An Unsteady Hydraulic Surface Water Model of the Lower Cosumnes River, California, for the Investigation of Floodplain Dynamics

BY

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THESIS

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I INTRODUCTION

Purpose

The purpose of this study is to investigate the hydraulic surface water relationships between the Cosumnes River and its floodplain, and the river's impact on the receiving waters of the northern portion of the Sacramento-San Joaquin Delta. Integral to the study is the development of a numerical hydraulic model to expand current understanding of the Cosumnes River and its riparian environment, and to allow for the efficient analysis of river management scenarios.

Study Area

The principal study area lies entirely within Sacramento and San Joaquin Counties. The Cosumnes River, its forks, and tributaries extend into the counties of El Dorado and Amador, with the uppermost reaches of the Mokelumne River found in Calaveras and Alpine Counties [Figures 1 and 2].

The headwaters of the North, South and Middle forks of the Cosumnes River are on the western slope of the Sierra Nevada, within El Dorado County. The Cosumnes River flows southwesterly after the confluence of these forks, as a single channel through the remainder of the Sierra Nevada section. Shortly after crossing into Sacramento County, the nature of the channel and its geologic environment changes drastically, from a bedrock-controlled morphology (Vick et al., 1997) within Mesozoic sediments, to an alluvial channel through younger Cenozoic deposits (Strand and Koenig, 1965). The upper limit of study is selected at this general transition, as the operating boundary between the lower and upper basins, which is in line with both the geomorphologic context of the river, and several other studies. Additionally, the availability of a well-maintained flow gauge with a significant record length assists in the boundary determination. Following the Cosumnes further, the river flows through Sacramento County, collecting Deer Creek and several other tributaries, to the San Joaquin County line, where it meets Dry Creek. These rivers then flow together a short distance before joining the Mokelumne River, at the upper limits of the North Delta of the Sacramento and San Joaquin Rivers. The Mokelumne splits into north and south forks, and interacts with a number of distributaries within the delta before rejoining itself and flowing into the San Joaquin River, at a point approximately 30 km upstream from the Sacramento–San Joaquin confluence [Figure 2]. The size, capacity, and dynamics of the channels at this downstream location are such that the effects of the Cosumnes River and its tributaries are damped by larger delta flows, and so provide a suitable frame for this study.

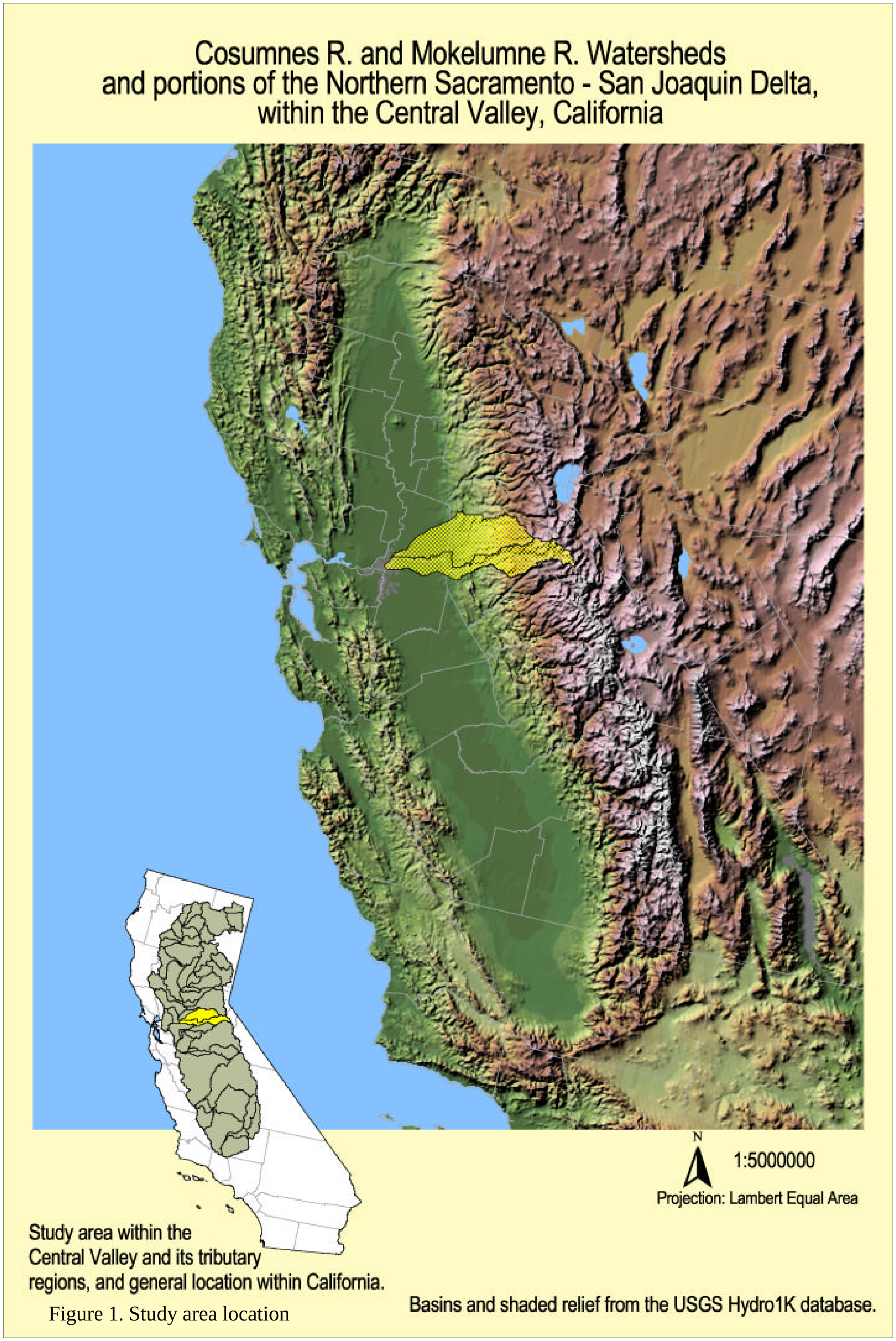


Figure 1. Study area location

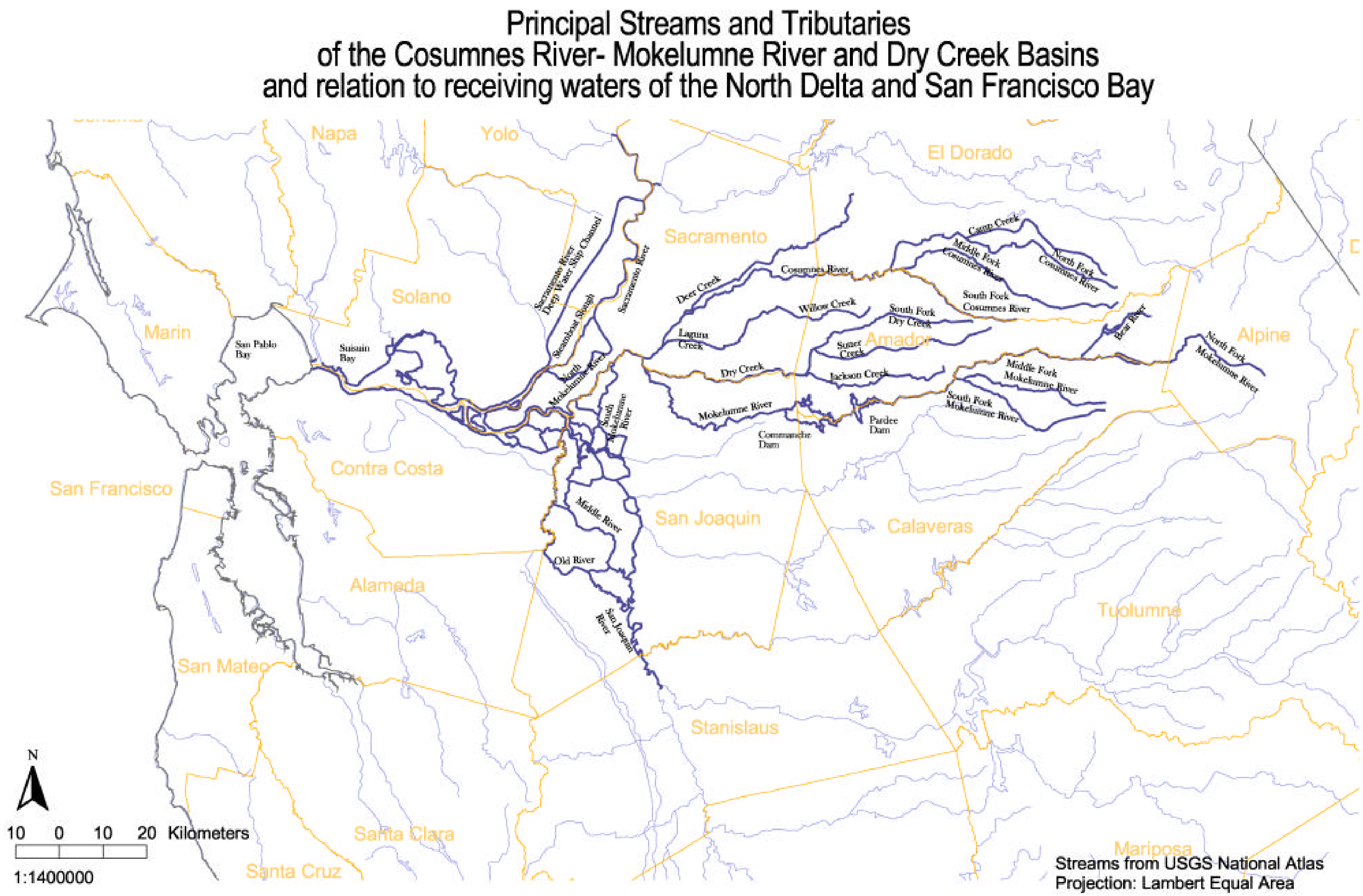


Figure 2. Study Area and Major Tributaries

Approach

The current study intends to develop a hydraulic model linking the main stem of the Cosumnes River to its receiving waters of the North Delta, to provide a vehicle for the further understanding of the relationship between upper basin hydrology, tributary interactions, and the relevant Cosumnes River floodplain functions. The central role in this model's development is its application to flood flows on the Cosumnes River and its floodplains. The model will provide a framework for the collection of hydraulic and topographic data, an extension of gauged stage and flow data to ungauged areas, and a numerical tool to support further studies of detailed floodplain phenomena.

The time variation inherent to storm flows and the tidally-forced lower Cosumnes River are provided for within the domain of an unsteady, one-dimensional model, with adaptations to the significant case of floodplain inundation and draining. An emphasis has been placed on the modeling of recent hydraulic events, for which a reasonable data distribution makes detailed analysis possible. This study progressed in three linked phases, increasing in both complexity and degree of predictability, as the model was refined.

The first phase was the development of a one-dimensional network representation of the major channels and tributaries in the North Delta system. This phase included the selection of modeling boundaries, descriptions of tributaries of significance, and the development of the data inputs for the network model. Required at this point are the upstream flow boundaries, downstream stage information (due to tidal influence), channel length and location of channel cross section information, and the location of channel connections and tributary inflows. The channel network itself was digitized from digital map sources of the North Delta, and verified with recent aerial photography and field observation. Cross section data were collected from numerous sources, which are described and displayed in Appendix A. Results from this phase indicate the general behavior of the channel system, the response to flood flows, and their interaction with the tides. Linear attenuation of flood peaks (due to channel processes of decelerating flow and channel variation) is observable at some locations. Missing from these results are the effects of the floodplains on channel flow, as either time varying storage elements, or as flooded areas capable of conveyance. In this fashion, the first phase provides the groundwork for more detailed modeling, and a baseline for the assessment of the effect of two-dimensional function of the flood system.

The second phase introduces floodplain characteristics to the one-dimensional model. This is achieved in an approximate manner with several floodplain channels described as links in the hydraulic model. Cross sections are estimated from available topography and chosen to represent average conditions across the floodplain width. The scale of floodplain phenomena described at this level of effort is still relatively coarse, with the gross effect of storage represented with this network. Results of this phase of modeling show the storage and release related attenuation of flood peaks superimposed on the purely one-dimensional representation. An assessment of the degree of realism associated with this stage of modeling reveals a vastly improved description of peak lag and attenuation, but shows shortcomings in the accuracy of the flow variables. The inclusion of the effects of the floodplains justifies the distribution of flow and water depth over the floodplain, with some similarity to actual flood conditions. However, in order to improve the predictability of the model, smaller scale floodplain interactions and conveyance must be described.

The third phase of the modeling entails a refinement of the second phase with an increase in the complexity of the modeled channel-floodplain interactions. The effects of secondary flood-storage areas are taken into account (off the main channel, along tributaries, etc.), as well as localized floodplain connections between tributaries, and a larger scale representation of channel-floodplain connectivity. Commensurate with increasing model scale is an increased need for geometry of floodplains and channels. Results at this phase show the highest level of agreement with validation data. Two-dimensional representations of the resulting distribution of flow and depth provide a great deal of utility, when used with this scale modeling, and can be applied to dynamic floodplain mapping efforts. At some point the accuracy of the input floodplain topography will limit substantial improvements afforded by increasing planform complexity. An associated risk of attempting larger scale modeling is the invalidation of the central hypothesis of one-dimensional applied modeling, in that a variable, non-bi-directional flow may occur and not be discretized at the model scale.

At this level of analysis, specific calibration information is only available for the channel flow parameters, and typically stage, and not flow, information is available. Due to the extensive floodplain inundation at work, the variability in channel discharge is not well represented by stage records alone for the area of interest. For these reasons, a formal calibration effort has not been undertaken for the Cosumnes–North Delta model. Agreement with observed channel stage records in the interior of the model is expected, and efforts to improve on the representation of the channel geometry and floodplain connectivity have been used to control the channel response. A fine-tuning of the channel and floodplain resistance coefficients has not been used outside of a realistic, measurable physical context.

Similarly, the existence of channel constricting structures such as bridges and floodplain levees is likely to have an impact on the behavior of the channel and floodplain water levels and discharge. The unsteady backwater behavior of such systems is outside the realm of the usual one-dimensional model, although modifications to the solution techniques are available for their description, and the study of such techniques, and their comparison with steady flow approximations, is a subject for future study. Due to the additional complexity of the computation of large numbers of structures, this effect has not been accounted for in the model, outside of the obvious reductions in conveyance and channel capacity at these constrictions.

A sensitivity analysis has been performed to indicate the robustness of the model and specific discretization. Sensitivity to roughness, floodplain volumes, and the elevation and geometry of links between channels and floodplains has been tested for selected locations. This information will be useful in the designation of areas where further data and geometry are needed. Further, the sensitivity results will guide alternative modifications to the model, and the interpretation of results.

Finally, a number of model simulations have been performed which aim to provide key information about the floodplain function of the Cosumnes River Preserve. These simulations should provide some understanding of the sensitivity of the real-world system to boundary conditions, channel geometry, and floodplain volume, which will be helpful in determining the future function and character of the lower Cosumnes River floodplain.

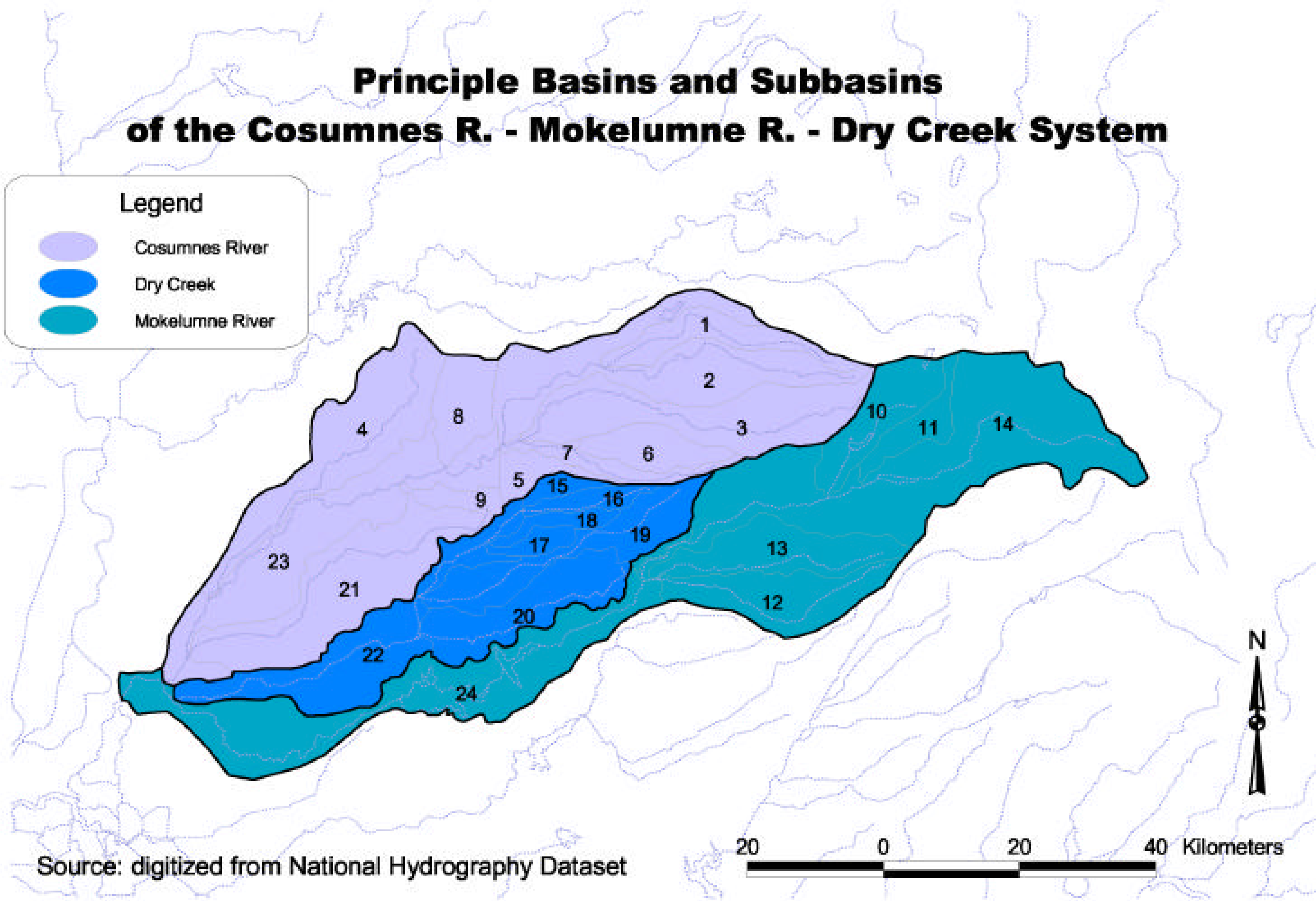


Figure 3. Study Area and Major Tributaries (for basin information see Appendix A)

II BACKGROUND

Existing Studies of Cosumnes River Geology and Hydrology

The Cosumnes River, from its tributary headwaters to its tidally-influenced deltaic reaches, has been studied for the purpose of water development, flood control, and environmental restoration. The understanding of issues of concern in the upper and lower watersheds has progressed on largely separate paths, and it can be noted that relevance of the individual studies, while targeted towards specific goals, often seems narrowly focused from a watershed point of view. Linking the upper and lower basins across social, political and spatial boundaries remains as an important element of a wider understanding and wiser management of the Cosumnes River, as in other basins.

A geologic context for the Sacramento - San Joaquin River Delta and surrounding environments is provided by Atwater and Belknap's "Tidal Wetland Deposits of the Sacramento-San Joaquin Delta" (Atwater and Belknap, 1988). A review was prepared of documented and observed modifications to the Cosumnes River (Strudley, 1999). The Cosumnes River watershed was reviewed in an available-information type study prepared for The Nature Conservancy (TNC), assessing the hydrologic and ecologic systems in place and plans for their preservation (Environmental Science Associates Inc., 1991). Corollary information on the upper Cosumnes River and deltaic environments, as well as hydrologic environment, is provided in the Environmental Impact Statement for the Stones Lake National Wildlife Refuge, located adjacent to the current study area (Jones & Stokes Incorporated, 1992).

The hydrology of the Cosumnes River has been studied within the context of flood control (U.S. Army Corps of Engineers, 1936; U.S. Army Corps of Engineers, 1965; U.S. Department of the Interior, 1979; and U.S. Army Corps of Engineers, 1991), including the application of hydraulic modeling to water surface determinations along the upper mainstem of the Cosumnes River (Guay et al., 1998). The extensive study of the delta system by the California Department of Water Resources (DWR) includes the North Delta Program Environmental Impact Report (EIR) (California Department of Water Resources, 1990), interim reports on North Delta hydrology (California Department of Water Resources Division of Planning, 1994;

California Department of Water Resources Division of Planning, 1995) and post-flood assessments of the 1983, 1986, 1995, and 1997 flooding (U.S. Army Corps of Engineers, 1999). The function of the Cosumnes as a river-floodplain system was the focus of a hydraulic modeling effort centered on the lower Cosumnes floodplain (Swanson and Hart, 1994), as well as a study of the complete Cosumnes mainstem, incorporating a hydraulic model and geomorphic assessment (Vick et al., 1997). The river reaches between Michigan Bar and the delta environments were studied with regard to ecologic function for TNC (Hart and Engilis 1995).

Groundwater resources of the Central Valley, including the Cosumnes River have been studied recently by the U.S. Geological Survey (USGS) (Bertoldi et al., 1991). A significant attempt at gaining an understanding of the low flow Cosumnes River system, as an aid in the augmentation of fall attracting flows, is found in a TNC supported modeling study in 1996 (McGurk and Leavesley, 1996).

The flow of water and sediment has been monitored sporadically along the Cosumnes River by various agencies. Historically, suspended sediment measurements and total load calculations were performed by the USGS at Michigan Bar (1957-1974, 1976-present) and McConnell (Highway 99) (in the 1960's and 70's). Sediment budget analyses have been constructed by the USGS (Porterfield et al., 1961) and revised in (U.S. Geological Survey 1966). Current continuous monitoring of water surface elevations and flow is performed by a number of agencies, whose efforts have been catalogued as part of this work [see Figure B1 and Table B2 in Appendix B].

Recent work by the University of California at Davis (UC Davis) is focused on the connections between basin hydrology, system hydraulics, floodplain processes, and ecologic function of the Cosumnes River Preserve and the surrounding environment. Interdisciplinary monitoring and study programs are intended to reveal the important linkages between these different fields for the study area.

Basin Hydrology

The Cosumnes River, Dry Creek, and Mokelumne River Basins form a combined watershed of 5375 km^2 (2075 mi^2) reaching from the western slope of the Sierra Nevada to the Sacramento and San Joaquin River delta, the natural drainage outlet of the Central Valley [see Figures 1 and 2]. Their tributary area and runoff generation represents a small fraction of the Central Valley's surface water resources, but the described basins represent an integral element of the region's water infrastructure and ecology. In understanding the hydrologic setting and relevance of the connection between these mountain and foothill streams and the delta estuary, it is helpful to reconstruct the nature of the receiving waters of these basins.

Prior to the historic damming, draining, and levee-building that created the modern delta-tributary system, the valley was dominated by the floodplain processes of the Sacramento and San Joaquin Rivers and their tributaries, with a flood season that could stretch for half the year. The depositional character of the rivers and streams of the Central Valley led to active floodplain building, decreasing downstream channel capacity, and the formation of a network of distributaries as they approached the delta. The deposition of sediments on the banks of these channels during floods formed levees reaching heights of twenty feet, isolating immense tracts of standing floodwaters known as the “tulares” (Thompson, 1960). These basins supported stands of freshwater tules and cattails (*Scirpus* and *Typha* sp.) (Katibah, 1981), and were named for the rivers and regions in which they seasonally formed (American, Sutter, Yolo) (Thompson, 1960). Frequently the basins became the terminal point for the flows of some rivers and distributaries, notably Cache, Putah, and Butte Creeks (Katibah, 1981). These levee building characteristics were primarily a northern tributary effect, forming on the Merced River and thence northward, including the Cosumnes and Mokelumne Rivers, and is largely absent in the southern Central Valley due to lower sediment loads of the San Joaquin and its southern tributaries (Katibah, 1981).

In addition to the seasonal lakes and flood basins of the Central Valley, the tributary streams sustained extensive riparian forests, estimated to be over 900,000 acres in total, and 57,000 acres along the Cosumnes and Mokelumne Rivers (Katibah, 1981). These supported complex variations with location, but valley oak, California sycamore, Fremont cottonwood, box elder, black walnut and willow species characterized the upper and intermediate forest layers (Katibah, 1981 ; Strahan 1981).

A third element of the pre-historic Central Valley was the upland grasslands and forests. These were found at further distances from the stream channels and in finer substrates, occurring as perennial grasslands and more dispersed valley oak, relying on groundwater at intermediate depths and soil moisture retention for sustenance (Holstein, 1981).

Each of these floristic communities evolved to complement a hydraulic structure of groundwater, surface-water, and floodplain regimes that in large part no longer exists. A significant task in the development of programs enabling these communities to thrive, and likewise for the species that depend on them, is to determine the location, timing, magnitude, and frequency of the hydraulic events on which they are dependant. For the Cosumnes-Mokelumne-Dry Creek system this involves an understanding of the relationships between the major tributaries.

For the purposes of comparison, the confluence of the Mokelumne River with its North Delta forks at New Hope Island, near the Cosumnes River Preserve (10 km downstream of the effective Dry Creek inflow to the Cosumnes River, and 7 km downstream of the Cosumnes-Mokelumne confluence at Bensons Ferry) provides a suitable point of demarcation for the basin delineation. To this point, the Cosumnes River provides a drainage area of 953 mi^2, Dry Creek 354 mi^2, and the Mokelumne River an additional 744 mi^2. Noting the basin map [Figure 3], the highest basin is the Mokelumne, with elevations reaching 11,000 ft above mean sea level (amsl), and a significant percentage of annual runoff occurring from snowmelt. The Cosumnes basin is intermediate in elevation, reaching 7700 ft amsl, and has a flow regime described by the individual characteristics of the North, Middle, and South Forks. The North Fork, and especially the Middle

Fork, produce the majority of the basin's late-season snowmelt runoff due to their higher elevation, with the South Fork contributing to the rainfall runoff events, and a smaller percentage of snowmelt (Environmental Science Associates Inc. 1991).

Table 1. Cosumnes River Upper Basin Characteristics

Tributary	Subbasin Area[1]	Avg. Annual Precipitation[2]	100 Year Estimated Flow[3]	Included in DS Flow Gauge[4]
North Fork[5]	184,103	28-65	36,067	Y
Middle Fork	85,600	30-70	20,252	Y
South Fork	17,950	30-46	5,577	Y

Data excerpted from Environmental Science Associates Inc., 1991 and where noted ESA below.
1. Approximate area in acres from mouth of tributary, from GIS.
2. Precipitation in inches, ranging from lower to upper basin [ESA].
3. Estimated streamflow from 100 year event, using National Flood Frequency Program of the USGS, 1993.
   While the North Coast region specifies a minimum H of 1, the lack of this restriction for the Sierra region imparts a strong altitude weighting factor for basin elevations below 1000 ft.
4. Tributary streamflow included in a downstream flow gauge, for flow routing purposes.
   (For Dry Creek, this includes USGS gauge at Galt, now only monitoring low flow events)
5. Including Camp Creek.

Dry Creek is the lowest of the basins, reaching 3000 ft amsl, with precipitation occurring almost entirely as rain. Despite the close proximity of these relatively small sub-basins, the runoff response to storms of varying temperature, intensity and precipitation pattern is quite distinct. The annual peak flows from the combined basin primarily occur due to rainfall-triggered events in the fall and early winter, with snow melt (Cosumnes and Mokelumne basins) providing sustained runoff volumes through the spring, with the Dry Creek basin augmenting the peak flows from the larger basins. These characteristics provided routine and sustained inundation for the floodplains of these three tributaries along their course, notwithstanding the additional backwater conditions of the San Joaquin and Sacramento Rivers.

Modifications were made to the main-stem Mokelumne River early in the last century, with the original Woodbridge Dam completed in 1901, and the current Woodbridge Dam (2,464 ac-ft) completed in 1910. Pardee Dam (210,000 ac-ft) reached closure in 1929, providing water to the Mokelumne Aqueducts, and Comanche Dam (431,500 ac-ft) followed in 1964. Pardee is the mainstay in East Bay Municipal Utility

District's (EBMUD's) water supply reservoirs, providing the majority of the water for its East Bay service area comprising 1.2 million people. Comanche's original purposes included the protection of lower Mokelumne River water needs and flood control (Federal Energy Regulatory Commission (FERC), 1993). Comanche joined Pardee as a producer of hydropower upon licensing in 1981 (Federal Energy Regulatory Commission, 1993). Current flood control agreements with the U.S. Army Corps of Engineers (USACE) and FERC re-licensing for fisheries protection constrain the operation of Comanche Reservoir (Federal Energy Regulatory Commission, 1993). In the upper basin, additional storage reservoirs of significance are located on the North Fork of the Mokelumne River and its tributaries, most notably Salt Springs Reservoir (completed in 1931), with a capacity of 130,000 ac-ft and Lower Bear Reservoir with a capacity of 49,000 ac-ft. The North Fork also supports eight power generation facilities operated by Pacific Gas and Electric (Pacific Gas and Electric, 2000). The Middle and South Forks of the Mokelumne River are largely un-regulated (Federal Energy Regulatory Commission, 1993).

The flow record at Mokelumne Hill presents a significant portion of the inflows to Pardee and the lower Mokelumne River, due to the limited tributary inflow below this point (basin area 544 mi.^{2} , approximately 70% of the total basin area). However, this record is not representative of natural flows (see references for discussion) due to power generation along the North Fork of the Mokelumne River. Prior to human intervention these flows, along with those from the Cosumnes River and Dry Creek, entered a delta subject to flooding via the Sacramento River and its tributaries, which is now constrained by reservoir operations, channel modification, and extensive levee systems. The peak instantaneous flows for the entire record have been plotted to provide an indication of longer-term hydrologic variation and the relative importance of these tributaries in generating north delta floods [Figure 4]. The basin areas at the gauges are 536 mi^2 for the Cosumnes River at Michigan Bar, 324 mi^2 for Dry Creek at Galt, and 544 mi^2 for the Mokelumne River at Mokelumne Hill. From Figure 4a, it can be seen that the two peak flows on the Cosumnes River (1903 and 1997) have dominated the measured record, and it is helpful to look at the flows below 50,000 cfs [Figure 4b], and then superimpose the three graphs [Figure 4c]. The inter-year variability in the peak flows is apparent, as is the importance of Dry Creek, as it remains a significant generator of peak flows. In several years Dry Creek had peaks representing 60-80 percent of the Cosumnes peak flow for that year, and their importance is increased by the absence of the Mokelumne peak flows due to the closure of Comanche and Pardee Dams. Notably, the missing data from 1988-present for Dry Creek include the 1997 storm, when the Dry Creek peak stage nearly reached its value from the 1986 event [Figure 5], when flows of 30,000 cfs were recorded. This occurred after the flow of record that occurred on the Cosumnes River in early January, and indicates that peak flows on Dry Creek, as well as minor tributaries of the lower Cosumnes River, may have dominated the flood regime for the late January storms. This would be the case for lower elevation rainstorms, dumping appreciable volumes on entirely saturated channels and floodplains.

An element missing from the peak flow analyses is, of course, the nature of the sustained flows, and the runoff volume presented by the basins. Looking to the DWR EIR/EIS for the North Delta Program, flow volumes for the hundred year event generated by the Mokelumne and Dry Creek basin may represent 40 percent of the 7 day flow volume for the total Cosumnes, Mokelumne, and Dry Creek basins in their current condition (Environmental Science Associates Inc., 1991).

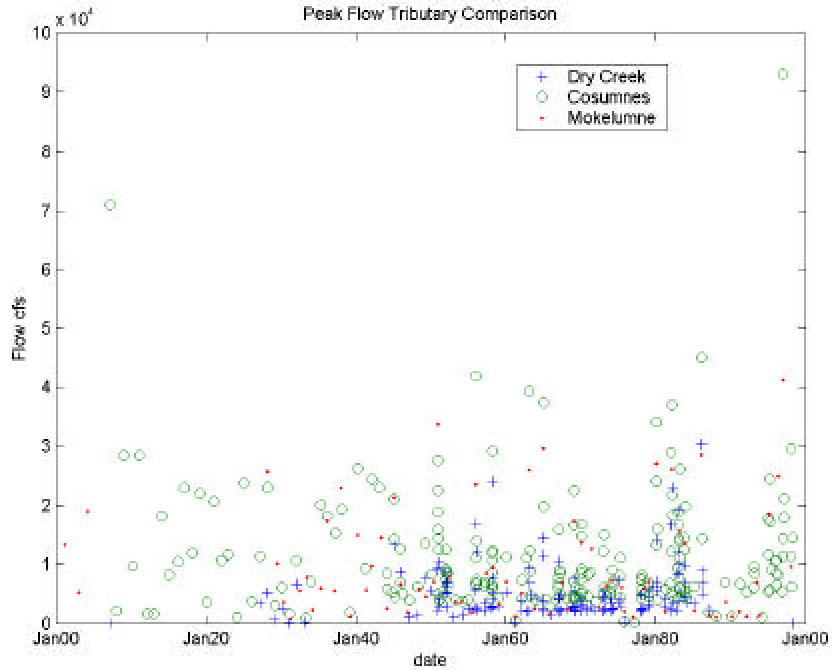


Figure 4a. Peak Flows Recorded for the Last 100 years on the Mokelumne R., Cosumnes R., Dry Creek

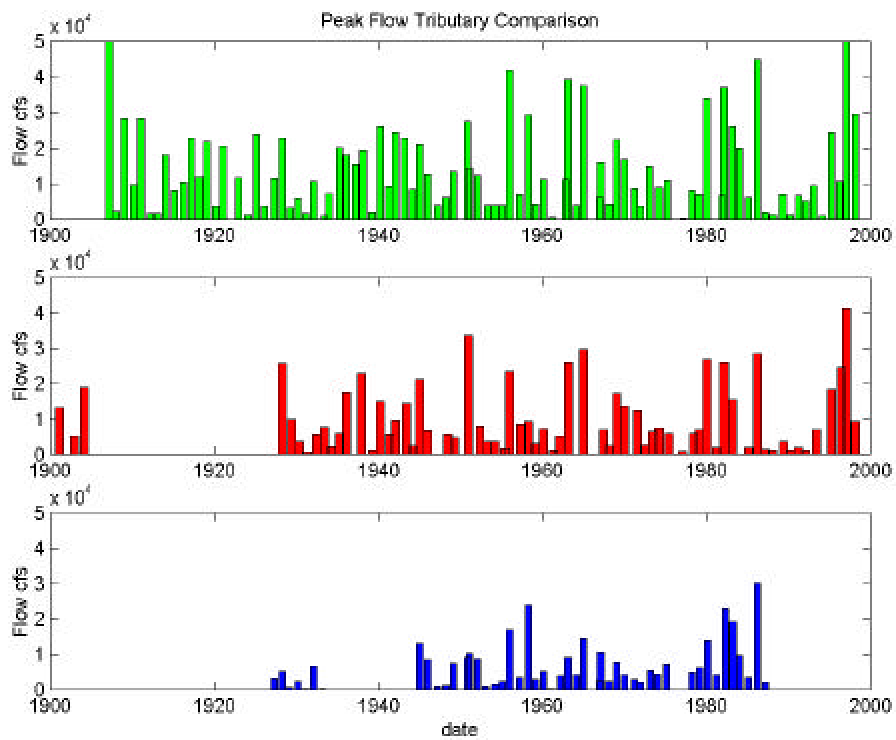


Figure 4b. A View of the 100-year Record in Figure 4a (without the two highest peak flows on the Cosumnes River)

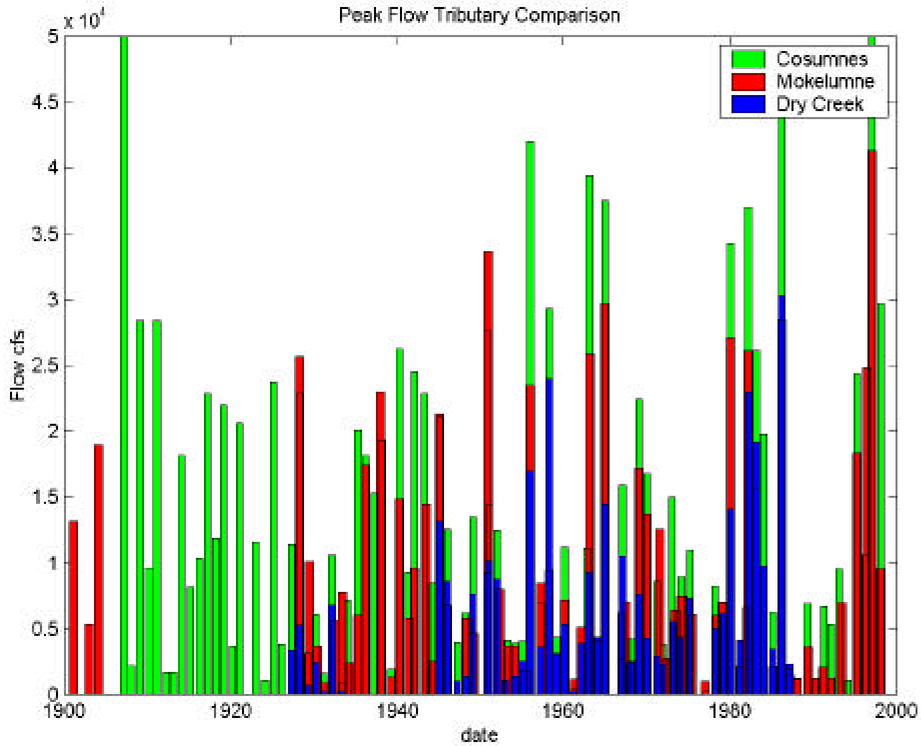


Figure 4c. A Superimposed View of the 100-year Record in Figure 4b (without the two highest peak flows on the Cosumnes River)

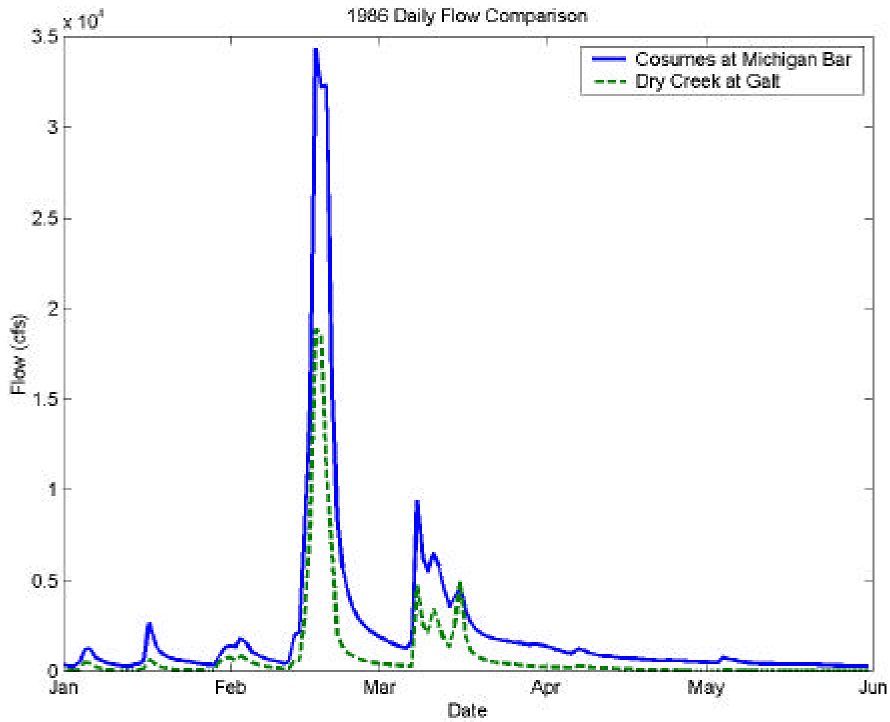


Figure 5a. Flow Record for the 1986 Flood Season on Dry Creek and the Cosumnes River

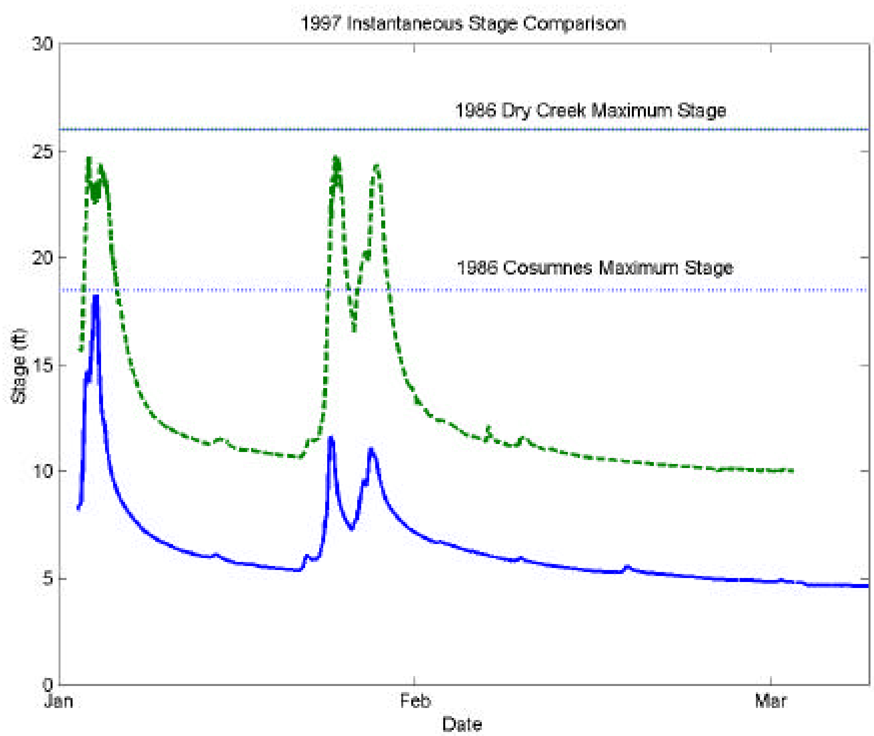


Figure 5b. Comparison of Dry Creek and Cosumnes River, 1997 Instantaneous Stage

Lower Tributaries

The importance of lower tributaries in generating flood flows resides in their basin area and precipitation characteristics, and the nature of the intercepting land surface, its soils, and vegetation. Normally the lower tributaries in the Cosumnes, Mokelumne, and Dry Creek basins do not generate flows that compare in magnitude to the upper tributaries receiving orographic precipitation. However the lower tributaries may respond with large flows when locally intense or long duration storms occur over the flooded channels, plains, and saturated surfaces of the basin, also known as the variable source areas. Due to the large inundation in areas of the lower Cosumnes River, Mokelumne River, and Dry Creek, this may be an important runoff generating mechanism during times of peak flows.

Table 2. Lower Cosumnes Tributaries

Tributary	**Subbasin Area[1]**	**Avg. Annual Precipitation[2]**	**100 Year Estimated Flow[3]**	**Included in DS Flow Gauge[4]**
Laguna Creek	100,788	16-22	30,048	N
Badger Creek	21,671	16-17	13,037	N
Deer Creek	87,688	15-30	21,686	N
Little Indian	10,126	20-27	3,726	Y
Big Indian	14,004	28-36	4,692	Y
Big Canyon	28,426	26-35	8,956	Y

See notes on Table 3.

Table 3. Major Dry Creek Tributaries

Tributary	Subbasin Area[1]	Avg. Annual Precipitation[2]	100 Year Estimated Flow[3]	Included in DS Flow Gauge[4]
North Fork Dry Creek	7,289	16-22[5]	1,559	Y
South Fork Dry Creek	11,924	16-22[5]	2,176	Y
Amador Creek	8,545	16-22[5]	2,005	Y
Rancheria Creek	9,823	16-22[5]	2,061	Y
Coyote Creek	12,598	16-22[5]	7,359	Y
Jackson Creek	53,876	16-36	10,048	Y
Sutter Creek	53,193	18-46	15,183	Y

Data excerpted from Environmental Science Associates Inc. , 1991 and where noted ESA below.
1. Area in acres from mouth of tributary, from GIS.
2. Precipitation in inches, ranging from lower to upper basin [ESA].
3. Estimated streamflow from 100 year event, using National Flood Frequency Program of the USGS, 1993.
   While the North Coast region specifies a minimum H of 1, the lack of this restriction for the Sierra region imparts a strong altitude weighting factor for basin elevations below 1000 ft.
4. Tributary streamflow included in a downstream flow gauge, for flow routing purposes.
   (For Dry Creek, this includes USGS gauge at Galt, now only monitoring low flow events)
5. Estimated from Laguna Creek annual estimated precipitation.

Modern Hydraulic System

The modified hydrologic system of the three North Delta tributaries is a result of the significant anthropogenic disturbance to the low flow and groundwater regime of these basins, as well as the modifications to the channels and floodplains that comprise the hydraulic system. In this study, those factors that exert a strong influence on the flood hydraulics have been studied in detail, in order to describe the system-wide hydraulics of the lower basin.

The current configuration of dams on the major tributaries to the North Delta, and a system of modified, leveed channels along these rivers, has greatly altered the complex natural flood regime of the Cosumnes, Mokelumne and Dry Creek basins. Backwater situations due to the floodwaters of the northern Central Valley tributaries are largely absent, except for the more limited effects of in-channel backwater on the forks of the lower Mokelumne River, and during extreme flood events. This present day backwater has a marked influence on the development of flood conditions in the North Delta, but exists in a condition altered from the pre-historic inundation patterns of the valley's free-flowing tributaries. It is noted that the combined present day peak flood flows on the three tributaries combined are dwarfed by the sustained flows regularly seen on the Sacramento River during flood season.

The flood regime of the basin is also significantly modified by the presence of roads, railroads, and highways which cross the basin streams and floodplains. The effect of these structures is to constrain channel flow to the location of bridges and causeways, divide the connectivity of the floodplains, and restrict the ability of the hydrologic system to change with time. Such structures are augmented by the presence of levees, which in dividing the channel from the floodplain, allow agricultural and urban use to proceed in near-channel environments.

The Cosumnes River travels 75 km from its emergence from the foothills at Michigan Bar, through a system of complex floodplains and levees, through multiple historic and active channels. Floods of varying intensity overtop and compromise the levee system, and drain back to the channels through a number of overflow channels and drainage ditches. The presence of road bridges along these reaches restricts the passage of flood flows, and lower in the system, creates extensive backwater environments. At the Highway 99 bridge crossing, there are three effective channels, and a historic channel since filled for agricultural access. Most of this floodplain can be characterized by a statement made in regard to the McConnell Bridge backwater, during the flood of 1997, by an employee of the USGS: “5 miles wide, and just sitting there”, but at times, the flooding and draining cycle can by very energetic. During the winter of 1998, overbank flows with sufficient energy to scour a ten-foot deep gash in the floodplain occurred, indicating the dynamic complexity of this backwater environment. It has been hypothesized, based on the botanical evidence at the site, that the extent and duration of the flood regime has been markedly increased at this location by the construction of Highway 99 (http://www.cosumnes.org).

The changes to the Cosumnes-Dry Creek-Mokelumne system, with reference to its lower reaches, has progressed in the same manner, resulting in an artificial system which provides for the local and regional needs of agriculture and transportation, as well as important remnants of a vanishing ecosystem. TNC has commissioned work that studies these changes and their impacts on the hydrology and ecology, as well as opportunities for restoration of missing and threatened habitats and ecologic function (Environmental Science Associates Inc., 1991; McGurk and Leavesley, 1996; Vick et al., 1997; and Strudley, 1999).

The restricted outflow from Comanche Reservoir limits the flooding of channels on the Mokelumne above and below Woodbridge. In major flood years, the historic peak flows due to the spill release at Comanche Dam and the relatively small source areas below this point are limited to approximately 6000 cfs, at the Bensons Ferry bridge. The USGS report on channel capacity assessed the flood prone regions for the leveed river at similar peak flows (Simpson, 1972). Larger flows are estimated for the 100 year event in this vicinity (California Department of Water Resources, 1990).

As the floodwaters of the Mokelumne River enter the upper delta, the floodplain is shared with Dry Creek flows to the north. Grizzly and Bear Sloughs convey flows from Dry Creek directly to the Cosumnes River. Storm flows are largely channelized, with rough, narrow floodplains directing high velocity currents towards the Cosumnes River, as indicated by the bent vegetation and scour observed post-flow. As part of the present thesis, bridge cross section records have been digitized for these locations (at the New Hope Road crossings) to provide an indication of floodplain width and channel geometry. However, recent geometry distributed along these sloughs, and the monitoring of flood stages and velocities are elements missing from the current understanding of flood pulses on and near the Preserve.

The Stone Lake system comprises the northwestern boundary of the Cosumnes–North Delta basin. Snodgrass Slough provides a direct year-round connection between the Lower Stone Lake outfall and the North Delta, specifically the North Mokelumne River. This connection is regulated by an inoperable flood gate at Lambert Road (U.S. Army Corps of Engineers, 1987), which allows tidal fluctuations to propagate into the Stone Lake system. During large flows, the roadway is overtopped and according to a particular report on the North Delta flood control, floodwaters flow north into the Stone Lakes system (Ensign and

Buckley Consulting Engineers, 1998). Since 1988, the Sacramento County Water Resources Department has monitored stage at the Lambert Road gate, and began recording 15-minute event data in 1998.

A significant factor during large floods is the interaction between the Cosumnes floodwaters and Snodgrass Slough. These floodwaters are present along the Western Pacific railroad embankment and Franklin Boulevard, and along the Lambert Road channel and adjacent fields. During periods of high stage, floodwaters form an area known as the Franklin pond, which eventually drains via Snodgrass Slough and the Cosumnes River. Flood analysis for this area has been described in the USACE report (U.S. Army Corps of Engineers, 1991). Channel connectivity between the Cosumnes River Preserve and Snodgrass Slough is provided by Middle Slough and Lost Slough, and the several roadways crossing these sloughs define an inter-connected complex of backwater environments [Figure 6]. The section view of these constraints [Figure 7] displays the nature of the constrained flood plain, from Twin Cities road, showing the both the historical multi-thread Cosumnes River road crossings, and the current day bridge locations, to the Interstate 5 bridges, crossing the rivers, sloughs, and portions of the floodplain. Within this defined zone, Thornton Road and railroad embankments apply similar floodplain constraints on the Cosumnes and Mokelumne Rivers, and Middle and Lost Sloughs. A complex of levees, and estimated breach locations, shown in the plan schematic [Figure 6] completes the picture of the managed local floodplain on the Cosumnes River Preserve. These interactions are the fundamental elements of the hydraulic system that feeds the North Delta, and particularly the area surrounding the McCormack-Williamson Tract and New Hope Island.

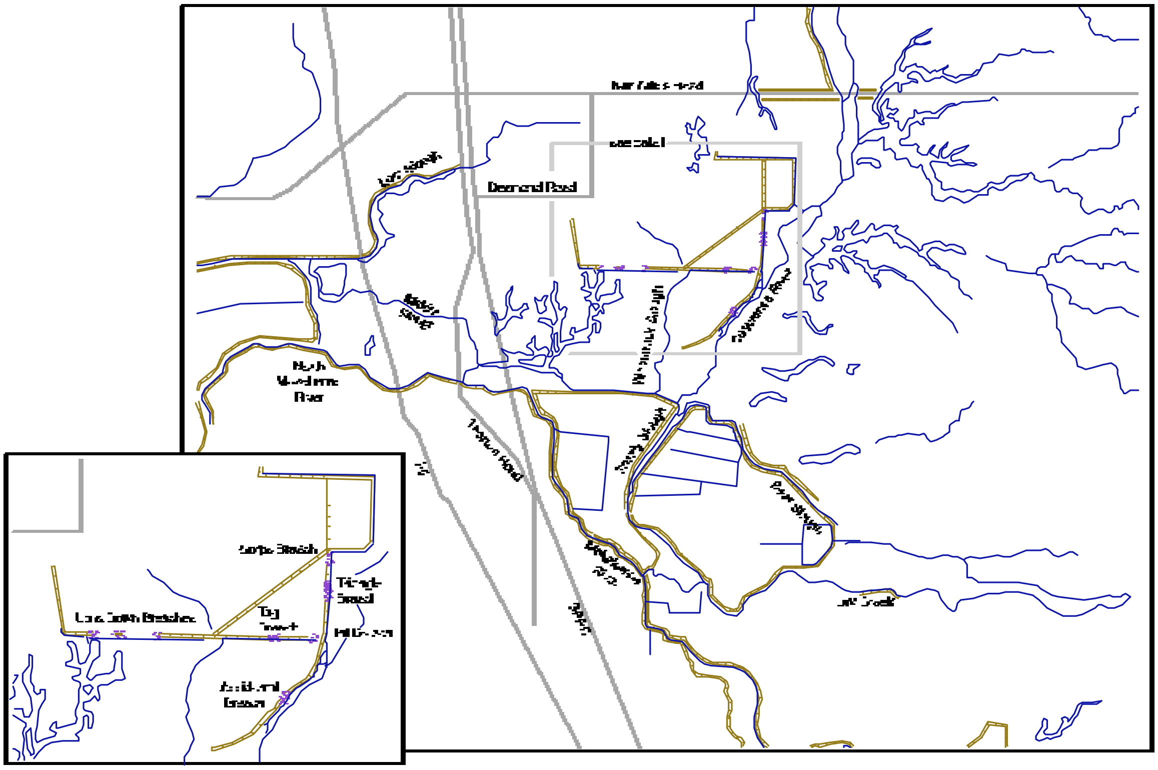


Figure 6. Cosumnes River Preserve Vicinity Channels, Sloughs, and Floodplain Constraints
Levee locations shown as linear hatchures. Inset shows location and designation of breaches, or associated breaches.

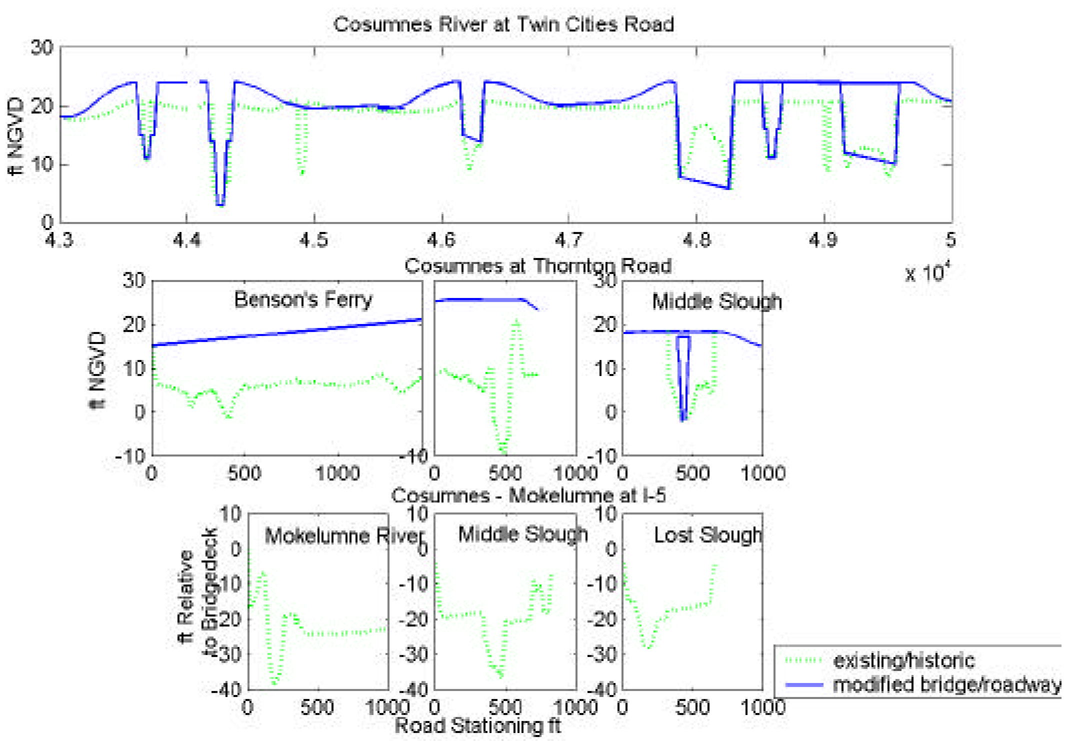


Figure 7. Cosumnes River Preserve Vicinity Profile View

On the Cosumnes River Preserve itself, a recent history of levee construction and breach activity is necessary to describe the ongoing evolution of the floodplain. The construction of levees along the Cosumnes River near the preserve began in the early 1900's. The construction of the "right angle levee", sometime around 1957, led to the capture of the adjoining borrow ditch, which significantly modifies the flow patterns in the vicinity of the preserve today. Additional levee building, in combination with road embankments has led to a cellular arrangement in this area, for the purpose of agricultural use. The formation of breaches, both natural and planned, in these levees, is the current dominant mechanism for change on the preserve. A levee failure in 1985 has led to the formation of the "Accidental Forest", in an area that did not revert to farming. The planned breach of the Cosumnes levee in the flood season of 1995-1996 allowed flood waters to access the floodplain again near the location of the failure ten years earlier. An intentional breach on the "triangular floodplain", funded in part by the USACE in 1997 has become the most dynamic channel floodplain connection, flooding regularly, and providing a natural laboratory for the study of floodplain restoration and rehabilitation techniques (http://www.tnc.org/news/magazine/nov_dec98). Additional breaches of the interior preserve levees have occurred in recent years, and a number of natural breaches are imminent, as the levees are eroded by high flows.

The flood mapping done for the estimated 100-year event on the Cosumnes River was focused on the reaches between Michigan Bar and State Route 99 (Guay et al., 1998). The dynamic nature of this region, with a composite Deer Creek–Cosumnes floodplain, was revealed in the January 1997 flood, when numerous levee failures preceded widespread inundation. The USGS analysis constructed a conservative envelope of the 100 year flood limits, by posing failure of the left and right banks separately in a steady flow model, and superimposing the planform extents of flooding. The study did not investigate the complicated hydraulics at the McConnell (Highway 99) bridge, and calculated the inundation in this area by extrapolation of results 2400 feet upstream. The opportunity may now exist to apply a one and two-dimensional unsteady model to this reach, as an aid in determining the effect of this region on downstream hydrology, and to determine some detail of the complicated hydraulics at the McConnell bridge. The current study is not suited to study this area in depth, due to a lack of field and topographic information.

Unsteady Channel-Floodplain Interactions

The importance of the unsteady nature of flood flows on the health of riparian systems in the Central Valley, and on the ecologic function of channel floodplain processes in general, is a topic of much current research and interdisciplinary collaboration. The concurrent, and at times competitive (Pelzman, 1973) processes of forest regeneration and sustenance, fisheries development, and material transport (sediment, organic material, and nutrients) are directly linked to the seasonal flood flows, which act to disturb, deliver, and distribute this material. The relevant spatial scales for these processes depend on the river's ability to transport material in the longitudinal and transverse direction (Schnitzler, 1997), and is thus related to the patterns of inundation, as well as the frequency of occurrence. While the presence of floods is necessary for the development of a floodplain ecology, it is not sufficient, and regeneration, recruitment, and survivability is a function of a host of independent factors (Warner, 1981). This leads immediately to the interdisciplinary requirements for the characterization of such riparian systems, and the understanding of processes that integrate riparian botany, fisheries biology, and surface and groundwater hydrology, and which are superimposed on a particular geo-climatic condition.

Within the Central Valley, the salix and populus species are the first to capitalize on disturbed floodplains and channel deposits, a common characteristic of riparian systems. The traits that allow this are an indication of the importance of flooding to these systems: the development and timing of seed dispersal, which coincides with flood season, the ability to regenerate from dispersed seeds as well as flood damaged and sediment covered members, and the rapid growth brought on by inundation-induced anoxia (Schnitzler, 1997). Similarly, the need of successional species such as quercus for a reduced inundation hydro-period, less disturbance and the ability to compete in shaded environs reflects a change in the local physiology of the floodplain. The time since disturbance characteristic describes succession following extreme events, as one mode of floodplain change (Strahan, 1981). The change in floodplain physiology can also be attributed to the sediment trapping, maturing and eventual senescence of salix and cottonwood species, providing an elevated, shaded bed for successional species. Another mechanism is the forced succession due to fluvial regime shifts, meander migration (Strahan, 1981), or that related to geomorphic or biologic-induced channel avulsion (i.e., log jams or beaver activity). This component is likely to be important in naturally multi-channel systems such as the Cosumnes River and its tributaries.

It has been acknowledged that the low-flow intervals provide an important ecologic component of the unsteady channel-floodplain interaction. The density of seed germination and survival of young trees is predicated on periodic (Strahan, 1981) or spatially-controlled low flows, emphasizing the importance of the natural flood regime's inherent variability.

The flood-surface water forcing of the channel-floodplain interaction is a prominent, and perhaps dominant, but isolated physical component of the riparian system. The spatial variability of floodplain environments is owed to the specific substrate material and the developing species composition, as well as flood inundation characteristics (Schnitzler, 1997). However, seasonal flooding is the integrating component of a floodplain ecology, providing the necessary material, creating a spatially varying disturbance, and prescribing an aqueous boundary in space and time within which the restoration of a floodplain ecology is possible. As such, the understanding of the magnitude, frequency, and duration of flood inundation is an elementary component of the characterization of pre- and post-development riparian systems.

As described previously, and in several references (Katibah, 1981), the anthropogenic modifications to the Central Valley floodplains, riparian systems, and surface and groundwater hydrology, are numerous and severe in their consequence. In addition to the hydrologic modification, channelization, levee building, and floodplain infringement have separated the streams and their floodplains, altering the frequency, duration and extent of inundation, and eliminating any channel-floodplain interactions in many areas. This process is in some places irreversible, as channelized rivers have incised their bed to a degree that cannot be easily remedied (Vick et al., 1997). Elsewhere, the inundation patterns provided by the modified floodplain support elements of floodplain forests along with an agricultural component; however, increasing levee repair costs, and flood damages to larger urban areas, make this system a precarious one.

Recent Flows on the Cosumnes River

The flow hydrographs for the recent five-year period (1996-2000) for the Cosumnes River at Michigan Bar, have been analyzed to investigate the modern flow regime prior to the modeling effort. Average daily flows were used for this analysis to eliminate the need for data manipulation, outlier removal and gap filling, while allowing a full seasonal analysis to be completed. The January-April season was selected, except for the 1997 flood season, which had appreciable flows in December of 1996, which were included in the analysis.

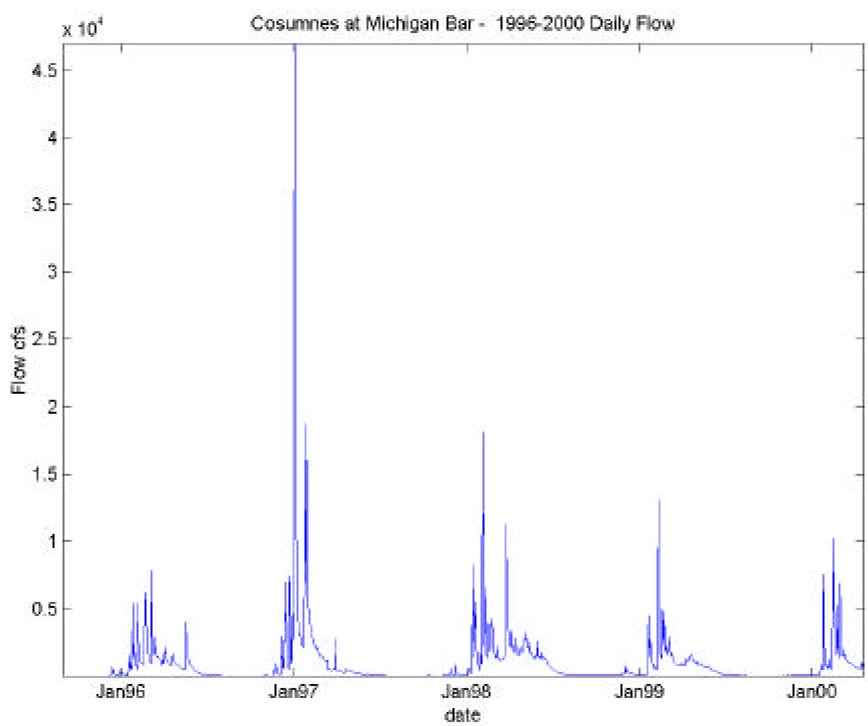


Figure 8a. Daily Flows on the Cosumnes River, 1996-2000

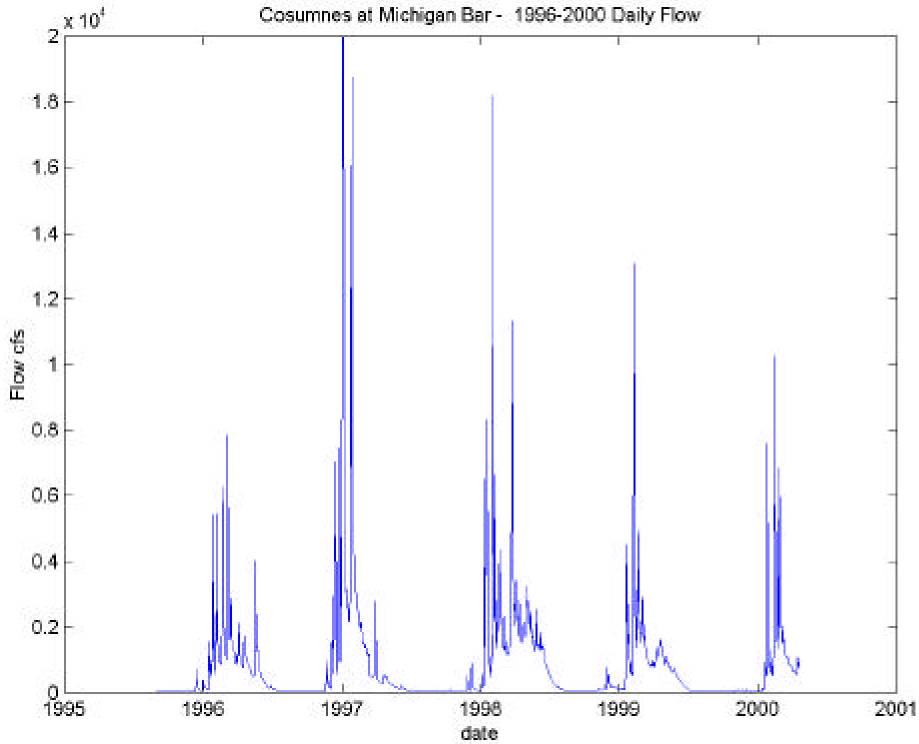


Figure 8b. Daily Flows on the Cosumnes River, Concentrating on Flows Below 20,000 cfs, 1996-2000.

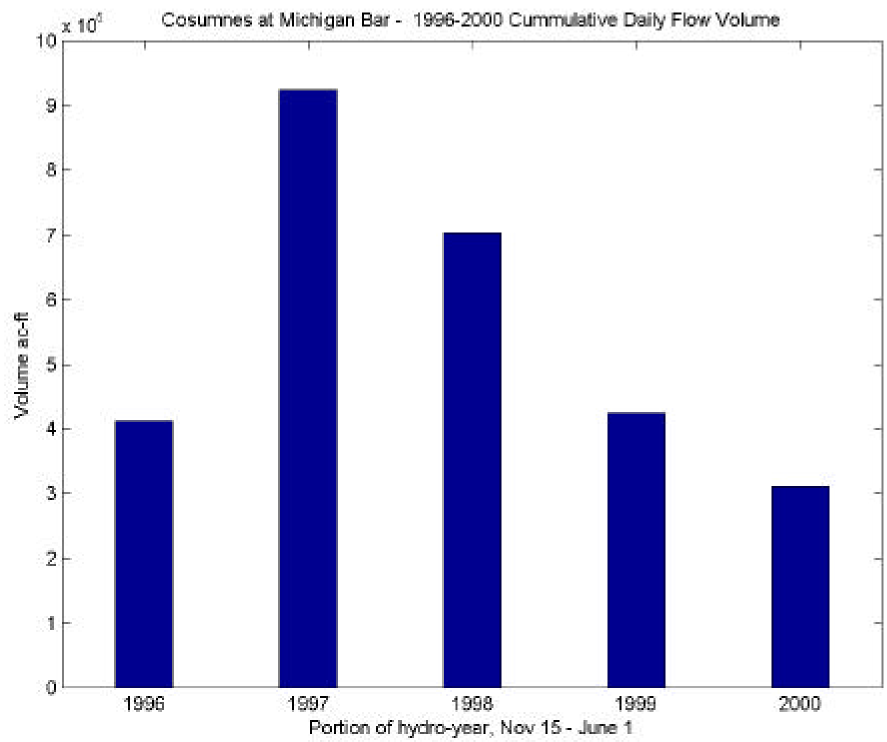


Figure 9. Cosumnes River Flow Volumes, 1996-2000

Table 4. Cosumnes River Peak and Volumetric Flow Statistics, 1996-2000

	1996	1997	1998	1999	2000
Peak Flow[1] (Daily)	7,850	46,958	18,189	13,097	10,240
Peak Flow[2] (instantaneous)	10,736	93,000	37,772	22,036	11,791
Peaks of Significance[3]	5	5	9	4	4
Return Period[4]	2+	150	10+	5	2+
Total Volume[5]	412,850	924,810	703,520	425,220	311,680

Data from record at Michigan Bar

1. Peak flow in cfs, from daily record.
2. Peak flow in cfs, from instantaneous record.
3. Peak flows above 3000 cfs daily average flow, representing sustained flood flows.
4. Return period from USGS relationship (Guay et al., 1998), based on peak instantaneous flow.
5. Total seasonal volume in acre-feet, from average daily flows.
6. Total seasonal volume in acre-feet, from instantaneous flows.

The time series plot for the five seasons [Figure 8a] shows the extrema common to the Cosumnes River. The form of the daily averaged hydrograph is more observable in the flows under 20,000 cfs [Figure 8b].

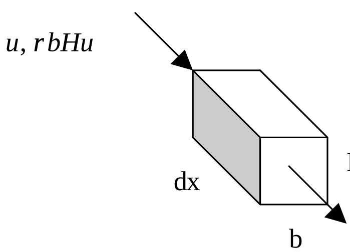
The peak flows, both instantaneous and daily, the corresponding return periods, and the number of significant peaks are displayed in Table 4. In addition to the peak flows, the seasonal flow volumes provide an accumulated statistic on the inter-year variability, and have been calculated from the daily average flows [Table 4, Figure 9]. Within the 1996-2000 period, the Cosumnes basin produced one storm in excess of a 100 year return period, estimated by the USGS as a 150 year event, in January 1997. A ten year storm occurred in 1998, with a five year and several two year events filling out the period of analysis. This variability provides a wide range of flow conditions for descriptive modeling of the Cosumnes River hydrodynamics.

Technical Background: One Dimensional Unsteady Flow Routing

The St. Venant equations form the basis for the one-dimensional representation of open channel hydraulics, relying on several key assumptions to form a simple yet descriptive model for hydraulic routing. These assumptions, as given by the Danish Hydraulic Institute (Danish Hydraulic Institute, 1995) are as follows:

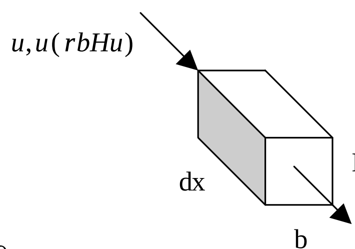
1) nearly horizontal and unidirectional flow, allowing vertical and lateral velocities to be ignored, and the use of a hydrostatic pressure distribution;
2) the flow is subcritical;
3) the fluid is both incompressible and without significant density gradients.

Employing the first and second assumptions, and neglecting lateral inflows, wind shear, groundwater connections, and velocity and momentum distribution corrections, the derivation of the conservation of mass and momentum equations can proceed in a differential form, following Abbott and Minns (Abbott and Minns, 1998).



$$u+\frac{\partial u}{\partial x}dx,\ rbHu+\frac{\partial}{\partial x}(rbHu)dx$$

Mass



$$u+\frac{\partial u}{\partial x}dx, u(rbHu)+\frac{\partial}{\partial x}(rbHu^2)dx$$

Momentum

The accumulation of mass within the cell volume during time dt is given by

$$\frac{\partial}{\partial t}(rbH)dxdt$$

The net mass flux during this time is

$$\left[rbHu-\left(rbHu+\frac{\partial}{\partial x}(rbHu)dx\right)\right]dt$$
$$-\frac{\partial}{\partial x}(rbHu)dxdt$$

Equating the two provides the conservation of mass equation, which leads to the one-dimensional continuity equation with the assumption of incompressibility.

$$\frac{\partial}{\partial t}(rbH)dxdt = -\frac{\partial}{\partial x}(rbHu)dxdt$$

$$\frac{\partial}{\partial t}(bH) + \frac{\partial}{\partial x}(bHu) = 0$$

The conservation of momentum follows similarly, except the time rate of change quantity and the net flux of momentum are equal in sum to the net impulse exerted on the cell. This requires inclusion of pressure forces, bed slope reaction forces, changing cross section (expansion and contraction) reaction forces, as well as shear at the wetted perimeter. Considering only the fluid pressure forces for clarity, equating the temporal change and advection of momentum with the resultant pressure impulse during time dt

$$\frac{\partial}{\partial t}(rbHu)dxdt + \frac{\partial}{\partial x}(rbHu^2)dxdt = F_R dt$$

$$F_R = \frac{1}{2}(rgH)Hb - \left[\frac{1}{2}(rgH)Hb + \frac{\partial}{\partial x}\left(\frac{1}{2}(rgH)Hb\right)dx\right] = -\frac{\partial}{\partial x}\left(\frac{1}{2}(rgH)Hb\right)dx$$

$$\frac{\partial}{\partial t}(rbHu)dxdt + \frac{\partial}{\partial x}(rbHu^2)dxdt = -\frac{\partial}{\partial x}\left(\frac{1}{2}(rgH^2b)\right)dxdt$$

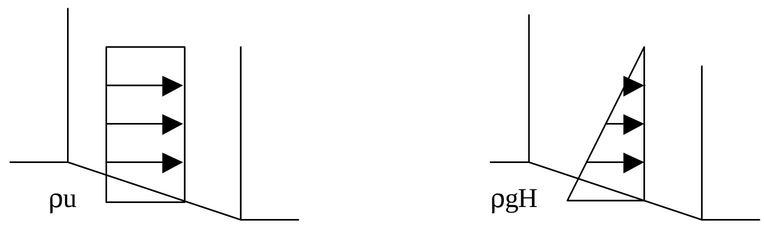
Regrouping with the incompressible fluid assumption reveals the conservative form of the conservation of momentum equation for horizontal channels with inviscid, incompressible flow.

$$\frac{\partial}{\partial t}(bHu) + \frac{\partial}{\partial x}(bHu^2 + \frac{1}{2}gH^2b) = 0$$

For small bed slopes (described as less than 1:1000 by Abbott and Minns (Abbott and Minns, 1998)), the inclusion of the driving bed slope impulse term is achieved by separating the components of the fluid cells weight ($F_w = \rho gH$) into vertical and horizontal components. Using the $\sin\theta = \theta$ convention for small angles the bed slope impulse term, for bed slope I, becomes

$$F_R dt = -rg \cdot Hbdx \cdot I \cdot dt$$

Channel contractions and expansions in the cross-stream direction exert wall pressure effects on the flowing fluid, with both dynamic momentum and hydrostatic components. Their representation is similar to that for the bed slope reaction force, except that the reaction force is integrated over the depth to sum the effect of the full wall depth on the flow. Since the terms are written in the total width derivative, the effects from each sidewall are combined in one term, for both the momentum and hydrostatic component.



Dynamic Momentum Component Hydrostatic Component

Figure 10a and 10b. Hydraulic Forces at Wall

$$F_{R1}dt = ruH\frac{\partial b}{\partial x}dxdt$$

$$F_{R2}dt = \frac{1}{2}\,rgH^2\,\frac{\partial b}{\partial x}\,dxdt$$

The net impulse term for varying channel width, a small bed slope driving the flow, and a hydrostatic pressure distribution is then

$$F_R dt = -\frac{\partial}{\partial x}\left(\frac{1}{2}\,rgH^2 b\right)dxdt - rgHbIdxdt + ruH\frac{\partial b}{\partial x}dxdt + \frac{1}{2}\,rgH^2\,\frac{\partial b}{\partial x}\,dxdt$$

Inserting into the momentum conservation equation

$$\frac{\partial}{\partial t}(rbHu)dxdt + \frac{\partial}{\partial x}(rbHu^2)dxdt = -\frac{\partial}{\partial x}\left(\frac{1}{2}\,rgH^2 b\right)dxdt - rgHbIdxdt + ruH\frac{\partial b}{\partial x}dxdt + \frac{1}{2}\,rgH^2\,\frac{\partial b}{\partial x}dxdt$$

$$\frac{\partial}{\partial t}(rbHu) + \frac{\partial}{\partial x}(rbHu^2) = -\frac{\partial}{\partial x}\left(\frac{1}{2}\,rgH^2 b\right) - rgHbI + ruH\frac{\partial b}{\partial x} + \frac{1}{2}\,rgH^2\,\frac{\partial b}{\partial x}$$

$$\frac{\partial}{\partial t}(rbHu) + \frac{\partial}{\partial x}(rbHu^2) = -\frac{b}{2}\frac{\partial}{\partial x}\left(\frac{1}{2}\,rgH^2\right) - rgHbI + ruH\frac{\partial b}{\partial x}$$

Using the water level instead of the depth in the water surface gradient term

$$\frac{\partial h}{\partial x} = I + \frac{\partial H}{\partial x}$$

$$\begin{aligned}\frac{\partial}{\partial t}(rbHu) + \frac{\partial}{\partial x}(rbHu^2) &= -rgHb\frac{\partial H}{\partial x} - rgHbI + ruH\frac{\partial b}{\partial x}\\ &= -rgHb\left(\frac{\partial h}{\partial x} - I\right) - rgHbI + ruH\frac{\partial b}{\partial x}\\ &= -rgHb\frac{\partial h}{\partial x} + ruH\frac{\partial b}{\partial x}\end{aligned}$$

The assumption of incompressible flow, and extending the premise of a hydrostatic fluid pressure to the wall reactions allows simplification to

$$\frac{\partial}{\partial t}(bHu)+\frac{\partial}{\partial x}(bHu^2)=-gHb\frac{\partial h}{\partial x}$$

The nature of the internal resistance of a turbulent fluid is poorly represented in a one-dimensional model. The mechanism of flow resistance, the associated free surface effects, and the propagation of momentum throughout the depth of flow to the bottom boundary is encapsulated within the flow resistance term (Abbott and Minns, 1998). The physically-based derivation from the integration of the shallow water equations reveals the additional resistance approximations in the effects of averaging the friction term (Liggett, 1993). The resistance at a boundary is usually modeled with an analogy to steady uniform flow, in which the resistance and driving gravitational impulse are in equilibrium. This simple relationship of the form $Q=KS_f$ is used to back-calculate the resistance slope S_f , a symbolic slope that drives a flow resisting force. This final term completes the momentum equation, for dynamic unsteady flow driven by a small bed slope in non-prismatic channels.

$$\frac{\partial}{\partial t}(bHu)+\frac{\partial}{\partial x}(bHu^2)=-gHb\frac{\partial h}{\partial x}-gHbS_f$$

For the application of this system of the St. Venant equations to natural channels, the equation can be piece-wise integrated over the transverse direction, and the conversion of the width and depth variables to areal functions of height provides a convenient representation for calculation. Additionally, the incorporation of a storage width, b_s, in the continuity equation allows a kinematic accounting of off-channel storage.

$$\frac{\partial A}{\partial t}=b_s\frac{\partial h}{\partial t}$$

$$\frac{\partial}{\partial t}(A)+\frac{\partial}{\partial x}(Au)=0$$

$$b_s\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0$$

$$\frac{\partial}{\partial t}(bHu)+\frac{\partial}{\partial x}(bHu^2)=-gHb\frac{\partial h}{\partial x}-gHbS_f$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)=-gA\frac{\partial h}{\partial x}-gAS_f+\frac{Q}{b}\frac{\partial b}{\partial x}$$

The solution of the St. Venant equations requires a numeric approximation with a suitably accurate algorithm. The techniques for this procedure are numerous and well developed, for both general application and the specific formulation of discontinuous phenomena, irregular grids, long term simulations, and coupling with transport. The model selected for this study is the MIKE11 model of the Danish Hydraulic Institute, a comprehensive modeling platform for the simulation of unsteady open channel hydraulics, transport, and floodplain analysis. The Abbott-Ionescu solution algorithm employed is an implicit finite difference procedure, determined to be both unconditionally stable and accurate for the Courant-Frederich-Levy (CFL) criteria (Danish Hydraulic Institute, 1995). This facility allows the use of varying spatial discretization and model input, and a numerically efficient solution of the resulting two tri-diagonal coefficient matrices (Abbott and Ionescu, 1967).

The template for this procedure is based on a staggered 6-point grid of h (water surface elevation) and Q (streamflow) points [Figure 11]. At the h points the time-averaged, space-centered continuity equation is solved. The momentum equation is centered on the Q points and is also time averaged and space centered. The time averaging is accomplished by iterating with a minimum of two calculations, which is deemed sufficient for "reasonably smooth data and representative Δx" (Abbott and Ionescu, 1967). The scheme provides second order accurate space and time derivatives, and first order approximation of the variable coefficients (since they are without derivatives), prescribing an overall accuracy limited by the coefficient truncation error (Abbott and Ionescu, 1967). Abbot and Minns also show this truncation error to be minimized to allow an approximate, overall second order accuracy using linearized homogenous operators (Abbott and Minns, 1998). Central to this derivation are the time and space weighting factors of the coefficient matrices, which may also provide a mechanism for the generation of instabilities with sparse data.

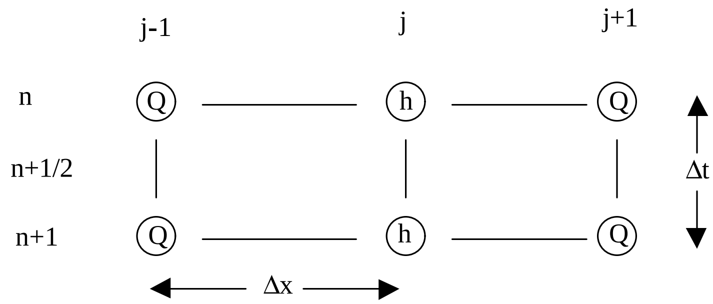


Figure 11a. Staggered Q-point Computational Template
Figure 11b. Staggered h-point Computational Template (obtained by exchanging Q and h)

The treatment of boundary conditions in the finite differencing of the St. Venant equations provides an integral component of computational hydraulic procedures. In addition to the upstream and downstream boundaries, which describe the boundaries of the computation, the joining of channels requires a compatibility condition, extraneous to the St.Venant equations themselves. For this reason, these locations are determined to be "interior boundary conditions", and provide a means of linking the branches hydraulically described by the St. Venant system, in tributary, distributary, or looped configurations. