



# **TECHNICAL STUDIES DOCUMENTATION**

## **APPENDIX E**

### **RISK ANALYSIS**



**US Army Corps  
of Engineers**  
Sacramento District

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**ATTACHMENTS**

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# **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.

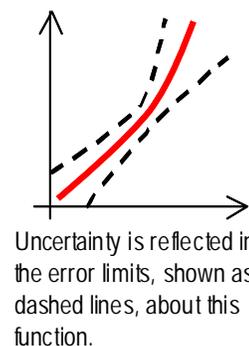
Today, advances in statistical hydrology and high-speed computerized analysis tools have made it possible to explicitly account for uncertainty. The Comprehensive Study has adopted a risk analysis approach that utilizes the Hydrologic Engineering Center's Flood Damage Assessment (HEC-FDA) computer model 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.

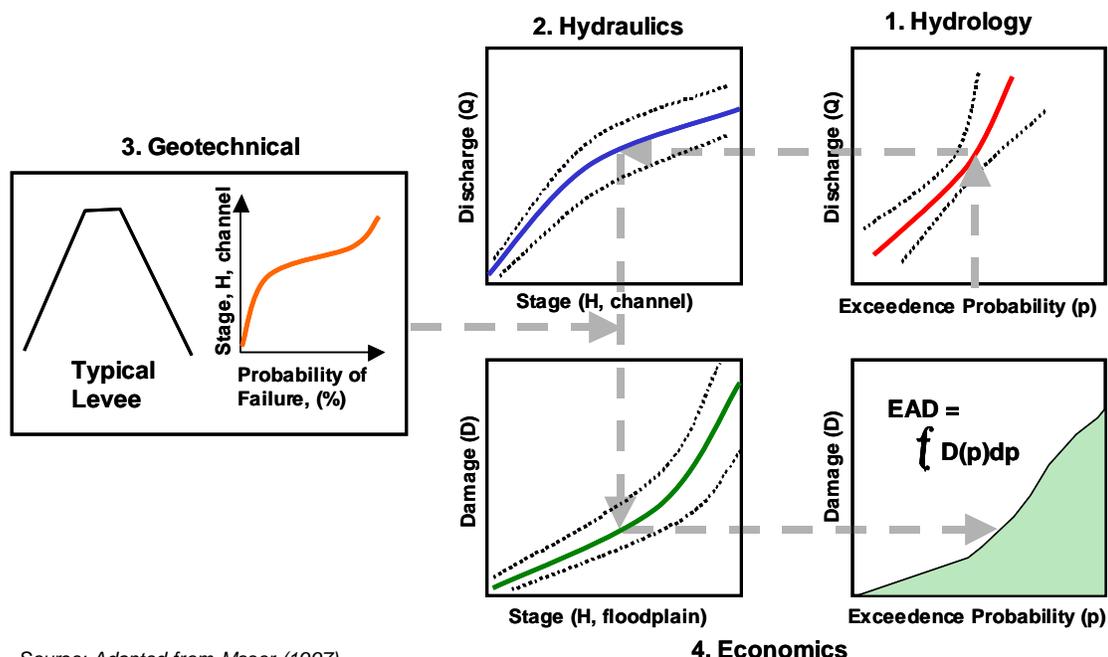


Rather than generating a series of random floods and estimating their consequences, a more sophisticated approach can be used to incorporate uncertainty in each of the key variables (hydrology, hydraulics, geotechnical performance, and economics). Monte Carlo simulation provides a way to estimate the 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.<sup>1</sup> 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

<sup>1</sup> 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.

