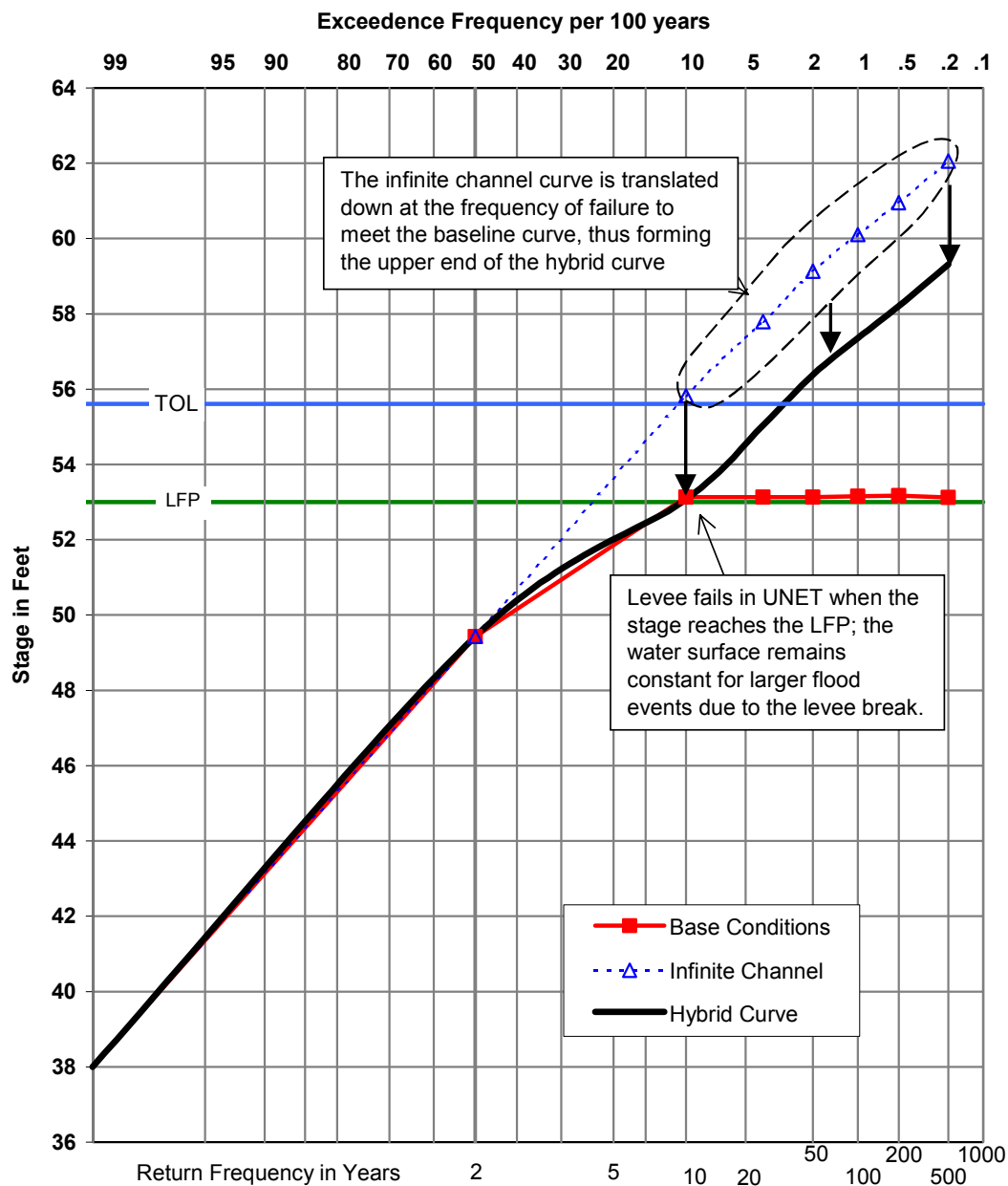


FIGURE 6 – DEVELOPMENT OF HYBRID STAGE-FREQUENCY CURVE

Key Findings and Considerations

The levee failure methodology can significantly influence simulated flood flows. The methodology was chosen to provide a conservative simulation of potential flooding extent for system-wide hydraulic and economic evaluations. It does not represent conditions that would occur during an actual flood event, when flood fighting and other emergency actions are likely to take place and fewer failures are likely to occur. While the LFP represents a 50% probability of geotechnical failure, a levee failure is triggered in UNET every time the simulated water surface reaches the LFP (failure is triggered in UNET 100% of the time the

LFP is reached). In some cases, the cumulative effect of multiple upstream failures can reduce the volume of flow in downstream reaches, or large breaches can produce pronounced reductions in stage. These effects are less pronounced in the San Joaquin basin where flood volumes are relatively smaller, levees tend to be shorter, and overbank flooding occurs more frequently than in the Sacramento River basin. While this levee failure methodology is appropriate for the basin-wide risk analyses performed by the Comprehensive Study, it should be considered when interpreting UNET results and may not be suitable for other applications or detailed studies.

