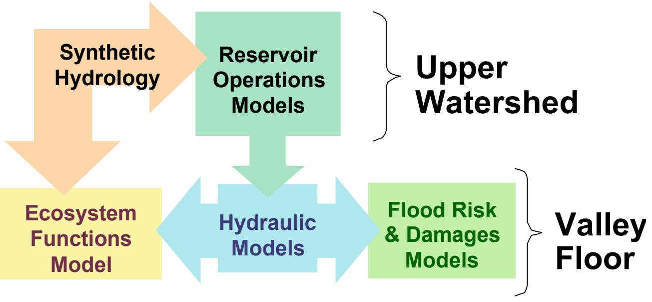
Guide to Technical Studies

The Comprehensive Study developed a suite of system-wide evaluation tools to gain a better understanding of the complex hydrologic, hydraulic, and ecologic processes that interact in the rivers and floodplains of the Sacramento and San Joaquin River basins. Prior to the Comprehensive Study, no models existed that evaluated Central Valley river systems on a watershed scale. The shear size of the study area warranted a new technical approach. The technical tools that were developed encompass the entire river systems, from reservoirs in the upper watersheds downstream to the Delta. They provide an unprecedented capability to evaluate the operation of the existing flood management system and develop future projects to reduce flood damages and improve the environment.



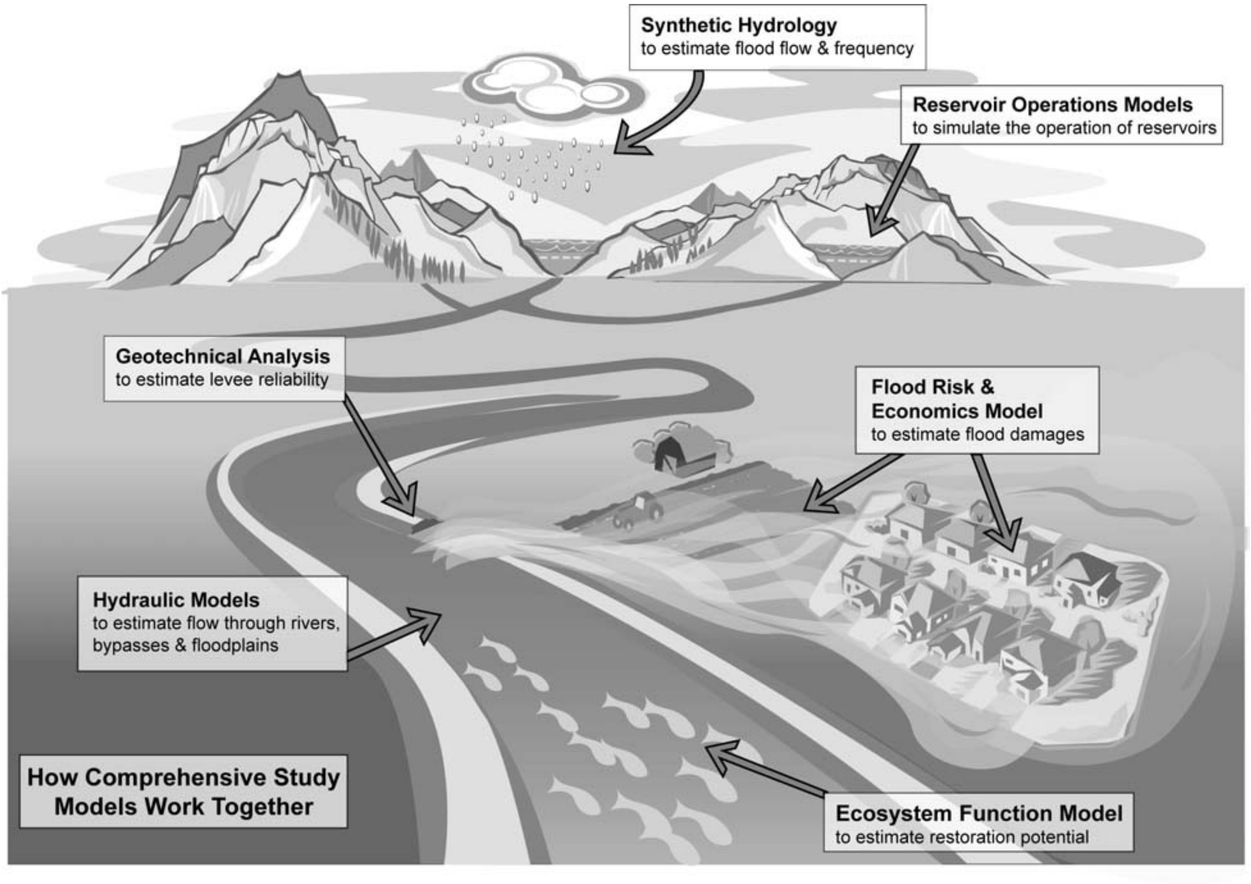
The technical tools consist of computer models and an extensive information database that allow a system-wide approach essential to future project planning. Rather than focusing on localized areas, the tools allow tracking the effects of potential projects throughout the river system. The study team used the tools to perform analyses of the existing system and evaluate an array of "what if" scenarios brought forth by participating agencies and stakeholders. The tools are a valuable resource for future studies.

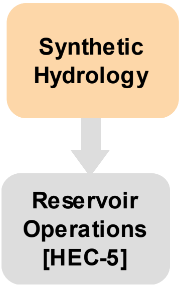
Central Valley Watershed Evaluation Tools

Discipline	Technical Product	Purpose / 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, in digital format for use in a CAD (computer aided design) or GIS environment.
Hydrology	Unregulated Hydrology	Basin-wide synthetic flood hydrology for multiple flood conditions, including events with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year.
	HEC-5 Models	Simulate the operation of over 70 headwater and foothill reservoirs tributary to the Sacramento and San Joaquin rivers.
Hydraulics	UNET Models	Simulate river system hydraulics along over 1,000 miles of Central Valley rivers, flood bypasses, and other major waterways.
	FLO-2D Models	Simulate the movement of water through valley floodplains.
	DSM2 (Delta Simulation Model 2)	Evaluate flood conditions in the Delta.
Geotechnical	Levee Reliability Evaluation	Information about the reliability of levees within the Sacramento and San Joaquin River basins.
Flood Damage Analysis	HEC-FDA (Flood Damage Analysis)	Evaluate flood risk and economic damages in the Central Valley, incorporating risk analysis
Ecosystem	EFM (Ecosystem Functions Model)	Evaluate functional relationships between hydrology/hydraulics, and riparian, wetland, and riverine habitats.
Information Management	GIS (Geographic Information System)	Geographic database of the Sacramento and San Joaquin River basins (including hydrography, habitat, development and infrastructure, flood management facilities, properties, levee alignments, geology, and much more).

The technical tools developed for the study can be used either individually or together to evaluate existing conditions or test the response of the flood management system to potential modifications. Model output and other information are passed from one model to the next, starting with hydrology and reservoir operations in the upper watersheds, moving downstream to the rivers and floodplains of the valley floor, and into the Delta.

There is a separate document entitled, "Technical Studies Documentation/Summary of Technical Studies" which has 7 appendices. The separate document with appendices is not a part of this report. Work on the appendices, which includes various models, will continue beyond the publication and distribution of this Interim Report. Planning for local or regional projects will provide the opportunity for updating the existing models or developing new models as needed. The tools and models of the appendices will not be used until they are updated considering the best available information, including information based on the expertise and experience of local stakeholders.





Synthetic Flood Hydrology

Flood hydrology describes the magnitude, timing, distribution, and frequency of floods. Floods in the Sacramento and San Joaquin River basins typically result from heavy rainfall or combined rainfall and snowmelt in the mountains and foothills, which flows through an extensive system of reservoirs before reaching the valley floor. Two tools were developed to simulate the foothill and upper watershed portion of the river system: hydrology to characterize the amount of stream flow generated by storms, and reservoir operations models to simulate the role of reservoirs in managing flood flows.

How Often do Floods Happen?

Flood risk is described in many different ways. It is traditional to describe flood risk in terms of a level of protection, such as "100-year level of protection." However, this simplification can be misleading and is often misinterpreted as meaning that flooding will occur only once during the specified number of years. Level-of-protection estimates are based on the average interval between failures of a flood prevention system, such as a levee. A 100-year level of protection means that on average, over a very long period of time (such as thousands of years), flooding would happen about once every one hundred years. But during that time, the actual spacing between 100-year floods could be much shorter or longer than 100 years. For example, during a recent 10-year period, two large storm events resulted in flows that approached the 100-year level on the American River.

