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Sacramento
and
San Joaquin
River Basins

Comprehensive Study

TECHNICAL STUDIES DOCUMENTATION

THE RECLAMATION BOARD
STATE OF CALIFORNIA

US Army Corps
of Engineers
Sacramento District

TABLE OF CONTENTS

REFERENCES

GLOSSARY OF TERMS AND ABBREVIATIONS

TABLES

FIGURES

TECHNICAL APPENDICES

SUMMARY OF TECHNICAL STUDIES

FOR THE

SACRAMENTO AND SAN JOAQUIN RIVER BASINS, CALIFORNIA COMPREHENSIVE STUDY

Numerous technical analyses were conducted during the Sacramento and San Joaquin River Basins Comprehensive Study (Comprehensive Study) to inventory resource conditions in the study area and to analyze problems and opportunities for flood management and ecosystem restoration. These studies were performed using an unprecedented suite of technical modeling tools developed by the U.S. Army Corps of Engineers, Sacramento District (Corps) and the California Department of Water Resources (DWR) to simulate the hydrology, hydraulics, ecosystem function, flood risk and associated economic damages in the Sacramento and San Joaquin river systems. Extensive data were collected to support these models and studies, including topography, historic stream flows, sedimentation and geomorphologic data, geotechnical data, land use, and economic data. The models will be used by the Corps, DWR, and others in developing future flood management and environmental improvement projects in the Sacramento and San Joaquin river basins. Opportunities for future projects and discussion of other aspects of the Comprehensive Plan can be found in the *Interim Report, Sacramento and San Joaquin River Basins Comprehensive Study, California*, 2002.

The following provides a summary of the technical tools and analyses performed to date under the Comprehensive Study and describes how the various technical tools can be used individually and collectively to evaluate potential system-wide solutions. The attached technical appendices contain detailed descriptions of the models and other technical tools used by the Comprehensive Study:

Appendix A – Information Papers

Appendix B – Synthetic Hydrology Technical Documentation

Appendix C – Reservoir Operations Modeling

Appendix D – Hydraulic Technical Documentation

Appendix E – Risk Analysis

Appendix F – Economics Technical Documentation

Appendix G – Ecosystem Functions Model

INTRODUCTION

The Sacramento and San Joaquin river basins cover a drainage area of over 43,000 square miles, shown in **Figure 1**. A mixture of climate conditions, geologic formations, river attributes, natural resources and habitats, flood management infrastructure, and rural and urban development characterizes this large study area. Past flood damage reduction and environmental restoration projects have typically examined single resources or relatively small portions of the system, with little consideration of impacts to adjacent reaches or cumulative impacts to the river system as a whole. The Comprehensive Study has performed more extensive, watershed-based analyses. A new set of technical tools was required to perform these system-wide evaluations of opportunities to improve flood management and the ecosystem in the diverse river systems of the Central Valley, summarized in **Table 1**.

TABLE 1
COMPREHENSIVE STUDY TECHNICAL EVALUATION TOOLS

Topic	Technical Product	Description
Surveys and Mapping	Topography Digital Terrain Models Aerial Photographs	Mapping along the river corridors of the Sacramento and San Joaquin rivers, their major tributaries, and bypass systems.
Hydrology	Synthetic Hydrology	Unregulated synthetic flood hydrology for multiple storm runoff conditions in the valley, including events with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurrence in any given year
	HEC-5 Models	Simulates the operation of 73 headwater and foothill reservoirs tributary to the Sacramento and San Joaquin Rivers
Hydraulics	UNET Models	Simulates river system hydraulics for over 1,000 miles of Central Valley rivers, flood bypasses, and other major waterways
	FLO-2D Models	Simulates the movement of water through valley floodplains
	DSM2 (Delta Simulation Model 2)	Evaluates potential impacts to complex hydrodynamic conditions in the Sacramento-San Joaquin Delta
Geotechnical	Levee performance curves	Series of curves approximating the probability of failure of levees within the Sacramento and San Joaquin River basins
Flood Risk and Economics	HEC-FDA (Flood Damage Analysis)	Evaluates existing flood risk and economic damages in the Central Valley, incorporating risk and uncertainty
Ecosystem	EFM (Ecosystem Functions Model)	Gauges the response of riparian, wetland, and riverine habitats to changes in hydrology and riverine hydraulics
Information Management	GIS (Geographic Information System)	Geographic database of the Sacramento and San Joaquin River basins (including hydrography, habitat, urban development and infrastructure, flood management facilities, properties, geology, and much more)
	CAD (Computer Aided Design)	Riverine topography and bathymetry, digital elevation models, aerial photos, river and levee alignments

The topography, hydrology, modeling tools, and other data developed for the Comprehensive Study will be a valuable resource for future studies in the Central Valley. The study tools, assumptions, and evaluation approach are tailored to be effective and efficient when applied to watershed-scale studies. While the level of detail is suitable for evaluation of the river systems as a whole, the tools and evaluation processes may not be suitable for detailed studies of smaller river reaches or local conditions. Future studies choosing to use the Comprehensive Study's tools should carefully consider their appropriateness and make individual determinations of whether the tools can fulfill their unique technical needs.

Study Area

The Comprehensive Study area shown in **Figure 1** includes the combined watersheds of the Sacramento and San Joaquin River basins. The study focuses on solving flooding and ecosystem problems within the floodplains of the Sacramento and San Joaquin rivers and the lower reaches of their major tributaries.

FIGURE 1 – STUDY AREA

The Tulare Lake basin is not included in the study area, although the contribution of flood flows from the Kings River to the San Joaquin River is considered. Flooding and related ecosystem problems on the Mokelumne, Calaveras, Cosumnes, and American rivers, and Cache Creek and other small streams are being addressed in other studies and are, therefore, not a primary focus of the Comprehensive Study. Similarly, while the Comprehensive Study has developed tools for evaluating impacts to the Sacramento-San Joaquin Delta, and the region may be included in future plans, the Delta it is not part of the primary study area.

Future Studies

It is anticipated that additional technical studies will be required in the future to support the development of specific regional and system-wide plans for flood damage reduction and ecosystem restoration. These include geomorphological studies; sediment transport tools; more detailed geotechnical analyses of levee performance; coordinated reservoir reoperation; and other studies to address local or regional concerns. These studies will be completed as part of future feasibility studies, as appropriate, and could utilize a variety of tools or methods; hence, they are not described in this document.

SURVEYS AND MAPPING

Many of the tools developed for the Comprehensive Study required updated surveys and mapping. This data includes topographic contour mapping, digital elevation models, and aerial photographs.

Extensive topographic data were collected to support development of the hydraulic models and is described in detail in *Appendix D - Hydraulic Technical Documentation*. In general, the mapping covers linear riverine reaches that include the main river channel, levees (if present), and the overbanks for a distance of approximately 300 feet landward of the levees. **Table 2** summarizes the river reaches where topographic data were collected. Black and white aerial photographs were also developed along the river corridors. Topographic data were collected using hydrographic, photogrammetric, and LIDAR mapping techniques. Bathymetric data provided detailed channel geometry below the waterline. In the overbanks, U.S. Geologic Survey (USGS) 30-meter digital elevation models (DEMs) and 10-meter DEMs, where available, were used in developing the hydraulic models.

At the onset of the study, current mapping in the Sacramento River basin was readily available from recent projects but data in the San Joaquin River basin was often dated or incomplete. Survey data in the Sacramento River basin was collected between 1995 and 1999 and consists primarily of 2-foot contour mapping above and below the waterline along the major watercourses. The exception is 5-foot contours developed in the Butte basin and 4-foot contour mapping along portions of the Feather River.

Due to the absence of current mapping, extensive topographic data were collected in the San Joaquin River basin specifically for the Comprehensive Study. Hydrographic and photogrammetric surveys of the San Joaquin River basin were conducted in 1998 and a survey of the overbank areas was conducted in 2000. Data were collected to produce 2-foot contour mapping above and below the waterline along the major watercourses.

TABLE 2
TOPOGRAPHIC DATA COLLECTION

Watercourse	**Reach**
Sacramento River Basin	
Sacramento River	Collinsville to Vina-Woodson Bridge
Steamboat Slough	Entire length
Sutter Slough	Entire length
Miner Slough	Entire length
Georgiana Slough	Entire length
Cache Slough	Lower end
Three Mile Slough	Entire length
Shag, Hass, and Lindsey Sloughs	Lower end
American River	Mouth at Sacramento River to Nimbus Dam
Yolo, Sutter, Tisdale & Sacramento Bypasses and Tributaries	Entire lengths of bypasses, lower ends of tributaries
Butte Basin	This data consists primarily of the east overbank between the Sutter Buttes and Vina-Woodson Bridge extending 3 to 11 miles to the east of the Sacramento River.
Feather River	Sutter Bypass to Oroville Dam
Yuba River	Feather River to the Narrows
Bear River	Feather River to Highway 65 (hydrographic data was not collected along the Bear River due to a dense canopy of vegetation which prohibited GPS equipment from functioning)
San Joaquin River Basin	
San Joaquin River	Stockton to Friant Dam
Middle River	North/Victoria Canals to Old River
Old River	Tracy Boulevard to San Joaquin River
Grant Line Canal	Tracy Boulevard to Doughty Cut
Doughty Cut	Grant Line Canal to Old River
Paradise Cut	Old River to San Joaquin River
Stanislaus River	San Joaquin River to Oakdale
Tuolumne River	Lower 12 miles
Laird Slough	Entire length
Merced River	San Joaquin River to above Highway 99
Bear Creek	San Joaquin River to East Side Canal
Deep Slough	Bear Creek to Eastside/Mariposa Bypasses
Mariposa Bypass	San Joaquin River to Eastside Bypass
Eastside/Chowchilla Bypass	Deep Slough to San Joaquin River
Ash Slough	Eastside Bypass to Highway 152
Berenda Slough	Eastside Bypass to Highway 152
Fresno River	Eastside Bypass too Road 16
Fresno Slough	San Joaquin River to James Slough
James Slough	Fresno Slough to James Road

Note: Data for the reaches listed above were collected along mainstem and tributary river corridors (extending approximately 300 feet landward of adjacent levees or natural banks) and within flood management bypasses and overflow basins.

HYDROLOGIC STUDIES

Historically, the Sacramento River basin has been subject to floods that result from winter and spring rainfall as well as rainfall combined with snowmelt. The San Joaquin River basin has been subject to floods that result from rainfall, during the late fall and winter months, and rapid melting of the winter snowpack during the spring and early summer months. The Comprehensive Study performed a system-wide update for Central Valley unregulated flood hydrology. The hydrology was specifically developed to provide a basis for defining existing hydrologic conditions on a regional scale, and support the analysis of an array of water resources opportunities in the Central Valley. *Appendix B - Synthetic Hydrology Technical Documentation* provides a detailed description of the development of study flood hydrology.

Technical Approach

Flooding dynamics of Central Valley tributaries were studied in order to quantify flood flows for individual tributaries and key mainstem locations along the Sacramento and San Joaquin Rivers. The large size of the study area required a unique hydrologic approach to reflect the occurrence of concurrent storms in the basins and account for natural, orographic influences (effects of topography on weather systems). Historic storm patterns were used to formulate storm runoff centerings that simulate flood scenarios involving multiple tributaries. Twenty-four different storm runoff centerings were created to emulate the diverse spectrum of floods that can occur in the Central Valley. Synthetic flood events were developed with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year. Because there are numerous ways to describe the statistical frequency of a flood event, **Table 3** provides a reference of equivalent terminology. Chance of occurrence and probability of exceedence are the preferred terms and are utilized in this summary documentation.

TABLE 3
COMMON FLOOD FREQUENCY TERMINOLOGY

Chance of Occurring in Any Year *The chance that a specific flood event will occur in any given year*	**Probability of Exceedence** *The probability that a flood of this magnitude will occur (or be exceeded) in any given year, commonly expressed as a percentage*	**Average Return Frequency, years** *The period of time between flood events of this magnitude, averaged over many thousands of years, expressed in years*[1]
1 in 2	50%	2
1 in 10	10%	10
1 in 25	4%	25
1 in 50	2%	50
1 in 100	1%	100
1 in 200	0.5%	200
1 in 500	0.2%	500
1 in 1000	0.1%	1000

1. A flood with an average return frequency of 100 years, commonly referred to as a 100-year flood, is often misunderstood to mean that this event will occur only once in a lifetime. However, because flood return frequency is a statistical average over many thousands of years, a 1% flood could occur multiple times during any given century, or not at all.

Method of Analysis

The analysis performed for this study was based on the "composite floodplain" concept. This concept recognizes that the floodplain with an X% probability of occurring (the area with an X% chance of being flooded in any year) is created by a combination of several flood events, each of which shapes the floodplain at different locations within the system and at different times. The synthetic hydrology for the Comprehensive Study was developed to ensure that the composite floodplain represents the maximum extent of inundation for any given flood frequency. A single storm runoff centering forms only a portion of the composite floodplain; other storm centerings are combined to define the maximum extent of the composite floodplain. The composite floodplain becomes increasingly complex the further one moves downstream due to the confluence of additional tributaries, each of which contribute to the shape of the composite floodplain. The composite floodplain approach is illustrated in **Figure 2**.

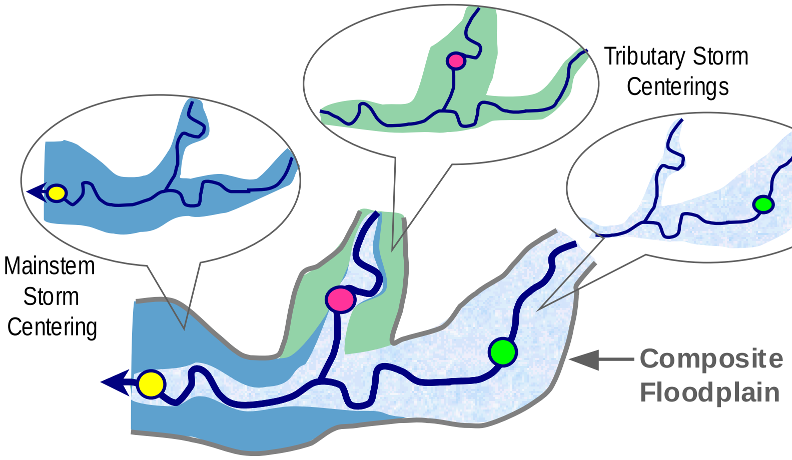


Figure 2 – Use of Storm Centerings to Develop Composite Floodplain

The synthetic hydrology analysis investigated three fundamental subjects during the formulation of synthetic flood events:

1) The total volume of runoff produced during a given flood event,
2) The contribution of individual tributaries to this total volume, and
3) The translation of these flood volumes and distributions to hourly time series for input to the reservoir simulation models.

Unregulated rain flood frequency curves were developed at 8 locations along the mainstems of the Sacramento and San Joaquin rivers, and at 43 locations along major tributaries. These frequency curves are "unregulated" because they do not reflect the influence of reservoirs. Curves were constructed for durations of 3-, 5-, 7-, 10-, 15-, and 30-days. Data from the tributaries were used to construct the curves for downstream mainstem points. The curves were developed or updated to reflect post-1997 hydrology.

Calibration

Flood flows in mainstem rivers were simulated by routing hydrographs from upstream tributaries. In order to verify that mainstem flows were representative of the frequency analysis, hydrographs at mainstem points were compared to unregulated frequency curves at each mainstem point. Storm runoff patterns were then adjusted iteratively until routed results balanced with flows from the unregulated frequency curves. This verification was performed for all durations and return periods at each mainstem location.

Results of Storm Centerings

Nineteen historic flood events were analyzed at tributary and mainstem locations in the Central Valley. The probability of occurrence for each event was recorded for all locations and tabulated into storm matrices for the Sacramento and San Joaquin river basins. Analysis of these matrices revealed several important trends that were used to formulate guidelines for storm centering development and construct synthetic storm runoff centerings. Storm runoff centerings were then developed for 5 mainstem locations and 18 tributaries for the seven flood frequencies.

The hydrology of each storm centering reflects a flood that stresses a single tributary or mainstem location. In **Figure 3**, each bar graph represents a storm centered at the adjacent index location (A, B, C, or D). The height of each bar indicates the relative frequency of flow at each location for that centering, with taller bars representing larger, less frequent events. For example, a large flood event centered at location A results from a combination of smaller floods on upstream tributaries B, C, and D; hence, the bar for A is taller than the bars for locations B, C, and D. In keeping with this methodology, a 2% flood centered on tributary B would likely be concurrent with somewhat smaller storm events on adjacent tributaries C and D, and result in flows with less than a 2% probability downstream at point A.