PROJECT PERFORMANCE

The three primary project performance or flood risk results reported by HEC-FDA are annual exceedence probability, long-term risk, and conditional non-exceedence probability.

Annual Exceedence Probability (AEP)

Annual exceedence probability is a measure of the likelihood that an area will be flooded in any given year, considering the full range of floods that can occur and all sources of uncertainty. AEP is typically expressed as a fractional or percentage probability. For example, the 0.01 exceedence probability flood has one chance in a hundred or a 1% chance of occurring in a given year. The 1% exceedence flood event is often termed the 100-year event (by taking the inverse of 0.01), but it does not statistically represent an event that will occur once in 100 years. Over a very long period of time (many thousands of years) the 1% exceedence event would occur, on average, about once every 100 years; however, over that extended period it could occur several times during a given century, or not at all.

Long Term Risk (LTR)

Long-term risk is the probability of damages occurring during a specified period of time. LTR is reported by HEC-FDA for 10-year, 25-year, and 50-year time periods. For example, a value of 0.850 for the 25-year reporting period reflects an 85% chance of flooding during a 25-year period.

Conditional Non-Exceedence Probability by Events (CNE)

Conditional non-exceedence is the probability of safely containing an event with a known frequency, should that event occur. CNE is reported by HEC-FDA for the 10%, 4%, 2%, 1%, 0.5%, and 0.2% exceedence floods. For example, a value of 0.04 for the 2% event corresponds to a four percent chance of passing the 2% exceedence flood.

Although these measures of performance and risk seem similar, there are distinct differences between them. AEP accumulates all the uncertainties into a single probability, whereas CNE is conditional on the severity of the flood event. Further, while AEP describes the likelihood that flooding *will occur*, CNE describes the likelihood that flooding *will not occur* during a given year (NRC 2000). Other agencies also use these measures of risk in flood management. For example, FEMA uses conditional non-exceedence in its certification criteria for levees, requiring a 90% or higher probability of containing the 1% event.

Existing Condition

Preliminary project performance statistics have been developed in the Sacramento and San Joaquin River basins for the existing condition. The results are summarized by impact area in **Tables 5 and 6**. The annual exceedence probability was generally lower (indicating a lower risk of flooding) in the Sacramento River Basin than in the San Joaquin River Basin. This can be attributed primarily to the higher level of flood protection that the Sacramento River Flood Control Project was designed to provide. The San Joaquin River Flood Control Project was generally designed to convey smaller, late-season snowmelt floods.

TABLE 5
EXISTING CONDITION PROJECT PERFORMANCE STATISTICS FOR THE
SACRAMENTO RIVER BASIN

| Impact Area | Impact Area Name | Annual Exceedence Probability (Expected) | Long Term Risk | | | Conditional Non-Exceedence Probability by Flood Event | | | | | |
|-------------|---------------------|--|----------------|----------|----------|---|--------|--------|--------|--------|--------|
| | | | 10 Years | 25 Years | 50 Years | 10% | 4% | 2% | 1% | 0.4% | 0.2% |
| SAC01 | Woodson Br East | 0.1400 | 0.7778 | 0.9767 | 0.9995 | 0.2356 | 0.0075 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC02 | Woodson Br West | 0.1870 | 0.8734 | 0.9943 | 1.0000 | 0.0659 | 0.0010 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC03 | Hamilton City | 0.4860 | 0.9987 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC04 | Capay | 0.4860 | 0.9987 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC05 | Butte Basin | 0.1550 | 0.8141 | 0.9851 | 0.9998 | 0.0403 | 0.0018 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC06 | Butte City | 0.1540 | 0.8129 | 0.9849 | 0.9998 | 0.0406 | 0.0014 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC07 | Colusa Basin North | 0.4380 | 0.9969 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC08 | Colusa | 0.3690 | 0.9901 | 1.0000 | 1.0000 | 0.4862 | 0.4038 | 0.3225 | 0.2288 | 0.0031 | 0.0000 |
| SAC09 | Colusa Basin South | 0.5190 | 0.9993 | 1.0000 | 1.0000 | 0.3382 | 0.1163 | 0.0027 | 0.0000 | 0.0000 | 0.0000 |
| SAC10 | Grimes | 0.5180 | 0.9993 | 1.0000 | 1.0000 | 0.3390 | 0.1176 | 0.0029 | 0.0000 | 0.0000 | 0.0000 |
| SAC11 | Rec Dist 1500 West | 0.2540 | 0.9467 | 0.9993 | 1.0000 | 0.5042 | 0.0648 | 0.0100 | 0.0000 | 0.0000 | 0.0000 |
| SAC12 | Sycamore Slough | 0.1140 | 0.7002 | 0.9508 | 0.9976 | 0.7133 | 0.3165 | 0.1750 | 0.0267 | 0.0000 | 0.0000 |
| SAC13 | Knight's Landing | 0.0700 | 0.5155 | 0.8366 | 0.9733 | 0.8227 | 0.3948 | 0.2753 | 0.0871 | 0.0000 | 0.0000 |
| SAC14 | Ridge Cut North | 0.1250 | 0.7368 | 0.9645 | 0.9987 | 0.6217 | 0.5669 | 0.5167 | 0.3437 | 0.0012 | 0.0000 |
| SAC15 | Ridge Cut South | 0.0740 | 0.5368 | 0.8540 | 0.9787 | 0.6901 | 0.3614 | 0.2567 | 0.1196 | 0.0000 | 0.0000 |
| SAC16 | RD2035 | 0.0790 | 0.5631 | 0.8738 | 0.9841 | 0.6859 | 0.5905 | 0.5481 | 0.5300 | 0.0620 | 0.0000 |
| SAC 17 | East of Davis | 0.0400 | 0.3380 | 0.6435 | 0.8729 | 1.0000 | 0.5463 | 0.0021 | 0.0000 | 0.0000 | 0.0000 |
| SAC18 | Honcut | 0.0260 | 0.2346 | 0.4874 | 0.7372 | 1.0000 | 0.7576 | 0.4562 | 0.1972 | 0.0707 | 0.0210 |
| SAC19 | Sutter Buttes North | 0.0010 | 0.0135 | 0.0330 | 0.0656 | 1.0000 | 0.9951 | 0.9950 | 0.9949 | 0.9159 | 0.3912 |
| SAC20 | Gridley | 0.0010 | 0.0116 | 0.0288 | 0.0568 | 1.0000 | 0.9950 | 0.9949 | 0.9948 | 0.9152 | 0.3920 |
| SAC21 | Sutter Buttes East | 0.0030 | 0.0280 | 0.0685 | 0.1323 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9188 | 0.0991 |
| SAC22 | Live Oak | 0.0030 | 0.0301 | 0.0736 | 0.1418 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.8653 | 0.0973 |
| SAC23 | District 10 | 0.0030 | 0.0298 | 0.0729 | 0.1405 | 1.0000 | 1.0000 | 1.0000 | 0.9969 | 0.8612 | 0.0638 |
| SAC24 | Levee District 1 | 0.0760 | 0.5476 | 0.8623 | 0.9810 | 0.6772 | 0.3377 | 0.2594 | 0.0863 | 0.0000 | 0.0000 |
| SAC25 | Yuba City | 0.0100 | 0.0979 | 0.2271 | 0.4027 | 1.0000 | 0.9119 | 0.8764 | 0.8074 | 0.2296 | 0.0019 |
| SAC26 | Marysville | 0.0050 | 0.0486 | 0.1172 | 0.2207 | 1.0000 | 0.9897 | 0.9813 | 0.9552 | 0.6036 | 0.0064 |
| SAC27 | Linda-Olivehurst | 0.0360 | 0.3100 | 0.6045 | 0.8436 | 0.9880 | 0.5989 | 0.3015 | 0.0983 | 0.0345 | 0.0131 |
| SAC28 | RD784 | 0.0100 | 0.0992 | 0.2299 | 0.4070 | 1.0000 | 0.9287 | 0.8673 | 0.7864 | 0.2069 | 0.0000 |
| SAC29 | Best Slough | 0.0650 | 0.4889 | 0.8132 | 0.9651 | 0.7299 | 0.4256 | 0.2106 | 0.0734 | 0.0721 | 0.0713 |
| SAC30 | RD1001 | 0.0790 | 0.5594 | 0.8711 | 0.9834 | 0.6472 | 0.4960 | 0.4421 | 0.3209 | 0.0035 | 0.0000 |
| SAC31 | Sutter Buttes South | 0.0380 | 0.3204 | 0.6193 | 0.8550 | 0.8694 | 0.7214 | 0.5960 | 0.4835 | 0.0351 | 0.0000 |
| SAC32 | RD70/1660 | 0.0400 | 0.3353 | 0.6398 | 0.8702 | 0.8524 | 0.7122 | 0.5850 | 0.4680 | 0.3564 | 0.0981 |
| SAC33 | Meridian | 0.0420 | 0.3478 | 0.6564 | 0.8820 | 0.8525 | 0.7123 | 0.5849 | 0.4406 | 0.0237 | 0.0000 |
| SAC34 | RD1500 East | 0.2550 | 0.9472 | 0.9994 | 1.0000 | 0.5031 | 0.0644 | 0.0102 | 0.0000 | 0.0000 | 0.0000 |
| SAC35 | Elkhorn | 0.4990 | 0.9990 | 1.0000 | 1.0000 | 0.0023 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC36 | Natomas | 0.0200 | 0.1869 | 0.4039 | 0.6447 | 0.9924 | 0.8062 | 0.6539 | 0.6029 | 0.0126 | 0.0000 |

TABLE 5 (CONT.)

| Impact Area | Impact Area Name | Annual Exceedance Probability (Expected) | Long Term Risk | | | Conditional Non-Exceedance Probability by Flood Event | | | | | |
|-------------|------------------|--|----------------|----------|----------|---|--------|--------|--------|--------|--------|
| | | | 10 Years | 25 Years | 50 Years | 10% | 4% | 2% | 1% | 0.4% | 0.2% |
| SAC37 | Rio Linda | 0.0060 | 0.0608 | 0.1452 | 0.2693 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0190 | 0.0000 |
| SAC38 | West Sacramento | 0.0070 | 0.0691 | 0.1639 | 0.3009 | 1.0000 | 1.0000 | 0.9967 | 0.9808 | 0.0208 | 0.0000 |
| SAC39 | RD900 | 0.0050 | 0.0493 | 0.1186 | 0.2232 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.2393 | 0.0089 |
| SAC40 | Sacramento | 0.0100 | 0.0918 | 0.2140 | 0.3823 | 0.9837 | 0.9826 | 0.9819 | 0.9517 | 0.0000 | 0.0000 |
| SAC41 | RD302 | 0.0060 | 0.0606 | 0.1446 | 0.2684 | 1.0000 | 1.0000 | 1.0000 | 0.9971 | 0.0684 | 0.0021 |
| SAC42 | RD999 | 0.1220 | 0.7276 | 0.9613 | 0.9985 | 0.6032 | 0.5683 | 0.5521 | 0.4847 | 0.0216 | 0.0000 |
| SAC43 | Clarksburg | 0.1220 | 0.7276 | 0.9613 | 0.9985 | 0.6032 | 0.5683 | 0.5521 | 0.4847 | 0.0216 | 0.0000 |
| SAC44 | Stone Lake | 0.1000 | 0.6508 | 0.9280 | 0.9948 | 0.5882 | 0.5004 | 0.4865 | 0.3488 | 0.0000 | 0.0000 |
| SAC45 | Hood | 0.1000 | 0.6509 | 0.9280 | 0.9948 | 0.5894 | 0.4877 | 0.4752 | 0.3502 | 0.0000 | 0.0000 |
| SAC46 | Merritt Island | 0.1510 | 0.8054 | 0.9833 | 0.9997 | 0.4893 | 0.0727 | 0.0212 | 0.0045 | 0.0000 | 0.0000 |
| SAC47 | RD551 | 0.0370 | 0.3172 | 0.6148 | 0.8516 | 0.8188 | 0.7555 | 0.6821 | 0.5548 | 0.0069 | 0.0000 |
| SAC48 | Courtland | 0.0370 | 0.3176 | 0.6153 | 0.8520 | 0.8179 | 0.7549 | 0.6815 | 0.5543 | 0.0063 | 0.0000 |
| SAC49 | Sutter Island | 0.1050 | 0.6694 | 0.9372 | 0.9961 | 0.6025 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC50 | Grand Island | 0.1160 | 0.7075 | 0.9537 | 0.9979 | 0.6188 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC51 | Locke | 0.0260 | 0.2305 | 0.4807 | 0.7303 | 0.9744 | 0.7931 | 0.7163 | 0.1445 | 0.0000 | 0.0000 |
| SAC52 | Walnut Grove | 0.0340 | 0.2951 | 0.5829 | 0.8260 | 0.9113 | 0.6957 | 0.5171 | 0.5104 | 0.0000 | 0.0000 |
| SAC53 | Tyler Island | 0.8490 | 1.0000 | 1.0000 | 1.0000 | 0.0023 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC54 | Andrus Island | 0.6710 | 1.0000 | 1.0000 | 1.0000 | 0.1599 | 0.1209 | 0.0605 | 0.0000 | 0.0000 | 0.0000 |
| SAC55 | Ryer Island | 0.1310 | 0.7557 | 0.9705 | 0.9991 | 0.4556 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC56 | Prospect Island | 0.3130 | 0.9766 | 0.9999 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC57 | Twitchell Island | 0.3050 | 0.9736 | 0.9999 | 1.0000 | 0.6120 | 0.5493 | 0.4936 | 0.1944 | 0.0000 | 0.0013 |
| SAC58 | Sherman Island | 0.5810 | 0.9998 | 1.0000 | 1.0000 | 0.2837 | 0.2558 | 0.2267 | 0.1897 | 0.0000 | 0.0000 |
| SAC59 | Moore | 0.1260 | 0.7407 | 0.9658 | 0.9988 | 0.0225 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC60 | Cache Slough | 0.0660 | 0.4949 | 0.8187 | 0.9671 | 0.9600 | 0.0343 | 0.0044 | 0.0174 | 0.0000 | 0.0000 |
| SAC61 | Hastings | 0.3370 | 0.9835 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SAC62 | Lindsey Slough | 0.0130 | 0.1215 | 0.2766 | 0.4767 | 1.0000 | 1.0000 | 0.7375 | 0.5036 | 0.0030 | 0.0000 |