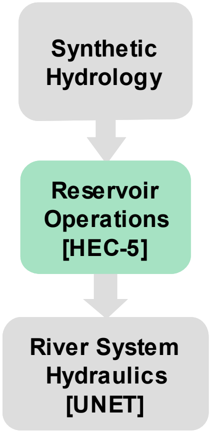
Other statistical terms can be used to more accurately describe flood risk. Two examples are provided in the table below with comparable return frequency terminology. These and other flood risk statistics can be estimated by the Corps' risk analysis model, HEC-FDA. Although these terms are cumbersome and can be difficult to understand, they allow a more complete and accurate description of flood risk than level of protection or return frequency.

Probability of Occurrence or Exceedence The probability that a flood of this magnitude will occur (or be exceeded) in any year, expressed as a statistical chance or percent probability		**Level of Protection (Return Frequency in Years)** The period of time between flood events of this magnitude, averaged over many (thousands) of years
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

The Comprehensive Study developed synthetic, unregulated hydrology for seven flood events: those with a 50%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% chance of occurring in any year. In general, the hydrology is termed 'synthetic' because the 30-day flood hydrographs are based on flows and volumes observed in historic floods, but are not exact replicas of historic events. The hydrology is termed 'unregulated' because it does not reflect the influence of reservoirs, which significantly alter flood flows entering the valley. In total, the study created over 13,000 unregulated hydrographs for the seven flood frequencies at over 50 locations.

The hydrology is unique because it acknowledges that floods are created by varying storm conditions throughout the basins – heavy rainfall at one end of the valley doesn't necessarily mean heavy rain elsewhere. Historic storm patterns across California provided representative storm centerings to simulate floods involving multiple tributaries and reflect the influence of the coastal and Sierra Nevada mountain ranges. Twenty-seven different storm centerings, stressing both tributaries and the main stems of the Sacramento and San Joaquin rivers, emulate the diverse spectrum of floods that can affect the Central Valley.

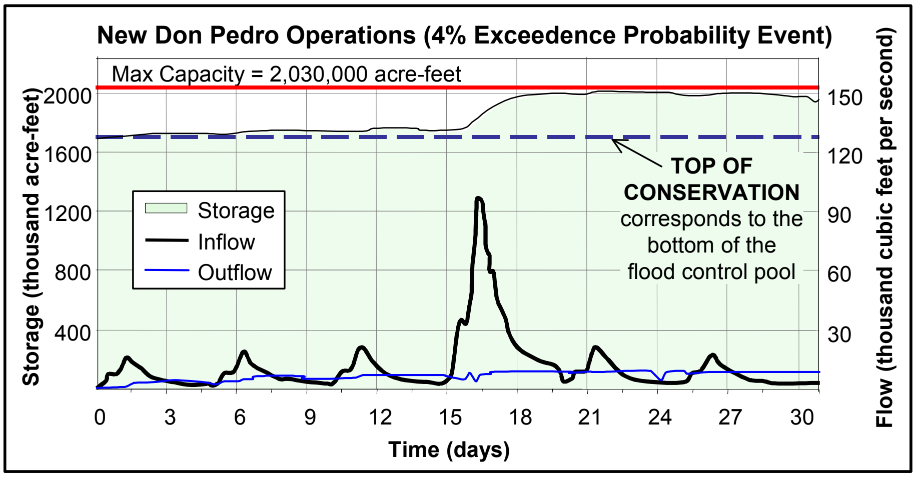
Reservoir Operations Models



Because the synthetic hydrology does not reflect the operation of the numerous reservoirs in the Sacramento and San Joaquin basins, the study developed computer models to simulate reservoir storage and release operations during flood events. The Corps' HEC-5 computer program simulates over 70 flood control, water supply, and multipurpose reservoirs that are currently operated for flood management or have an active storage space greater than 10,000 acre-feet. Due to the large number of reservoirs, the study developed two separate HEC-5 models in each basin, one for the smaller, but more numerous headwater reservoirs, and another for the larger foothill reservoirs. The San Joaquin HEC-5 models simulate 17 headwater reservoirs and 19 foothill reservoirs tributary to the San Joaquin River, while the Sacramento HEC-5 models simulate 27 headwater reservoirs and 9 foothill reservoirs. These models represent the largest known application of HEC-5 and are the most inclusive source of information on the operation of reservoirs tributary to the Central Valley.

The HEC-5 models reflect mandatory, "by the book" operations established in the Water Control Manual for each flood control reservoir. These manuals define the operational rules and release criteria that must be followed by reservoir operators during the flood season. 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. However, historic reservoir operations may deviate somewhat from the HEC-5 simulations because severe floods sometimes dictate deviations from established operational criteria.

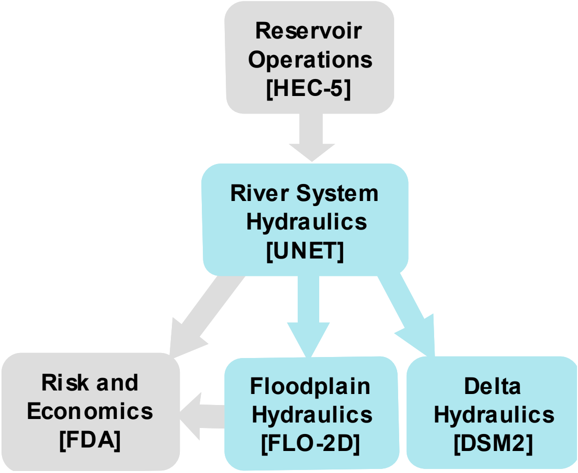
The unregulated hydrographs are used as input to the headwater reservoir models. Some foothill reservoirs have agreements with upstream reservoirs whereby they can be credited for unused storage space. Credit space is determined then results from the headwater reservoirs are used as input to the foothill reservoir models. The result is regulated flood flows downstream from the foothill flood management reservoirs. The regulated hydrographs are then used as input to the hydraulic models that simulate flood flows in the valley.



The adjacent figure is an example of a flood routing through New Don Pedro Reservoir during a flood event with a 4% chance of occurring in any year (1-in-25 chance), under existing conditions. As shown, the reservoir fills to near capacity, but maintains low releases during peak inflows.

River System and Floodplain Hydraulic Models

Hydraulic models simulate the complex network of rivers and channels that flow out of the foothills and through the Central Valley, eventually entering the Delta. The Comprehensive Study's modeling approach differs from the traditional approach in which rivers or reaches are examined individually. The study's models compute water surface elevation, discharge, average velocities, flooding extent, and track flood volume changes as a flood moves through the river system. An extensive data collection effort provided up-to-date topographic and bathymetric (in-channel) data necessary to develop these models. The study developed aerial photography, contour mapping, and digital terrain models along the river corridors of the Sacramento and San Joaquin rivers, their major tributaries, and bypass systems.

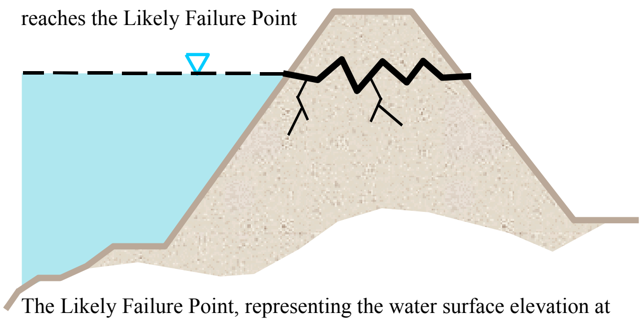


Two computer models are used jointly to simulate channel and overbank hydraulics in the Sacramento and San Joaquin River systems. Flows within the river channels and bypasses are simulated using the UNET model, and the movement of water in the floodplains (after it has escaped the river channel) is simulated with the FLO-2D model. The study used a third model, the Delta Simulation Model 2 (DSM2), to estimate flood conditions in the Delta.

River System Hydraulic Models

The UNET computer model simulates unsteady flow (flow that changes over time) through the river channels, weirs, bypasses, and storage areas of the Sacramento and San Joaquin River basins. The study developed separate UNET models for the Sacramento River and the San Joaquin River systems, starting downstream from the major flood control reservoirs and terminating at the Delta. In general, model construction consisted of collecting and processing extensive topographic data, developing river channel alignments, developing cross-sectional geometry, and including structures that affect flows (bridges, levees, weirs, etc). Channel geometry is simulated in the models by cross sections spaced at approximately $^1/_4$-mile increments. Overall, the UNET models simulate over 1,000 miles of Central Valley waterways.

The regulated hydrology, in the form of 30-day flood hydrographs for each of the seven frequency floods and various storm centerings, provides input for the UNET models. Downstream boundary conditions in the Delta reflect tidal and estuary influences. The UNET models simulate levee failures, storage interactions with adjacent overflow basins, weirs and overflow structures, and bridges. The UNET models represent vegetation and other channel obstructions by varying channel roughness coefficients.



A levee failure is triggered in UNET when the water surface reaches the Likely Failure Point

The Likely Failure Point, representing the water surface elevation at which there is a 50% chance of levee failure, was determined reach-by-reach based on available geotechnical data, extensive interviews with levee district personnel, past levee performance, and engineering judgement.

In order to understand what potential damage could occur from flooding, the study team devised a levee failure methodology to determine when simulated flows would cause levees to fail and a floodplain to be formed. The methodology provides a conservative estimate of potential flooding extent for system-wide hydraulic and economic evaluations. To ensure that all potential economic damages are accounted for, the failure approach reflects a worst-case condition without flood fighting or other emergency actions. Levee failure is initiated in UNET when the simulated water surface elevation reaches the likely failure elevation for a given levee, defined as the stage at which there is a 50% chance of levee failure. Flow through levee breaches is then passed to the FLO-2D floodplain model.

The levee failure methodology can significantly influence simulated flood flows. 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. In some cases, the cumulative effect of multiple upstream failures simulated in UNET can reduce the volume of flow in downstream reaches, or large breaches can produce pronounced reductions in water stage. Consequently, this levee failure approach may not be appropriate for every model application. In addition, the models do not account for sediment movement, scour, or deposition; they assume no exchange with groundwater; and they do not simulate water temperature. The model calibration used historic flood events (1995 and 1997 floods); as such, they may not be accurate simulating low flows. The spacing of cross sections in the UNET models (typically between $^1/_5$- and $^1/_4$-mile) may preclude the direct application of the models to studies requiring more detail or evaluating localized hydraulic conditions.

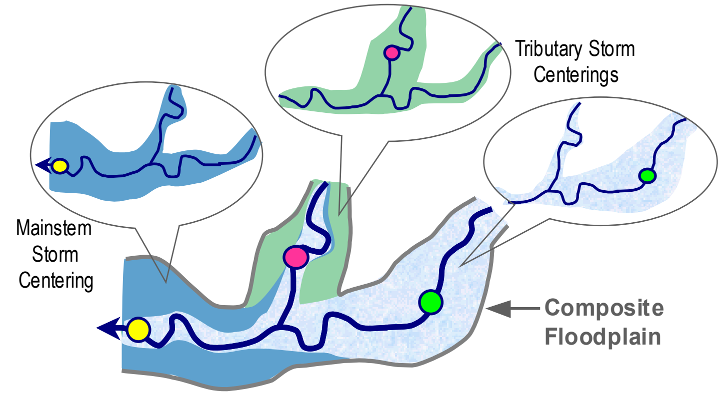
The UNET models generate a tremendous amount of information, including flow, stage, velocity, and other hydraulic parameters at every cross section. Model output produced data to develop stage-frequency and discharge-frequency relationships at key index points for subsequent use in the flood risk and damages model.

Floodplain Hydraulic Models

The study team selected the FLO-2D model to simulate floodwater that has broken out of the river channel and is moving across the topography of the valley floodplain. Simulated UNET out-of-bank flows from overtopping or levee failure are the input to FLO-2D. Because out-of-bank flows are more common in the San Joaquin Basin, the FLO-2D models cover nearly the entire basin, whereas the FLO-2D models in the Sacramento Basin primarily cover the major historic overflow basins.

Unlike the channel cross sections used in UNET, topography is represented in FLO-2D as a two-dimensional grid network developed from U.S. Geological Survey (USGS) 30-meter digital elevation data. Due to the considerable size of the FLO-2D models, grid sizes are relatively large - about 2,000 feet on edge. Bridges, streets, and other features are not specifically modeled in FLO-2D, but raised highways, levees, and other topographic features are captured by the grid elements.

The FLO-2D model predicts how water moves through the floodplain, calculates its depth, and estimates the extent of flooding. The study team used inundation areas resulting from multiple storm centerings to delineate a single 'composite floodplain' for various flood frequencies. It is important to note that these are not FEMA floodplain maps, nor are they intended to replace or supersede existing FEMA maps. The composite floodplains areas provide input to the flood risk and economic damages model.



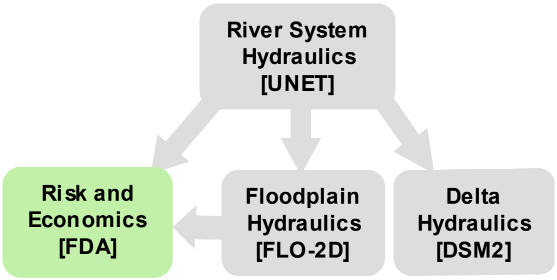
The 'Composite Floodplain' concept recognizes that a floodplain is not created by a single flood event, but by a combination of flows from different storm events on the various tributaries – each shaping the floodplain at different locations. Each storm centering produces a different component of the composite floodplain, capturing the full extent of inundation possible.

Delta Simulation Model

The study team adopted the DWR's DSM2 model to evaluate the effects of potential projects on flows and stages in the Delta. The Delta is a very complex hydraulic system influenced by tides, tributary inflows, water supply pumping, and many other factors.

DWR originally created DSM2 to evaluate water quality within the Delta under low-flow conditions. The study team re-calibrated the model to simulate floods. The study team truncated the DSM2 model such that DSM2 flow input locations coincide with the downstream limits of the UNET models, facilitating handoff of data between the two models. Output from the DSM2 model includes stage, flow, and storage volume data. The DSM2 model is not capable of simulating levee failure and does not take into account the extended high stages that often occur in the Delta and can affect levee stability. DSM2 input includes inflows provided by the UNET models and flood flows from other Delta tributaries, such as the Mokelumne and Calaveras rivers. The model helps in understanding existing flood conditions in the Delta and can evaluate the effects of potential changes to Delta inflows or channels.

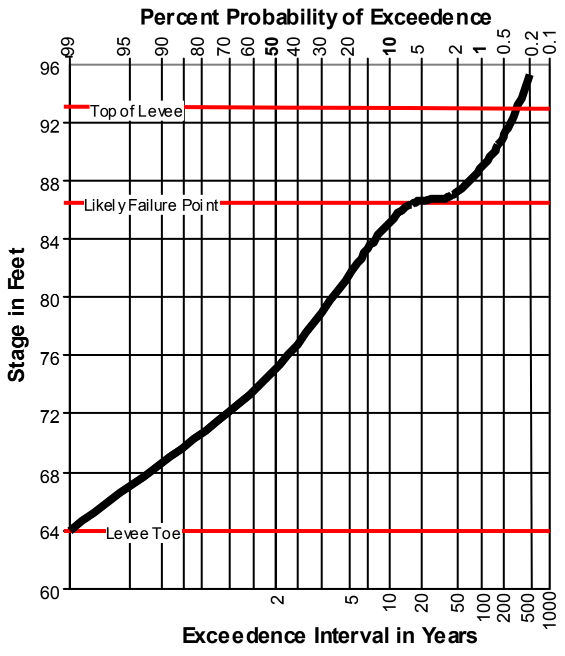
Flood Risk and Economic Damages Model



The Comprehensive Study used the Corps' Flood Damage Assessment (HEC-FDA) computer model to estimate economic damages resulting from floods and quantify the risk of flooding. HEC-FDA uses input from the UNET and FLO-2D models, along with geotechnical data and information on land use, property value, and other floodplain attributes. HEC-FDA expresses flood damages as Expected Annual Damages (EAD), a single, annualized measure of the damages that could be caused by a full range of possible flood events. HEC-FDA calculates flood risk in three ways: the expected probability of flooding in any given year, the long-term risk of flooding over a specific time period, and the probability of successfully passing specific flood events.

Risk Analysis is an approach used in Corps flood management studies based on statistical techniques to characterize the performance of a proposed project. There are numerous uncertainties associated with flood damage reduction studies, related to both natural systems (variations in climate, stream flow, river stage) and engineered systems (reliability of levees, floodgates). Risk Analysis recognizes that the information used in a flood damage analysis is not perfect. For example, many years of historic stream gage data may not be available to develop the hydrology, or the models used to simulate reservoir operations may deviate somewhat from actual operations. Unseen features, such as cracks hidden within the levee, could influence the performance of a levee. Similarly, economic damage figures rely on the best estimates of structure locations and values, flood duration, the crops grown on farmland, and other variables.

HEC-FDA allows users to assign uncertainty "error bands" to hydrologic, hydraulic, geotechnical, and economic input. The program calculates economic damages and flood risk thousands of times using values that are randomly picked within these error bands. The result is a range of possible answers, with some answers having been calculated more often. For example, HEC-FDA calculations might determine that the range of potential annual flood damages for a project is somewhere between $5- and $45-million dollars; but the value that was calculated most often - the Expected Annual Damage - is $35-million. Based on a series of similar statistical calculations, HEC-FDA might estimate that a project has a 68% chance of safely containing the 1% flood, or that a particular area has a 15% chance of flooding during a 25-year period. HEC-FDA can be applied to existing and with-project conditions to determine economic benefits or estimate the reduction in flood risk.



Hydraulic input to HEC-FDA includes stage-frequency curves developed at the index points from UNET model simulations.