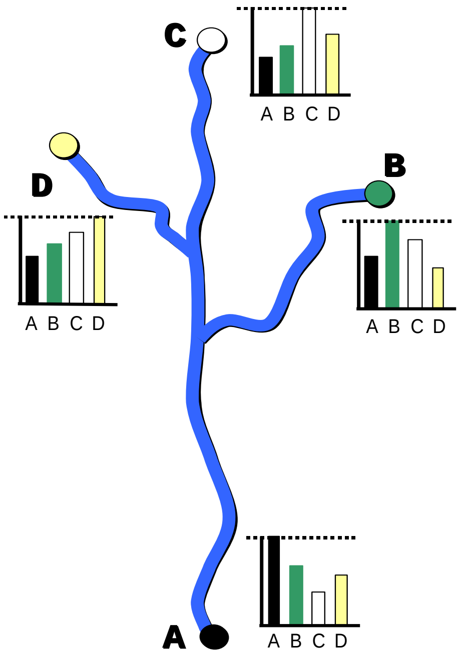


FIGURE 3 – STORM RUNOFF CENTERING APPROACH

An example of a storm centering at Ord Ferry on the Sacramento River is shown in **Table 4**. The table illustrates that a mainstem storm is composed of a combination of smaller storms on the tributaries. Although the tributaries downstream from Ord Ferry do not contribute to flows at the centering location, their frequencies reflect patterns observed in historic storm events. For example, a flood with a 2% probability of occurring in any year at Ord Ferry is typically characterized by flows with a 2.41% chance of occurring on the Sacramento River at Shasta, a 5.62% chance of occurring on Clear Creek at Whiskeytown, and so forth. A description and complete listing of flood centering tables for mainstem locations and tributaries can be found in *Appendix B - Synthetic Hydrology Technical Documentation.*

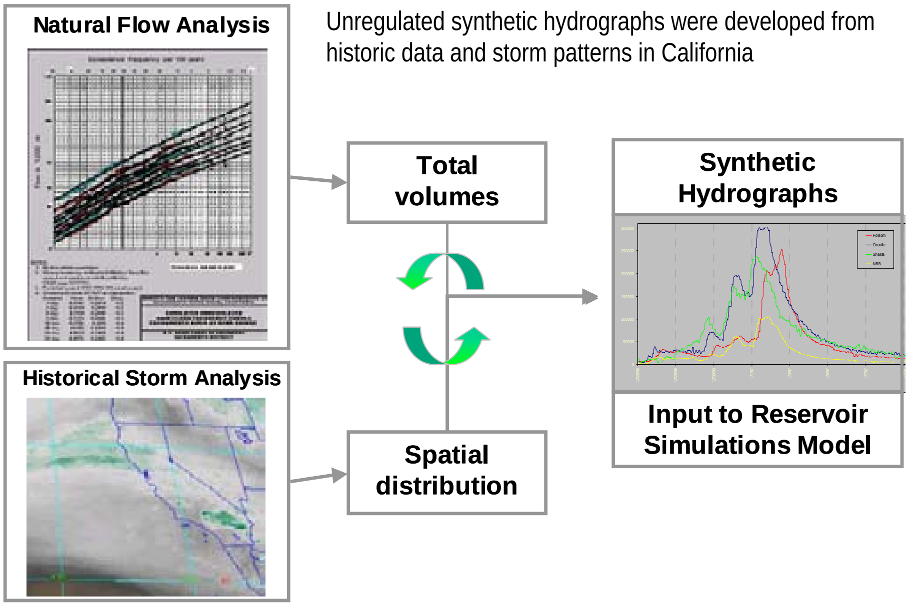
TABLE 4
EXAMPLE OF A MAINSTEM FLOOD CENTERING TABLE

Sacramento River Mainstem at Latitude of Ord Ferry

Index Point	Index No.	Flood Event (% Chance of Occurring in any Year)						
		50%	**10%**	**4%**	**2%**	**1%**	**0.50%**	**0.20%**
Sacramento R at Shasta	1	81.97	16.92	5.71	2.41	1.25	0.65	0.28
Clear Cr at Whiskeytown	2	61.73	15.04	9.03	5.61	2.92	1.52	0.65
Cow Cr nr Millville	4	61.73	13.53	8.02	3.89	2.02	1.05	0.45
Cottonwood Cr nr Cottonwood	3	61.73	15.04	9.03	5.61	2.92	1.52	0.65
Battle Cr below Coleman FH	5	61.73	13.53	8.02	3.89	2.02	1.05	0.45
Mill Cr nr Los Molinos	6	87.72	**15.04**	7.22	5.94	3.10	1.61	0.69
Elder Cr nr Paskenta	7	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Thomes Cr at Paskenta	8	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Deer Cr nr Vina	9	87.72	15.04	7.22	5.94	3.10	1.61	0.69
Big Chico Cr nr Chico	10	87.72	15.04	7.22	5.94	3.10	1.61	0.69
Stony Cr at Black Butte	11	87.72	19.34	12.50	10.10	5.26	2.74	1.17
Butte Cr nr Chico	12	87.72	15.04	10.20	8.42	4.39	2.28	0.97
Feather R at Oroville	13	87.72	19.34	9.62	8.42	4.39	2.28	0.97
Yuba R at New Bullards Bar	14	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Yuba R at Englebright	16	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Deer Cr nr Smartsville	15	87.72	19.34	11.76	9.18	4.78	2.49	1.06
Bear R nr Wheatland	17	87.72	19.34	12.03	10.10	5.26	2.74	1.17
Cache Cr at Clear Lake	18	87.72	19.34	18.05	12.63	6.58	3.42	1.46
N Fk Cache Ck at Indian Valley	19	87.72	19.34	18.05	12.63	6.58	3.42	1.46
American River at Folsom	20	87.72	19.34	14.29	12.63	6.58	3.42	1.46
Putah Cr at Berryessa	21	87.72	19.34	18.05	12.63	6.58	3.42	1.46

Notes:
The values listed for each index point and flood event represent the % chance of occurrence in any year. For example, during a 10% flood centered at Ord Ferry, concurrent flows would be experienced on Mill Creek that correspond to about a 15% chance at Mill Creek near Los Molinos (bold).

The final step of the synthetic hydrology development involved the translation of frequencies to hourly flood hydrographs for all tributaries. Mainstem flood hydrographs were determined from the routed results of upstream tributaries. This translation process involved three steps: 1) obtaining the average flood flow rates from the unregulated frequency curves; 2) converting these flows into wave volumes; and 3) distributing these volumes into six 5-day wave series. **Figure 4** illustrates the development of the synthetic hydrographs. These hydrographs were then used as input for reservoir simulations and hydraulic modeling, discussed in later sections.



Unregulated synthetic hydrographs were developed from historic data and storm patterns in California

FIGURE 4 – DEVELOPMENT OF SYNTHETIC RAIN FLOOD HYDROGRAPHS

Assumptions and Limitations

The hydrology for the Comprehensive Study was created with the following assumptions and limitations:

- The data are stationary. Hydrology is based on statistics that change over time, requiring periodic update.
- The natural flow frequency curves are strictly rainflood frequency curves. Snowmelt runoff is not directly incorporated into the analysis.
- Centering hydrographs are predicated on flood runoff, not precipitation. The approach was driven entirely by historic flow data; precipitation never entered into any portion of the methodology.
- Storm runoff centerings were formulated based on the composite floodplain concept.
- The unregulated frequency curves computed for the Comprehensive Study were created by following procedures outlined in Bulletin 17B “Guidelines for Determining Flood Flow Frequency”.
- Travel times and attenuation factors (Muskingum coefficients) are fixed for all simulated exceedence frequencies.
- Mainstem unregulated flow frequency curves were designed to quantify the total flows that the basins produced in rainfloods, not the average natural flows expected at mainstem locations during any of the synthetic exceedence frequency storm events.
- Patterns for synthetic floods are formulated based on historic storms.

RESERVOIR OPERATIONS STUDIES

Reservoir operations models were used to simulate the affects of reservoirs on flood flows within the study area. The reservoir operation models translate unregulated flood inflow hydrographs into regulated hydrographs below the reservoirs. These regulated hydrographs are then used as input into the hydraulic models, which perform detailed routings of flood flows throughout the valley. Reservoirs were included in the operations model if they had existing flood management functions or a storage capacity greater than 10,000 acre-feet. In total, 73 reservoirs were modeled, making this the largest application of the Corps' HEC-5 model for flood simulation. The Comprehensive Study's HEC-5 models were not designed to reflect all the details of complex reservoir operations, but rather to serve as a tool that simulates the functions of a highly managed system. *Appendix C – Reservoir Operations Modeling* provides a more detailed description of the development and use of the HEC-5 models.

Technical Approach

HEC-5 simulation models were developed for both the Sacramento and San Joaquin River basins. Due to the large number of facilities and control points, the models were further split into headwater and lower basin models (4 separate models). Headwater reservoirs include smaller facilities in the upper watersheds that operate primarily for hydropower, water supply, or other purposes. The headwater reservoirs are upstream from the lower basin reservoirs, which include the large flood management facilities located primarily in the foothills. These models were designed with two goals in mind. The first was to develop models that accurately depict present operations in the existing flood management system (baseline conditions). Guidelines established within each reservoir's water control manual were strictly observed. The second was to assure that the models used to define the baseline conditions had the versatility to analyze proposed reservoir system modifications effectively. Modifications could include changes to the operation of existing reservoirs or the addition of new flood management reservoirs.

A three-step process was required to analyze each storm runoff centering. First, the headwater reservoirs were simulated. Second, results from those headwater facilities that have credit space agreements with lower-basin reservoirs were used to determine top of conservation storage for those reservoirs. Finally, the results from the headwater reservoir models and the computed top of conservation storage series were used as input to the lower basin models for simulation. The result is regulated flood flows downstream from the lower basin flood management reservoirs.

Calibration

The HEC-5 models were calibrated individually using the design flood routings specified in the water control manual of each reservoir. Comparisons were also made between the 1995 and 1997 flood events and manual routings. HEC-5 simulations were performed for various design floods found in these manuals. The results were compared to manual routings and the recession constant was adjusted iteratively until results reflected the operations outlined by the emergency spillway release diagram as closely as possible. The objective of this calibration procedure was to accurately portray the "by the book" operations found in the water control manuals.

Assumptions and Limitations

The HEC-5 models developed for the Comprehensive Study were created with assumptions and limitations as documented in the "Expectations of Use" preface to Appendix C. They were created for use with the synthetic 30-day hourly hydrographs developed specifically for the Comprehensive Study. Adjustments may be needed to simulate other time steps or series. In particular, assumptions should be noted regarding starting storage levels for both the headwater and lower basin reservoirs; the simulation of stepped and multi-parameter release schedules; routing parameters; local flows; and losses.

Model Output

Figure 5 shows an example of a flood routing through Don Pedro Reservoir. Similar information was developed at each modeled reservoir for each flood event and storm runoff centering.

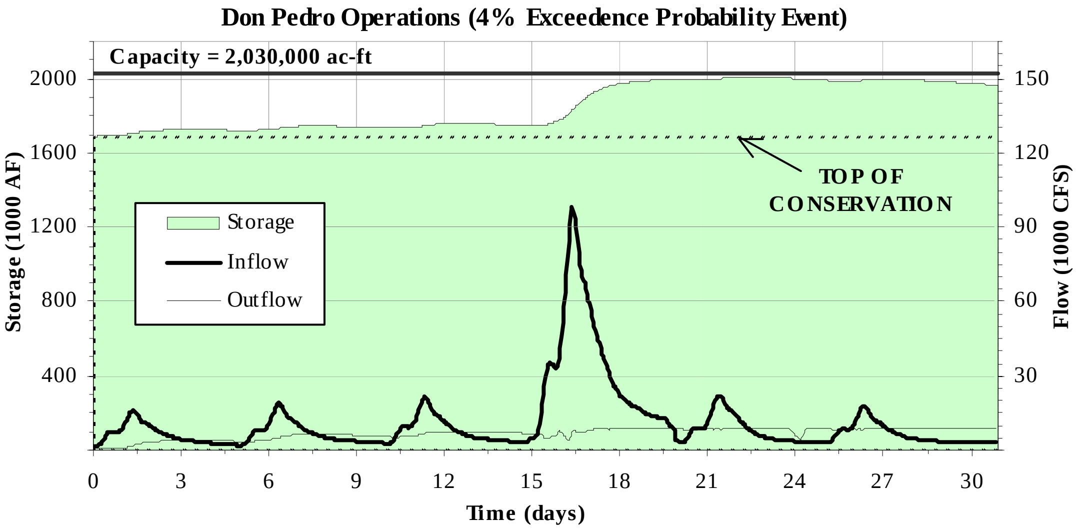
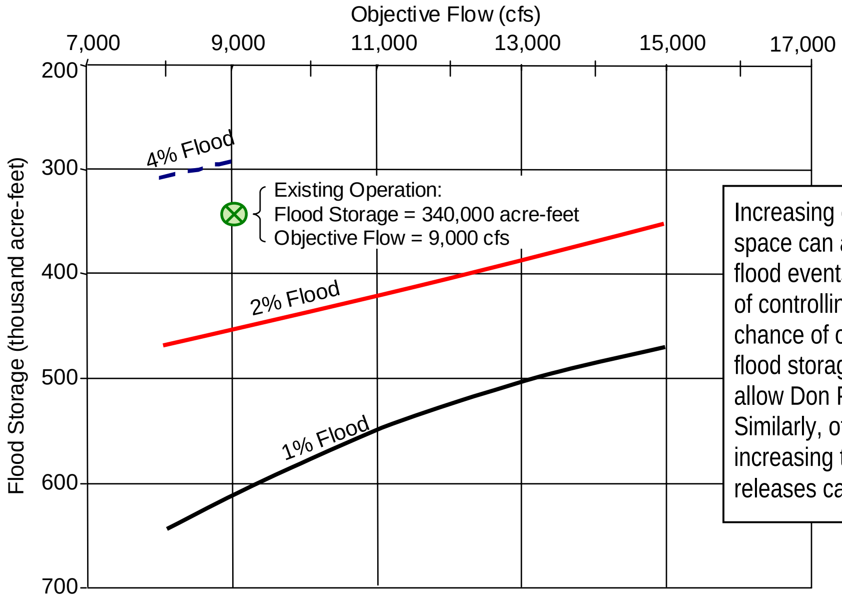


FIGURE 5 - SAMPLE RESULTS FROM HEC-5 LOWER-BASIN SIMULATION

The HEC-5 models were also used to evaluate opportunities to reoperate or modify the existing reservoir system. These evaluations were completed by modifying the HEC-5 model's representation of an individual reservoir's flood operating criteria; for example, increasing its available flood storage space, or increasing its objective release criteria. Such adjustments were made based on knowledge gained from historical operations, physical constraints of the existing flood conveyance system, and engineering judgement. These scenarios provided information on potential physical and operational changes to existing flood management reservoirs. An example analysis of Don Pedro Dam is shown in **Figure 6**.

Another approach to flood management is to find areas to which peak flood volumes can be diverted. In the case of off-stream storage for flood management, excess flood flows are diverted from the river channel into an adjacent storage area to reduce the flow or stage within the main channel. Several off-stream storage areas in the floodplain were incorporated into the baseline simulation model to represent how the existing flood management system would function with additional floodplain storage. This modified baseline model was used assess the effect on in-stream flow peak volumes and durations.



Existing Operation:
Flood Storage = 340,000 acre-feet
Objective Flow = 9,000 cfs

Increasing objective flow or flood storage space can allow a reservoir to control larger flood events. Don Pedro is currently capable of controlling a flood with less than a 4% chance of occurring in any year. Increasing flood storage to about 450,000 acre-feet could allow Don Pedro to control the 2% flood. Similarly, other reservoirs can benefit from increasing their objective flow, provided the releases can be accommodated downstream.

FIGURE 6 – OPERATIONAL ANALYSIS OF DON PEDRO DAM

Future Reservoir Operations Studies

The HEC-5 flood operations simulation models developed for the Comprehensive Study are dynamic in nature and will continue to be refined and modified as the current applications demand. Future changes might include: refining reservoir storage zones; detailing release priority zones within the active flood storage zone; adding additional river locations to which reservoirs must operate to maintain specified flows; or detailing some of the physical constraints of the model, such as starting reservoir storages, outlet and channel capacities, or release change rates. Future technical studies using the reservoir operations models could include the following:

Modification of Headwater Operations

The current structural design of the models dictates that the headwater reservoir models exist separately from their respective lower basin models. Future efforts might include eliminating this separation and combining the headwater models with the lower basin models, allowing a more seamless accounting of headwater storage space credited to lower basin reservoirs.

Systematic/Coordinated Reservoir Operations

Within the Sacramento and San Joaquin river basins, one of the existing operating practices of each flood managment reservoir requires that the reservoir maintain downstream flows at a rate specific for that individual tributary. It is the primary objective of each flood control facility to provide regulation for the stream on which it is located: hence, the release criteria focus mainly on the immediate impacts downstream from the reservoir and, in so far as possible, managing to lessen potential impacts of concurrent releases from other reservoirs. The baseline HEC-5 simulation model could be modified to acknowledge and operate for flows occurring elsewhere in the system, minizing the cumulative impact that a reservoir's releases might have on the timing and volume of peak flows outside its immediate sphere of influence.

Potential Foresight and Pre-Release Mechanisms

In real-time operations, flood management personnel forecast capabilities are limited to accumulated real-time gage data and the weather predictions of various agencies. Improved forecasting would allow reservoirs to anticipate potentially dangerous events, permitting "pre-release" decisions to evacuate storage and lower the pool elevation before the beginning of the actual event. The HEC-5 program has the capability to consider foresight in determining reservoir releases during operation; to remain within realistic boundaries, the baseline models provide 24 hours of foresight capability. However, the models could be used to determine the benefits of improved forecasting and foresight capability.

Conjunctive Use in Flood Management

The Corps' Hydrologic Engineering Center conducted a pre-reconnaissance study to assess the role that cooperative management of both surface water and groundwater resources (conjunctive use) might play in flood management within the Sacramento and San Joaquin river basins. Conjunctive use for flood management is based on the principle that increased flood protection could be attained by lowering reservoir conservation storage temporarily and conserving the water released from storage within a groundwater aquifer for later, beneficial use. Future modification to the baseline HEC-5 models could help evaluate this management tool.

GEOTECHNICAL STUDIES

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.

Various factors 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. The large hydraulic gradients that occur 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 Corps and DWR. All others are either privately owned and maintained or owned by the State, which typically delegates maintenance responsibilities to local levee or reclamation districts. However, the Corps' Sacramento River Bank Protection Project has assessed both Federal project levees and non-project levees (State or private).

Risk analysis incorporates the chance of levee failure, typically expressed through a geotechnical reliability model. This model leads to a relationship between water elevation (stage) and probability of geotechnical failure, 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. The relationship of geotechnical reliability to risk and uncertainty is described later in this document and in *Appendix E – Risk Analysis*.

Technical Approach

Levees can fail for many reasons and, unfortunately, it is difficult to predict exactly where or when 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, stages have exceeded the design water surface of a levee without breaching or without significant damages. The geotechnical performance of a levee depends on local soil conditions and construction details. These conditions are generally not known in detail at the start of a planning study. The 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 failure, an 85 percent chance. Likewise, the probable non-failure point is the stage or height associated with a low probability of 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 failure 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. The annual exceedance probability (probability of failure in any given year), including geotechnical uncertainty, is then derived in association with the expected annual damages. A set of annual exceedance probabilities and a corresponding set of conditional non-exceedance probabilities are obtained by repeating this calculation using a Monte Carlo simulation. These values are averaged to find the expected annual exceedance probability.