TABLE 6
EXISTING CONDITION PROJECT PERFORMANCE STATISTICS FOR THE SAN
JOAQUIN RIVER BASIN

| Impact Area | Impact Area Name | Annual Exceedance Probability (Expected) | Long Term Risk | | | Conditional Non-Exceedance Probability by Flood Event | | | | | |
|-------------|--------------------|--|----------------|----------|----------|---|--------|--------|--------|--------|--------|
| | | | 10 Years | 25 Years | 50 Years | 10% | 4% | 2% | 1% | 0.4% | 0.2% |
| SJ 01 | Fresno | 0.0170 | 0.1548 | 0.3433 | 0.5688 | 0.9976 | 0.9976 | 0.9521 | 0.0003 | 0.0000 | 0.0000 |
| SJ 02 | Fresno Slough East | 0.0280 | 0.2436 | 0.5023 | 0.7523 | 0.9942 | 0.9690 | 0.1795 | 0.0001 | 0.0000 | 0.0000 |
| SJ 03 | Fresno Sl West | 0.4970 | 0.9990 | 1.0000 | 1.0000 | 0.4937 | 0.2502 | 0.2477 | 0.2452 | 0.0000 | 0.0000 |
| SJ 04 | Mendota | 0.3280 | 0.9813 | 1.0000 | 1.0000 | 0.4531 | 0.2857 | 0.2834 | 0.2787 | 0.0000 | 0.0000 |
| SJ 05 | Chowchilla Bypass | 0.0340 | 0.2940 | 0.5812 | 0.8246 | 0.9630 | 0.8810 | 0.0955 | 0.0001 | 0.0000 | 0.0000 |
| SJ 06 | Lone Willow Sl | 0.1110 | 0.6912 | 0.9470 | 0.9972 | 0.7092 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 07 | Mendota North | 0.0900 | 0.6112 | 0.9057 | 0.9911 | 0.5920 | 0.3008 | 0.2874 | 0.2780 | 0.0017 | 0.0000 |
| SJ 08 | Firebaugh | 0.0700 | 0.5150 | 0.8362 | 0.9732 | 0.7395 | 0.5397 | 0.0034 | 0.0033 | 0.0000 | 0.0000 |
| SJ 09 | Salt Slough | 0.1390 | 0.7750 | 0.9760 | 0.9994 | 0.4292 | 0.1704 | 0.1293 | 0.1243 | 0.0000 | 0.0000 |
| SJ 10 | Dos Palos | 0.1380 | 0.7738 | 0.9757 | 0.9994 | 0.4323 | 0.1852 | 0.1084 | 0.1062 | 0.0000 | 0.0000 |
| SJ 11 | Fresno River | 0.1320 | 0.7562 | 0.9707 | 0.9991 | 0.5144 | 0.1665 | 0.1154 | 0.1092 | 0.0000 | 0.0000 |
| SJ 12 | Berenda Slough | 0.4500 | 0.9975 | 1.0000 | 1.0000 | 0.0015 | 0.0001 | 0.0001 | 0.0001 | 0.0000 | 0.0000 |
| SJ 13 | Ash Slough | 0.3030 | 0.9731 | 0.9999 | 1.0000 | 0.1014 | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 14 | Sandy Mush | 0.0910 | 0.6158 | 0.9085 | 0.9916 | 0.5706 | 0.5680 | 0.4708 | 0.0000 | 0.0000 | 0.0000 |
| SJ 15 | Turner Island | 0.1310 | 0.7535 | 0.9698 | 0.9991 | 0.5362 | 0.0028 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 16 | Bear Creek | 0.0550 | 0.4342 | 0.7592 | 0.9420 | 0.8674 | 0.5322 | 0.4780 | 0.1019 | 0.0000 | 0.0000 |
| SJ 17 | Deep Slough | 0.0650 | 0.4900 | 0.8143 | 0.9655 | 0.7933 | 0.5318 | 0.3788 | 0.0000 | 0.0000 | 0.0000 |
| SJ 18 | West Bear Creek | 0.1310 | 0.7535 | 0.9698 | 0.9991 | 0.4464 | 0.1465 | 0.0168 | 0.0000 | 0.0000 | 0.0000 |