Because there are over 2.2 million acres potentially at risk of flooding in the Central Valley, floodplains were divided into smaller impact areas to facilitate the HEC-FDA analysis. The impact areas were delineated based primarily upon flooding characteristics (sources and flow patterns) and the underlying land uses. The outermost extent of the impact areas is based upon the 0.2% (1-in-500) floodplain. There are 68 impact areas in the Sacramento River Basin and 42 impact areas in the San Joaquin River Basin. One index point along a river channel is assigned to each impact area, providing a location to pass flood stage and flow frequency information from the hydraulic models to HEC-FDA.

Risks

The economic analysis includes an inventory of over 2 million acres of floodplain with about 600,000 people at risk of flooding, about 196,000 structures valued at about $47 billion, and croplands with annual production of $1.8 billion.

Economic Damages

The economic analysis component of HEC-FDA utilizes a variety of information about each impact area:

- Flood inundation extent and depth for events with a 2%, 1%, 0.5%, and 0.2% chance of occurrence.
- Characteristics of various flood damage categories, such as residential, industrial, and farmsteads.
- Land use, crop types, and inventories of structures in each damage area.
- Estimated values of structures and their contents, based primarily on county assessor data.
- Relationships between flood depth and property damage, for both urban and agricultural areas.

The study team calculated EAD valley-wide for existing conditions. HEC-FDA can also evaluate proposed projects, establish economic benefits, and be used to perform cost-benefit analyses.

Flood Risk

The flood risk component of HEC-FDA uses input from the hydrology, hydraulic models, and levee stability analysis to estimate the likelihood of flooding. The risk of flooding is reported by HEC-FDA in three ways:

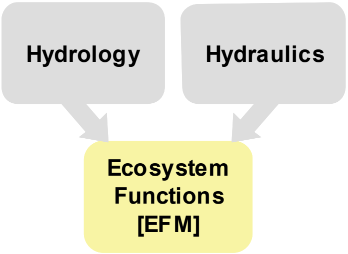
- **Annual Exceedance Probability -** the likelihood that an area will be flooded in any given year, considering the full range of floods that can occur and all sources of uncertainty.

- **Long Term Risk -** the probability that damages will occur during a specified timeframe, reported for 10-year, 25-year, and 50-year 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.

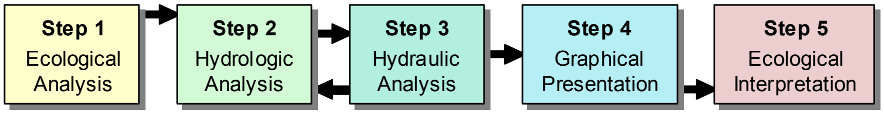
- **Conditional Non-Exceedance Probability** - the probability of safely containing a flood with a known frequency, reported for the 10%, 4%, 2%, 1%, 0.5%, and 0.2% floods. For example, a conditional non-exceedance probability of 0.900 for the 1% flood indicates a 90% probability that the system will be able to contain the 1% flood event without failure.

Although the flood risk outputs may seem similar, they each describe a different aspect of flood risk. Annual exceedance probability accumulates all uncertainties into a single risk value, whereas conditional non-exceedance probability depends upon the severity of the flood event. While annual exceedance probability describes the likelihood that flooding *will occur*, conditional non-exceedance probability describes the likelihood that flooding *will not occur* during a given year. Project performance statistics were used to evaluate several of the basin-wide scenarios, and can be used to evaluate the performance of potential modifications to the existing systems. Together, they provide a more complete description of flood risk than can be conveyed by traditional return frequency terminology.

Ecosystem Functions Model



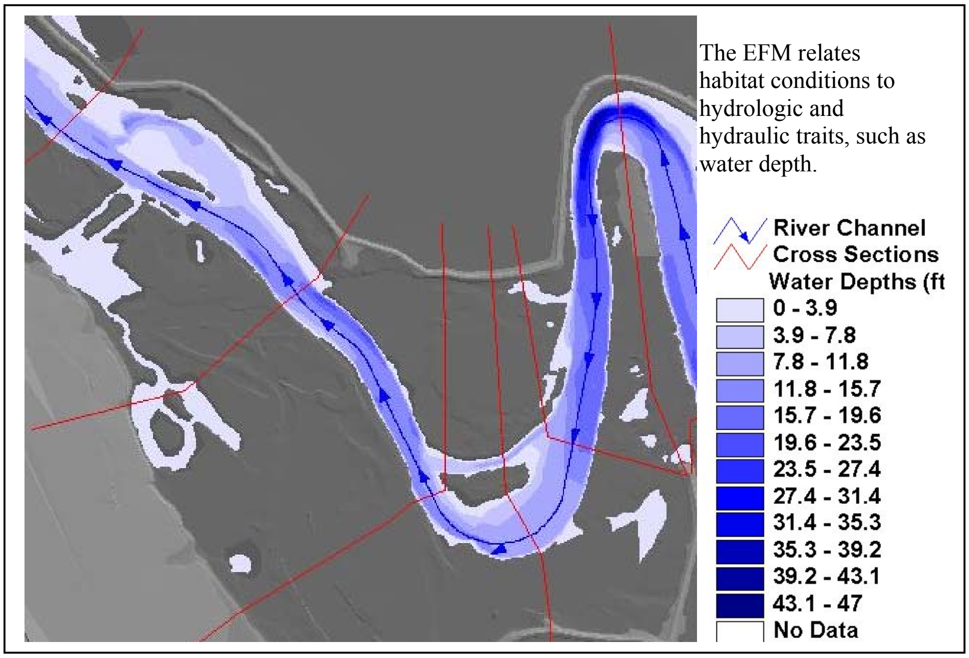
The Comprehensive Study developed the Ecosystem Functions Model (EFM) to help predict differences between existing and potential with-project conditions in river reaches that would be affected by changes to the flow regime or physical changes to the floodway. Using input variables such as stream flow, land use, soil type, vegetation, and topography, the model provides an evaluation of how potential projects might change conditions that are favorable to various types of habitat. The EFM differs from other tools in the Comprehensive Study modeling suite in that it is applied on a reach-by-reach basis rather than to the entire watershed. In addition, the EFM is not a single computer program, but rather a series of analyses that are interpreted by ecologists to predict a biological response. The five major steps in the EFM are described below:



Step 1 - Ecological Analysis. The ecological analysis step identifies biological relationships between river hydrologic and hydraulic conditions and the riverine ecosystem. These relationships reflect the different stream flow duration, flow frequency, and stage recession requirements of different types of habitats. 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 hydrologic and hydraulic information developed in Steps 2 and 3. The ecological analysis addresses two major elements: the aquatic ecosystem and the terrestrial ecosystem.

The aquatic relationships focus on factors that affect the life stages of salmonids and Sacramento splittail, which are used as representatives of the entire aquatic community. In-channel aquatic relationships examine the dependence of suitable streambed materials, instream cover, and bank vegetation on changes in flow and river morphology. Aquatic floodplain relationships identify overbank flow conditions that benefit floodplain spawning and rearing. The terrestrial ecosystem element evaluates existing riparian and wetland zones, rates of ecosystem change in these communities, and associated wildlife habitat values. Changes in riparian/wetland habitat are predicted by overlying maps of various attributes – such as inundation frequency, depth, or extent - that relate to terrestrial ecosystem health and development.

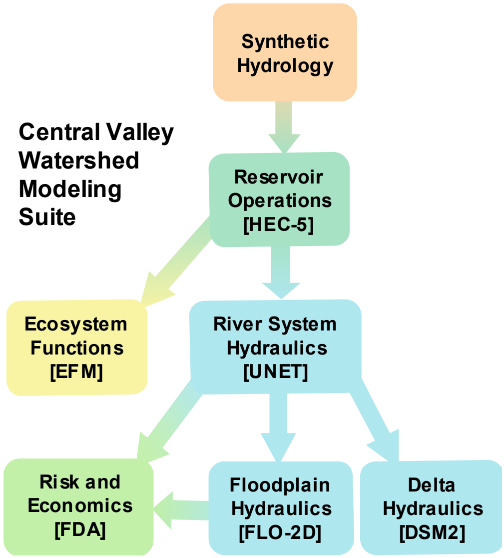
Step 2 - Hydrologic Analysis. A statistical analysis translates the ecosystem relationships developed in Step 1 into discharges (stream flows) for specified durations, flow frequencies, and stage recession rates. The statistical analysis uses historical, existing, and potential with-project conditions that result from modified reservoir operations, changes to levees, or other modifications that could be considered. Because there is no existing computer software package that meets the needs of the EFM, the study team developed a customized computer software package. This program allows the model to be efficiently applied to multiple study areas within the Sacramento and San Joaquin River basins. The program reads daily flow gage records and stage records and lets users select the ecosystem functions to be evaluated.


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

Step 3 - Hydraulic Analysis. Step 3 simulates the hydraulic response of the river system to the stream flows estimated in the hydrologic analysis step. The discharges are simulated in a Hydrologic Engineering Center - River Analysis System (HEC-RAS) hydraulic model (other models can also be used) to obtain simulated stages and flood inundation areas. HEC-GeoRAS can be used to create existing and potential with-project river cross-sections of study reaches for the HEC-RAS model, and export simulation results into a GIS environment for evaluation in Step 4.

Step 4 - Graphical Presentation. A GIS computer program is used to display the hydrologic/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. The graphical presentation helps ecologists spatially evaluate the biological relationships throughout the study reach.

Step 5 - Ecological Interpretation. The final step in the EFM involves interpretation of the modeling results and various environmental and landform features by ecologists. Based on predicted changes in terrestrial and aquatic habitat, conclusions or recommendations can be made on potential flood management and ecosystem restoration modifications.



What We Learned

The models work together to characterize the hydrology, hydraulics, ecosystem conditions, potential flood risk and economic damages in the Central Valley. The study team used them to gain a better understanding of the existing flood management system, perform various system-wide analyses, and evaluate "what if" scenarios suggested by team members, agencies, and stakeholders. Although these evaluations were performed at a watershed scale, they provide valuable information and insight on how the flood management system might be changed in the future.

The Sacramento and San Joaquin River basins each have distinct characteristics relating to climate, topography, land use, flood management, and the ecosystem. The timing and magnitude of flood flows varies significantly between the Sacramento and San Joaquin River basins. Flood peaks tend to last longer on the Sacramento River than in the San Joaquin River basin, which has a more arid climate. System-wide evaluations confirmed that a variety of approaches will be needed to effectively address the flood management and ecosystem needs of the two basins. One thing is common to both basins: the entire river system – including flood processes and ecosystem functions – is interdependent, and changes to one facet affect all others.

Assessment of the Existing Flood Management System

The existing flood management systems do not currently provide the levels of flood protection or sustainable ecosystem function desired by many people. The system's design did not provide a uniform level of protection to all lands. In general, urban areas were provided with the highest levels of protection followed by reclaimed lands, based on what the original system planners deemed appropriate and cost effective at that time. However, flood protection needs are different today, and ecosystem needs were not fully understood when the system was designed. Early designers did not fully understand the effects of constructing hundreds of miles of levees along such dynamic river systems. Over time, the natural erosive force of the rivers have affected levee integrity and made the system difficult to maintain.

- **Flood Conveyance Capacity.** Reaches of the flood management system may not be able to convey design flood flows due to factors such as reduced flow area, poor levee foundation conditions, deteriorating levees, and subsidence. Sediment accumulation, vegetation growth, and development encroaching on the floodway can cause reduced flow area. Although it was assumed when the system was designed that vegetation in the floodways would be maintained, conflicting maintenance practices and environmental protection laws along with local funding burdens have made maintenance increasingly difficult. In other areas, conveyance capacity is uncertain because levees are constructed on ancient river deposits that are prone to seepage. Repairing or improving these levees can be extremely costly, or infeasible.

- **Choke Points.** Constrictions or choke points in the flood management system can reduce conveyance capacity and/or increase stage. Some of these choke points are natural or were built into the system unintentionally (floodway constrictions), while others are the result of sediment accumulation, bridge construction, or infrastructure development. Bridge piers and abutments could be modified to improve flow capacity and reduce the potential for debris impoundment. Water supply intakes and other infrastructure could be modified in a similar manner, while maintaining their operation. Sediment removal by excavation or dredging can be a solution in some instances and can be considered on a case-by-case basis. Dredging could be effective in combination with other modifications where excessive sediment deposits cause a localized backwater effect, or where necessary to re-establish a primary channel. However, without other modifications to prevent reoccurrence, it is generally not a long-term solution. Federal participation in large-scale dredging projects does not appear feasible due to the extensive mitigation requirements and the inability of local entities to continually fund future dredging.

  While the hydraulic models developed by the Comprehensive Study lack the detail needed to identify highly localized choke points, the study team used them to identify constrictions that affect the system regionally. For example, Knights Landing is a major choke point in the Sacramento River system, hindering drainage from the Colusa Basin and constricting flows in the Sacramento River upstream from the Fremont Weir. The effect of this man-made floodway constriction can be seen as far upstream as Grimes in model simulations. Further, this portion of the river is perched above the surrounding floodplain, which limits potential actions to physically reduce the constriction by widening the Sacramento River floodway or the Knights Landing Ridge Cut. Other choke points in the Sacramento River Basin include Daguerre Dam on the Yuba River, various floodway constrictions on the lower Feather and Bear rivers, the earthen railroad and freeway embankments in the Yolo Bypass, the Highway 32 Bridge, and Woodson Bridge on the Sacramento River.

  In the San Joaquin River Basin, the conveyance capacity of the Chowchilla Bypass is constrained by several bridge crossings with earthen abutments that extend into the floodway. Other choke points in the San Joaquin River Basin include floodway encroachments on the Tuolumne River in Modesto, floodway and infrastructure constrictions on the San Joaquin River at the Washington Road and Grayson bridge crossings, and floodway constrictions on the San Joaquin River near Firebaugh. Many of the choke points on the San Joaquin River only cause problems during large flood events when the full capacity of the floodways and bypasses are utilized.

  > The general public does not have a common understanding of the actual risk of flooding and urban development continues in flood-prone areas.

- **Weir and Bypass Systems.** The Sacramento River basin has a complex weir and bypass system, effectively redirecting excess flood flows away from the Sacramento River. The Fremont Weir acts as a hinge point for the system, dramatically changing conditions in the Sacramento River, Feather River, and Sutter Bypass when it spills water into the Yolo

Bypass. The San Joaquin basin weir and bypass system functions differently, primarily intercepting flows from the major eastside tributaries before they reach the San Joaquin River. In contrast to the Sacramento River, some reaches of the San Joaquin River carry relatively little flow during flood events.

- **Ecosystem Conditions.** The river system supports only a fraction of the natural processes and habitat essential for a healthy, functioning ecosystem. Riverine ecosystems are dynamic and their health depends on an equally dynamic river system to drive ecological processes. These natural processes have been restrained by levees that constrict the river channels; reduction in seasonal flow variation due to reservoir regulation; water diversions; fragmentation and degradation of existing habitat; and the invasion of exotic species.

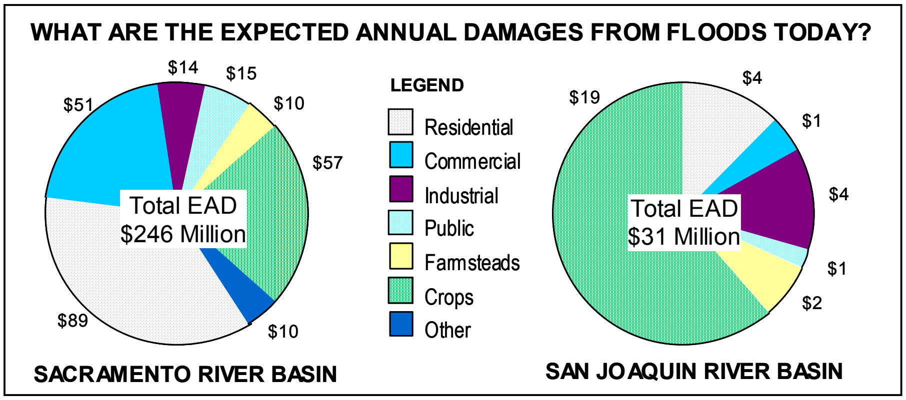
Ecosystem restoration in the Central Valley can improve water quality, groundwater exchange, sediment transport, flood flow attenuation, and support a wide variety of habitat for special-status and other species.

- **Existing Reservoir Operation.** The study evaluated major flood control reservoirs to determine their ability to manage a range of flood events under their existing operational criteria. The table below provides an estimate of the level of controlled operations provided by each reservoir, or the flood frequency at which the reservoir can no longer maintain its objective flow criteria. The objective flow is shown in cubic feet per second (cfs). Model simulations evaluated the 50%, 10%, 4%, 2%, 1%, 0.5% and 0.2% flood events centered on each tributary; results can not pinpoint exact flood frequencies, but can provide a good indication of performance relative to the modeled floods.

Reservoir	Drainage	Objective Flow	Existing Flood Storage (TAF)	Flood that can be controlled without exceeding objective flow
Shasta	Sacramento River	79,000 cfs	1,300	1% flood
Black Butte	Stony Creek	15,000 cfs	136	almost the 2% flood
Oroville	Feather River	150,000 cfs	750	Between the 1% & 0.5% floods
New Bullards Bar	So. Fork Yuba River	50,000 cfs	170	1% flood
Pine Flat	Kings River	4,950 cfs	475	almost the 1% flood
Friant	San Joaquin River	8,000 cfs	170	4% flood
Hidden	Fresno River	5,000 cfs	65	almost the 1% flood
Buchanan	Chowchilla River	7,000 cfs	45	Between the 2% & 1% floods
New Exchequer	Merced River	6,000 cfs	350	almost the 2% flood
Don Pedro	Tuolumne River	9,000 cfs	240	4% flood
New Melones	Stanislaus River	8,000 cfs	450	1% flood

- **Land Subsidence.** Subsidence in the Sacramento and San Joaquin basins is caused primarily by groundwater overdraft. Portions of the southern San Joaquin River Basin have subsided more than 20 feet, prompting levees to be raised along the Eastside Bypass in 2000. In the Sacramento River basin, subsidence may also have affected the flow capacity of the Knights Landing Ridge Cut. If it continues, subsidence could threaten the basic function and efficiency of the flood management systems.

- **Flood Damages Today.** The HEC-FDA model was used to determine the EAD from floods. Total EAD was estimated in the Sacramento Basin at $246 million, and in the San Joaquin River Basin at $31 million. In the Sacramento River Basin, residential damages accounted for the highest proportion of flood damages ($89 million), followed by crops ($57 million), and commercial property ($51 million). In the San Joaquin River Basin, crop damages accounted for the highest proportion of damages ($19 million), followed by residential ($4 million), and industrial property ($4). These figures reflect differences in land development between the two basins. The Sacramento Valley has large urban areas at risk of flooding, whereas larger urban areas in the San Joaquin Valley tend to be located outside the 0.2% floodplain.



System-Wide Evaluations

The study used the models to perform various system-wide evaluations that provided a new understanding of how the system would react to large-scale changes to the flood management system. These “what if” scenarios varied widely, ranging from an approach that would restore the designed conveyance capacity system-wide, to an approach that would greatly increase the capacity of the floodways while allowing environmental restoration. The evaluations were both investigative and informative in nature, exploring the response of the flood management system to an array of flood damage reduction and ecosystem improvement scenarios, while developing analysis procedures using the Comprehensive Study modeling suite. The scenarios are not alternative plans. Highlighted below are some of the general findings from the system-wide evaluations:

- Because the original flood management systems were not designed uniformly, some levees were likely to fail before others. When levees fail and cause flooding in the adjacent floodplain, a substantial amount of floodwater leaves the rivers or bypasses, reducing flow rates and water surfaces downstream. Levee improvements that reduce the likelihood of failure reduce this temporary storage of water in the floodplain, increasing flow rates and flood risk downstream. To address the potential for redirected hydraulic impacts, solutions need to include measures to address the additional flow and volume of floodwater that could be transferred to downstream areas.

- All of the preliminary system-wide evaluations indicated that some amount of new flood storage is needed in the Sacramento River Basin, regardless of the type of flood management improvements implemented. Depending upon the types of modifications evaluated, new flood storage was needed to prevent transfer of hydraulic impacts to downstream reaches; reduce peak flows to levels that can be conveyed by the levee system; mitigate increases in flood flow entering the Delta; and accommodate ecosystem improvements within the flood management system.

- Most of the major tributaries to the San Joaquin River are controlled by reservoirs. However, these reservoirs provide widely varying levels of flood protection and, in general, provide less flood storage and management than reservoirs in the Sacramento River Basin. The only reservoir tributary to the San Joaquin River capable of controlling the 1% event is New Melones, while Friant Dam and New Don Pedro control about a 4% flood event. This is due, in part, to the type of development (primarily agricultural) that was present in the San Joaquin Valley when the flood management system was designed. Additional flood storage in the San Joaquin River Basin could provide significant flood benefits to the valley.

- The weirs and bypasses in the Sacramento River flood control system tend to dampen the effects of changes to the flood management system; as a result, some improvements provide less benefits than would be expected. Preliminary modeling indicated that new upstream storage provided the most benefit immediately downstream from the facility, but often had little effect farther downstream. This was due to differences in the timing of flood peaks on the tributaries and mainstem river and the redistribution of flows by the weirs and bypasses. For example, new storage in the Yuba River basin benefited Yuba City / Marysville, but had negligible benefits downstream from the Feather River.

- Under existing flood conditions, flow out of the Tuolumne River system overwhelms flow in the San Joaquin River downstream from the Tuolumne confluence. Thus, new flood control storage or other actions on the Tuolumne River would also have a significant influence on the lower San Joaquin River.

- The reach of the San Joaquin River south of Turner Island, which currently does not receive year-round flow, is an effective route for diverting flood flows and reducing stress on the Eastside Bypass. However, this reach can only convey an estimated 300-cfs and would require significant improvements to convey substantial flood flows.

- Vegetation was incorporated into some features of the flood management system (for example, trees planted to slow flows entering the lower Butte Basin), though much of the system was designed under the assumption that vegetation would be managed. The river system models developed by the Comprehensive Study have the ability to evaluate the regional and system-wide effects of

Habitat in the Flood Management System – While many people are concerned that vegetation is incompatible with a flood conveyance system, hydraulic modeling has shown how vegetation can be incorporated without adversely affecting flood stages or levee reliability. Enlarging the floodway with realigned levees, often to locations with more suitable foundation conditions, or locating vegetation in low velocity overbank areas, can reduce erosion potential and contribute to ecosystem restoration without reducing conveyance capacity. Enlarging the floodway can also help attenuate flood flows. Restoration with native habitat or farming -- similar to the existing bypass system -- are viable options for land within the expanded floodway. Habitat maintenance may be needed to preserve flood conveyance capacity.

different types and densities of vegetation on flood flows and stage. Vegetation in wide and shallow floodways, such as bypasses, has less impact than vegetation in narrow or constricted channels. Because flows move slower in the shallow bypasses, vegetation removal in the Sutter Bypass would provide less benefit than would be expected, and may actually increase damaging erosion on the levees. Model simulations also show that vegetation can be successfully incorporated into future flood damage reduction projects without affecting system capacity or reliability. In addition to providing habitat, vegetation can also provide benefits to the flood management system if it is properly incorporated into the design. For example, vegetated buffer strips or berms adjacent to levees can reduce levee scour and ease restraints on the management of vegetation growing on levee slopes. If floodways are widened, vegetation can help attenuate flows and reduce erosion.

- During floods, water leaves the foothills and moves through the different rivers and channels of the flood management system at different rates. The flood peak from one tributary might reach the mainstem hours or days before the peak from another tributary, and the mainstem flood peak might not coincide with either. Similarly, water moves more slowly through a wide bypass than it does through deep river channels, influencing the timing and duration of flood peaks downstream. Changing the flow capacity or velocity of a bypass changes the timing of downstream flood peaks, and might not produce desirable results. For this reason, it is important to evaluate potential changes to the flood management system basin-wide.

- A large portion of the lower and middle Sacramento River is perched, meaning that sediment deposition has raised the bed of the river above the surrounding floodplain lands. Widening the floodway in these areas may be difficult or infeasible because the land slopes away from the river and levees would need to be very tall. System-wide evaluations identified other methods to reduce stage in these regions, including additional upstream flood storage and modifications to the weir and bypass system that would divert more water into the bypasses. Preliminary model simulations found that widening the Fremont Weir could reduce flood stages on the Sacramento River as far upstream as the Tisdale Bypass, while also reducing flood stages in and around the City of Sacramento. The effects were less pronounced along the Sutter Bypass and Feather River.

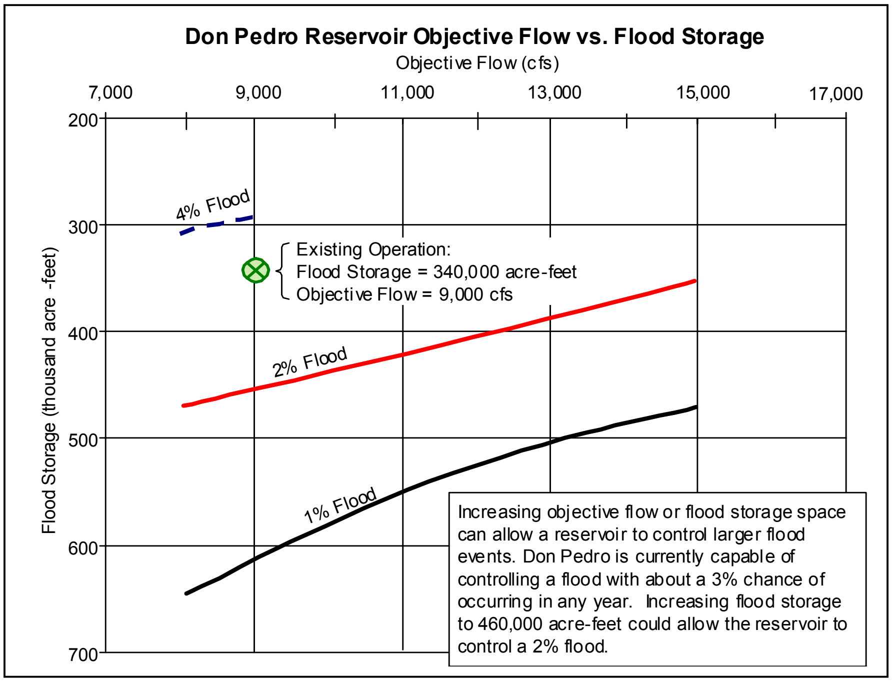
Floodwater Storage Evaluations

The study used the reservoir operations models to evaluate the benefits of re-operating existing reservoirs, additional flood storage in new or existing reservoirs, and temporary storage in floodplain areas that can tolerate (and be compensated for) infrequent flooding. Additional flood storage could provide flood damage reduction and ecosystem restoration benefits, or it could be used to offset redirected hydraulic impacts associated with conveyance improvements. New flood storage can be costly both financially and environmentally, but multipurpose projects – those that also provide water supply or hydropower benefits, for example - could be feasible when developed in collaboration with others. The CALFED Storage Program is considering opportunities for additional water supply reliability and other purposes through the reoperation or enlargement of reservoirs and the development of conjunctive use projects. Many of the potential CALFED storage projects also provide opportunities for additional flood storage.

The study evaluated a suite of potential storage projects near Friant Dam, based on previous CALFED investigations to determine the flood control benefits. The scenarios included various combinations of the following elements: raising Friant Dam, construction of Temperance Flat Dam on the San Joaquin River upstream from Friant, and construction of Fine Gold Dam on Fine Gold Creek upstream from Friant. All of the scenarios offered significant flow reductions as far downstream as El Nido for the 2% and 1% flood events, and one scenario offered significant flow reductions up to the 0.2% event (1-in-500 chance of occurring in any year). These preliminary results indicate that storage projects in this region could have flood control benefits for the San Joaquin River.

Another potential CALFED storage project involves raising Shasta Dam. However, preliminary Comprehensive Study model simulations indicate that increasing flood storage in Shasta would not provide significant flood benefits because Shasta already has a large flood storage allocation - enough to contain the 1% event. Under controlled flood operations, releases from Shasta account for a relatively small portion of flow in the Sacramento River downstream from Ord Ferry. Even if releases from Shasta were stopped completely, the numerous uncontrolled tributaries downstream from Shasta contribute a significant amount of flow to the Sacramento River during floods.

- **Reservoir Operation and Flood Storage Analysis.** The study performed a series of model simulations to evaluate how changes to flood operations could affect the performance of existing flood control reservoirs. The results of this analysis were plotted on grids, which show how increases in flood storage and/or objective flow could be used to increase the level of flood control provided by a reservoir. The "grid analysis" provides valuable insight into what benefits could, or could not, be achieved through modifications to the existing reservoir system.



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 about a 3% chance of occurring in any year. Increasing flood storage to 460,000 acre-feet could allow the reservoir to control a 2% flood.

- **Floodplain Storage.** Historically, low-lying basins adjacent to the Sacramento and San Joaquin rivers stored large volumes of floodwater that broke out of the river channels. Some of this water stayed in the basins and slowly evaporated, and some of the water was transitory, gradually draining back into the river system. Today, a similar principle could be applied to store excess floodwater off-stream, in floodplains adjacent to the rivers. The primary benefit of this type of temporary storage is that water is removed from the channel when and where it is needed most. Because foothill reservoirs can be very far away from the valley lands they protect, the timing of flood peaks from multiple tributaries can reduce the flood benefits farther downstream.

However, floodplain storage has limited applications in the Sacramento and San Joaquin basins. The storage area must be large enough to reduce the flood peak to safe levels, and flows often need to be diverted rapidly. Basin-wide evaluations found that flood peaks on the Sacramento River last for such a long time that few areas could store the large volume of water necessary, and very large capacity weirs were needed to divert the floodwater rapidly enough to be effective. Ideally, storage areas should also rely on topography to contain, and drain, the floodwater. Landowners must also be compensated; compensation could be in various forms, such as a one-time easement or reimbursement for damages each time the storage area is used. If the storage area is also used for agriculture, the crops must be compatible with infrequent, seasonal flooding or the area should be designed for use only during the most extreme floods, such as in the existing bypass system. Some high value permanent crops can sustain brief duration flooding.

Valuable floodplain habitat can sometimes be established in floodplain storage areas if the land is publicly owned or under conservation, but many habitat types require more frequent inundation than is desirable for flood management purposes. Model simulations of potential levee breaches along publicly owned land that is part of the San Luis National Wildlife Refuge found that the area becomes inundated before the flood peak arrives, providing negligible flood benefits. The area could provide flood attenuation benefits and conditions conducive to certain types of terrestrial ecosystems, but does not have the characteristics suited to floodplain storage.

- **Off-stream Storage.** Unlike typical in-stream reservoirs, off-stream storage is not located along the watercourse it benefits. Instead, water must be diverted to the off-stream storage area from a river that could even be located in another watershed. Typically, the diversions themselves do not provide the flood management benefits. Rather, additional flood space is made available in another reservoir by storing a portion of that reservoir's conservation pool (water supply) in the off-stream storage reservoir prior to the flood control season. Preliminary modeling investigated the potential flood management benefits of off-stream storage in the Sacramento River Basin. The analysis was not intended to evaluate specific locations, rather, to determine the effectiveness of any off-stream storage project in the basin.

  The modeling included simulated diversions to a hypothetical off-stream storage reservoir from the Sacramento River below Keswick and Stony Creek below Black Butte. Water diverted to the off-stream storage reservoir was exchanged for additional flood storage in six existing reservoirs: Shasta, Black Butte, Stony Gorge, East Park, Oroville, and Folsom. The representative off-stream storage reservoir in this analysis would function similar to Sites Reservoir, currently under investigation by CALFED. Results showed localized flood benefits on the tributaries where flood storage was added, but no significant flood flow reductions on the main stem of the Sacramento River. This is likely due to several factors: flows from unregulated tributaries; the difference in timing between tributary flood peaks (where flood space was added) and main stem flood peaks; and that Oroville and Shasta already control large floods (up to the 1% exceedence event).

- **Conjunctive Use.** Conjunctive use for the purpose of flood control would involve lowering reservoir storage levels below the flood control pool and storing the displaced conservation water in an aquifer for later, beneficial use. In this manner, flood storage is increased without sacrificing water supply or making costly dam modifications. Other potential benefits include reduction of groundwater overdraft and supplemental water supply. If the lowered pool is completely refilled later in the season, the stored groundwater may be reserved for dry years. The preliminary study found that conjunctive use could provide flood control benefits in both basins and warrants additional consideration. Although it is unlikely that a conjunctive use project could be successfully developed for flood management purposes alone, conjunctive use projects are being considered throughout the state to manage limited surface and groundwater resources.

Flood Conditions in the Delta

The study performed preliminary modeling in the Delta to gain a better understanding of the complex hydrodynamic conditions in the Delta during floods. Although the simulations were generalized, the results are informative and indicate how changes to the flood management system could affect the Delta.

Major factors that affect the flow of water through the Delta include tributary inflows, tidal cycles, water project operations, and the physical configuration of the levee and waterway network. The Sacramento River flood peak usually arrives at the Delta before the San Joaquin flood peak during smaller flood events, but for larger events, the peaks overlap due to the extended duration of Sacramento River flood flows. Studies indicate that the relative timing of peak flows arriving at the Delta may be more significant than the magnitude of the flows themselves, as a wide range of inflows result in similar stages.

During large flood events, sustained peak flows from the Sacramento River Basin strongly influence stages in the north and central portions of the Delta. Sacramento River inflows create a hydraulic barrier to flood flow from the San Joaquin River, and results in water “backing up” in the south Delta area. This effect is particularly strong during high tide conditions.

Channel improvements in the South Delta, including widening Paradise Cut, dredging Old River, and widening Middle River could evacuate San Joaquin River flood flows more rapidly during more frequent flood events, but the effectiveness of these improvements is reduced in larger flood events, when inflow from the Sacramento River dominates Delta hydrodynamic conditions.

The effect of this hydraulic barrier was evident during the 1997 flood, when high tide conditions and high flow from the Sacramento River dominated Delta hydrodynamic conditions. Flows

from the San Joaquin River were high, but less significant when compared with Sacramento River flood flows. Despite lower peak flows from the San Joaquin, most damages from flooding occurred in the south Delta because high stages from the Sacramento River prevented these flows from exiting the Delta. In addition, peak flows in the Cosumnes River were almost as high as those in the San Joaquin River, demonstrating the effect of the eastside tributaries.
Model simulations showed that the western Delta typically experiences increases in flood stage during low tide, but not during high tide periods. These results suggest that flood flows cannot overcome the influence of the ocean during high tide periods, but effectively ‘fill in’ the void left by the receding tide. This effects prolongs high stages. This effect also indicates that stages in the estuary downstream from Martinez are dominated by ocean tides and are less likely to be affected by changes in flood flows.

A 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 stage primarily in the central Delta region, with less significant stage increases to the west and the south. Increasing flows from the San Joaquin River resulted in an increase in peak stage primarily in the southern portion of the Delta, with less significant increases to the north, central and western Delta areas. This exercise provides an indication of the areas that would be most sensitive to projects that change the timing or magnitude of flows entering the Delta.

Because of their construction material, Delta levees are highly sensitive to changes in peak water elevation or increases in duration of peak stage. An increase in Delta inflow could raise peak stage and duration on hundreds of miles of Delta levees, thereby increasing flood risk. Preliminary evaluations suggest that a slight increase in peak discharge (less than 10 percent for some events) may be feasible if it is coordinated and implemented with improvements made under the CALFED Delta Levee System Integrity Program. However, more significant increases in flood flow to the Delta would likely increase peak water surface elevation and duration to levels that would not be economically feasible to mitigate and would pose unacceptable risk to critical water supply and transportation infrastructure. Additional detailed study is required to identify how levees would be affected by specific changes to Delta inflow.

Flood damage reduction studies are often based on a level of protection defined by storm frequency or return frequency. However, this approach is not appropriate to define the occurrence of tidal cycles, which also have a significant effect on flood stage in the Delta. Variations in tides originate from gravitational forces and planetary movements, and have little relationship, if any, to the recurrence frequency of flood events.

Ecosystem Functions

The study applied and tested the EFM in two pilot studies, one on the San Joaquin River near Vernalis and the other on the Sacramento River near Princeton. EFM results for the Vernalis pilot study, which evaluated existing conditions along a study reach, indicated that several locations along the pilot reach should support riparian vegetation. Field visits verified that areas predicted to have riparian vegetation by the EFM did in fact have willow and cottonwood seedlings that sprouted following the 1997 flood. The Princeton pilot study evaluated a hypothetical levee realignment that would re-connect floodplain land to the Sacramento River. Although the hypothetical project alleviated a choke point and reduced water surface elevations, EFM results predict that the extent of riparian vegetation would not increase significantly because the reconnected floodplain lands would not be inundated frequently enough. The two pilot studies demonstrate how the EFM can be used during planning and feasibility studies to predict biological response to proposed changes to the flood management system and help envision potential ecological improvements.

Floodplain and Watershed Management

- **Floodplain Management.** The Comprehensive Study included an evaluation of existing and potential floodplain management programs and measures that could be implemented in the Central Valley. The potential modifications considered included those that could be implemented locally, such as flood-proofing structures, and programs that could be implemented basin-wide, such as educational programs or flood risk mapping to encourage more appropriate land use in the floodplain. While many of the local measures will be considered during planning of future projects, the State of California or other agencies would be needed to implement basin-wide programs.

  The National Flood Insurance Program (NFIP), administered by FEMA, and other programs have significantly contributed to reducing flood damages through regulation of the floodplain. However, flood risk will rise as population in the regulatory floodplain grows and land adjacent to regulated areas is developed. Some of the causes of continued flood risk include:

  - Encroachment of urban development in the floodplains, sometimes aggravated by the limitations of and non-compliance with NFIP and State floodplain management guidelines.
  - Lack of updated floodplain and floodway maps that reflect changes in flood hydrology and channel geometry.
  - Approval of projects that do not address negative hydraulic impacts or effects outside the immediate project area.
  - Deferred channel and levee maintenance.
  - Lack of funding for flood protection projects and buyout programs for repeatedly flooded structures.
  - Lack of understanding or awareness of the actual risk of flooding, both within and outside of the regulated floodplain.

- **Residual Risk.** After a flood management project is built, some risk of flooding will always remain from unexpected problems, larger floods, or uncertainty associated with the technical data used to design the project. Information about the threat of flooding needs to be communicated throughout the study area in a manner

As future projects are developed, there is a need for technical assistance to communicate flood risk to emergency services and management; provide floodplain management education and outreach programs; and develop multi-parameter flood threat maps that can be used with traditional floodplain maps to make more informed land use decisions.

that will broaden the current level of understanding. Typically, floodplain mapping is used by local entities to guide land use decisions in areas that are subject to flooding and require flood insurance. In their current form, these maps do not illustrate residual risk or risk to adjacent lands. In addition to the frequency of potential damages, citizens and decision-makers also need to understand the potential severity of damage (five inches versus five feet of floodwater) and threat of loss of life that would result from flooding. For example, residual risk is higher in densely developed areas that would be subject to rapid, deep flooding – such as areas protected by high levees or areas with limited evacuation routes.

The Corps Hydrologic Engineering Center is developing ways to visually communicate residual risk through multi-parameter flood threat mapping. While traditional floodplain mapping is typically limited to flood frequency and extent, risk-based mapping identifies other hazard factors such as the depth of flooding, flood warning time, and the velocity of floodwaters. HEC's effort is near completion and a draft document is anticipated the first week of December 2002.

Residual risk is the portion of the flood risk that still exists following completion of a flood damage reduction project.

- **Emergency Preparedness.** The existing flood management system includes flood warning and response features that provide information to emergency response personnel throughout the river basins. Because of the rapid rainfall-runoff characteristics of the Sacramento and San Joaquin River basins, current warning time is measured in mere hours. Additional data collection and dissemination features, along with improvements in current weather forecasting capabilities, could lengthen warning time and increase opportunities to implement forecast-based reservoir operations. The Reclamation Board, DWR, and the Corps, working with the State and Federal Joint Operations Center - the emergency response center for flooding and hazardous weather - are conducting a study to determine if there is a feasible project to improve existing flood warning time and emergency preparedness. This study is the Enhanced Flood Response and Emergency Preparedness project. (see Potential System-Wide Measures section in this report for more information).

Because of the rapid flooding nature of the Sacramento and San Joaquin River basins, warning time is measured in hours in some locations.

- **Urbanization.** The Corps' Hydrologic Engineering Center performed a preliminary study to evaluate the effect of urbanization on flood flows. Urban land development results in an increase in impervious area, reducing percolation and increasing rainfall runoff. Study results confirmed that increased land development is accompanied by an increase in both peak flow and runoff volume, with the greatest increases observed in runoff volume. Urbanization had the greatest effect on more frequent storm events (more frequent than the 4% event), and the location of urbanization within the watershed influenced its effect on runoff flows and volumes.

The Comprehensive Study Provided System-Wide Understanding

Hydrology – Nineteen historic flood events (including the January 1997 storm) were used to estimate the runoff that would result if no reservoirs existed in the watershed.

Reservoir Operations – Over seventy reservoirs were modeled to determine regulated flood flows, making this the largest application ever of the Corps' reservoir modeling tool.

Levee Reliability – Levees can fail when the river overtops them, when they erode, or when water seeps through or under them. A preliminary system-wide assessment estimated how levees could perform during various flood events.

Hydraulics – Generally, floodwaters flow within the defined system of channels, weirs, and bypasses. Hydraulic models assessed the flow and water surface in these systems and how the flows moved onto the floodplain when banks were overtopped or levees failed.

Composite Floodplains – When flood flows leave the channels because of overtopping or levee breaks, the floodplain could be inundated. Because no one storm would produce the same frequency of flood flows throughout the Sacramento and San Joaquin River basins, composite floodplains were developed. Detailed topography and hydraulic models estimated the rate and depth of water flow over the floodplain.

Economic Damages – Land uses in the inundation areas were analyzed to estimate potential economic impacts of flooding. Economic impacts result from agricultural damage and production losses, damage to structures and their contents, damage to infrastructure, and the movement of goods and services.

Flood Warning and Response – The existing flood management system includes tools to examine data to determine if a flood threat exists and forecasting tools to determine if a threatening situation may develop. These tools were reviewed to identify opportunities to increase warning time through improved data collection and dissemination and additional emergency response planning.

Floodplain Management Programs and Measures – Existing Federal, State and local floodplain management programs were reviewed to identify potential improvements and new floodplain management measures that would promote flood safety and ecosystem restoration in the floodplain.

Biological Response to Flows – The EFM was developed to assess how changes in the river flow would affect the river-floodplain environment. Successful pilot testing at two locations indicates this tool has value in estimating ecosystem response to future projects.

Basin-wide Storage Opportunities – Major flood storage reservoirs in the Central Valley were reviewed to identify the potential effects of additional flood space or changes to controlled flood releases. Some reservoirs coincide with sites considered in the CALFED Integrated Storage Investigation (ISI) Surface Water Storage Program.

Conjunctive Use – Assessment of system-wide opportunities to lower reservoir storage levels below the flood control pool and then transfer this displaced water to groundwater storage found this method to be potentially feasible.

Watershed Land Use Changes – Evaluation of a test site concluded that increases in urban development in the watersheds would cause a measurable increase in the runoff for more frequent (storms up to the 1-in-25 year event), but the increases were less pronounced for larger storms.

Subsidence – Subsidence, or the lowering of ground surface, can significantly affect flood system design and performance. Topographic data show that subsidence has had a more pronounced effect on flood conveyance facilities in the San Joaquin River Basin than in the Sacramento River Basin.