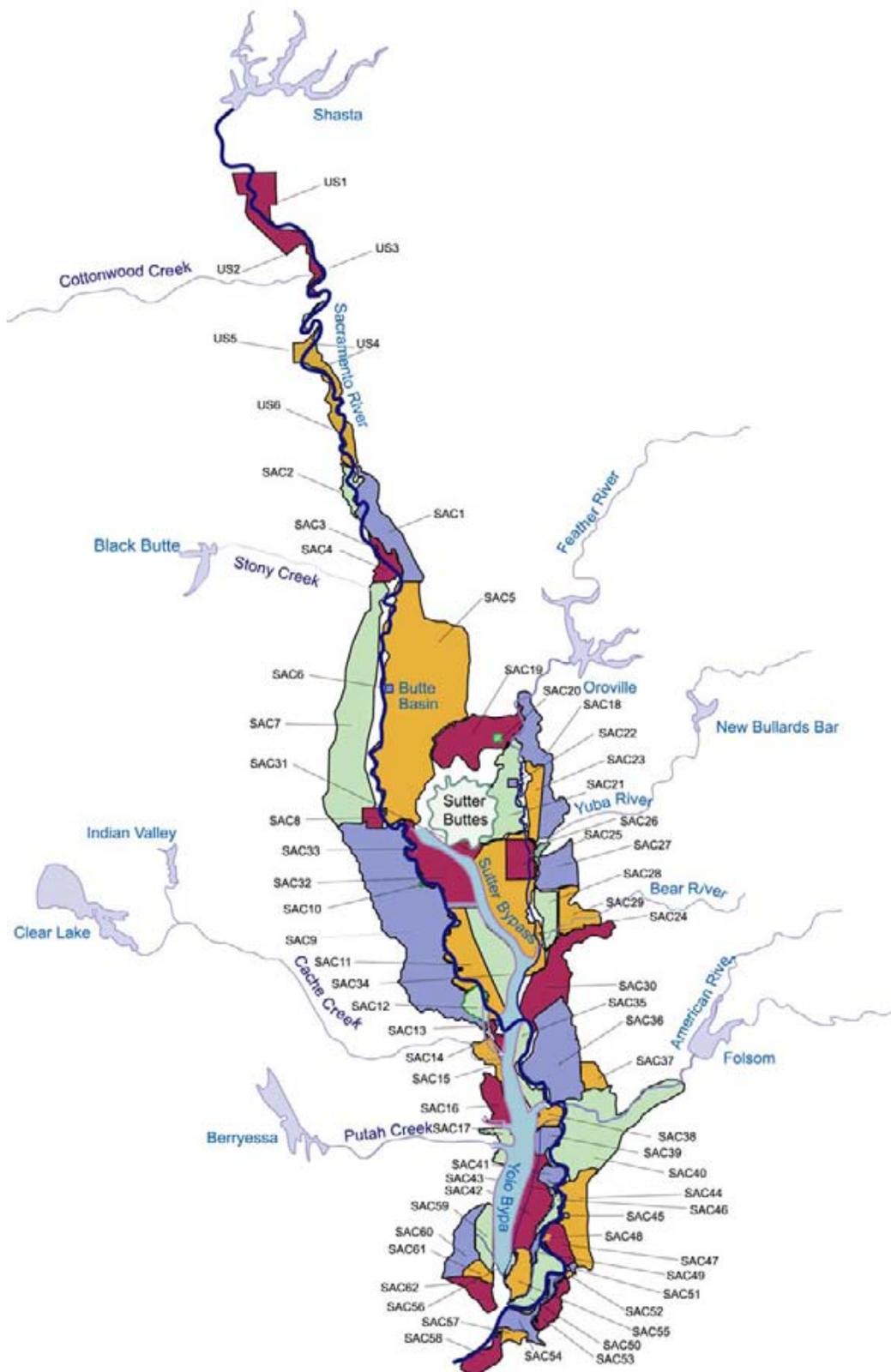


FIGURE 2 – SACRAMENTO RIVER BASIN ECONOMIC IMPACT AREAS

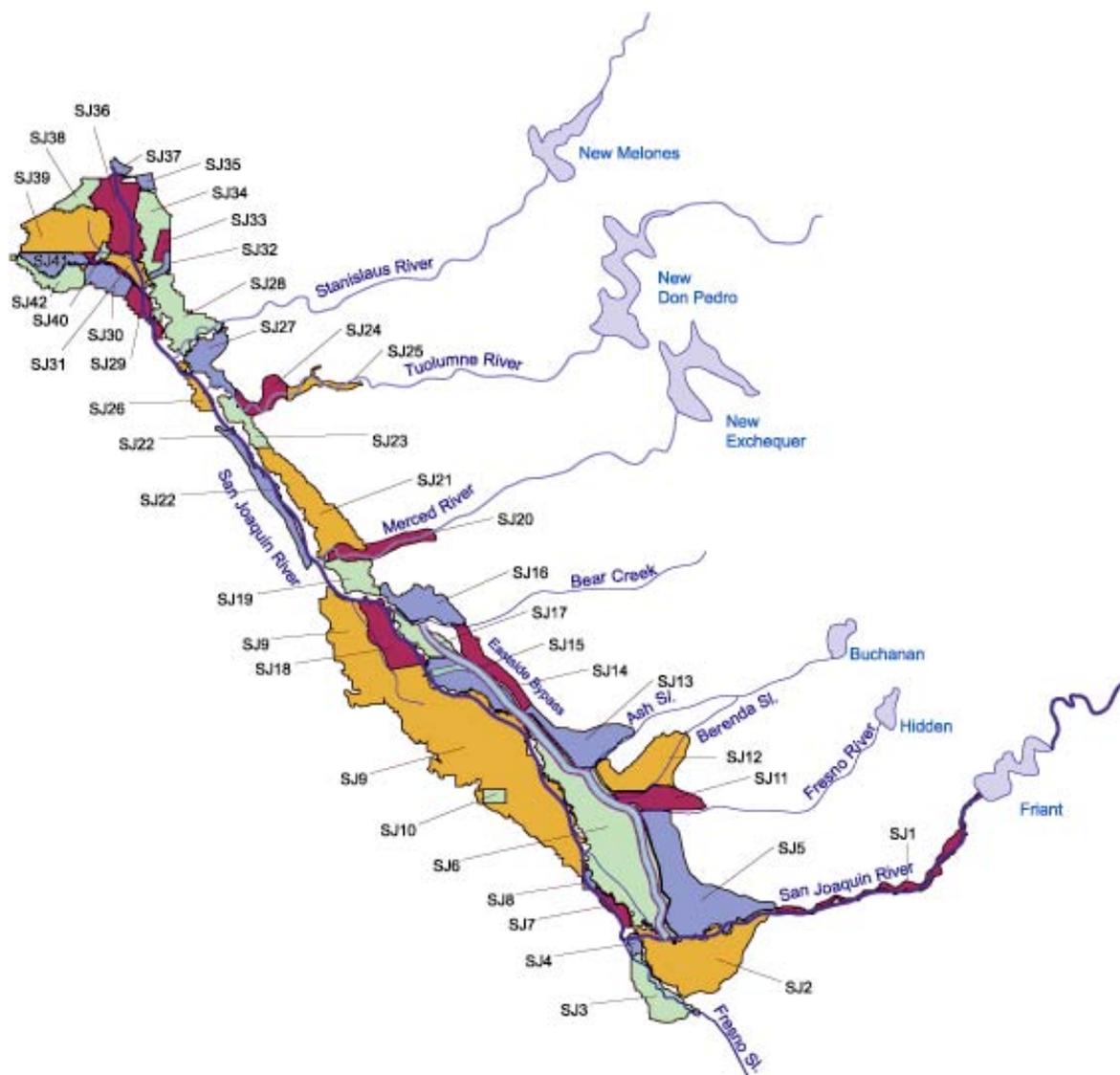


FIGURE 3 – SAN JOAQUIN RIVER BASIN ECONOMIC IMPACT AREAS

**TABLE 1**  
**SACRAMENTO RIVER BASIN IMPACT AREAS**

<b>Impact Area No.</b>	<b>Impact Area Name</b>	<b>Area in Acres</b>	<b>Impact Area No.</b>	<b>Impact Area Name</b>	<b>Area in Acres</b>	
<i>Upper Sacramento Reach</i>						
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>	<i>46,774</i>
<i>Sacramento River Basin</i>						
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>	<i>1,500,226</i>
<b>Total Acreage:</b>					<b>1,547,000</b>	

**TABLE 2**  
**SAN JOAQUIN RIVER BASIN IMPACT AREAS**

<b>Impact Area No.</b>	<b>Impact Area Name</b>	<b>Area in Acres</b>	<b>Impact Area No.</b>	<b>Impact Area Name</b>	<b>Area in Acres</b>
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
<b>Total Acreage:</b>					<b>654,189</b>

## 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 flow<sup>2</sup>. 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

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<sup>2</sup> 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* methods<sup>3</sup>. 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

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<sup>3</sup> 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:

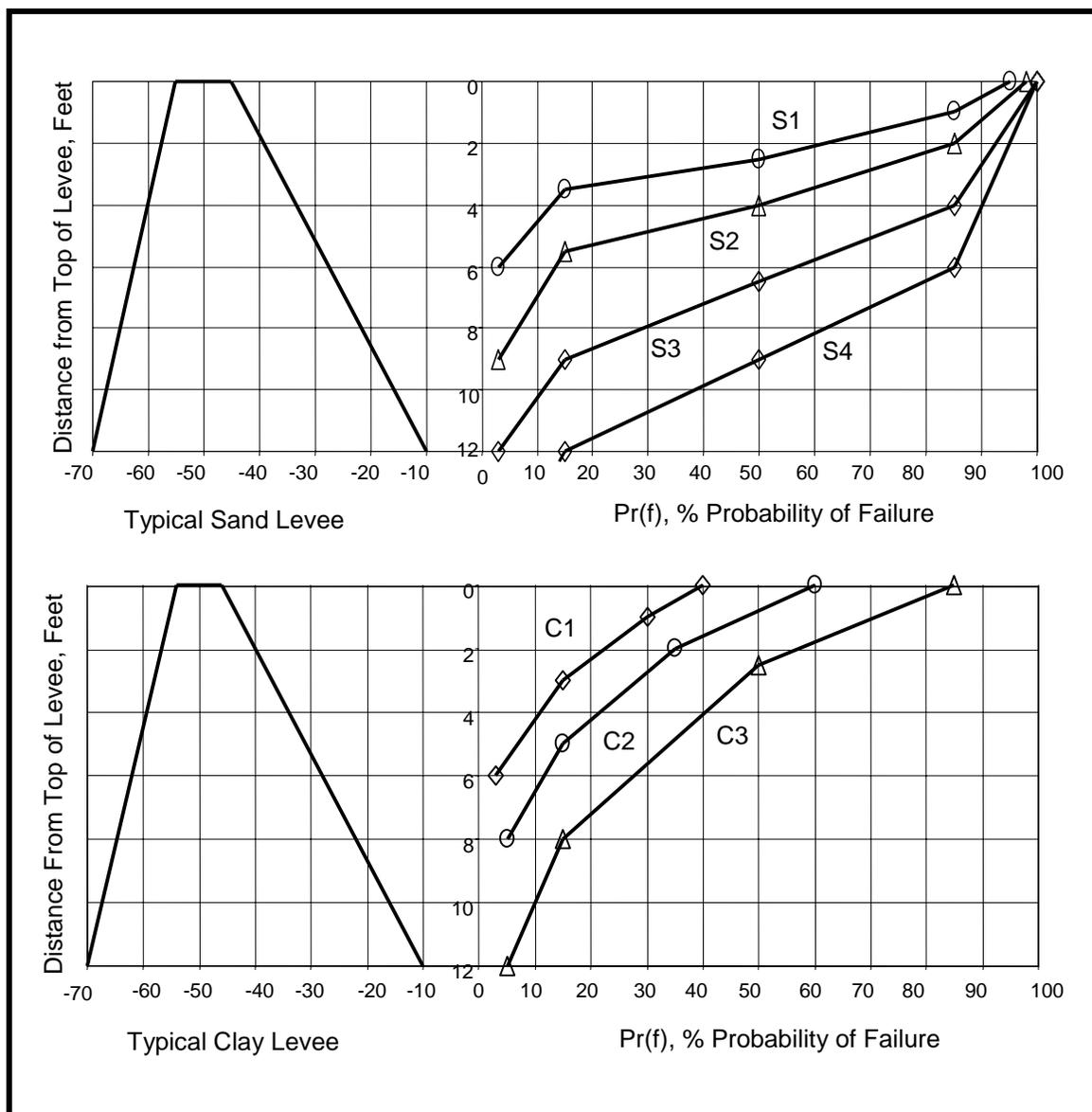
- Initial system evaluation reports submitted by the Mark Group in 1988 and 1989
- Flood Control System Evaluation reports of 1992, 1993, and 1994; and
- Supplemental evaluation reports from 1996, 2000, and 2001.

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

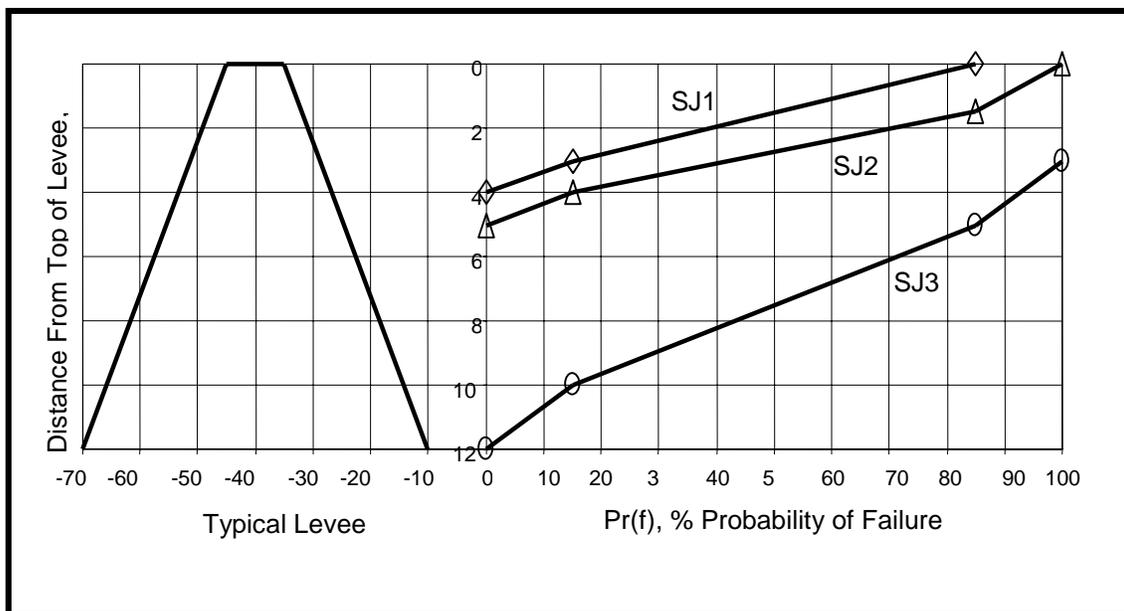
levee curves. Since levees in the Sacramento River basin are constructed of a variety of levee material ranging in composition from loose sand to engineered pervious and impervious materials, geotechnical probability of failure curves were created to reflect a variety of levee materials. Three geotechnical 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 <sup>a</sup> (cfs)	Selected P(f) <sup>b</sup> Model	
				LB <sup>c</sup>	RB <sup>c</sup>
<b>1</b>	<b>Shasta Dam to Red Bluff</b>	<b>315 -245</b>	No Levees		
<b>2</b>	<b>Red Bluff to Chico Landing</b>	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	
<b>3</b>	<b>Chico Landing to Colusa</b>	<b>194 - 146</b>			
	<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	
<b>4</b>	<b>Colusa to Verona</b>	<b>146 - 80</b>			
	<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 <sup>a</sup>	Selected P(f) <sup>b</sup> Model	
				LB <sup>a</sup>	RB <sup>a</sup>
5	<b>Verona To Steamboat Slough</b>	<b>80 - 32.3</b>			
	<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	<b>Steamboat Slough To Collinsville</b>	<b>32.3 - 0</b>			
	<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 <sup>a</sup> (cfs)	Selected P(f) <sup>b</sup> Model
<b>A</b>	<b><i>Mendota Dam to Friant Dam</i></b>	<b>205 To 286</b>		
	<i>San Joaquin River</i>		2,500 – 8,000	SJ1
	<i>Fresno Slough &amp; James Bypass</i>		4,750	SJ1
<b>B</b>	<b><i>Sand Slough Control Structure to Mendota Dam</i></b>	<b>168 to 205</b>		
	<i>San Joaquin River</i>		4,500	SJ2
	<i>Chowchilla Bypass / Eastside Bypass</i>		5,500 – 17,000	SJ2
	<i>Tributaries</i>			
	<i>Fresno River – San Joaquin to Road 18</i>		5,000	SJ2
	<i>Berenda Slough - San Joaquin to Route 152</i>		2,000	SJ2
	<i>Ash Slough - San Joaquin to Route 152</i>		5,000	SJ2
<b>C</b>	<b><i>Merced River to Sand Slough Control Structure</i></b>	<b>118 to 168</b>		
	<i>San Joaquin River</i>			
	<i>Merced River to Eastside Bypass</i>		26,000	SJ2
	<i>Eastside Bypass to Control Structure</i>		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
<b>D</b>	<b><i>Stanislaus River to Merced River</i></b>	<b>75 to 118</b>		
	<i>San Joaquin River</i>		45,000 – 46,000	SJ3
	<i>Merced River</i>		6,000	SJ2
	<i>Tuolumne River</i>		15,000	SJ3
	<i>Dry Creek</i>		N/A	SJ3
	<i>Stanislaus River</i>		8,000	SJ3
<b>E</b>	<b><i>Deep Ship Channel to Stanislaus River</i></b>	<b>40 to 75</b>		
	<i>San Joaquin River</i>		37,000 – 52,000	SJ3
	<i>Tributaries</i>			
	<i>Paradise Cut – Old River to San Joaquin River</i>		15,000	SJ3
	<i>Old River - Tracy Boulevard to San Joaquin River</i>		-	SJ3
	<i>Grant Line Canal - Tracy Blvd to Doughty Cut</i>		-	SJ3
	<i>Doughty Cut - Grant Line Canal to Old River</i>		-	SJ3
	<i>Middle River - Victoria Canal to Old River</i>		-	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.

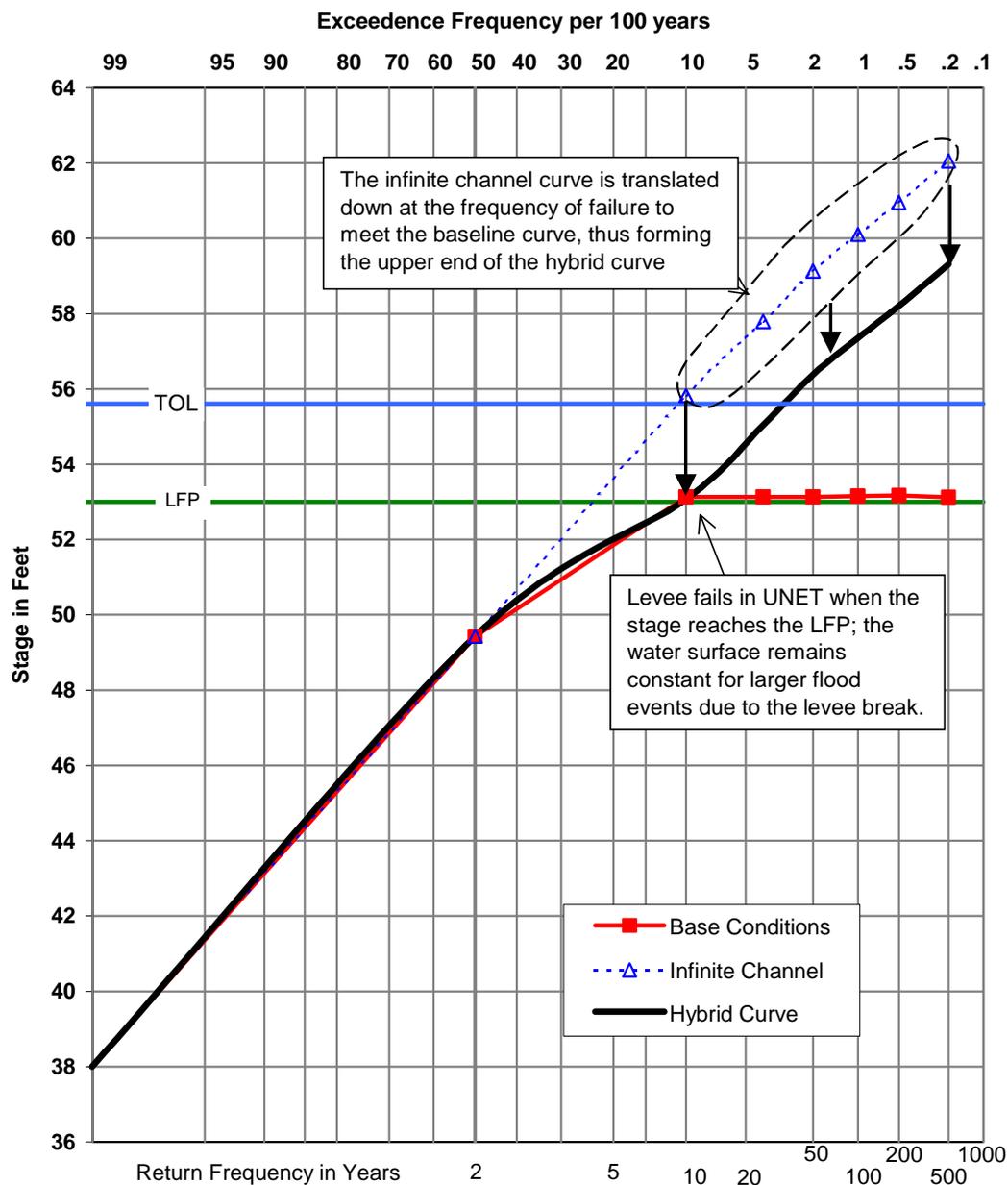


FIGURE 6 – DEVELOPMENT OF HYBRID STAGE-FREQUENCY CURVE

**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

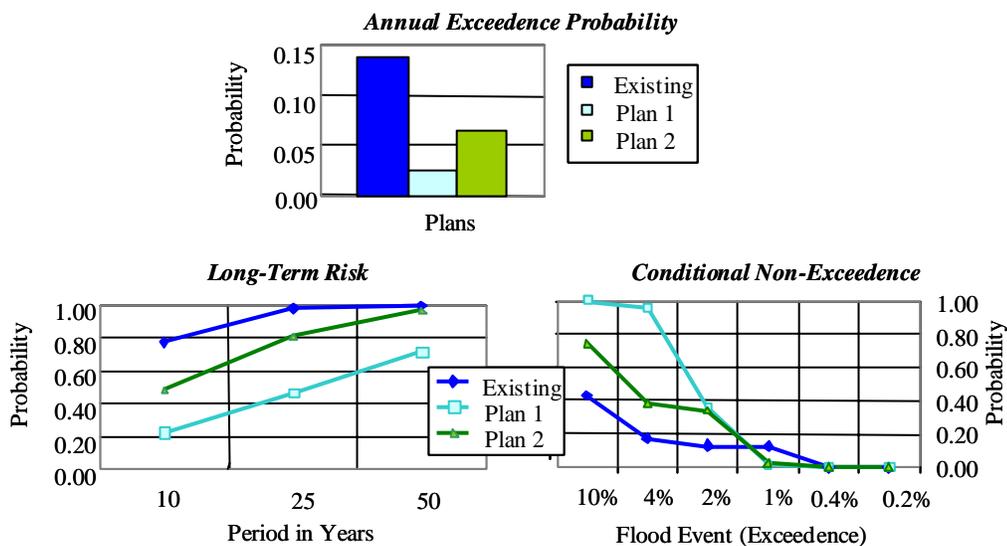
### **Future Without-Project and With-Project Condition**

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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# ATTACHMENT E1

## GEOTECHNICAL OFFICE REPORT

### INTRODUCTION

The Sacramento and San Joaquin river basins have highly developed flood management systems, which rely primarily on high earthen structures, or levees, to protect adjacent floodplain lands. High levees essentially function as long dams but lack the inherent safety features that well-constructed dams possess such as spillways, outlets, and internal drains. Typically, floodwater velocities are erosive by definition and move along normally unprotected levees. These waters need only to encounter one weak spot in the system before causing a breach and potentially the loss of life or property. Extremely high hydraulic gradients can find other weak spots in the foundation materials with high hydraulic conductivity (permeability) such as loose sand and begin to migrate, or erode, material from the levee or near-surface foundation creating unstable conditions quickly followed by total or significant structural failure.