| SJ 19 | Fremont Ford | 0.2370 | 0.9330 | 0.9988 | 1.0000 | 0.2019 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 20 | Merced River | 0.1680 | 0.8414 | 0.9900 | 0.9999 | 0.3111 | 0.3036 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 21 | Merced R. North | 0.5460 | 0.9996 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0001 |
| SJ 22 | Orestimba | 0.0090 | 0.0851 | 0.1994 | 0.3590 | 0.9972 | 0.9972 | 0.9811 | 0.7473 | 0.0000 | 0.0000 |
| SJ 23 | Tuolumne South | 0.3070 | 0.9743 | 0.9999 | 1.0000 | 0.2981 | 0.0271 | 0.0000 | 0.0000 | 0.0004 | 0.0000 |
| SJ 24 | Tuolumne River | 0.0060 | 0.0623 | 0.1486 | 0.2752 | 0.9974 | 0.9974 | 0.9974 | 0.9902 | 0.0559 | 0.0000 |
| SJ 25 | Modesto | 0.0130 | 0.1225 | 0.2788 | 0.4799 | 0.9974 | 0.9974 | 0.9974 | 0.0393 | 0.0000 | 0.0000 |
| SJ 26 | 3 Amigos | 0.8540 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 27 | Stanislaus South | 0.6260 | 0.9999 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 28 | Stanislaus North | 0.3140 | 0.9770 | 0.9999 | 1.0000 | 0.0032 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0000 |
| SJ 29 | Banta Carbona | 0.2720 | 0.9580 | 0.9996 | 1.0000 | 0.2236 | 0.0174 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 30 | Paradise Cut | 0.3120 | 0.9764 | 0.9999 | 1.0000 | 0.3025 | 0.0037 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 31 | Stewart Tract | 0.3120 | 0.9762 | 0.9999 | 1.0000 | 0.2721 | 0.0146 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 32 | East Lathrop | 0.3080 | 0.9749 | 0.9999 | 1.0000 | 0.2397 | 0.0272 | 0.0096 | 0.0002 | 0.0000 | 0.0000 |
| SJ 33 | Lathrop/Sharpe | 0.2220 | 0.9192 | 0.9981 | 1.0000 | 0.2542 | 0.0009 | 0.0005 | 0.0000 | 0.0000 | 0.0000 |
| SJ 34 | French Camp | 0.2220 | 0.9191 | 0.9981 | 1.0000 | 0.2542 | 0.0009 | 0.0005 | 0.0000 | 0.0000 | 0.0000 |
| SJ 35 | Moss Tract | 0.2230 | 0.9203 | 0.9982 | 1.0000 | 0.2435 | 0.0340 | 0.0006 | 0.0000 | 0.0000 | 0.0000 |
| SJ 36 | Roberts Island | 0.3720 | 0.9905 | 1.0000 | 1.0000 | 0.2193 | 0.0050 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 37 | Rough & Ready Is | 0.2470 | 0.9417 | 0.9992 | 1.0000 | 0.1780 | 0.0721 | 0.0155 | 0.0000 | 0.0000 | 0.0000 |
| SJ 38 | Drexler Tract | 0.3540 | 0.9874 | 1.0000 | 1.0000 | 0.2380 | 0.0290 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| SJ 39 | Union Island | 0.3210 | 0.9793 | 0.9999 | 1.0000 | 0.2405 | 0.0600 | 0.0003 | 0.0000 | 0.0000 | 0.0000 |
| SJ 40 | SE Union Island | 0.2180 | 0.9147 | 0.9979 | 1.0000 | 0.2462 | 0.0297 | 0.0037 | 0.0000 | 0.0000 | 0.0000 |
| SJ 41 | Fabian Tract | 0.2240 | 0.9205 | 0.9982 | 1.0000 | 0.2259 | 0.0119 | 0.0001 | 0.0000 | 0.0000 | 0.0000 |
| SJ 42 | RD 1007 | 0.2140 | 0.9097 | 0.9975 | 1.0000 | 0.2516 | 0.0181 | 0.0002 | 0.0000 | 0.0000 | 0.0000 |

Future Without-Project and With-Project Condition

Project performance statistics have not yet been developed for future without-project conditions. The Corps' future without project condition only includes those projects that have been authorized for construction; projects that are in various stage of planning but have not been authorized are not considered. Examples of projects that may affect flood risk in the future without-project condition include: authorized flood management construction in the American River Basin, authorized levee improvements that are part of the Sacramento River Flood Control Project System Evaluation, and the ongoing Sacramento Bank Protection Project.

Project performance statistics can also be used to formulate and compare alternative plans. Although no alternative plans were developed by the Comprehensive Study, HEC-FDA was used to calculate project performance statistics for various basin-wide modeling scenarios and evaluations. The purpose of these basin-wide evaluations was two-fold: (1) to develop a greater understanding of the river systems and how various types of flood damage reduction and environmental restoration measures could affect project performance, and (2) to test and refine the technical evaluation process, including risk analysis, and identify any problems or limitations.

Generating hybrid stage-frequency curves from the hydraulic models and passing this data to HEC-FDA is one of the most time-consuming steps in the basin-wide evaluation process. During conceptual planning stages, it may not be necessary or time-efficient to examine all of the index points and damage areas. Instead, the study developed a procedure in which the index points and damage areas were grouped into larger, "bubble" areas for quick, initial analysis. Nine of these bubble areas were delineated in the Sacramento River basin and seven in the San Joaquin River basin. One index point was chosen to represent all damage areas within a given bubble area. The index point was chosen based on several factors including stage conditions, topography, initial breakout, and significance of damages caused. The hydrology and reservoir operation steps of the evaluation process do not change, and hydrographs from all frequency events are still run through UNET. However, fewer stage-frequency curves are developed and iterations are stopped when the HEC-FDA risk results are within an acceptable margin of the desired targets. Although this process does not permit the calculation of economic damages, it was believed that if project performance was improved over existing conditions for most (if not all) of the representative locations, then it could reasonably be expected that flood damages would also be reduced for the entire basin. Because not all index points are evaluated in the expedited analysis, there is a potential to over- or underestimate the success of an evaluation in meeting its goals. Thus, the expedited analysis process is limited to conceptual planning.

Figure 7 shows an example project performance comparison for a hypothetical impact area. The top panel compares annual exceedence probabilities for existing conditions with two alternative plans. Both alternative plans have lower annual exceedence than for existing conditions, thus both represent an improvement. Similarly, long-term risk is lower for both plans compared to existing conditions. Both plans also have improved non-exceedence values (i.e., the ability to pass specific events) for the 10-, 25-, and 50-return frequency events, although values for the 100- year return frequency event are slightly less than existing conditions.

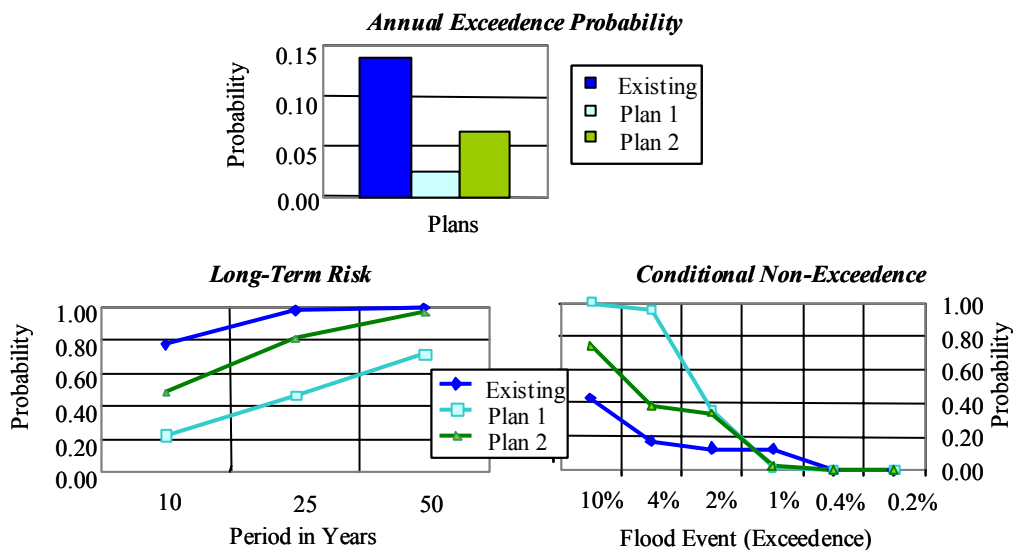


FIGURE 7 – EXAMPLE OF PROJECT PERFORMANCE COMPARISON BETWEEN ALTERNATIVE PLANS

EXPECTED ANNUAL DAMAGES

In a risk analysis, expected annual damages is defined as the average or mean of all possible values of damage determined by Monte Carlo sampling of discharge-exceedence probability, stage-discharge, and stage-damage relationships and their associated uncertainties. It is calculated as the integral of the damage-probability function, as shown in **Figure 1**. A detailed description of the economic analysis is included in *Appendix F – Economic Technical Documentation*. A brief overview of the key elements and results of the economic analysis are included below.

HEC-FDA Input Parameters

Damage Categories - Damage categories used in the Comprehensive Study economic analysis include: residential, mobile homes, commercial, industrial, public / semi-public, farmsteads, crops, and others (including damage to autos, roads, traffic disruption, and emergency response costs, primarily within urbanized areas).

Land Use/Structural Inventories - GIS was used to develop crop and other land use inventories for both basins utilizing DWR digitized land use files. GIS was also used to develop the structural inventories using digitized county parcel map files, geocoding of street addresses, or by physically comparing floodplain maps with county assessor parcel maps.

Structural and Contents Values - Parcels were linked to assessor data files to obtain structural improvement values and other information. Adjustments were made to the assessed values to reflect October 2001 prices. Publicly owned parcels, which are not assessed property taxes, are not currently included in the structural inventories but work is underway to assign improvement values by applying construction factors. Contents values were assigned based

upon percentages developed by previous Corps studies: residential and mobile homes, 50%; commercial, 100%, industrial, 150%, public/semi-public, 50%; and farmsteads, 65%.

Urban Depth-Damage Relationships - Damage generally increases as depth of flooding increases. Generic residential depth-damage functions developed by the Corps' Institute for Water Resources were used in the Comprehensive Study. For other urban damage categories, depth-damage functions developed by the Sacramento District and based upon FEMA information were used.

Agricultural Depth-Damage Relationships - About 1.9 million acres out of the total 2.2 million acres in the study area is in agricultural production, making crop damage analysis an important element in the Comprehensive Study. Although over 100 different crops are grown within the area, only predominant crop types were evaluated to facilitate the analysis: row crops, fruit crops, alfalfa, mixed pasture, rice, truck crops, and vine crops. The types of agricultural flood damage being evaluated include direct production costs incurred prior to flooding, the net value of crop, the depreciated value of perennial crops, and clean-up and rehabilitation costs, with consideration for the seasonality and duration of flooding.

Existing Condition

Existing condition expected annual damages exceed \$280 million (October 2001 price levels) for both basins combined. Most of the damage is expected to occur in the Sacramento River Basin (about \$251 million EAD) compared to the San Joaquin River Basin (about \$31 million EAD). The distribution of damage within the two basins is significantly different, with urban structural damage representing about 77 percent of total Sacramento River Basin EAD compared to about 39 percent within the San Joaquin River Basin. Refer to *Appendix F – Economics Technical Documentation* for a detailed accounting of economic damages.

Future Without-Project Condition

The estimation of existing condition expected annual damage is only part of the “without-project” analysis. A complete analysis should take into account future development likely to occur over the planning horizon. “Future without project” population and economic development levels, and associated flood damage, have not been estimated at this time.

Alternative or With-Project Economic Evaluations

Economic analyses are performed for proposed alternative plans in the same manner as described for the existing and future without project conditions. Plan components are simulated using the hydrology, hydraulics, and geotechnical tools and this information is passed to HEC-FDA for a determination of EAD. The with-project EAD can then be compared with the existing condition and future without-project EAD to estimate the benefits of the alternative plan. Because no alternative plans were developed by the Comprehensive Study, no with-project economic evaluations were performed.

ENVIRONMENTAL RESTORATION

Uncertainty is also associated with the environmental restoration element of the Comprehensive Study. Like flood damage reduction studies, environmental restoration projects also rely on information and analytical methods associated with varying degrees of uncertainty and reliability. For example, the Ecosystem Function Model developed by the Comprehensive Study uses hydrologic data, topography, and simplified algorithms to guide the formulation of ecosystem restoration plans. There is uncertainty in the gage data upon which the hydrology was developed, accuracy of mapping, and ability of the algorithms to address ecological complexity. It may be possible to incorporate risk and uncertainty in future enhancements of the EFM. For example, a relationship between flow duration and acres of habitat could become part of a Monte Carlo simulation. Similar to the stage-damage relationships used in HEC-FDA, several different stage-acres of habitat curves could be created for each distinct type of habitat (i.e. riparian wetlands, seasonal wetlands, uplands, etc).

Formal risk analyses are uncommon in environmental restoration projects and the Corps currently does not have a standard approach or model. Although risk analysis for environmental restoration cannot be quantified at this time, it can be incorporated into project formulation through the development of plans that are flexible or provide the opportunity for adjustment in the future. The Comprehensive Study has advocated adaptive management as one method of addressing the uncertainties associated with the success of environmental restoration.

SUMMARY & CONCLUSIONS

The risk analysis performed by the Comprehensive Study provides economic damages and project performance information suitable for basin-wide flood management and ecosystem restoration planning in the Sacramento and San Joaquin River basins. The models and other technical tools developed by the Comprehensive Study, including the HEC-FDA model, are expected to continue to be updated and improved as they are utilized by future projects. Future work related to risk analysis will likely involve the collection of additional economic data, and evaluation of future without-project conditions.

The Comprehensive Study seeks to address two critical problems affecting Central Valley river systems and their floodplains - ecosystem restoration and flood damage reduction - through a watershed-based approach that requires continued input and involvement across a broad range of public interest groups. Upon evaluating the risk analysis practices of the Corps of Engineers, The National Resource Council's Committee on Risk-Based Analysis for Flood Damage Reduction made the following statement that supports the planning strategy adopted by the Comprehensive Study:

“The Corps’s risk analysis techniques and flood damage reduction studies will produce their greatest benefits if these techniques and studies are executed within a comprehensive planning paradigm and framework designed to make the best social, economic, and environmental uses of the nation’s floodplain resources.” – Risk Analysis and Uncertainty in Flood Damage Reduction Studies, NRC 2000

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