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. 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 failure modes of concern (such as seepage or overtopping)
- Develop reliability curves or conditional 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 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 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 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 has the greater danger of failing to account for the obvious.

Geotechnical Analysis

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, DWR 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. Conditional probabilities of failure curves were generated from this information. 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.

In addition to these reports, on-going flood management projects in construction, nearing construction, or recently completed were referenced. Engineering judgment, based primarily on 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 materials ranging in composition from loose sand to engineered pervious and impervious materials, levee probability of failure curves were created to reflect a variety of levee materials. Three levee curves were generated representing strongly constructed levees, generally of clay or sandy clay, and four levee curves were generated for poorer quality constructed levees and some non-project or privately maintained levees.

The probability of failure curves, illustrated in **Figures 7** and **8,** 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). The geotechnical studies, including construction of the conditional probability of failure curves, are discussed in detail in *Appendix E - Risk Analysis*.

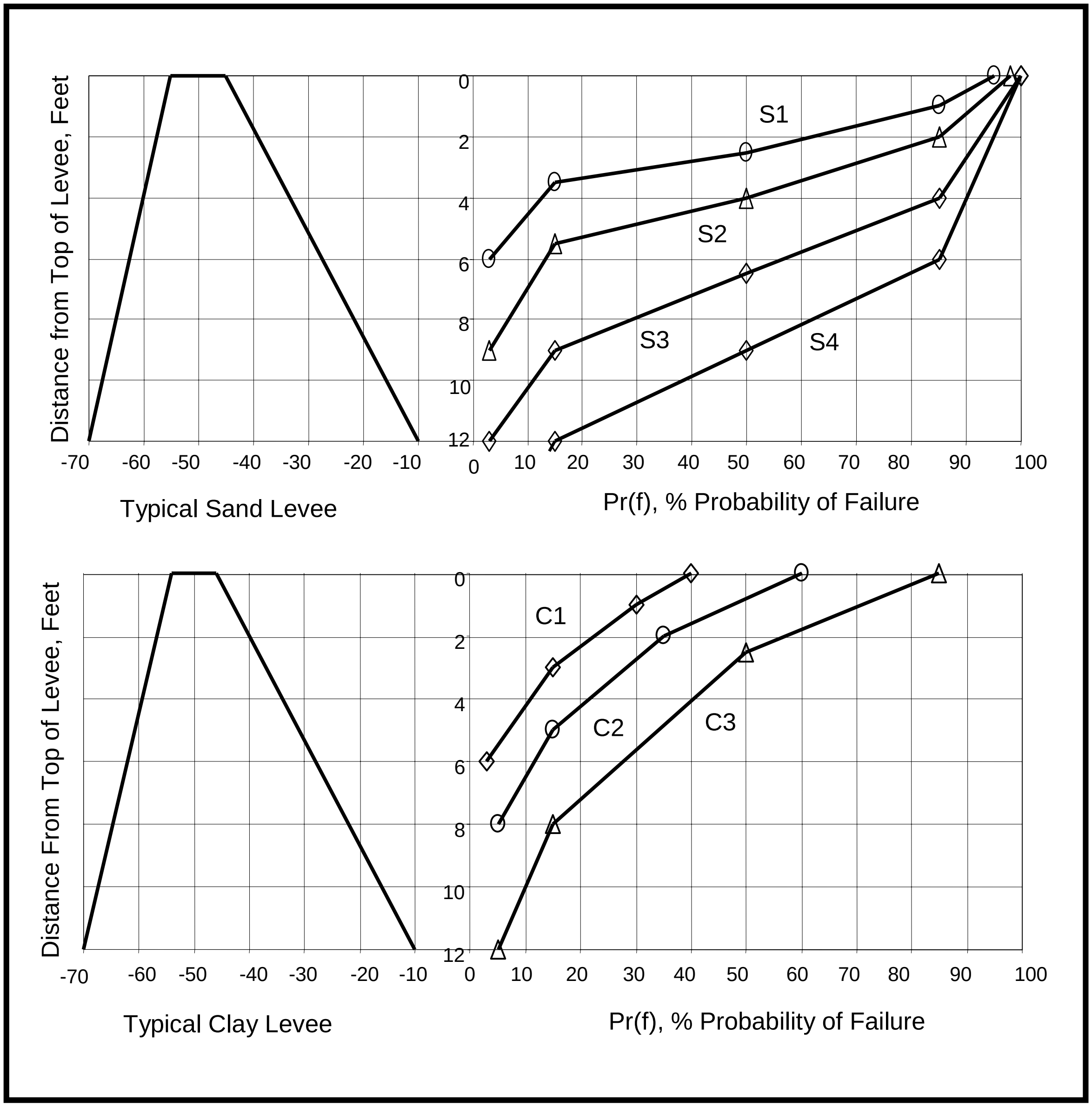


FIGURE 7 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SACRAMENTO RIVER BASIN PROJECT LEVEES

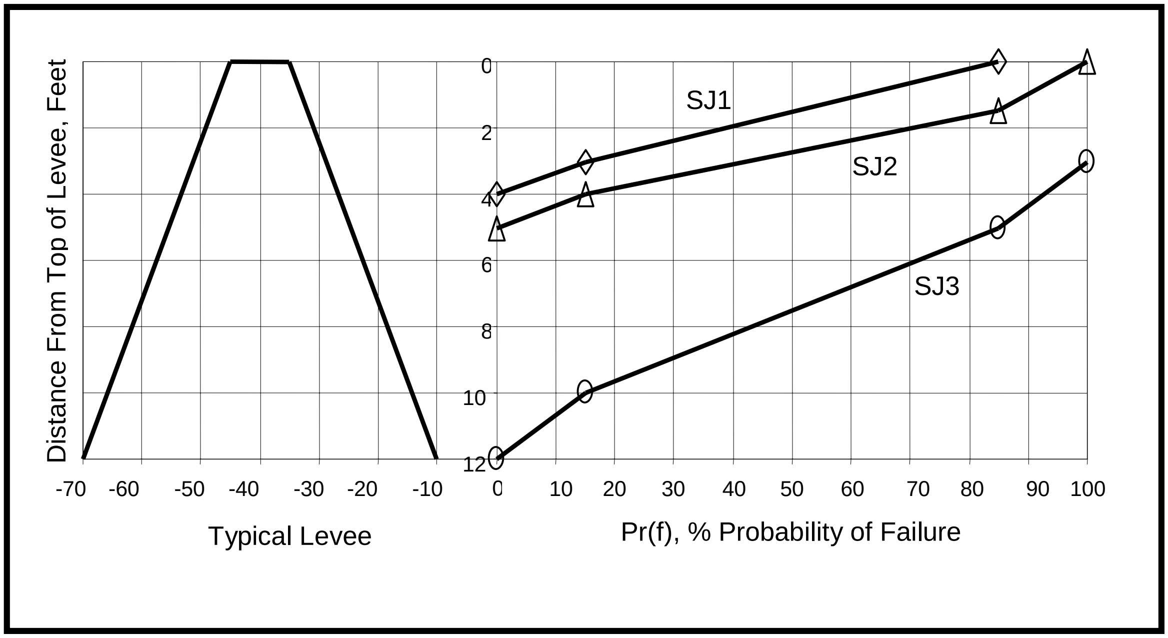


FIGURE 8 - CONDITIONAL PROBABILITY OF FAILURE CURVES FOR TYPICAL SAN JOAQUIN RIVER BASIN PROJECT LEVEES

Application of Performance Curves

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 management 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 5** and **6** summarize the geotechnical probability of failure curves applied to reaches in the Sacramento River and San Joaquin River basins.

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.

It should be noted that the curves should only be used for comparative economic analyses of the flood management 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. Furthermore, the frequency of flood events and other physical stresses affect levee integrity. Physical conditions will naturally change over time and may lead to unsatisfactory performance. Hence, the conditional probability of failure function assigned to any of the levees within the study area is time-dependent and subject to change.

TABLE 5
ASSIGNMENT BY REACH OF SACRAMENTO RIVER BASIN CONDITIONAL PROBABILITY OF FAILURE CURVES

Reach No.	Reach Description	River Miles	Design Capacity [a] (cfs)	Selected P(f)[b] Model	
				LB[c]	RB[c]
1	**Shasta Dam to Red Bluff**	**315 –245**	No Levees		
2	**Red Bluff to Chico Landing**	245 - 194			
	Sacramento River				
	Red Bluff to Elder Creek	245 - 230.5	N/A	-	-
	Elder Creek to Deer Creek	230.5 - 220	N/A	-	-
	Deer Creek to Chico Landing	220 - 194	N/A	-	-
	Tributaries				
	Elder Creek		N/A	C2	C2
	Deer Creek		N/A	C2	C2
3	**Chico Landing to Colusa**	**194 - 146**			
	Sacramento River				
	Chico Landing to head of east levee	194 - 176	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
	Tributaries				
	Mud Creek		N/A	C1	C1
	Butte Creek		3,000	C1	C1
	Cherokee Canal		12,500	S3	S3
4	**Colusa to Verona**	**146 - 80**			
	Sacramento River				
	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
	Tributaries				
	Colusa Basin Drainage Canal		20,000		
	Tisdale Bypass		38,000	S3	S3
	Sutter Bypass				
	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
	Feather River				
	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
	Tributaries				
	Yuba River	0-5	120,000	S2	S3
	Bear River	0-3	40,000	S2	S2

TABLE 5 (CONT.)

Reach #	**Measure Reach Description**	**River Miles**	**Design Capacity, Q**[a]	**Selected P(f)**[b] **Model**	
				LB[a]	RB[a]
5	**Verona To Steamboat Slough**	**80 - 32.3**			
	Sacramento River				
	Verona to Sacramento Weir	80 - 63	107,000	S2	S4
	Sacramento Weir to American River	63 - 60	107,000 - 108000	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
	Tributaries				
	Natomas Cross Canal	0 – 5	22,000	C2	C3
	American River		115,000	S3	S2
	Yolo Bypass				
	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		510,000	C3	C3
	Cache Creek to Mouth Old River		N/A	C3	C3
	Tributaries				
	Knight’s Landing Ridge Cut	0 - 6	20,000	S3	S3
	Cache Creek		N/A	S3	S3
	Willow Slough	0 - 7	6,000	C3	C3
	Putah Creek	2 - 7	62,000	C3	C3
	Miner Slough	0 - 2	10,000	S4	S4
	Cache Slough	0 - 5	N/A	S4	S4
6	**Steamboat Slough To Collinsville**	**32.3 - 0**			
	Sacramento River				
	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	-
	Tributaries				
	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
	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 6
ASSIGNMENT BY REACH OF SAN JOAQUIN RIVER BASIN CONDITIONAL PROBABILITY OF FAILURE CURVES

Reach No.	Reach Description	River Miles	Design Capacity [a] (cfs)	Selected P(f)[b] Model
A	**Mendota Dam to Friant Dam**	**205 To 286**		
	San Joaquin River		2,500 – 8,000	SJ1
	Fresno Slough & James Bypass		4,750	SJ1
B	**Sand Slough Control Structure to Mendota Dam**	**168 to 205**		
	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	**Merced River to Sand Slough Control Structure**	**118 to 168**		
	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	**Stanislaus River to Merced River**	**75 to 118**		
	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	**Deep Ship Channel to Stanislaus River**	**40 to 75**		
	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) Estimated design flow capacity per DWR (May 1985)*
b) P(f) = Conditional Probability of Failure (applies to left and right bank levees) **.**

Wherever possible, geotechnical information from past or current 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

Marysville / Yuba City study and on-going levee reconstruction work either in-progress or authorized for construction.

Findings

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. Furthermore, geotechnical conditions are not static, and the geotechnical data used in developing projects should be re-evaluated and updated whenever information becomes available. While suitable for the basin-wide evaluations performed by the Comprehensive Study, the geotechnical levee performance curves may not fulfill the technical requirements of site-specific investigations.

HYDRAULIC STUDIES

Hydraulic models were developed to be comprehensive representations of the entire Sacramento and San Joaquin river basins, capable of simulating the complex interaction of multiple stream systems and waterways. This approach differs from the traditional “piecemeal” approach in which individual rivers or reaches are examined out of context from the greater, more complex system to which they belong. The models compute water surface elevation, discharge, average velocities, flooding extent, and track how flood volume changes as a flood moves through the river system. These models were used to characterize current, baseline conditions, develop an understanding of how the overall flood management system functions, delineate flood inundation areas, and gain an understanding of how the flood management system might respond to various types of modifications.

Technical Approach

Two models were used jointly to simulate channel and overbank hydraulics in the Sacramento and San Joaquin River systems. Flows within the river channels and bypasses were simulated using the UNET model, and the FLO-2D model was used to simulate the movement of water in overbank and floodplain areas after it has escaped the main channel. *Appendix D – Hydraulic Technical Documentation* provides a detailed description of the UNET and FLO-2D hydraulic models. Although the Delta is not a primary focus of the Comprehensive Study, a third model (DSM2) was used to evaluate flood conditions in the Delta. The adaptation and use of DSM2 is described in a separate information report, *Existing Hydrodynamic Conditions in the Delta During Floods, Sacramento and San Joaquin River Basins Comprehensive Study*, September 2001, and summarized herein.

Floods with a 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year were modeled in the hydraulic analysis. However, flows with less than a 10% chance of occurring in any year typically remain within channel banks and do not cause levee failures or lead to serious economic impacts on a system-wide basis. For this reason, the 2% flood was not simulated in all hydraulic evaluations.

UNET Model Development

The computer model UNET is designed to simulate unsteady flow through a full network of open channels, weirs, bypasses, and storage areas. For this study, use of the UNET model was limited primarily to the riverine channels. A modified version of the August 1998 UNET Version 4.0, with modifications included in April 2000 specifically for the Comprehensive Study, was used for this study. For more information about the capabilities of this model, refer to the August 1997 *UNET User's Manual*. The hydraulic models were subject to independent technical review throughout their development and assessed professionals in the public, private, and academic sectors.

Separate UNET models were developed for the Sacramento River and the San Joaquin River systems. In general, model construction for both basins consisted of collecting and processing topographic data, developing river channel alignments, developing cross-sectional geometry from the topographic and hydrographic data, and including structures that affect flows (bridges, levees, weirs, etc). The Sacramento and San Joaquin River systems were subdivided into various study reaches, with cross sections spaced at 0.20 to 0.25 mile increments.

The hydrologic and reservoir operation studies described previously provide input for the UNET models. Upstream boundary conditions in the form of 30-day flow hydrographs of discharge vs. time for each flood event and centering were supplied at the upstream end of each tributary or stream that was modeled. Downstream boundary conditions at the model's terminus in the Delta consisted of stage hydrographs and rating curves representative of tailwater conditions, including tidal or estuary influences. Internal boundary conditions coded in UNET were used to represent levee failures or storage interactions, spillways or weir overflow/diversion structures, bridge or culvert hydraulics, or pumped diversions. Vegetation and other channel obstructions are represented in UNET by varying channel roughness coefficients (expressed as Manning's n values).

Levee Failure Methodology

As described, a levee failure methodology was devised to determine when simulated flows would cause levees to fail and a floodplain to be formed. A likely failure point (LFP) profile was developed for levees in the Sacramento and San Joaquin river basins on a reach-by-reach basis, as described previously and in *Appendix E – Risk Analysis*. Levee failure was initiated in UNET when the water surface elevation reached the LFP for a given levee. Levee failure is simulated in UNET as a levee breach, with no distinction made between seepage failures, partial structural failures, or any other levee failure modes. 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.

Subsidence

Subsidence can have significant impacts on river system and floodplain hydraulics. The portion of the Sacramento and San Joaquin river basins flood management systems most significantly affected by subsidence is the southwestern part of the San Joaquin Valley, upstream from the San Joaquin – Merced River confluence. When the Corps conducted the 1998 survey of the various watercourses in the San Joaquin River basin, the vertical datum used in the survey was the NGVD of 1929. The vertical control utilized benchmarks that likely have been affected by subsidence. Therefore, in 2000, the Corps conducted a subsequent survey of the southern San Joaquin River basin to extend the control to outlying benchmarks, known to be free from subsidence, and to determine the adjustments necessary to modify the 1998 mapping so that it would more accurately represent true topographic conditions. An unintended by-product of the 2000 survey was the development of a sufficient amount of elevation data with which estimates could be made regarding the rates of subsidence over the past 3 to 70 years (depending on location). These estimates indicated that the overall areal extent of subsidence is somewhat larger than originally thought, extending further to the north and east, and the rates of subsidence are somewhat less than those originally estimated prior to the 2000 survey.

The 1998 riverine topography was adjusted to account for subsidence of survey benchmarks, however, new cross section geometry using this adjusted data has not been developed and incorporated into the San Joaquin River basin UNET model. It was determined that the information presently in the models is adequate for characterizing the base-condition, as well as considering future conditions at a programmatic level of planning. This decision was based on engineering judgment and by the fact that the maximum adjustment to the 1998 topography was 1.8 feet for the base-condition.

Calibration

The UNET model for the Sacramento River basin was calibrated to the 1997 flood and the model of the San Joaquin River basin was calibrated using both the 1995 and 1997 floods. Model result hydrographs were compared to gage records and peak stage data where available. The UNET model parameters for Manning’s n, weir coefficients, and levee breaches were then adjusted as needed in an iterative procedure to modify the model results to more closely match the calibration data. The model calibration task produced satisfactory results that were generally more accurate for stage than for flow.

Assumptions and Limitations

It is important to note some of the basic capabilities, assumptions, and limitations inherent with the UNET models. UNET is used to simulate one-dimensional, unsteady flow. It is a fixed bed analysis and does not account for sediment movement, scour, or deposition. The models assume no exchange with groundwater. The models are intended to reproduce levee breaks and breaches and simulate channel hydraulics. The spacing of cross sections in the UNET models (typically between 1/5- and 1/4-mile) may preclude the direct application of these models to studies requiring more detail.

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 flood risk evaluations. It does not represent conditions that would occur during an actual flood event, when flood fighting and other emergency actions would take place, and fewer failures are likely to occur. While the LFP represents a 50% probability of geotechnical failure, the UNET model will trigger a levee failure every time the water surface reaches the LFP. In some cases, the cumulative affect 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 smaller, levees tend to be shorter, and overbank flooding occurs more frequently than in the Sacramento River basin. Other projects that choose to use the Comprehensive Study's hydraulic models should develop levee failure assumptions that are appropriate for their technical needs.

Model Output

UNET models of this size generate a tremendous amount of output. Consequently, numerous index points were selected in the Sacramento and San Joaquin river basins to facilitate the evaluation of results and passage of information to the HEC-FDA model. Model output was used to develop stage-frequency and discharge-frequency relationships at the index points, shown in **Figure 9**.

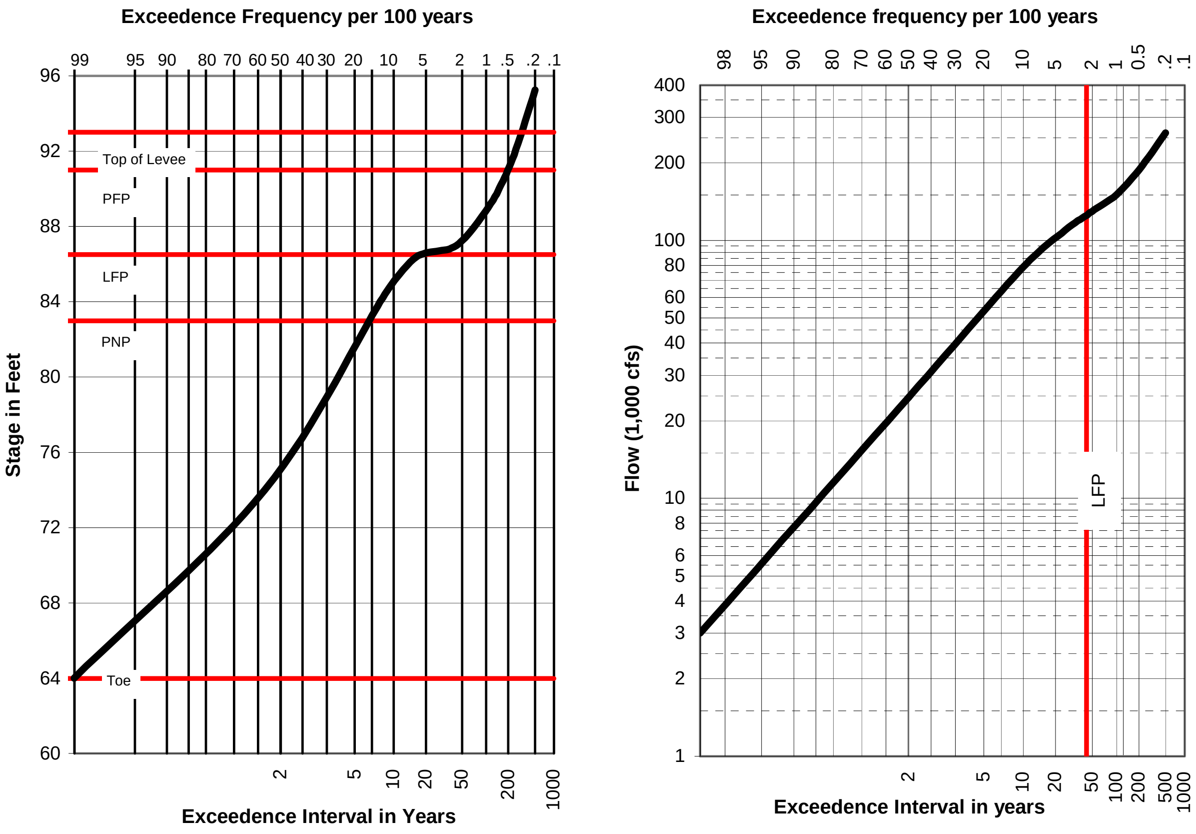


FIGURE 9 - SAMPLE STAGE-FREQUENCY AND FLOW-FREQUENCY CURVES

For reaches with levees, two sets of simulations were required to construct these curves: one that assumed levee failures occur and one that assumed all flow is contained within the channel (termed infinite channel). The portion of the curve below the LFP was developed using the with-failure simulations. After failure, the water surface elevation or flow remained relatively constant for all higher flood frequencies because flows were escaping into the floodplain through the levee break. In order to develop a complete curve that acknowledges the possibility that the breakout will not occur, the upper portion of the curve was formed using the infinite channel simulation. The portion of the infinite channel frequency curve above the frequency of levee failure was translated down to meet the baseline (with-failure) curve where it intersected the LFP and flattened. The resulting hybrid curve was used to evaluate model output in reaches where there are levees.

FLO-2D Model Development

The hydraulic model FLO-2D was used to model overbank flows that break out of stream channels and flow across the topography of the floodplain. Out-of-bank flows were generated in UNET and passed to corresponding grid elements in FLO-2D to calculate flood depth and delineate the floodplain. The October 1999 Version 99.1 of FLO-2D was used in this effort. More information about FLO-2D can be found in the October 1998 *FLO-2D User's Manual*.

FLO-2D has the capability of modeling both one-dimensional channel flow and two-dimensional overbank flow. River channels in the Sacramento River basin tend to be well defined and overbank flows occur less often. In the San Joaquin River basin, channels tend to be less defined and have minimal capacity, making overbank flows more common. For this reason, FLO-2D models were developed to cover almost the entire San Joaquin River basin while the models in the Sacramento River basin primarily cover historic overflow basins.

Similar to the procedure for developing the UNET model, assembling topographic data was the first task in developing the FLO-2D models for the Sacramento and San Joaquin River basins. Flows are simulated in FLO-2D using a two-dimensional grid network; a finite difference grid system was established in each basin, defining contiguous grid elements in the four compass directions, using USGS 30-meter Digital Elevation Models (DEMs).

The types of boundary conditions in the FLO-2D computer model include levees, inflow and outflow boundary nodes, tailwater conditions, and one-dimensional channel inflow hydrographs and tailwater hydrographs. Inflow hydrographs were provided either from the UNET model or directly from the synthetic hydrology. The outflow boundary conditions were based on either a rating curve or a stage hydrograph at the downstream end of the channel.

Calibration

The FLO-2D model in the Sacramento River basin was calibrated primarily using the 1997 flood; however, the 1937 flood was also used for calibration in the Colusa basin. The FLO-2D model of the San Joaquin River basin was also calibrated primarily with the 1997 flood, but calibration also included comparisons to the 1938, 1952, 1955, and 1958 floods. In general, the calibration involved comparing the areal extent of flooding in simulated and actual flood events; experience from recent flood events that caused levee breaches was also considered.

Assumptions and Limitations

Two-dimensional flow simulation in FLO-2D is limited to the eight directions of the compass (north, northeast, east, southeast, and so forth). The model routes channel and overland flow using the full dynamic wave or the diffusive wave approximation to the momentum equation. The simulations performed represent a fixed bed analysis (no sediment transport). Bridges, streets, and other features were not specifically modeled in this application of FLO-2D. However, raised highways, levees, and other topographic features are represented in the grid elements, as appropriate. In order for FLO-2D to run efficiently, individual models are typically limited to 10,000 grid elements. This required large grid sizes of about 2,000 feet on an edge to be used throughout both basins. The only exception is in the Sutter basin, where 1,000-foot grids were used to provide better resolution.

Since the topography for the FLO-2D model in the southern San Joaquin River basin is based on DEM data that is approximately 40 years old, an approximation of the subsidence that occurred over this time period was developed. As described previously, approximate subsidence rates were developed based on survey data and historical subsidence documented to have occurred between the 1920s and 1966. These rates were used to adjust the 30-meter DEMs upon which the FLO-2D grids are based. However, these rates can only be considered approximate due to the limited amount of survey data available.

Output

The FLO-2D model was used to determine the distribution and depth of overbank flood flows. The UNET model was used to identify the breakout or overtopping locations and outflow hydrographs, and FLO-2D was used to delineate the footprint that the outflows would generate. The resulting floodplains from multiple storm centerings were used to delineate a single composite floodplain for the various frequency flood events (illustrated previously in **Figure 2**). It is important to note that these are not FEMA floodplain maps, nor are they intended to replace or supersede existing FEMA maps. They were developed for use in the Comprehensive Study's watershed-scale hydraulic and economic analyses.

Results and Findings

The UNET models are capable of reporting flow, stage, and velocity in the form of instantaneous peaks or hydrographs that cover the duration of the simulated 30-day flood event. Water surface profiles, at-latitude flows, and a variety of other model output were used to characterize the hydraulic performance of the flood management system. The primary outputs of the hydraulic models are flow-stage-frequency relationships and composite floodplain delineations. Model output is summarized below and included in *Appendix D – Hydraulic Technical Documentation*.

<u>Flow-Stage-Frequency Relationships</u> **-** Rating tables were developed in both basins for baseline conditions to relate frequency, flow, and stage at the index points. Both baseline and with-project condition stage-frequency curves were also used as input to the risk and economics evaluation, described later in this document.

<u>Composite Floodplains</u> **–** The UNET and FLO-2D models were used in combination with multiple storm centerings to delineate floodplains for the 10%, 2%, 1%, 0.5%, and 0.2% flood events. The risk and economics evaluation also used floodplain extent and depth to

characterize damages and identify structures at risk. The composite floodplains were developed for the economic studies performed by the study and are not traditional design-event floodplains. As described previously and illustrated in **Figure 2**, the composite floodplains represent the combined floodplains of storm runoff centerings for each frequency event. It is important to note that these are not FEMA floodplain maps, nor are they intended to replace or supercede FEMA maps. The Comprehensive Study floodplains are used to characterize the maximum extent of flooding under a range of potential hydrologic conditions, and evaluate flood risk and economic damages.

Delta Modeling

A detailed hydraulic model was not developed in the Delta specifically for this study because this region is not a primary focus of the Comprehensive Study. However, because changes to the Sacramento and San Joaquin River flood management systems could affect conditions in the Delta, a method was needed to estimate potential impacts. A study of hydrodynamic conditions in the Delta during floods was performed using the DWR Delta Simulation Model II (DSM2). DSM2 simulates complex hydrodynamic conditions in the delta, including tidal influence and flows in tributaries.

DSM2 was originally designed to evaluate water quality within the Delta under low-flow conditions. The model was truncated for the purpose of this evaluation such that DSM2 flow input locations coincided with the downstream limits of the Sacramento and San Joaquin River UNET models, facilitating handoff of data between the two models. Output from the DSM2 model includes stage, flow, and storage data. DSM2 is not capable of simulating levee failure and does not consider the effect of high water duration.

DSM2 was used to simulate “existing” flood flow conditions within the Delta using simulated flows from the UNET models and flood event hydrology from Delta tributaries such as the Mokelumne and Calaveras rivers. The model was also used to evaluate how channel modifications in the South Delta could affect flood flows through the Delta. The results of the Delta hydrodynamics study are documented in two reports covering the North Delta (lower Sacramento River to central Delta) and South Delta (San Joaquin River, from Stanislaus River to central Delta). These reports are referenced at the end of this document in the section titled Other Studies and Reports.

A subsequent sensitivity analysis was performed using DSM2 to identify how conditions in the Delta could be affected if flood flows in the Sacramento or San Joaquin rivers were increased. In general, these simulations found that increasing flood flows from the Sacramento River resulted in an increase in peak water surface elevation primarily in the central Delta region, with this increase dissipating to the west and the south. Increasing flows from the San Joaquin River resulted in an increase in peak water surface elevations primarily in the southern portion of the Delta, dissipating to the north, central and western Delta areas. It should be noted that these results are very generalized and do not reflect changes in the entire Delta, the effect of potential Delta levee failures, or changes in hydrograph shape that could result from increased flood volume. The results are informative, however, regarding the general hydrodynamic response in the Delta and the potential to convey higher flood flows through Delta channels.

Upper Sacramento River Hydraulic Modeling

The modeling approach for the Sacramento River upstream from Woodson Bridge differs from the approach previously described. Rather than using UNET to simulate river hydraulics, the DWR Division of Planning and Local Assistance, Northern District, developed a HEC-RAS hydraulic model extending from Woodson Bridge to Keswick Dam. The alternate modeling approach is suitable for this region due to the geomorphic characteristics of the upper Sacramento River, which differ significantly from the highly modified lower Sacramento River. Moving upstream, the Sacramento River gradually becomes more entrenched as it enters its foothill and mountain headwaters. Upstream from Woodson Bridge, the river is confined primarily by natural topography and less out-of-bank flow occurs, with flooding generally restricted to lands immediately adjacent to the river. HEC-RAS is efficient and widely accepted for calculating water surface profiles in natural channel systems such as this. HEC-RAS also has graphical user interface, which facilitates model development, troubleshooting, and visualization of results. In contrast, the lower Sacramento River is characterized by extensive floodplains, levee failures, and overflow basins; UNET is better suited to model these complex interactions.

In general, model construction consisted of collecting and processing topographic data, developing cross sectional geometry, and constructing the HEC-RAS model. Topographic data were collected from various sources for the upper Sacramento River reach and processed electronically into digital terrain surfaces. These terrain surfaces were used to extract cross sections and delineate floodplains based on calculated water surface elevations. Cross section spacing in the HEC-RAS model varies from a few hundred feet to over one mile HEC-RAS 3.0 was used in combination with AutoCAD and BOSS RMS (a-computer aided engineering application that provides an interface between AutoCAD and HEC-RAS) to produce water surface profiles and floodplain inundation mapping. Digital orthophotos obtained from the USGS were used as base maps for displaying the inundation areas.

Some key assumptions and technical considerations regarding the upper Sacramento River HEC-RAS model are included below:

- Hydrology from four storm centerings (Ord Ferry, Shasta, Sacramento, and Stony Creek) and three flood events (2%, 1%, and 0.5% chance of occurring in any year) were simulated in the HEC-RAS model. Lower flow events (50%, 10%, and 4% flood hydrology) were not simulated as part of the initial modeling work. However, this hydrologic flow data is available and can be included in future studies.
- Although HEC-RAS Version 3.0 is capable of performing unsteady flow analyses, the modeling performed for this study simulates a one-dimensional, steady flow regime. Hydraulic simulations were made using instantaneous peak flows only. This limits the volume-tracking capabilities of the model, as required for analyzing storage scenarios.
- Unlike UNET, no levee failures are assumed in the HEC-RAS model; flow stays in-channel until the top of levee or bank elevation is exceeded. HEC-RAS can track overbank flow, but does not consider geotechnical conditions.

The development of the upper Sacramento River HEC-RAS model is described in more detail in a technical memorandum included in *Appendix A – Information Papers*.

RISK ANALYSIS

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 an expression of doubt in the accuracy of knowledge or information. Flood damage reduction studies regularly use and estimate information, such as stream flow records or stage predicted by hydraulic models, with varying degrees of accuracy and reliability. Uncertainty is also associated with environmental conditions and assumptions that could affect the success of restoration efforts.

The Corps 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. 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 HEC'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.

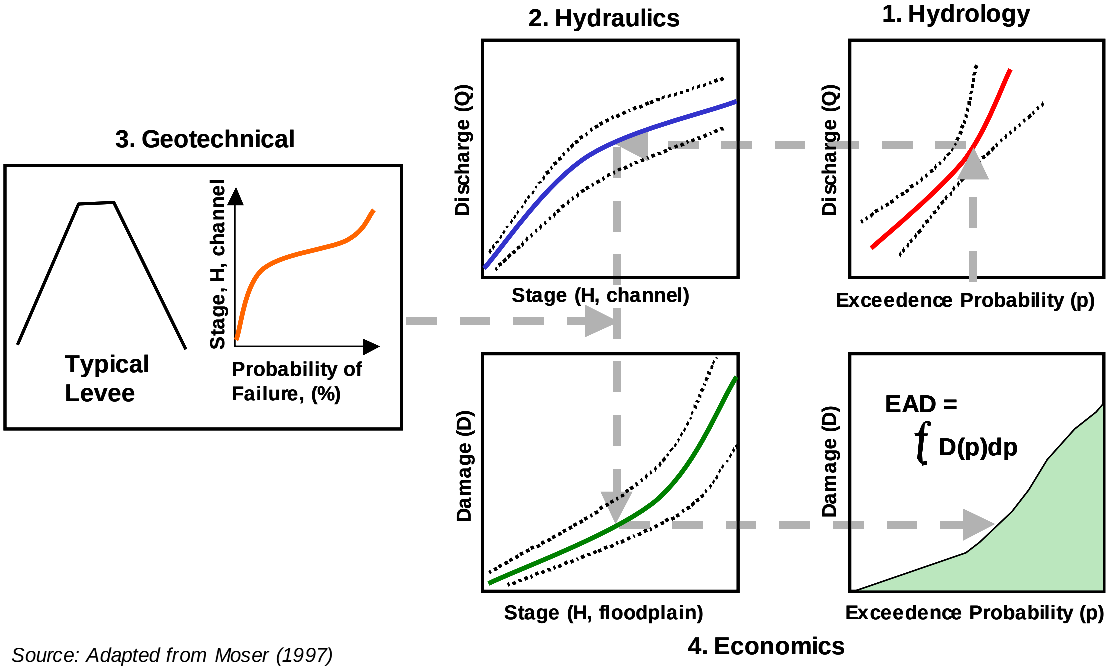
Traditional Risk Analysis Approach

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 location where hydrology, hydraulics, geotechnical considerations, and types of damage are equated to flood damages or flood risk. The discharge-frequency, stage-frequency, and stage-damage functions describe the hydrologic, hydraulic, geotechnical, and economic conditions at each index point.

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. There are error limits around the discharge in the discharge-frequency relationship, around stage in the stage-discharge relationship, around stage in the stage–probability of failure relationship, and damage in the stage-damage relationship.

Monte Carlo simulation provides a way to estimate the statistical properties of outputs when the inputs are random variables. For flood damage reduction, Monte Carlo sampling of the stage-discharge, discharge-frequency, stage-probability of failure, and stage-damage relationships is repeated an indefinite number of times until the outputs, such as expected annual damages (EAD) and annual exceedance probability (AEP), are statistically accurate.

Figure 10 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 thousands of times using Monte Carlo analysis and the results are plotted to form the damage-frequency curve (shown in **Figure 10** as the box at lower right).



Source: Adapted from Moser (1997)

FIGURE 10 –THE CONCEPTUAL RISK AND UNCERTAINTY MODEL

Comprehensive Study Risk Analysis

The risk analysis methodology used during the Comprehensive Study deviates slightly from traditional methodology. The Monte Carlo simulation starts with a random number sampling of the stage-frequency, stage-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 (10%, 2%, 1%, 0.5%, and 0.2% chance of occurrence in any year) input into the hydraulic model. The risk analysis methodology can be applied to existing, baseline, and with-project conditions.

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 10** as dashed "error bands" located above and below the hydrologic, hydraulic and economics curves. Some of the important uncertainties specific to the Comprehensive Study include:

Hydrologic **-** Uncertainty factors include hydrologic data record lengths (period of record) that may be shorter than desired or are not available on un-gaged tributaries; precipitation-runoff computational methods or statistics; and methods or models used to simulate reservoir operations that may deviate somewhat from actual operations. For the Comprehensive Study, the hydrologic periods of record were identified for each impact area.

Hydraulic **-** Uncertainty arising from the use of simplified models to describe complex hydraulic phenomena, including the availability of detailed geometric data, potential misalignments or misrepresentations of hydraulic structures, channel bed material variability, debris loading on structures (such as bridge piers) 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 estimated 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 a levee, or other localized defects.

Economic **-** 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.

Index Points and Impact Areas

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 (sources and flow patterns) and land uses within the 2% floodplain. Within the Sacramento River basin, 62 impact areas were initially identified covering about 1.5 million acres. An additional six impact areas were delineated along the upper Sacramento River. In the smaller San Joaquin basin, 42 impact areas were identified covering about 654,000 acres. The impact areas are shown in **Figures 11** and **12.** The impact areas generally cover the 0.2% floodplains of the Sacramento and San Joaquin river mainstems and their major tributaries. The impact areas were not delineated to include the floodplains of smaller streams and waterways outside the focus of the Comprehensive Study.

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.

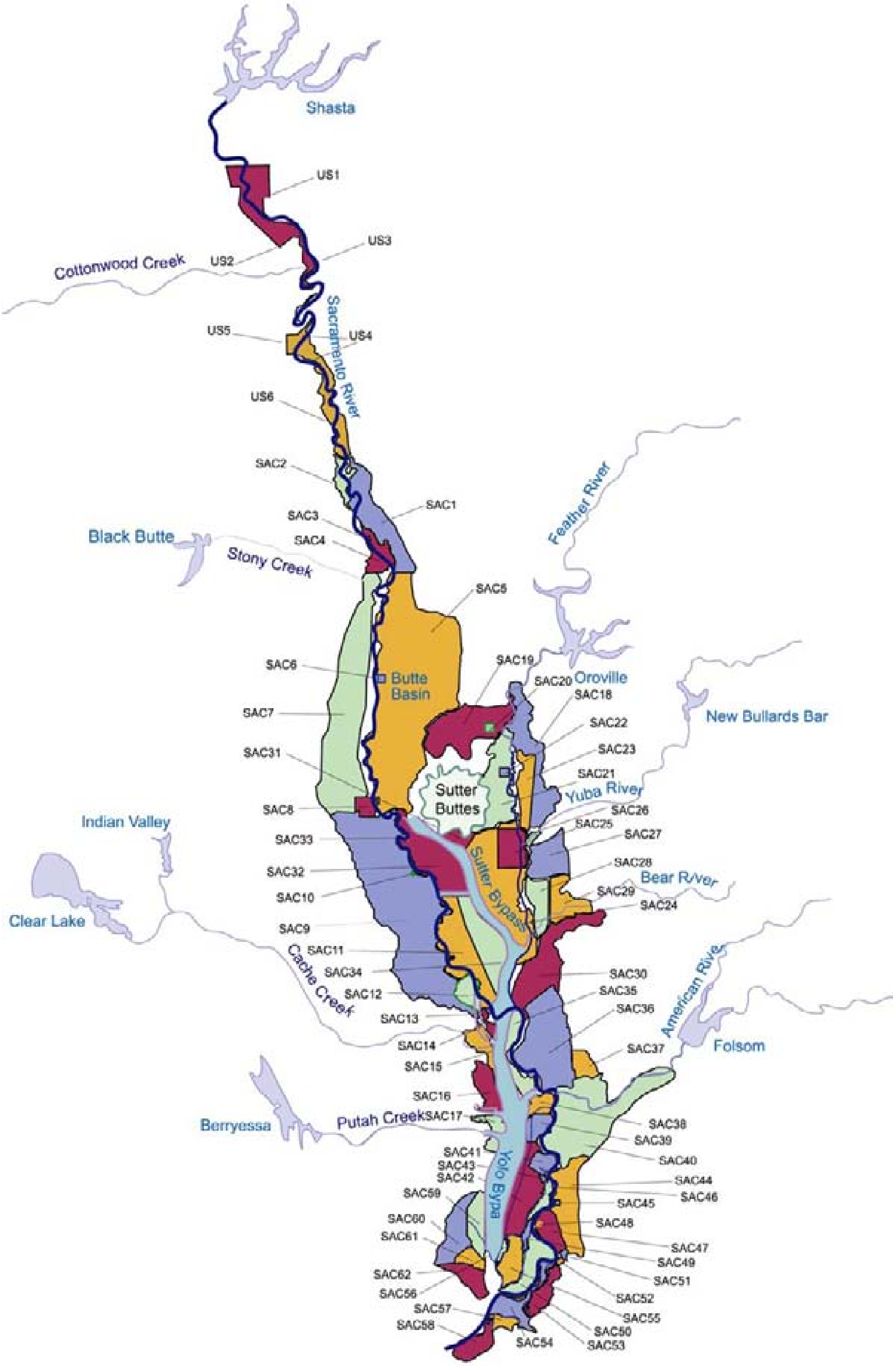


FIGURE 11 – SACRAMENTO RIVER BASIN ECONOMIC IMPACT AREAS

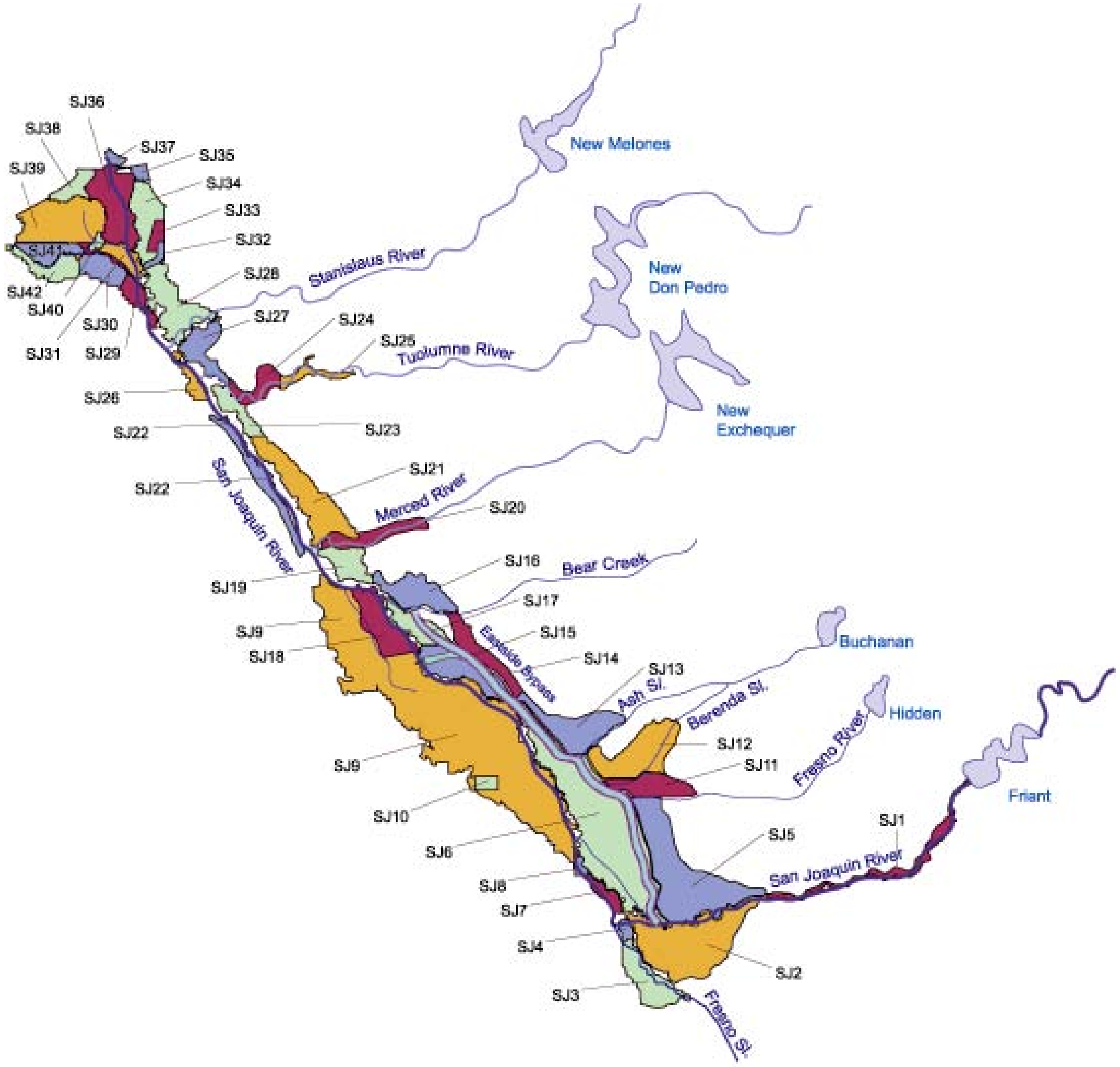


FIGURE 12 – SAN JOAQUIN RIVER BASIN ECONOMIC IMPACT AREAS

Technical Tools

While no model is a perfect representation of actual conditions, the models developed for the Comprehensive Study are of sufficient detail to provide appropriate results for a systematic flood damage analysis of the two basins. The models and tools that are directly related to risk analysis are described briefly below.

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, stage-probability of failure, and damage-stage relationships, and their respective uncertainty distributions. The primary outputs of HEC-FDA are expected annual damage (EAD) and project performance statistics. 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).

@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. @RISK was used to develop the stage-damage curves using parcel and depth information developed in a geographic information system (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*.

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.

Perhaps the most significant assumption is the failure methodology, which can significantly influence simulated flood flows. The methodology was chosen to provide a conservative and consistent 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. In some cases, the cumulative affect 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 River 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 sufficient for the basin-wide risk analyses, it should be considered when interpreting model results.

Project Performance

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

<u>Annual Exceedance Probability (AEP)</u> **-** AEP 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 1% probability flood event has one chance in a hundred of occurring in any

given year. The 1% exceedance flood event is often termed the 100-year event, but it does not represent an event that will only occur once during a century. Over a very long period of time (many thousands of years) the 1% exceedance 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 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-Exceedance Probability by Events (CNE) - Conditional non-exceedance 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 events. For example, a value of 0.04 for the 2% exceedence event corresponds to a four percent chance that the river system will contain a flood with a 2% chance of occurring in any year.

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 and uncertainty in flood management. For example, FEMA uses conditional non-exceedance in its certification criteria for levees, requiring a 90% or higher probability of containing the 1% flood event.

Existing Condition

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 7 and 8**. The annual exceedance 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 provided by the Sacramento River Flood Control Project. The San Joaquin River Flood Control Project was generally designed to convey smaller and late-season snowmelt floods. These differences are largely due to the level of urban and agricultural development that was present at the time the systems were designed.

TABLE 7
EXISTING CONDITION PROJECT PERFORMANCE STATISTICS FOR THE SACRAMENTO 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% (1 in 10)	4% (1 in 25)	2% (1 in 50)	1% (1 in 100)	0.5% (1 in 200)	0.2% (1 in 500)
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
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

TABLE 7 (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% (1 in 10)	4% (1 in 25)	2% (1 in 50)	1% (1 in 100)	0.5% (1 in 200)	0.2% (1 in 500)
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 8
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% (1 in 10)	4% (1 in 25)	2% (1 in 50)	1% (1 in 100)	0.5% (1 in 200)	0.2% (1 in 500)
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

TABLE 8 (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% (1 in 10)	4% (1 in 25)	2% (1 in 50)	1% (1 in 100)	0.5% (1 in 200)	0.2% (1 in 500)
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

Risk and 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 for the Comprehensive Study uses hydrologic data, topography, and simplified algorithms to estimate ecosystem health and predict the success of riparian habitat restoration. There is uncertainty in the hydrologic data, accuracy of mapping, and ability of the algorithms to address ecological complexity. The Comprehensive Study has advocated adaptive management as one method of addressing the uncertainties associated with the success of environmental restoration. It may also be possible to incorporate risk analysis in future versions of the Ecosystem Functions Model.

Summary & Conclusions

The risk analysis performed during 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 for the Comprehensive Study, including the HEC-FDA model, will continue to be updated and improved as projects are completed and implemented under the Comprehensive Plan.

ECONOMIC STUDIES

The Comprehensive Study performed basin-wide economic evaluations that incorporated a risk-based analysis. The primary tool for the economic studies was the Corps' Flood Damage Analysis Model, or HEC-FDA. This model uses a risk-based analysis to express economic performance in terms of expected annual damages (EAD). This section provides an overview of the development of system-wide economic tools and their use in performing economic analyses. A complete description of the economic studies performed during the Comprehensive Study is included in *Appendix F – Economics Technical Documentation*.

Flood Damage Reduction Analysis

The Corps of Engineers economic analysis is based upon the *Principles and Guidelines* (P&G) published in 1983 by the U.S. Water Resources Council. A primary Corps objective in flood damage reduction studies is to determine the expected annual damage along a river reach, taking into account all possible flood scenarios, and to compare changes in the damage resulting from various alternative plans. The determination of EAD in a flood management study must take into account interrelated hydrologic, hydraulic, geotechnical and economic information and their associated uncertainties. Specifically, EAD is determined by combining the discharge-frequency, stage-discharge (or frequency), and stage-damage functions and integrating the resulting damage-frequency function. Uncertainties are present for each of these functions and are carried forth into the EAD computation. In addition, for the Comprehensive Study most of the rivers being studied have levees on one or both sides for part or all of their studied length. Levees prevent water from breaking out into adjacent floodplain areas. As river stage increases the probability of levee failure also increases. Thus, the derivation of geotechnical levee probability of failure curves, which define relationships between river stage and levee failure probability, becomes very critical to the analysis.

Modeling Tools

The Comprehensive Study used three primary tools to perform the system-wide economic analysis: HEC-FDA, @Risk, and GIS. The GIS component is summarized below, and HEC-FDA and @RISK are described briefly in the previous section and in *Appendix E – Risk Analysis*. The exception is the Upper Sacramento River reach (Vina to Keswick), described later, where a spreadsheet was used to calculate economic damages in lieu of HEC-FDA.

GIS - Although not an economics program, the use of geographic information system software allowed the efficient identification of thousands of structures within the floodplains where digitized parcel maps were available. Where possible, other corresponding data required for flood damage analysis was also developed using GIS.

In addition to these models, critical input into HEC-FDA comes from hydraulic models: UNET (river channel stage-frequency relationships) and FLO-2D (floodplain depths and delineations).

Input Data

Input to the economic analysis models includes composite floodplain delineations, the designation of impact areas, damage categories, land use and structural inventories, structural and content values, and depth-damage relationships.

Floodplains **-** One of the most important steps in a flood damage analysis is the identification of areas subject to flooding. As described previously, the Comprehensive Study's composite floodplains capture a range of potential flood conditions through the use of storm centerings, and the probability of levee failure through identification of a likely failure point. The economic analyses utilize composite floodplains with a 2%, 1%, 0.5%, and 0.2% chance of occurrence in any given year, developed using UNET and FLO-2D. The exception was the use of 2%, 1%, and 0.5% floodplains along the upper Sacramento River (Vina to Keswick Dam) that were developed using HEC-RAS water surface profiles.

Impact Areas **-** Because the Comprehensive Study floodplains cover approximately 2.2 million acres, the floodplains were divided into smaller impact areas to facilitate the analysis. **Figures 11** and **12** in the Risk Analysis section illustrate the 68 impact areas in the Sacramento basin and the 42 impact areas in the San Joaquin basin, respectively.

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 (corn, beans, wheat, cotton, safflower); fruit crops (almonds, walnuts, peaches, pears, prunes); alfalfa; mixed pasture; rice; truck crops (melons, tomatoes); and vine crops (grapes). The types of agricultural flood damage evaluated included the loss of direct production costs incurred prior to flooding, the loss of net value of crop, the loss of depreciated value of perennial crops, and clean-up and rehabilitation costs, with consideration for the seasonality and duration of flooding.

Existing Condition Expected Annual Damage

Existing condition expected annual damage is over $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. **Figure 13** summarizes existing condition EAD estimates by damage category in each basin.

For the Upper Sacramento reach (Vina to Keswick), a different method was used to calculate expected annual damage. The stage-frequency curves required by HEC-FDA were not generated because hydraulic studies for this reach were performed using HEC-RAS rather than UNET. In addition, only three frequency events were evaluated (the 2%, 1% and 0.5% events), rather than the eight events evaluated in UNET. Expected annual damage was based upon simulated flood depths for these three events at individual parcels and economic computations were performed using spreadsheets rather than within HEC-FDA. Damages for these impact areas are included in **Figure 13**. A detailed accounting of EAD by impact area is included in *Appendix F – Economics Technical Documentation*.

As with other Comprehensive Study tools, the HEC-FDA models are a work-in-progress. Potential future work to the existing condition damages analysis includes refinements to damage estimates for the public service sector and other damage categories (autos and roads, traffic disruption and emergency response costs).

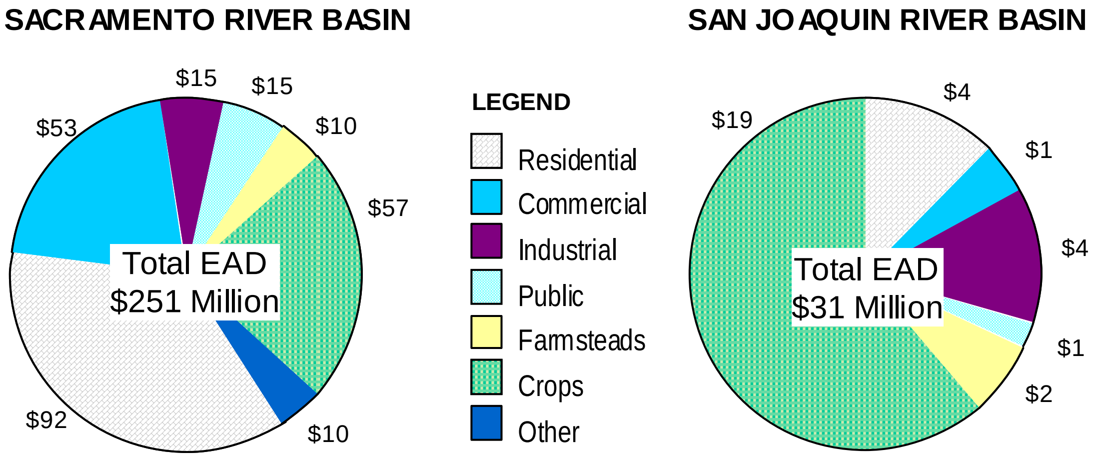


FIGURE 13 –EXISTING CONDITION EXPECTED ANNUAL DAMAGE BY DAMAGE CATEGORY

Future Without-Project and With-Project Conditions

The estimation of existing condition expected annual damage is only part of the "without-project" analysis. A complete analysis would take into account future development likely to occur with and without proposed alternatives. "Future without project" population and economic development levels, and associated flood damage, have not been estimated at this time. It is anticipated that a complete "without project" analysis including future development will be conducted during future studies.

Although the Comprehensive study did not develop alternatives, the HEC-FDA model is capable of performing economic analyses for proposed plans in the same manner as described for the existing and future without project conditions. Plan components are simulated using the hydrologic and hydraulic modeling tools and with-project stage-frequency information is passed to HEC-FDA for a determination of EAD. The with-project EAD can be compared with the existing condition and future without-project EAD to estimate the benefits of alternative plans.

EVALUATION PROCESS

This section includes a synopsis of the iterative technical evaluation process that was developed over the course of the study and used to perform preliminary system-wide evaluations. This process was developed for use in reconnaissance-level, basin-wide analyses; future studies using the Comprehensive Study modeling tools should take care in developing assumptions and evaluation procedures appropriate for their needs or level of detail.

The basic flow of information through the Comprehensive Study technical modeling suite involves initial processing of the hydrology through the reservoir operations models, which pass flood flow data to the hydraulic models, which in turn pass stage-frequency information to the risk and economics model. This process used to perform the basin-wide evaluations is outlined in **Figure 14** and described in the following sections.

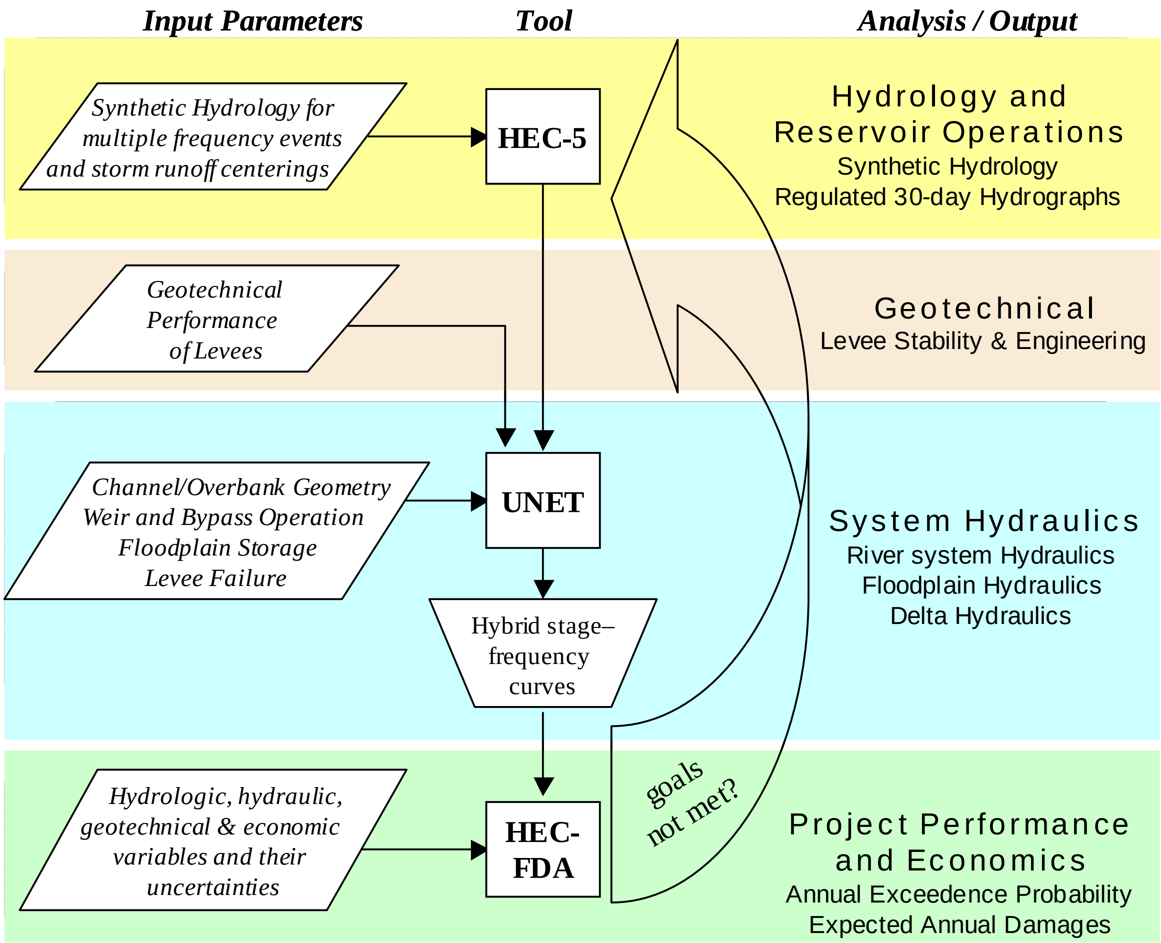


FIGURE 14 – FLOW OF INFORMATION BETWEEN COMPREHENSIVE STUDY TECHNICAL TOOLS

Hydrology and Reservoir Operations

Hydrology, in the form of 30-day unregulated hydrographs, is the starting point for any evaluation. The Comprehensive Study's hydrology was designed for basin-wide and regional analyses, but additional hydrologic evaluations may be required for site-specific projects, feasibility studies, or design. Synthetic hydrographs are fed into the reservoir operations models to simulate the effects of existing storage facilities, and/or to evaluate the benefits of changes to reservoir storage or release operations. For each evaluation, regulated hydrographs below the major flood control reservoirs are developed for each of the flood frequencies and dominant storm centerings.

Geotechnical Performance

As described previously, the chance of levee failure is represented through a geotechnical performance curve that relates river stage to probability of geotechnical failure. For basin-wide evaluations, curves are assigned by reach in the same manner as for the baseline condition but may be modified to reflect proposed levee improvements that would affect the LFP, PFP or PNP. The synopsis describes an evaluation using the Comprehensive Study's

LFP (50% probability of failure) approach, which may not be suitable for all model applications.

Hydraulics

Next, the UNET hydraulic models route the regulated flood hydrographs through the system of tributary and mainstem channels in each basin for the various storm events and centerings. UNET modeling results are reported at each index point as a plot of event frequency versus water surface elevation. For example, the peak simulated water surface elevation produced by the various storm centerings for a flood event with a 2% probability of occurring in any year forms one point on the curve, the peak from the event with a 1% probability of occurring forms another point, and so forth. Peak water surface elevations from UNET are plotted for each of the event frequencies and connected to form a stage-frequency curve.

For reaches with levees, the stage-frequency curve flattens or becomes horizontal at the point where the levee in that reach fails (at the LFP elevation), or sometimes when adjacent upstream levees fail. After a levee failure, the water surface elevation remains relatively constant for all higher flow frequencies because flows are escaping into the floodplain through the levee break. The HEC-FDA model needs a complete stage-frequency curve to the top of the levee, so the upper end of the curve is extrapolated above the frequency of levee failure using the infinite-channel UNET run. The infinite channel run assumes that no levee breaks occur (infinitely high failure elevation) and that all water is contained within the main channels. The portion of the infinite channel frequency curve above the frequency of levee failure is translated down to meet the baseline (with-failure) curve where it intersects the LFP and flattens. The resulting hybrid curve, a combination of the with- and without levee failure scenarios, is then entered into HEC-FDA.

Floods with greater than a 50% probability of exceedence were not modeled because more frequent events typically stay within natural channels and do not cause damage. In the Sacramento River basin, the hybrid curve was manually extended to include these frequent events using the slope of the curve between the 50% and 10% exceedence plot points and the adjacent ground elevation. Similarly, stage-frequency curves in the San Joaquin River basin were extended below the 50% flood using the water surface elevation at the time the topographic surveys were performed, which corresponds to nearly a 100% chance of occurring in any year. The development of the hybrid stage-frequency curve is shown graphically in **Figure 15**.

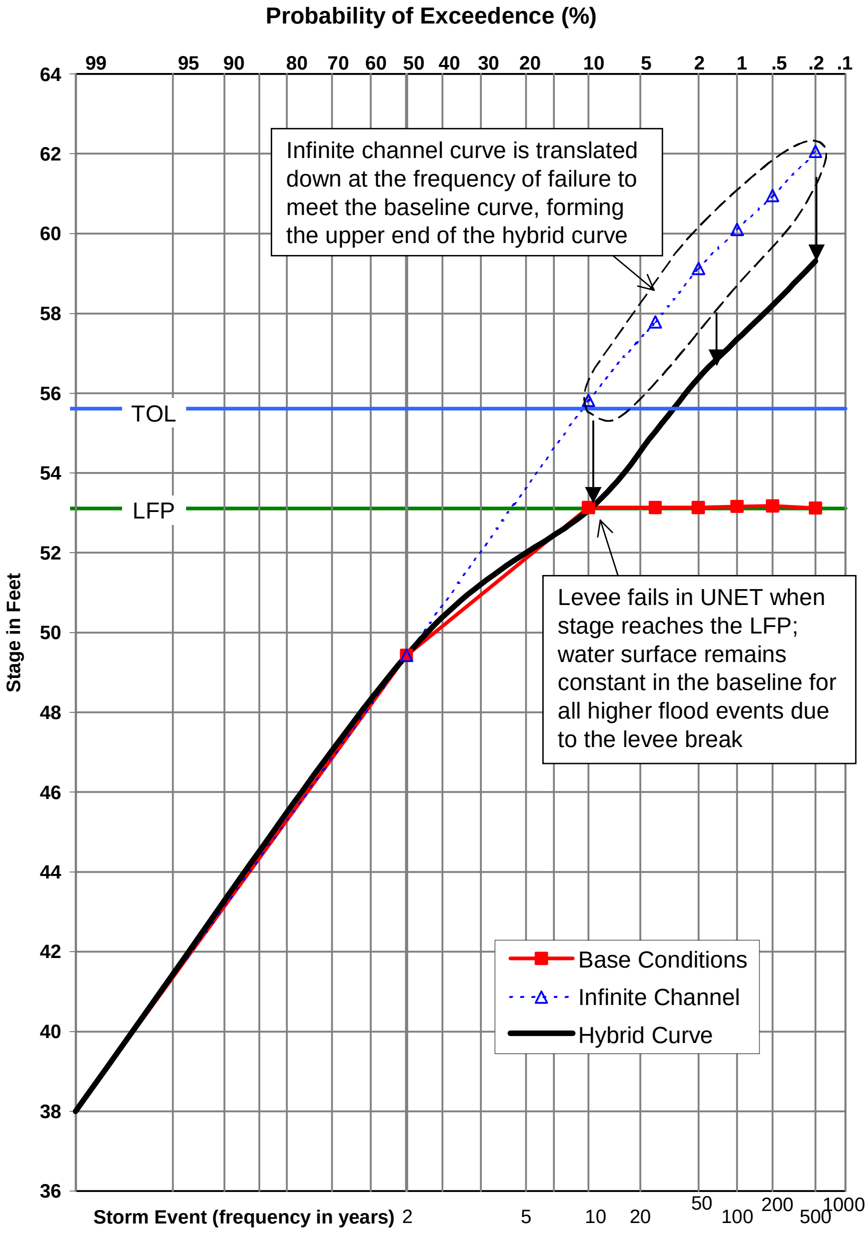


FIGURE 15 – CONSTRUCTION OF THE HYBRID STAGE-FREQUENCY CURVE

Project Performance and Economics

HEC-FDA integrates input from the hydrologic, geotechnical and hydraulic technical tools in a risk-based analysis. Input data includes information relating to the uncertainty of the hydrologic data, levee performance curves, stage-frequency curves from UNET, and economic data. As described previously in the Risk Analysis section, the primary outputs of HEC-FDA that are used in project formulation and evaluation are project performance (flood risk statistics) and economic damages.

Iteration Process

Iterations are performed within each model and between analysis steps until all of the planning goals or objectives of an evaluation are met. For example, successive iterations might be performed within UNET until a target water surface is achieved only to find that the desired flood risk, calculated in HEC-FDA, was not achieved. In this case, additional iterations between UNET and HEC-FDA may be required until the risk target is also achieved. The number of iterations performed both within the models and between the models is largely dependent upon the type and number of planning objectives set for a particular plan, and the level of detail desired. Initial simulations may be performed that examine only a few representative index points or risk statistics to quickly narrow in on the targets, followed by final simulations examining all index points to refine the plan. In this manner, an expedited analysis process was developed to decrease the amount of time required to arrive at desired targets or objectives.

Expedited Basin-wide Analysis

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. 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.

Interpreting Evaluation Results

Figure 16 provides an example comparison of project performance statistics in a representative impact area. The top panel compares annual exceedance probabilities for existing conditions with two hypothetical alternative evaluations. Both alternative evaluations have lower annual exceedance than for existing conditions, thus both plans represent an improvement. Similarly, the middle panel indicates that long-term risk is lower for both of the hypothetical evaluations compared to existing conditions. In the bottom panel, both plans show improved non-exceedance values (the ability to pass specific events) for the 10%, 4%, and 2% flood events, but values for the 1% event are slightly less than existing conditions.

When evaluating results between UNET and HEC-FDA, it is important to remember that HEC-FDA applies uncertainty to all aspects of a plan. For example, safely conveying a 1% flood flow in UNET may not be sufficient to achieve a 1% AEP in HEC-FDA. This is because UNET does not consider the possibility that the computed hydrology or water surface for the 1% event could be inaccurate.

Consider the hypothetical evaluation of a levee that is intended to provide a CNE of at least 0.90 for the 2% flood event (a 90% chance of passing the 2% flood). UNET modeling is performed to determine the peak water surface elevation for the 2% flood and the LFP of the new levee is set to this elevation. A stage-frequency curve is prepared for the index point in this reach and passed to HEC-FDA. However, the calculated CNE reflects only a 65% probability of passing the 2% flood because the hydrology for this reach is based on only 15-years of gage record, introducing uncertainty. Fine-tuning of the stage-frequency curve indicates that an additional 1.5 feet will need to be added to the top of the levee in order for the project to achieve the CNE target of at least 0.90 for the 2% flood.

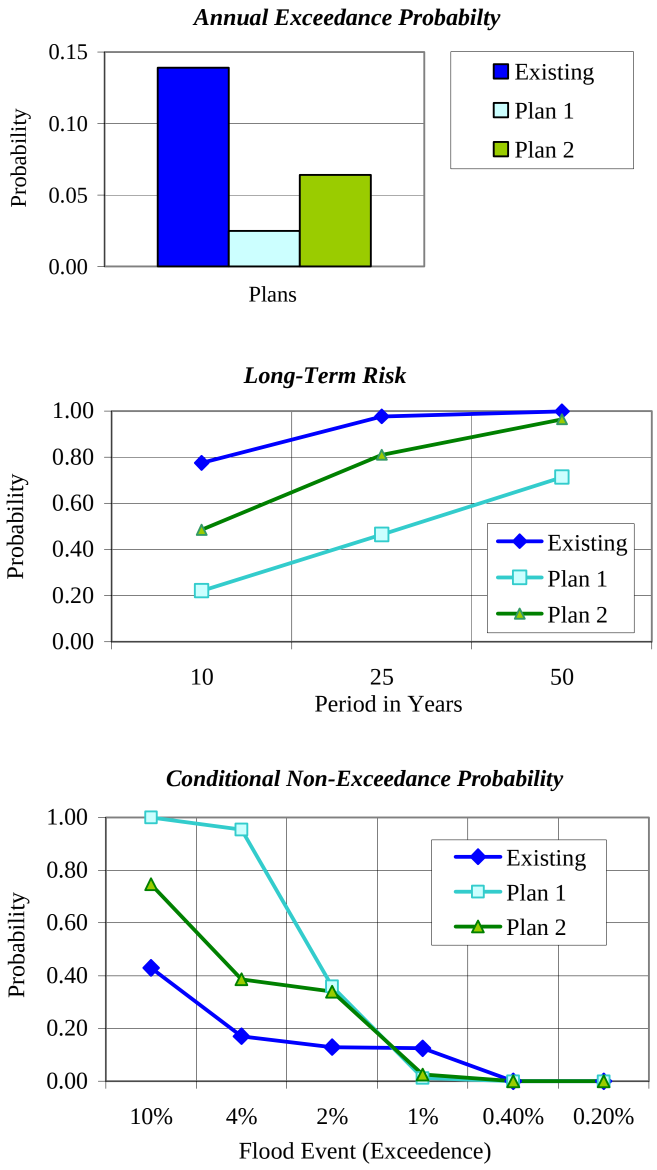


FIGURE 16 – SAMPLE COMPARISON OF PROJECT PERFORMANCE RESULTS

ECOSYSTEM FUNCTIONS STUDIES

The Comprehensive Study developed the Ecosystem Functions Model (EFM) to predict differences between without-project and with-project conditions in river reaches that would be affected by modifications to the flood management system. The functional relationships identified in the EFM are highly dependent on hydrologic and hydraulic characteristics of the river channel and floodplain. Using input variables such as stream flow, land use, soil type, vegetation, and topography, the EFM provides an indication of how potential floodway modifications could preserve, reduce, or enhance biological response. The EFM is described in detail in *Appendix G – Ecosystem Functions Model*.

Technical Approach

Unlike other models developed for the Comprehensive Study, the EFM is not a single computer program. Rather, the evaluation of ecosystem functions requires five major steps, shown **Figure 17**. Computer code has been developed to help automate portions of the EFM, but evaluation and interpretation are an important part of the EFM.

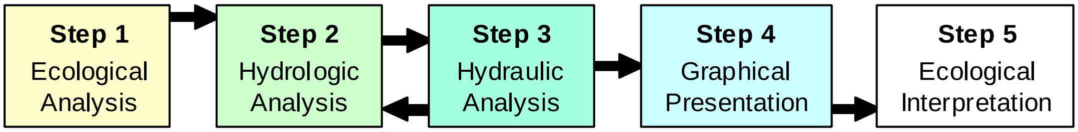


FIGURE 17 – ECOSYSTEM FUNCTION MODEL PROCESS

Step 1 - Ecological Analysis

The ecological analysis step identifies functional relationships between river hydrologic and hydraulic conditions and the riverine ecosystem/geomorphic system. These relationships reflect the different stream flow duration, flow frequency, and stage recession rate requirements of different types of habitats. The ecological analysis addresses two major elements: the aquatic ecosystem and the terrestrial ecosystem.

Aquatic ecosystem – The aquatic ecosystem consists of in-channel habitats, seasonally inundated floodplain, and flood bypass habitats. Relationships focus on factors that affect all the life stages of salmonids and Sacramento splittail, which are used as representatives of the entire aquatic community. The in-channel element includes relationships that reflect the dependence of suitable substrate, instream cover, and bank vegetation on changes in flow and morphologic parameters. The floodplain element incorporates conditions for suitable overbank flows to benefit floodplain spawning, rearing, and avoidance of stranding, and predicts spatial changes in the extent of suitable floodplain habitat.

Terrestrial ecosystem - The terrestrial ecosystem consists of existing riparian and wetland zones, rates of ecosystem change in these communities, and wildlife habitat values of these dynamic systems. Predicted changes in potential riparian/wetland zones would be inferred spatially by overlying suitability maps reflecting particular attributes, as identified in several relationships. Other relationships specify how several ecosystem processes would be temporally affected (such as fluctuations in the rates of change).

The ecological analysis has identified fifteen biological relationships to date, but others may be developed and added to the EFM in the future. Twelve of these relationships require a hydrologic analysis to provide stream discharges for subsequent hydraulic modeling, as described below in Step 2.

Step 2 - Hydrologic Analysis

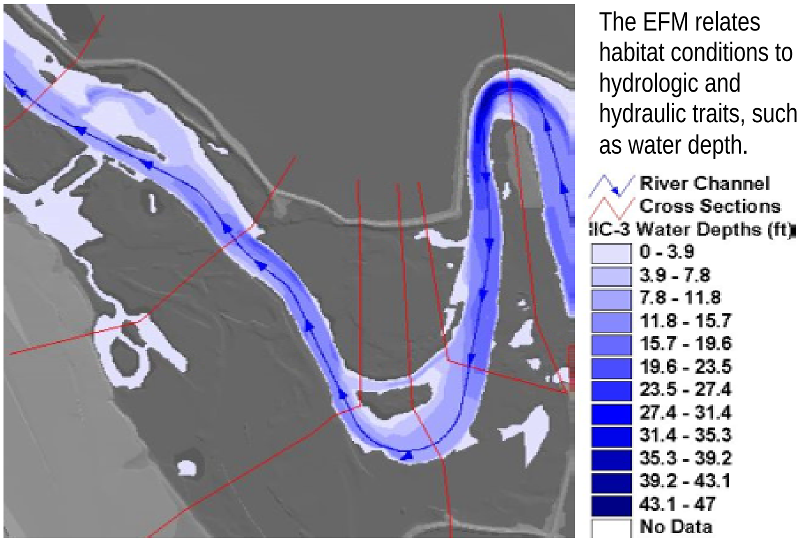
A statistical analysis translates the ecosystem relationships developed in Step 1 into hydrologic discharges (stream flows) for specified durations, flow frequencies, and stage recession rates. The statistical analysis uses historical, existing, and/or with-project conditions (resulting from modification of reservoir operations, changes to levees, addition of transitory storage, or other proposed elements). The statistical analysis is conducted in a spreadsheet environment. The ecosystem requirements and statistical analysis are then coded into a computer software package for use in Step 3.

Step 3 - Hydraulic Analysis

Step 3 simulates the hydraulic response of the river system to the discharges (stream flows) estimated in the previous steps. Discharges developed in Step 2 are input to a HEC-RAS hydraulic model to obtain simulated stages and flood inundation areas. HEC-RAS is a river-system modeling package that is capable of simulating steady or unsteady flow in a network of open channels. HEC-GeoRAS, a geographic information system interface module developed for use with HEC-RAS, is used to create existing and/or with-project geo-referenced river cross-sections of the study reaches for the HEC-RAS model, and export simulation results into a GIS environment for presentation and evaluation.

Step 4 - Graphical Presentation

A GIS tool (such as ArcView) is used to display the hydrologic and hydraulic simulation results together with other available geographic information, such as vegetative cover, soil types, land use, historic and existing topography, and ground water elevations. A sample is shown in **Figure 18**, which displays water depth in a study reach. The graphical presentation helps ecologists evaluate how proposed flood management and ecosystem restoration measures will impact existing terrestrial and aquatic habitat.



The EFM relates habitat conditions to hydrologic and hydraulic traits, such as water depth.

FIGURE 18 – GRAPHICAL PRESENTATION OF EFM RESULTS

Step 5 - Ecological Interpretation

The final step in the ecosystem function evaluation involves interpretation of the modeling results and various ecological and landform features by ecologists. Comments, conclusions, or recommendations are then made on the proposed flood management and/or ecosystem restoration measures.

EFM Pilot Studies

Two pilot studies have been completed using the EFM, one on the San Joaquin River near Vernalis and the other on the Sacramento River near Princeton. The Vernalis reach was selected because 1) there is no significant backwater effect in the reach; 2) the reach has a relatively wide floodplain confined by a levee on one side and a natural terrace and levee on the other side, making it easier to differentiate inundation areas for different flows; and 3) a nearby USGS gage provided a daily flow record of sufficient length for a statistical analysis. The Princeton site was selected because 1) there is no significant backwater effect in the reach; 2) the left bank levee constricts the river near the town of Princeton, offering a logical location to straighten the levee; 3) a nearby USGS gage provided a daily flow record of sufficient length for a statistical analysis.

Preliminary Results

Vernalis - A statistical analysis of the model algorithms and hydraulic data for the 1997 flood season was completed. Mapping of analysis results indicated that there were several locations in the pilot reach that should support riparian vegetation. These model outputs were field-verified for accuracy during a visit to the pilot reach. The areas projected to have riparian vegetation by the EFM did in fact have willow and cottonwood seedlings of the appropriate age class to have sprouted following the 1997 flood season.

Princeton – Mapped results indicate that a portion of the 480-acre floodplain reconnected to the river by a hypothetical levee realignment would be flooded about every 2 years. The realignment reduced the flow constriction such that water surface elevations in the reach were decreased by about 2.5 inches for an event with a 10% chance of occurrence in any year. A large portion of the new floodplain area would be suitable for floodplain fish-rearing habitat. The EFM suggests that the spatial extent of riparian vegetation will not increase as a result of the levee realignment because plant establishment flows remain in-channel and would not inundate the reconnected floodplain.

The two pilot studies demonstrate how the EFM can be used during planning and feasibility studies to indicate biological response to proposed changes to the flood management system and envision potential ecological improvements. As with other Comprehensive Study tools, the EFM is expected to evolve and develop additional capabilities as it is used in future studies.

GEOMORPHOLOGIC STUDIES

Geomorphology is the interdisciplinary and systematic study of landforms and their landscapes as well as the earth surface processes that create and change them (International Association of Geomorphologists). Fluvial geomorphology is the study of the geologic formation, configuration, and natural processes of riverine landforms. Understanding the relationships between rainfall runoff, geology, and erosion is critical to understanding how the shape of rivers and streams will change over time. The factors that influence fluvial geomorphology are complex, and the influence of many of these factors is relative to the timescale under consideration. For instance, while a geomorphic trend may be recognized in geologic time (several hundred thousand years) there can be significant deviations from this trend in human time (several decades).

Historical channel morphology is often used as a template for stream restoration because riparian habitats rely on the dynamic nature of rivers and streams to support natural habitat succession. The success of ecosystem restoration must consider existing and future channel conditions in both a regional and basin-wide context. Flood damage reduction components can also benefit from geomorphologic studies because they can identify unstable reaches or areas with high migration potential that may not be ideal for levees, weirs, or other flood management facilities.

The Comprehensive Study has undertaken reconnaissance fieldwork and data collection to support future geomorphological studies. A separate report titled *Geomorphic and Sediment Baseline Evaluation of the San Joaquin River from the Delta to the Confluence with the Merced River and Major Tributaries,* 2000, documents reconnaissance-level geomorphic and sediment transport studies on the San Joaquin River between Old River and the confluence with the Merced River at Hills Ferry. Data used in the evaluation includes historical maps of the system prior to significant human intervention; hydrographic and other surveys of the San Joaquin River from 1914, 1930, 1974, 1983, and 1998; levee profiles and thalweg measurements from the 1950's; geological maps showing surface and subsurface geology; and soil samples along the study reach. The report indicates general aggradation and degradation trends during the period of available records. The Comprehensive Study also performed a literature search for documents containing sediment, dredging, geology, soil boring, bed profiles, and other information that would be useful for future geomorphological studies in the basins.

Future geomorphological studies are likely to evaluate topics such as basic river behavior and sediment transport characteristics, and how they affect future decisions regarding flood management and ecosystem restoration in the rivers and floodplains of the Central Valley. Numerous geomorphological studies have been conducted within the Comprehensive Study planning area in the past. The intent of future work is not to replicate those studies but to compile existing information and fill any gaps in this information, as appropriate. It is anticipated that these studies would adopt a watershed focus consistent with the Comprehensive Plan that considers both the regional and basin-wide implications of the findings.

Existing Conditions

On most streams and rivers in California today, the flow regime and the sediment supply have changed significantly from historical conditions. Stream diversions have modified in-stream flows and reservoirs have changed the hydrologic regime and have trapped sediment. Because river channels are continually seeking a state of geomorphic equilibrium, human-induced constraints on the river systems can produce highly unstable conditions.

The Sacramento River basin has experienced major changes to its hydrology and sediment yield. Early hydraulic mining caused massive amounts of erosion in the upper watersheds and released millions of cubic yards of sediment into the river system. Large reservoirs have greatly reduced peak flood flows and diversions have reduced base flows. Levees and bypasses have confined river channels that once migrated or overflowed into the floodplain. Land use development and gravel mining have further changed the dynamic equilibrium of the system.

The San Joaquin River basin has generally experienced similar impacts to the Sacramento River but has a more arid climate. As such, there is rarely enough water to satisfy natural, agricultural, and municipal demands and much of the upper reaches of the San Joaquin River have run dry. Both base flows and flood peak flows have been regulated to the extent that they no longer support natural geomorphic and ecosystem functions.

Future Geomorphology Studies

Geomorphologic studies collect and map information on geologic features and geomorphic characteristics to provide information that can be used to support plan formulation efforts, such as identifying favorable ecosystem restoration areas or stable levee alignments. Basic geomorphic relationships are commonly used to develop width, depth, meander amplitude, and meander wavelength estimates that define hydraulic geometry. Migration rates are often estimated to evaluate long-term maintenance requirements and habitat community succession rates for proposed floodway modifications. Typical elements of geomorphology studies include: data collection (field sampling, surveys, and data management); meander zone evaluation; development of hydraulic geometry and basic geomorphic relationships; bank full discharge; and bank migration.

Future Sedimentation Studies

Although the concept of stability is used widely to describe a natural stream or river, natural rivers and streams are rarely stable. The movement of sediment within a river system drives channel aggradation (raising of the channel bed) and degradation (lowering of the channel bed) as the river continually adjusts to the environment. Sedimentation can often be detrimental to the flood management system when it reduces the capacity of the river to carry flood flows. On the other hand, the deposition of sediment in overbank and floodplain areas after floods can be beneficial, enriching soils and encouraging natural vegetation recruitment. Rapid degradation of a channel can be detrimental to flood management facilities, bridges, and other infrastructure.

Sedimentation studies that are performed in conjunction with feasibility studies typically focus on identifying upstream sediment sources, and assessing channel stability. This information can be useful in planning studies to ensure that proposed projects are not detrimental to flood management or ecosystem restoration opportunities in adjacent regions. Typical elements in sedimentation studies include the following: sediment load and budget analysis; sediment accounting and transport modeling; and channel stability assessment.

USE OF COMPREHENSIVE STUDY MODELS AND TECHNICAL DATA BY OTHER STUDIES

The basin-wide tools developed by the Corps and DWR for the Comprehensive Study represent a significant step in the ability to evaluate the existing river system and develop future projects in the Central Valley. The tools described herein were developed for the purpose of basin-wide analyses, or those performed at a watershed scale. Consequently, the level of detail, technical approach, or assumptions may not be appropriate for some studies, particularly detailed studies or evaluations of highly localized conditions. In some cases, supporting data collected by the study, such as topography and aerial photographs, could be used to supplement or enhance the models for other applications. In other cases, future studies may choose not to use the Comprehensive Study's tools and instead develop other models or information that better fulfills their technical needs. It is also anticipated that the technical tools will be updated and enhanced over time, similar to the manner in which hydrology must be updated following severe weather events.

The Comprehensive Study's technical tools are intended to be a resource for future studies, but they should not be applied blindly without consideration for their technical appropriateness. Some considerations for future applications are described below, but the individual needs and objectives of future studies will ultimately determine how the Comprehensive Study's suite of technical tools can provide assistance.

Synthetic Hydrology

The intent of the synthetic hydrology developed for the Comprehensive study is to provide a basis for defining existing hydrologic conditions on a regional basis, and support an array of systematic analyses of potential water resources development opportunities in the Central Valley. While traditional hydrologic approaches are well suited to single rivers or watersheds, the Comprehensive Study hydrology was tailored for use in a 43,000 square-mile study area. The hydrology offers sufficient detail in the storm centerings, local-flow contributions, and ungaged stream contributions to be applied in basin-wide and pre-feasibility evaluations. However, further investigation may be needed to use this information for more detailed or site-specific studies. Additional information on the use of Comprehensive Study hydrology can be found in the "Expectations of Use" preface to *Appendix B –Synthetic Hydrology Technical Documentation*.

Reservoir Operation Models

The reservoir operations models developed for the Comprehensive Study are excellent representations of the existing flood control system, and were developed specifically for use in regional, broad-concept studies. As developed, the models are capable of facilitating the technical needs of most pre-feasibility studies, but more detailed models may need to be developed for site-specific applications. The existing condition HEC-5 reservoir simulation models were constructed using operational criteria and procedures published in the Water Control Manual of each flood control reservoir. For reservoirs that do not have formalized flood operations or published criteria, operational criteria were developed through discussions with facility owners and operators and by analyzing historic gage data. Several operational assumptions were needed for the modeling effort, including estimates of starting storage, flow splits, credit space, release ramping, and river routing parameters. It should be noted that the models reflect ‘by the book’ operations, which may not conform to historic operations when severe floods can dictate deviations from the Water Control Manuals. Additional information on the use of Comprehensive Study reservoir operations models can be found in the “Expectations of Use” preface to *Appendix C – Reservoir Operations Modeling*.

Hydraulic Models

The UNET models that simulate river system hydraulics in the Sacramento and San Joaquin river basins were developed at a level of detail suitable for basin-wide river system analyses. River channel geometry is reflected in the model as cross sections spaced at 0.20- to 0.25-mile increments. This cross section spacing may not be sufficient for the study of localized river conditions or for small study reaches. Similarly, localized model applications may call for additional detail at bridges, natural and man-made constrictions, or other in-channel features. Furthermore, the levee failure assumptions used by the Comprehensive Study were adopted for the purpose of basin-wide flood risk analyses. The geotechnical data supporting the levee failure designations are reconnaissance-level; hence, levee reliability data is not based on detailed field explorations, sampling, or testing of levee materials, with the exception of information available from recent studies. The levee failure assumptions have a significant effect on the volume and magnitude of flow in the river systems and may not reflect historic flood events or be suitable for designing changes to the flood management system. Additional information on the use of Comprehensive Study hydraulic models can be found in the “Expectations of Use” preface to *Appendix D – Hydraulic Technical Documentation*.

Comprehensive Study Floodplains

The synthetic hydrology, levee failure assumptions, and hydraulic models all influence the floodplains developed by the Study, which were delineated specifically for use in basin-wide flood risk analyses. Comprehensive Study floodplains are intended to encompass the full extent of possible flooding, reflecting the influence of multiple storm conditions on the shape and extent of the floodplain. These floodplains may differ from those developed by other studies (including FEMA floodplains that are used for regulatory purposes) due to fundamental differences in the technical approach, assumptions, hydrology, and intended end-use. Comprehensive Study floodplains are not intended to replace or supercede existing regulatory floodplains. Instead, they are an additional resource for studies and local planning efforts.

As with other Comprehensive Study models, the FLO-2D hydraulic models used to delineate the floodplains were developed for regional use. Large grid sizes (about 2,000 feet on edge) were used in the models for efficiency and stability. Bridges, streets, and other features are not specifically modeled in FLO-2D, although raised highways, levees, and other topographic features are discerned in the grid elements. This level of detail is satisfactory for conceptual evaluations, but may not be suitable for all applications of the model.

Flood Risk and Economics Models

The HEC-FDA models of the Sacramento and San Joaquin basins were developed for basin-wide use and additional detail or investigation may be required to use them on a regional or local level. It is expected that the models will continue to be enhanced over time. This could include refinements to damage estimates for the public service sector and inclusion of other damage categories (autos and roads, traffic disruption and emergency response costs). Publicly owned parcels, which are not assessed property taxes, are not currently included in the structural inventories. It is anticipated that future feasibility studies will require more detailed risk analysis models, for which the extensive data and HEC-FDA models developed by the Comprehensive Study can be a valuable resource.

Ecosystem Functions Model

The EFM differs from other models developed for the Comprehensive Study in that it is a process for evaluating potential biological approach, rather than a single input/output computer program, and relies on the professional judgement of ecologists or other experts to draw conclusions from the results. In addition, the EFM is applied on a reach-by-reach basis, rather than for the Sacramento or San Joaquin River basins as a whole. The biological relationships developed for the model are representative of a broad range of aquatic and terrestrial ecosystems but do not necessarily characterize individual species. For example, the model’s aquatic relationships focus on the life stages of salmonids and Sacramento splittail, which are used as representatives of the entire aquatic community. Future studies that choose to use the EFM may need to develop additional ecological relationships to address the unique characteristics of the local ecology.

INFORMATION PAPERS

Appendix A – Information Papers includes a collection of short, informational papers and technical memoranda relating to various technical issues encountered during the Comprehensive Study. The purpose of the information papers varies, from documenting research or findings about key planning topics to providing simplified summaries of complex technical issues. These papers are for informational purposes only and do not intend to recommend or promote specific flood damage reduction or environmental restoration measures, indicate the importance of specific issues, or represent every issue brought to the attention of the study. They document preliminary findings and information that may be useful for future studies. A list of the technical focus papers can be found at the beginning of Appendix A.

OTHER STUDIES AND REPORTS

Various other studies and reports were developed for or concurrent with the Comprehensive Study. These are described briefly below:

Post-Flood Assessment, Sacramento and San Joaquin River Basins, California, 1999 - Authorization and funding for a Post-Flood Assessment was established concurrently with the Comprehensive Study in the Energy and Water Development Act of 1998. It gave directions for "*preparation of a comprehensive post-flood assessment for the California Central Valley (Sacramento River Basin and San Joaquin River Basin)…*" The Post-Flood Assessment focuses on the impact of major floods in the Sacramento and San Joaquin River basins during 1983, 1986, 1995, and 1997, including maps of flooded areas and an estimation of economic damages. It also chronicles the development of flood protection in the Central Valley during the past 150 years, including descriptions of major facilities and their operating objectives and constraints.

Geomorphic and Sediment Baseline Evaluation of the San Joaquin River from the Delta to the Confluence with the Merced River and Major Tributaries, 2000 – This report documents reconnaissance-level geomorphic and sediment transport studies on the San Joaquin River between Old River and the confluence with the Merced River at Hills Ferry. Data used in the evaluation includes historical maps of the system prior to significant human intervention; hydrographic and other surveys of the San Joaquin River; levee profiles and thalweg measurements; geological maps; and soil samples along the study reach. The report indicates general aggradation and degradation trends during the period of available records.

Existing Hydrodynamic Conditions in the Delta During Floods, 2002 and **Lower San Joaquin River Assessment, 2002 –** These information reports were developed for the Comprehensive Study to gain a better understanding of the complex hydrodynamic conditions in the Delta during floods. They describe the modification and use of DWR's Delta Simulation Model II to characterize flood conditions and evaluate potential project impacts in the Delta.

Conjunctive Use for Flood Protection, 2002 - The Corps' Hydrologic Engineering Center performed a reconnaissance study to assess whether employing conjunctive use within the Sacramento and San Joaquin River basins produces sufficient flood protection benefits to warrant future investigations. Conjunctive use is the cooperative management of both surface water (reservoirs, rivers, canals) and groundwater (aquifers) resources to expand the utility and reliability of both. Conjunctive use for flood protection involves lowering the flood-season reservoir pool and storing the displaced water in an aquifer for later, beneficial use. While flood protection is not the first priority of conjunctive use operations in California, this investigation indicated that it could potentially increase flood protection at reservoirs, with potential incidental water supply benefits.

Ecosystems Functions Model—Conceptual Design Report, 1999 and **Functional Relationships for the Ecosystem Functions Model, 2000** – These reports document the original conceptual design of the EFM and the development of relationships between physical, hydrologic, and biological variables that are used in the model. The Conceptual Design Report was included as Appendix D of the Comprehensive Study's Phase I

Documentation Report, and the Functional Relationships for the Ecosystem Functions Model describes the development of terrestrial and aquatic habitat indicators.

Watershed Impact Analysis, 2000 – The Corps' Hydrologic Engineering Center prepared a report on the impact of urbanization on rainfall runoff. The Hydrologic Modeling System (HEC-HMS) was used to simulate hypothetical land use changes in a representative watershed and evaluate how increases in land development affect peak flow and runoff volume.

San Joaquin River Basin Levee Reliability Survey, 1999 – DWR's Division of Flood Management conducted a reconnaissance field inspection of levees in the San Joaquin River basin. The survey was performed because data on the reliability of levees was limited in the San Joaquin River basin at the start of the Comprehensive Study. The field survey delineated historic problem areas and potential problem areas through extensive discussions with levee maintenance personnel, on-site evaluations, cross sectional data, location and mapping of previous trouble spots or failures using a Global Positioning System (GPS), identifying remnant sand bag rings constructed during floods to control boils and seepage, and engineering judgment.

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GLOSSARY

OF TERMS AND ABBREVIATIONS

acre-foot - a measurement of volume equal to 43,560 cubic feet; the volume of water that would cover an area of one acre, one foot deep; abbrev. AF or TAF (thousand acre-feet)

AFRP - Anadromous Fish Restoration Program

aggradation – the deposition of sediment in a stream; an aggrading stream is characterized by a general raising of the bed elevation over time, indicating that sediment is being deposited within the channel (the opposite of degradation)

Anadromous fish - Anadromous fish are born in fresh water, migrate to the ocean to grow into adults, and then return to fresh water to spawn.

Annual Exceedence Probability (AEP) – 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.

@RISK – a risk analysis and decision making tool by Palisade Software that works within a spreadsheet environment; uncertainty is associated with input variables through probability distribution functions and risk analysis is performed using Monte Carlo simulation to define probable outcomes.

average return frequency – the average length of time between flood events of a specific magnitude, averaged over many thousands of years. A flood with an average return frequency of 100 years could occur multiple times during a given century, or not at all; for this reason, probability of exceedence (chance of occurrence, expressed as a percentage) is the preferred term for describing the probability that a flood will occur. For example, a flood event with an average return frequency of 50 years has a 2% probability of occurring in any given year.

bankfull discharge – the maximum flow that can be carried within the natural banks of a river channel, or the flow that occurs when a river’s stage is at the top of bank. Bankfull flows typically occur every one to two years.

CALFED - a cooperative effort of more than 20 state and Federal agencies working with local communities to address water supply, water quality, and ecosystem improvements in the Sacramento-San Joaquin Delta.

CEQA - California Environmental Quality Act, a law applying to all projects that require State or local government approval. It requires (1) disclosure to the public of potential environmental impacts of a proposed project; (2) identification of ways to reduce adverse impacts through changes to the project; (3) presentation of alternatives to the project, and (4) disclosure to the public of the reasons why the governmental agency approved the project if significant impacts are involved.

CNE - Conditional Non-Exceedence, the probability of passing a specific flood event (i.e. a 90% chance of passing a flood with a 2% chance of occurring in any year)

Comprehensive Study - the Sacramento and San Joaquin River Basins Comprehensive Study, California

Comprehensive Plan – guidance for the development of modifications tot he flood management systems of the Sacramento and San Joaquin River Basins, as outlined in the *Interim Report, Sacramento and San Joaquin River Basins Comprehensive Study, California*, 2002

calibration – adjusting or fine-tuning a process such that expected results are achieved; in the case of model simulations, the process of adjusting model parameters until simulated results compare closely with actual or historic conditions.

Central Valley – the Central Valley of California, encompassing the Sacramento Valley in the North and the San Joaquin Valley in the South.

composite floodplain – term describing the floodplains developed by the Comprehensive Study for use in basin-wide flood risk analyses; the composite floodplain combines the floodplains from multiple storm conditions on tributaries and mainstem rivers to delineate the full extent of potential flooding for any given flood frequency.

Conditional Non-Exceedence Probability (CNE) – the probability of safely containing an event with a known frequency, should that event occur. For example, a value of 0.04 for the 2% flood event corresponds to a four percent chance that the river system will be able to contain a flood with a 2% chance of occurring in any year. While annual exceedence probability (AEP) reflects the likelihood that flooding <u>will</u> occur, CNE describes the probability that a flood event will <u>not</u> occur.

conjunctive use – the cooperative management of both surface water resources (rivers, streams, water bodies) and ground water resources (aquifers) for beneficial uses. Conjunctive use for the purpose of flood control is based on the principle that increased flood protection could be attained by lowering reservoir conservation storage temporarily and conserving the displaced water in a groundwater aquifer for later, beneficial use; the additional reservoir space could then be used as flood control storage.

conservation pool – the reservoir elevation corresponding to the top of the storage pool that is conserved for water supply or other beneficial uses; also the bottom of the flood control pool.

CVP - Central Valley Project, the Federally owned and operated water storage and delivery system that transports water from Northern California to arid regions south of the Sacramento-San Joaquin Delta

DEM – Digital Elevation Model, a three-dimensional computer representation of surface topography based on a fixed grid (square grid elements spaced at regular intervals); this format is used widely by the USGS to describe topography

DFG - California Department of Fish and Game

DSM2 –Delta Simulation Model II, a computer model developed by the CA Department of Water Resources to simulate water quality in the Sacramento-San Joaquin Delta; adapted by the Comprehensive Study to model complex hydrodynamic conditions in the Delta

DSOD – California Division of Safety of Dams

DTM – Digital Terrain Model, a three-dimensional computer representation of surface topography; this format can be based on a fixed grid (square grid elements spaced at regular intervals) or triangular irregular network of grid elements

DWR - California Department of Water Resources

EAD - Expected Annual Damages, an annualized measurement of economic damages caused by a full range of potential flood events

EFM - Ecosystem Functions Model, a methodology developed for the Comprehensive Study to evaluate the functional relationships between hydrology, hydraulics, and riparian, wetland, and riverine habitats

ESRD - Emergency Spillway Release Diagram, describes operating criteria for reservoirs with gated spillways; used when making emergency releases (in excess of normal operating criteria) before available flood space is exhausted, design freeboard limits are encroached, and/or the dam is overtopped

FEMA - Federal Emergency Management Agency

FERC - Federal Energy Regulatory Commission

FLO-2D – a two-dimensional hydraulic computer model developed by FLO Engineering and used by the Comprehensive Study to simulate the movement of water through floodplains and overbank areas

FWS - U.S. Fish and Wildlife Service

geomorphology - the interdisciplinary study of landforms and the earth surface processes that create and change the topography of the planet. Fluvial geomorphology is the study of the geologic formation, configuration, and natural processes of riverine landforms

GIS - Geographic Information System, a computerized data management tool for storing, generating, evaluating, and displaying geospatially-referenced data

gross pool – reservoir elevation corresponding to the crest of the spillway or the point at which the reservoir must begin to release flows in excess of normal operational limits.

headwater reservoir –reservoirs located in the upper portions of a watershed, typically upstream from major flood control reservoirs (lower basin reservoirs)

HEC - Hydrologic Engineering Center, a unit of the U.S. Army Corps of Engineers

HEC-FDA - Flood Damage Assessment computer program developed by the Corps of Engineers for calculating economic damages and project performance

HEC-5 – Simulation of Flood Control and Conservation Systems, a computer model developed by the Corps of Engineers to simulate the operation of reservoir systems; used by the Comprehensive Study to simulate the operation of 73 reservoirs tributary to the Sacramento and San Joaquin Rivers.

HEC-RAS - River Analysis System, a computer modeling program developed by the Corps of Engineers to simulate river and channel hydraulics.

hydraulic conductivity – a material property characterized by the extent to which a given substance allows water to flow through it; in the case of levees, the hydraulic conductivity of levee materials or soils influences the potential for seepage during flood events.

hydrograph – a plot of the variation of streamflow (or stage) over time

left bank – the left bank of a watercourse, looking downstream, independent of its geographic course relative to the four compass directions (e.g. for a stream that flows due east to west, the left bank would refer to the southern stream bank)

LFP - Likely Failure Point, a statistical representation of the potential for levee failure developed for use by the Comprehensive Study in basin-wide hydraulic and economic evaluations; represents the river or water stage at which a levee has a 50% probability of failing.

LIDAR – LIght Detection And Ranging, a survey method that determines distance based on the time it takes a laser beam to be reflected from a surface; this technology is commonly applied to atmospheric measurements, ground based surveys, and aerial mapping

Long Term Risk (LTR) – the probability of flood damages occurring during a specified length 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 a 25-year reporting period reflects an 85% chance of flooding during a 25-year period.

Monte Carlo Simulation - a stochastic technique used to solve mathematical problems that involves randomly generating values for uncertain variables. The random selection process is repeated many times to develop a range of possible solutions, each with an associated probability of occurring. Monte Carlo Simulation is often used in cases where there is no mathematical solution or when mathematical expressions are too complex or difficult to use.

NAD83 - North American Datum of 1983; topographic data collected by the Comprehensive Study references this horizontal datum

NAP – Normal Annual Precipitation, or the average total precipitation experienced over one year; typically expressed in inches or centimeters

NED - National Economic Development, an account used to evaluate a proposed project’s contribution to national economic development and determine if there is a Federal interest in the project

NEPA - National Environmental Policy Act, the mandate that requires all Federal agencies to consider the values of environmental preservation for all significant actions and prescribes procedural measures to ensure that those values are in fact fully respected.

NER - National Ecosystem Restoration, an account used to evaluate a proposed project’s contribution to national ecosystem restoration and determine if there is a Federal interest in the project

NGVD29 - The National Geodetic Vertical Datum of 1929, a vertical geodetic datum formerly called "Sea Level Datum of 1929" or "mean sea level"; topographic data collected by the Comprehensive Study references this vertical datum

NMFS - National Marine Fisheries Service, a unit of the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce

NRCS - Natural Resource Conservation Service, a unit of the United States Department of Agriculture; formerly the Soil Conservation Service (SCS)

NWR - National Wildlife Refuge

objective flow – a common operating criterion for reservoirs, referring to the maximum allowable streamflow (discharge) at some point downstream from the reservoir

orographic – associated with or influenced by topography or landforms, especially mountains; precipitation patterns in the Sacramento and San Joaquin Basins reflect the orographic influence of the Coastal and Sierra Nevada mountain ranges

overbank flow – flow that occurs outside the main channel when a river overflows its natural banks; overbank flows are important factors in riparian habitat recruitment and health

P&G – the United States Water Resources Council's *Principles and Guidelines*, 1983, which describes the Federal objective of water and related land resources planning; used by Federal agencies in water resources panning projects

period of record – the length of time for which records have been kept at a gaging station.

PFP – Probable Failure Point, a term used by the Corps of Engineers to designate the stage at which levee failure is probable, corresponding to an 85% probability of failure

PNP – Probable Non-failure Point, a term used by the Corps of Engineers to designate the stage at which levee failure is improbable, corresponding to a 15% probability of failure

probability of exceedence – expression used to describe the probability that a flood event of a specific magnitude will occur in any given year. A flood with a 1% probability of exceedence has a 1 in 100 chance of occurring in any year. This terminology is preferred over the return frequency method, which can be misleading because return frequencies are statistical averages over many thousands of years.

right bank – the right bank of a river or stream, looking downstream, independent of its geographic course relative to the four compass directions (e.g. for a stream that flows due east to west, the right bank would refer to the northern stream bank)

RM - river mile, a measurement of distance along the centerline of a watercourse, with river mile zero at the downstream terminus of the watercourse

SRFCP - Sacramento River Flood Control Project

State Plane Zone 2 – a geographic reference system commonly used by geographic information systems; topographic data collected by the Comprehensive Study uses this reference.

storm centering – simulation of the effect of storms that are positioned (centered) over particular locations in a watershed to produce the maximum peak flow at those locations; a pattern of storms based on historic observations of flood events on multiple tributaries; part of a methodology used by the Comprehensive Study in developing hydrology for the Sacramento and San Joaquin watersheds that emulates the diverse spectrum of floods that can occur from different combinations of concurrent storms on tributaries, accounting for orographic influences and other factors that influence regional rainfall runoff events.

subsidence – (land subsidence) a lowering in elevation of the land surface that can result from manmade actions or natural processes, including groundwater withdrawal (pumping), soil consolidation, and geophysical events (tectonic or volcanic activity). In the Comprehensive Study planning area, groundwater extraction in excess of recharge (overdraft) is the primary cause of subsidence and has caused up to 30 feet of subsidence in some areas.

SWP - State Water Project

TAF - thousand acre-feet

top of conservation – reservoir elevation corresponding to the top of the dedicated conservation pool.

UNET – a one-dimensional hydraulic computer model that simulates unsteady flow through a full network of open channels, weirs, bypasses, and storage areas; used by the Comprehensive Study to simulate the riverine channels of the Sacramento and San Joaquin basins

unregulated rain flood frequency curves - plots of probability versus stream flow at a particular location, typically based on historic flood events, not including the influence of upstream reservoirs (unregulated). The curves can be used to predict the magnitude of flow associated with a particular rain flood event, such as the stream flow that could be expected during a flood event with a 2% chance of occurring in any year.

USACE - U.S. Army Corps of Engineers

USBR - U.S. Bureau of Reclamation

USED – United States Engineering Datum, a vertical elevation datum frequently used by the Corps of Engineers prior to the 1980’s

USGS - U.S. Geological Survey

Water Control Manual - publication of a reservoir’s flood damage reduction criteria and operational rules, as established by the Corps of Engineers under the Flood Control Act; required for all reservoirs with allocated flood space.