Even if not overtopped by floods, levees may fail for geotechnical reasons. Risk analysis procedures incorporate the chance of such failures through a geotechnical reliability model. This model leads to a relationship between water height and probability of geotechnical failure, which is then applied individually to each damage reach of river. This calculation 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 significantly enough to cause geotechnical failure.

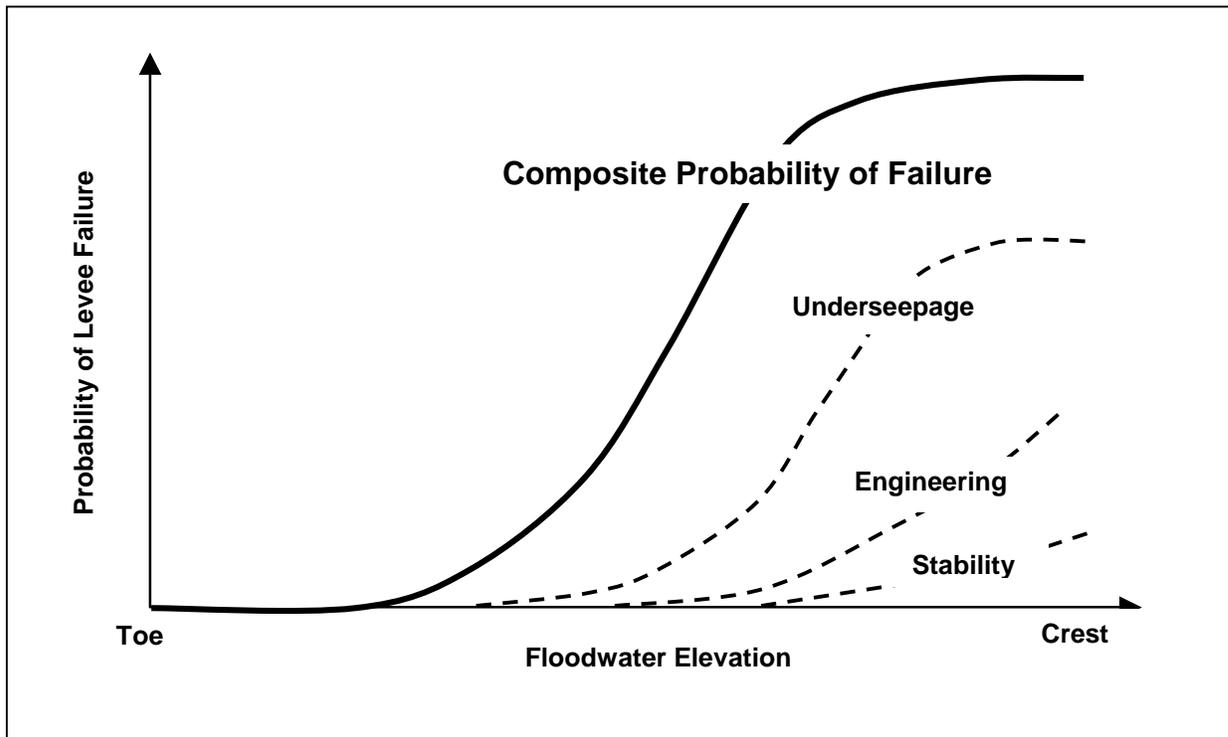
### LEVEE FAILURE ANALYSIS METHODOLOGY

In the past, levees have often failed in unpredictable areas and at stages well below the design water surface. In other cases, water has encroached into the design freeboard (or safety level) without breaching or without significant damages. The geotechnical performance of a levee depends on local soil conditions and construction details. These details are generally not known in detail during the initial start of any planning study. Many of the levees of concern to the Sacramento and San Joaquin River Basins Comprehensive Study are neither owned nor maintained by the Corps of Engineers (Corps) or other federal agencies.

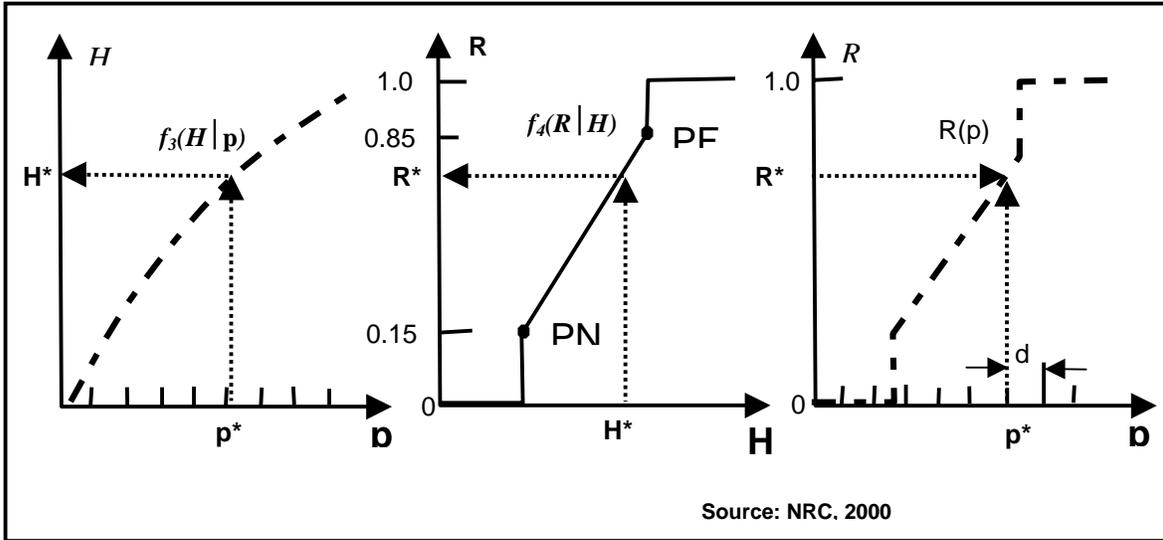
The geotechnical reliability model is generally a good first step in fulfilling the practical needs of planning studies and risk analysis. The Corps's original geotechnical reliability model began as a simple relationship between two stage heights for the levee: the probable failure point (PFP) and the probable non-failure point (PNP) (USACE, 1991). By definition, the probable failure point is the stage height associated with a high probability of failure. Numerically, this number is set at 0.85 (85% probability of failure). Likewise, the probable non-failure point is the stage height associated with a negligible probability of failure. Numerically, this number is set at 0.15. These points are assessed for local conditions only

and frequently change from reach to reach. In some instances, these reaches can measure many miles in distance.

To better reflect a more sophisticated understanding of geotechnical performance this model was updated (USACE, 1999). The updated model considers multiple modes of failures including underseepage, through seepage, and strength instability as illustrated in **Figure G2-1**. These risk measures are calculated as shown in **Figure G2-2**.

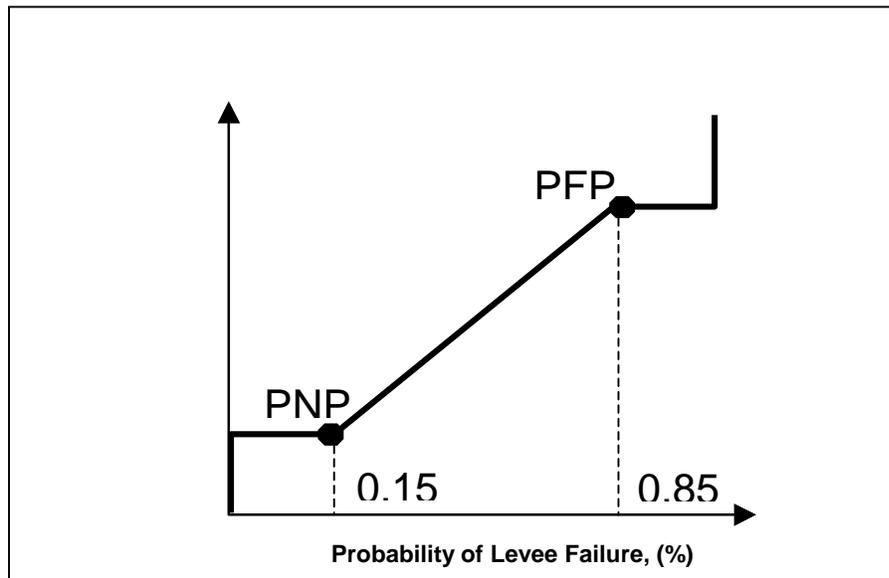


**FIGURE G2-1 - CONTINUOUS MODEL OF GEOTECHNICAL LEVEE RELIABILITY**



**FIGURE G2-2 - COMPUTATION OF RISK MEASURES INCLUDING GEOTECHNICAL RELIABILITY**

The first panel of this figure shows the stage-frequency curve,  $f_3(H|p)$ , which was determined from hydrologic and hydraulic models and their uncertainties. For each frequency value ( $p^* = 0.5, 0.2, 0.1, 0.4, 0.2, 0.01, 0.004, 0.002$ ), a corresponding stage height  $H^*$  is determined. The middle panel of the figure is the risk of levee failure  $R$  as a function of stage,  $f_4(R|H)$ , derived either from the PNP/PFP relationship, shown in **Figure G2-3**, or a composite probability of geotechnical levee reliability, shown in **Figure G2-1**.



**FIGURE G2-3 - TWO-POINT MODEL OF GEOTECHNICAL LEVEE RELIABILITY**

For the given value of  $H^*$ , the corresponding risk of failure  $R^*$  is thereby determined. The pairs of values ( $R^*$ ,  $p^*$ ) are combined to form a risk-frequency curve,  $R(p)$ , as shown in the last panel of **Figure G2-2**. The annual exceedence probability  $p_e$  including geotechnical uncertainty is then found in an analogous manner to the expected annual damage using the equation:

$$P_e = \int_0^1 R(p) dp$$

The conditional nonexceedence probability for any given value of  $p^*$  is expressed as:

$$1 - R^* \quad (\text{as shown in Figure G2-2})$$

By repeating this calculation numerous times using a Monte Carlo simulation, a set of  $p_e$  and  $1 - R^*$  values is obtained. The  $p_e$  values are averaged to find the expected value of the annual exceedence probability. For the construction of a levee with a specified conditional probability of, for example, 90 percent or 95 percent for a 100-year flood, the procedure described in this paragraph is executed with a specific value of  $p^* = 0.01$ , and the levee height is adjusted upwards or downwards until the required conditional nonexceedence probability is obtained.

### Levee Evaluation

Geotechnical evaluation and risk assessment is critical in flood damage reduction projects involving levees. These analyses are necessary to account for the risk of a levee to breach through soil failure even when the water surface elevation is not sufficient to over top the levee. The assessment does not generally separate the differences between *natural variability* and *knowledge uncertainty* (NRC, 2000). Natural variability arises from variations in soil conditions, or soil characteristics, and levee construction. The knowledge uncertainty arises from modeling assumptions made in calculating levee performance. These modeling assumptions are most likely to be very general. Natural variability varies independently from reach to reach and typically from sub-reach to sub-reach. The knowledge uncertainty is systematic across all reaches and is highly correlated. The important implication comes into view when calculating the probability of at least one levee failure anywhere on the river. If the reaches are truly independent, the probability generally rises according to a relation in the form,

$$Pr\{\geq 1 \text{ levee failure}\} = 1 - 1(1 - p)^n$$

Where  $p$  is the probability of failure in any one reach and  $n$  is the number of reaches. As  $n$  increases, the probability of failure quickly rises. If the reaches are highly correlated, the probability of one levee failing anywhere along the river is represented by

$$Pr\{\geq 1 \text{ levee failure}\} = p$$

### Comprehensive Study Geotechnical Analysis

For the Comprehensive Study, the locations and likelihood of initial levee failure for the existing project and non-project levees in both the Sacramento and San Joaquin river basins

are based on an analysis of weak points in the levee system. The weak points were identified through a reconnaissance-level geotechnical assessment of levee stability within predetermined damage impact areas. To define these weak points within any particular area, the PNP and PFP were defined for levee reaches on each impact area. The PNP and PFP were based on the results of field investigations, past levee stability calculations, and levee performance in the 1997 and 1998 flood events. To more clearly define the geotechnical conditional probability of failure for the 2,000 miles of levees evaluated in this study, probability of failure points in addition to the PNP and PFP values were defined for the 3-, 50- and 100- percent probability of failure.

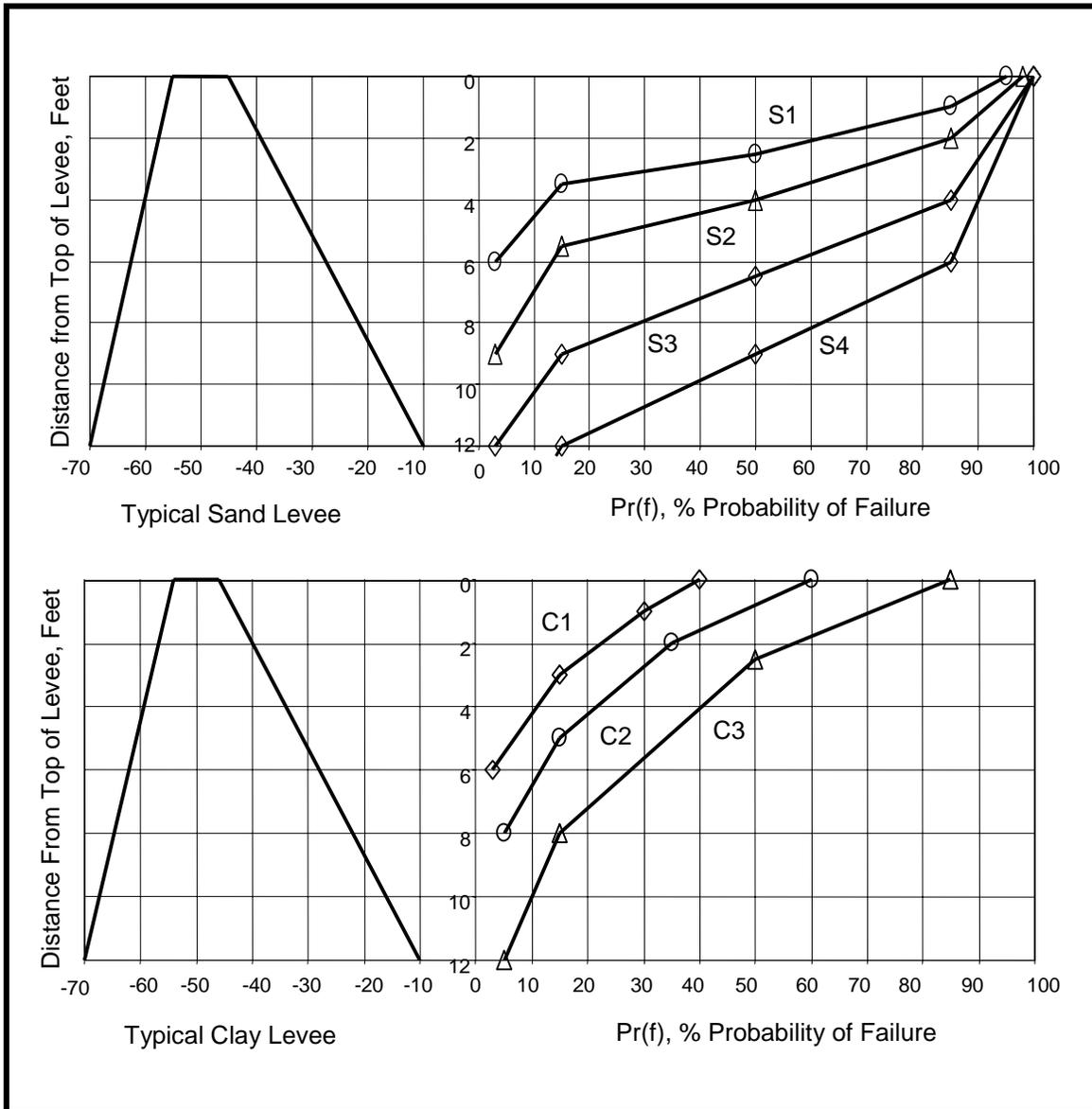
For the San Joaquin River basin levees, very little information was available for inclusion into the analysis. As a result, the State of California, Department of Water Resources (DWR) conducted an in-depth reconnaissance-level field inspection detailing existing and potential problem areas through discussions with levee maintenance personnel and on-site evaluations. Field work included collecting cross sectional data, identifying remnants of sand bag rings during flood fighting efforts to control boils and seepage, discussions with levee district personnel, and engineering judgment. From this knowledge, conditional probabilities of failure curves were generated. As a result of this field study, three general levee curves highlight the state of the levees in the San Joaquin River basin. Essentially, these curves typically depict the levees as behaving similar to sand levees.

In the Sacramento River basin, geotechnical information was gathered from Corps system evaluation reports dating from the initial system evaluation reports submitted by the Mark Group in 1988 and 1989, the Flood Control System Evaluation Reports of 1992, 1993, and 1994, and supplemental evaluations reports of 1996, 2000, and 2001. In addition to these reports, on-going flood system projects in construction, nearing construction, or completed were considered as work completed, or study “without project” conditions. Engineering judgment based on past performance during the 1997 and 1998 flood events contributed a significant amount to the creation of the levee curves. Since a majority of the levees in the Sacramento River basin were constructed of a variety of levee material ranging in composition from loose sand to engineered pervious and impervious materials, levee curves were created to reflect these diverse differences in levee material. As a result, three levee curves representing the strongly constructed levees, generally of clay or a sandy clay material, were generated. For the poorer quality constructed levees and some of the non-flood control system levees, four levee curves were generated. These curves reflect both known and unknown inherent levee deficiencies.

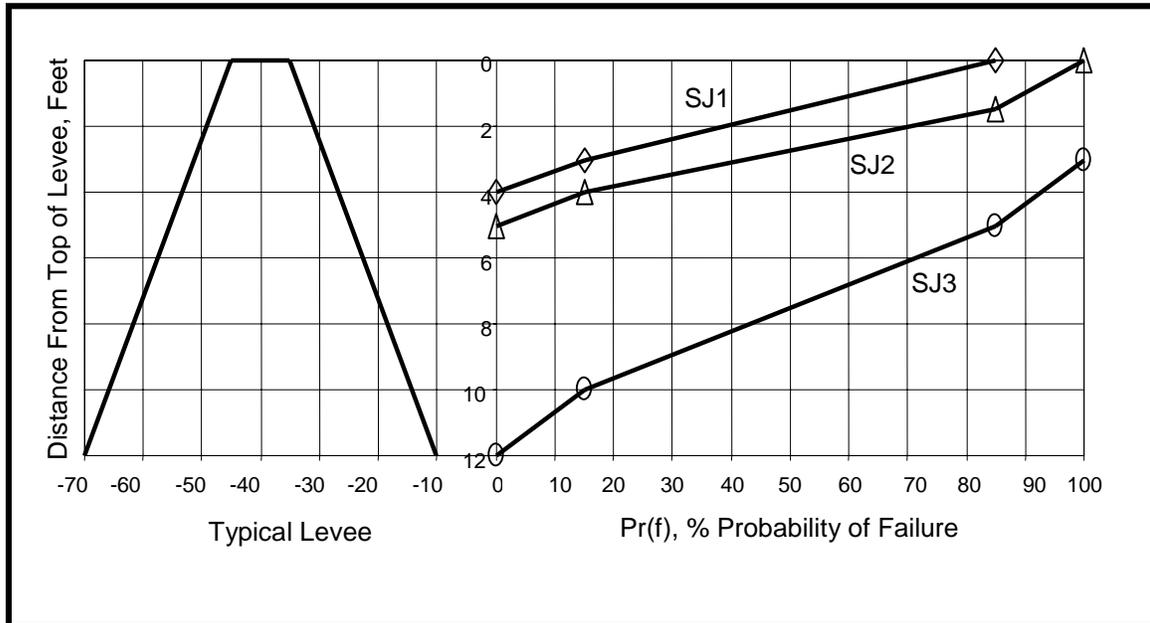
### ***Conditional Probability of Failure Curves***

The geotechnical conditional probability of failure curves developed for the Comprehensive Study are presented in **Figures G2-4 and G2-5** for the Sacramento and San Joaquin river basins, respectively. Levee reaches were assigned a conditional probability of failure curve representing the estimated weakest point in the reach. The designations were assigned by either the Corps Soil Design Section, Geotechnical Branch for the Sacramento District, or the Levees and Canals Division of DWR. Aspects of the evaluations include levee through-seepage, foundation (or under-seepage), and static stability. Judgment reflects the uncertainty in loading, performance, severity of unknown defects, and other unseen features.

These curves represent a more qualitative approach to evaluating the major aspects of levee integrity for very large flood control systems.



**FIGURE G2-4 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SACRAMENTO RIVER BASIN PROJECT LEVEES**



**FIGURE G2-5 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SAN JOAQUIN RIVER BASIN PROJECT LEVEES**

Tables G2-1 and G2-2 summarize the initial curves assigned reach by reach or area in the Sacramento and San Joaquin river basins, respectively. Both tables indicate river mile and tributary information. The curves can only be used for comparative economic analyses for the flood control systems and thus do not 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.

**TABLE G2-1  
ASSIGNMENT BY REACH OF SACRAMENTO RIVER BASIN  
CONDITIONAL PROBABILITY OF FAILURE CURVES**

Reach No.	Reach Description	River Miles	Design Capacity <sup>a</sup> (cfs)	Selected P(f) <sup>b</sup> Model	
				LB <sup>c</sup>	RB <sup>c</sup>
<b>1</b>	<b>Shasta Dam to Red Bluff</b>	<b>315 -245</b>	No Levees		
2	<b>Red Bluff to Chico Landing</b>	245 - 194			
	<i>Sacramento River</i>				
	Red Bluff to Elder Creek	245 - 230.5	N/A	N/A	
	Elder Creek to Deer Creek	230.5 - 220	N/A	N/A	
	Deer Creek to Chico Landing	220 - 194	N/A	N/A	
	<i>Tributaries</i>				
	Elder Creek		N/A	C2	C2
Deer Creek		N/A	C2	C2	
3	<b>Chico Landing to Colusa</b>	<b>194 - 146</b>			
	<i>Sacramento River</i>				
	Chico Landing to head of east levee	194 - 176	N/A	N/A	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	<b>Colusa to Verona</b>	<b>146 - 80</b>			
	<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 G2-1 (CONT.)**

Reach No.	Measure Reach Description	River Miles	Design Capacity, Q <sup>a</sup>	Selected P(f) <sup>b</sup> Model	
				LB <sup>a</sup>	RB <sup>a</sup>
5	<b>Verona To Steamboat Slough</b>	<b>80 - 32.3</b>			
	<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	<b>Steamboat Slough To Collinsville</b>	<b>32.3 - 0</b>			
	<i>Sacramento River</i>				
	Steamboat Sl. To head of Georgiana Sl.	26.5 - 32.3	56,500	S3	S3
	Georgiana Sl. To Cache Sl. - Junct. Pt	14 - 26.5	35,900	S3	S3
	Cache Sl. To 3-mile Sl.	9 - 14	N/A	S4	
	3-Mile Slough to Collinsville	0 - 9	N/A	S4	
	<i>Tributaries</i>				
	Elk Slough	0 - 9	N/A	S3	S3
	3-Mile Slough	0 - 3	65,000	S4	S4
	Steamboat Slough	0 - 6.5	43,500	S2	S3
	<i>Sutter Slough - Steamboat to Miner</i>	0 - 2.5	15,500	S3	S3
	<i>Sutter Slough - Miner to Sacramento River</i>	2.5 - 7	25,500	S4	S3
Georgiana Slough	0 - 10	20,600	S4	S4	

Notes

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

**TABLE G2-2  
ASSIGNMENT BY REACH OF SAN JOAQUIN RIVER BASIN  
CONDITIONAL PROBABILITY OF FAILURE CURVES**

Reach No.	Reach Description	River Miles	Design Capacity <sup>a</sup> (cfs)	Selected P(f) <sup>b</sup> Model
A	<b>Mendota Dam to Friant Dam</b>	<b>205 To 286</b>		
	San Joaquin River		2,500 – 8,000	SJ1
	Fresno Slough & James Bypass		4,750	SJ1
B	<b>Sand Slough Control Structure to Mendota Dam</b>	<b>168 to 205</b>		
	San Joaquin River		4,500	SJ2
	Chowchilla Bypass / Eastside Bypass		5,500 – 17,000	SJ2
	Tributaries			
	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	<b>Merced River to Sand Slough Control Structure</b>	<b>118 to 168</b>		
	San Joaquin River			
	Merced River to Eastside Bypass		26,000	SJ2
	Eastside Bypass to Control Structure		1,500-10,000	SJ2
	Eastside Bypass		13,500 – 16,500	SJ2
	Deep Slough		18,500	SJ2
	Bear Creek		7,000	SJ2
	Mariposa Bypass		8,500	SJ2
D	<b>Stanislaus River to Merced River</b>	<b>75 to 118</b>		
	San Joaquin River		45,000 – 46,000	SJ3
	Merced River		6,000	SJ2
	Tuolumne River		15,000	SJ3
	Dry Creek		N/A	SJ3
	Stanislaus River		8,000	SJ3
E	<b>Deep Ship Channel to Stanislaus River</b>	<b>40 to 75</b>		
	San Joaquin River		37,000 – 52,000	SJ3
	Tributaries			
	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) Advertised design flow capacity per DWR (May 1985)  
b) P(f) = Conditional Probability of Failure (applies to left and right bank levees).

The frequency and magnitude of physical changes and failure events affect levee integrity. Physical conditions will naturally change within the project's life. These changes may lead to unsatisfactory performance. Hence, a conditional probability of failure function for any of the levees within the systems is time-dependent and subject to change.

### ***Additional Changes to the Levee Curves***

Initial hydraulic modeling using the conditional probability of failure curves and subsequent generation of inundation areas in the Sacramento River basin indicated that the initially selected conditional probability of failure curves required adjustment. The modeling results obtained using a LFP corresponding to a 50 percent probability of failure did not reflect expected conditions for the left and right bank of the American River, and the left bank of the Sacramento River from Verona to Freeport. This issue was reviewed and the decision was made to select a more appropriate curve that would better describe the conditional probability of failure for these reaches:

1. For levees on the American River, the S3 curve (representing a LFP of 6-1/2 feet below top of levee) was replaced with the S1 Curve (representing a LFP of 2-1/2 feet below top of levee).
2. For the left bank of the Sacramento River from Verona to Freeport (a distance of about 33 miles), the S2 curve representing a LFP of 4 feet below top of levee was deemed appropriate.

References used to assist in this re-evaluation were: 1) MFR dated 23 March 1998, Review of Alternative 7 Flood Elevation of the Left Bank levee Sacramento River from I Street to Freeport; 2) MFR dated 30 April 1999, FEMA Certification for 100-year Water Surface, Sacramento River and American River Levees; and 3) MFR for PD dated 12 May 2000.

### ***Considerations***

Use of the likely failure point 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. 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. Furthermore, geotechnical conditions are not static, and the geotechnical data used in developing projects should be re-evaluated and updated whenever information becomes available.

## **SUMMARY AND CONCLUSIONS**

It is anticipated that the geotechnical levee performance curves and their application in the basins will change as additional technical evaluations are performed. These curves were developed for use in regional and basin-wide analyses. Therefore, additional work will be required if they are to be used for more detailed feasibility studies.

Probable failure point and probable non-failure point elevations were estimated for the existing levee system in the San Joaquin River basin. However, geotechnical explorations and evaluations were very scarce, and soil explorations and testing will be necessary to obtain geotechnical information in some reaches of the San Joaquin River during later studies. Previous geotechnical investigations performed for the Corps' Sacramento River Flood Control System Evaluation were used for an initial evaluation of Sacramento River levees. Additional information based on past performance, especially through the 1997 and 1998 flood seasons and sound engineering judgment, were also used.

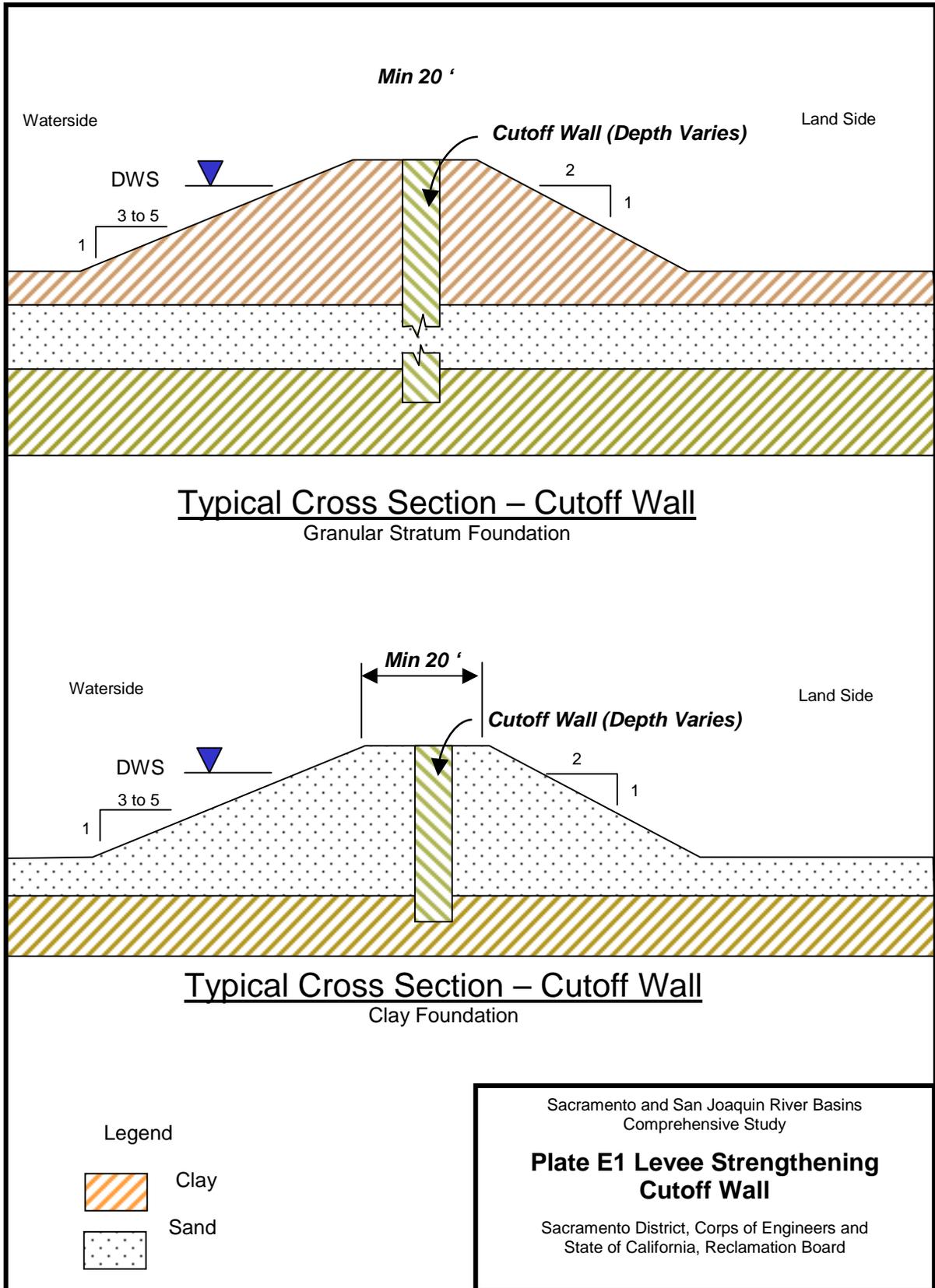
For future studies, more detailed geotechnical design will be required to provide alternate remedies for levees with structural problems and to provide designs for proposed new levees. Foundation design may also be required for some proposed structural measures. Levee strengthening alternatives are likely to include the following: berms both with and without landside toe ditches; cut-off walls for pervious levees, pervious foundations, or both; and levee raising with and without landside berms. **Plates E1, E2 and E3** illustrate six typical alternatives for levee strengthening. Typical cross sections for new engineered levees are illustrated in **Plate E4**.

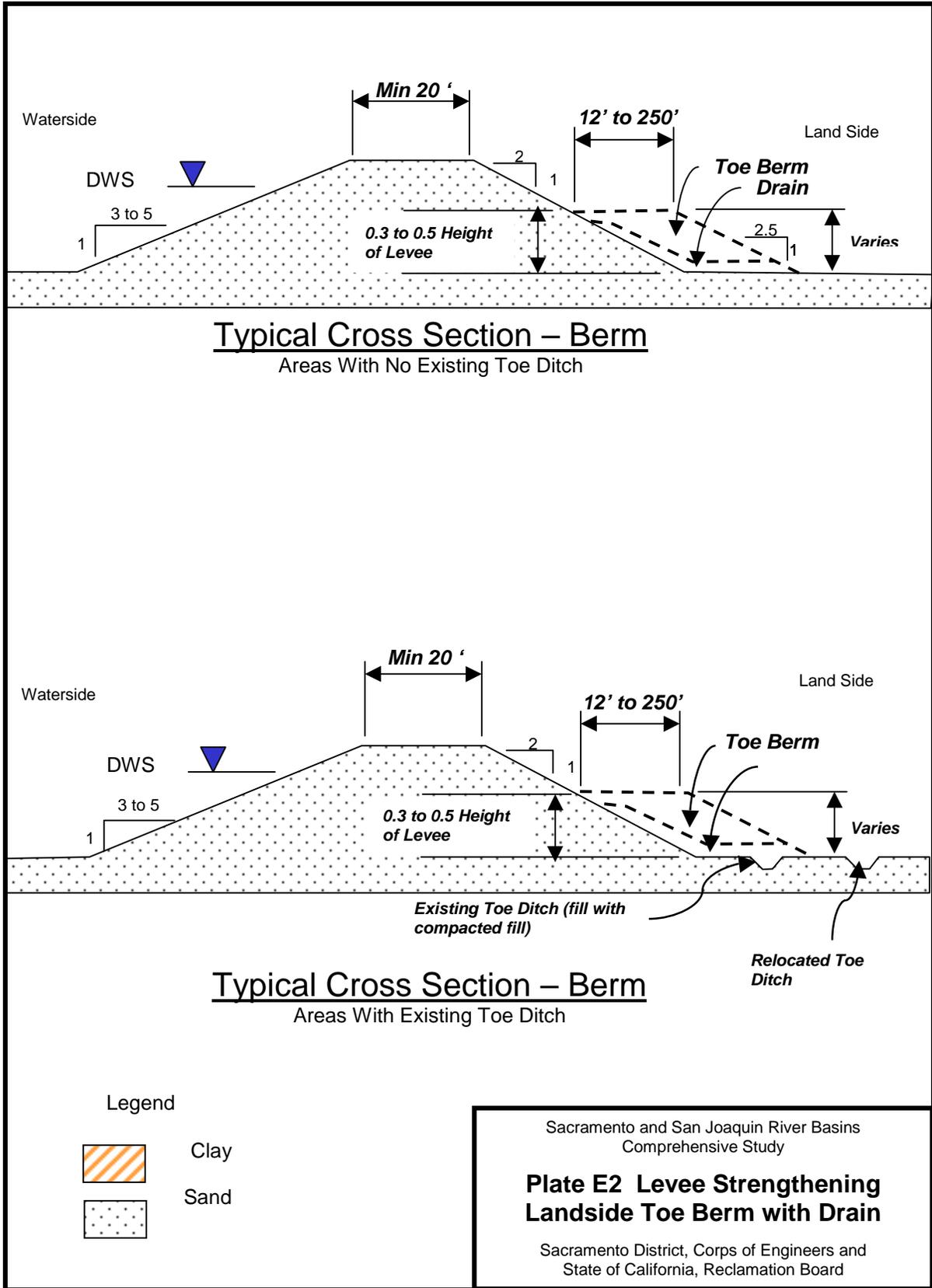
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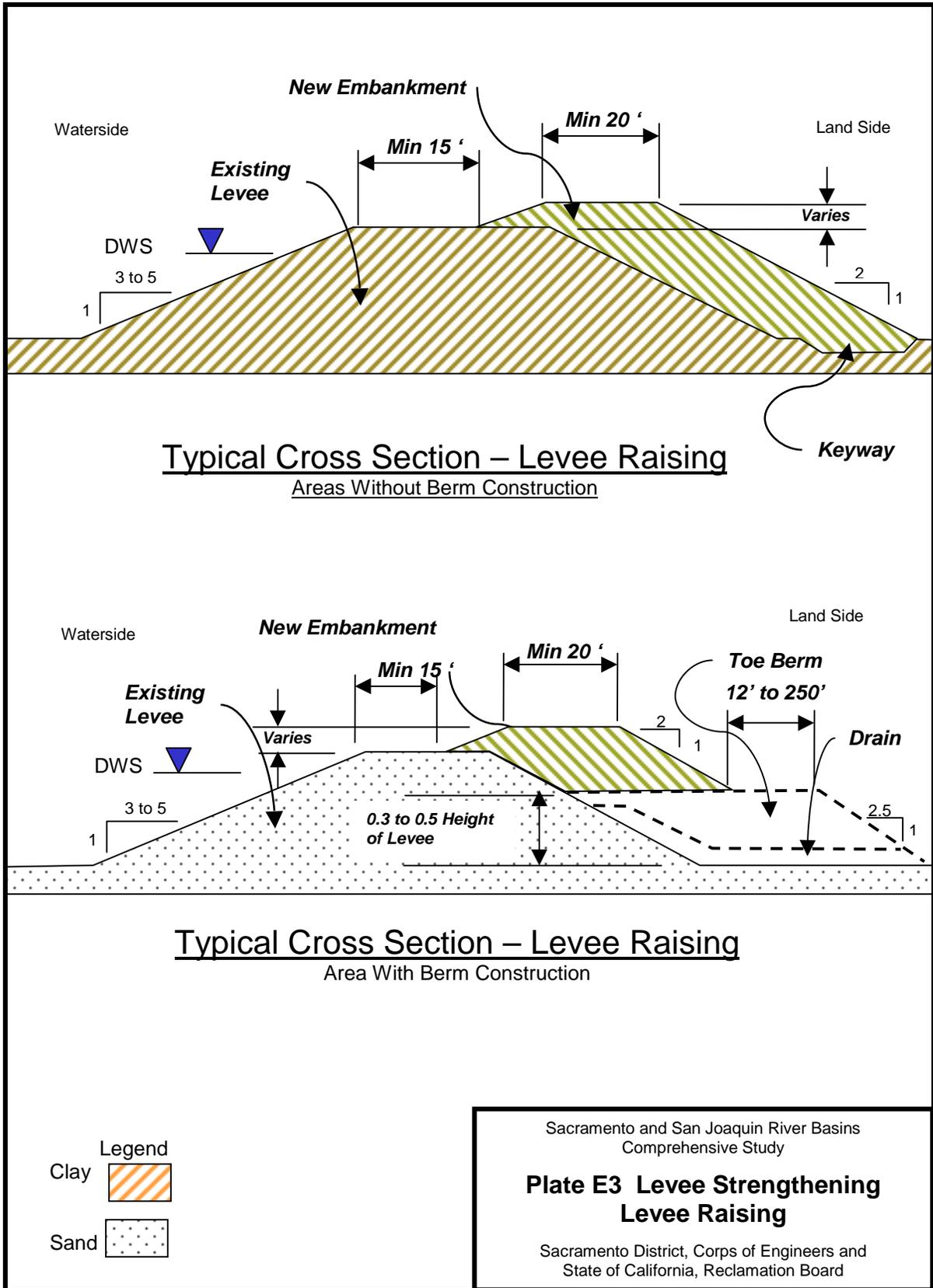
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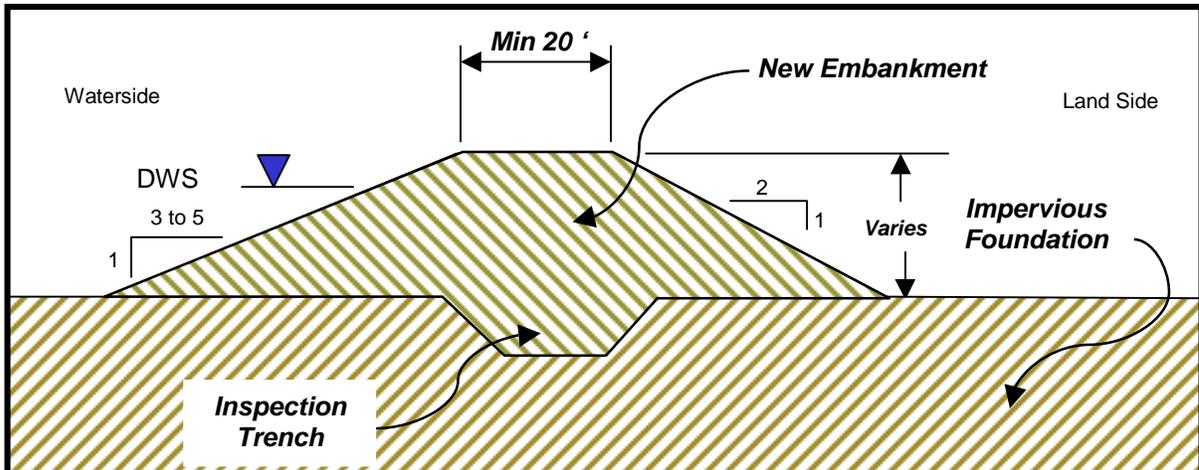
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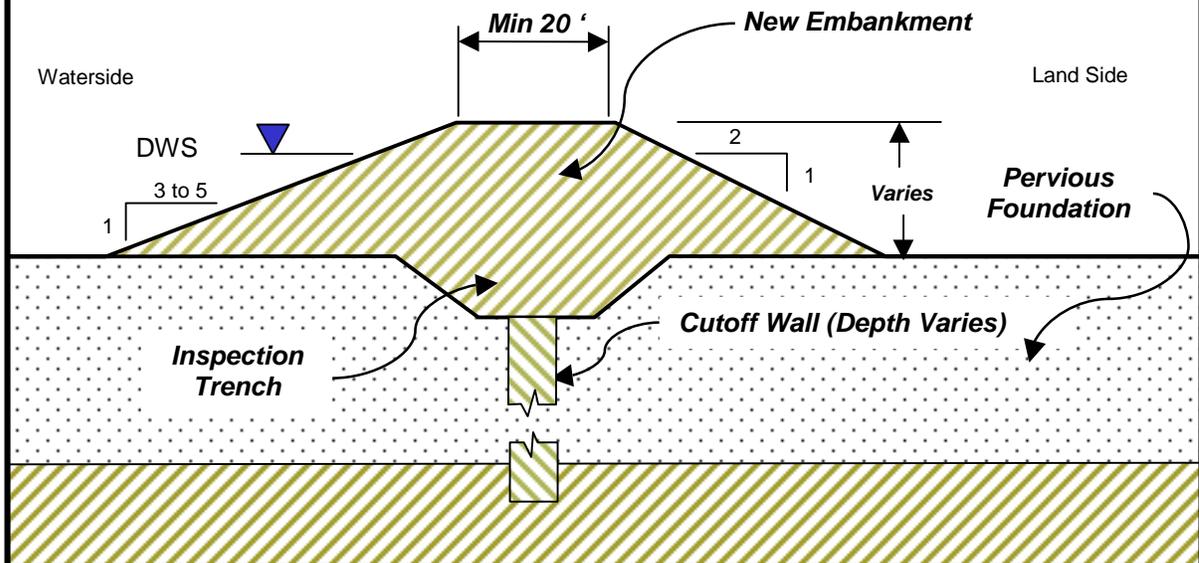




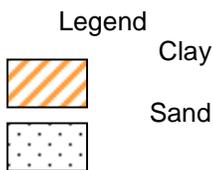




**Typical Cross Section – New Levee**  
Areas With Impervious Foundation



**Typical Cross Section – New Levee**  
Areas With Pervious Foundation



Sacramento and San Joaquin River Basins  
Comprehensive Study

**Plate E4 Levee Alternatives  
New Levee**

Sacramento District, Corps of Engineers and  
State of California, Reclamation Board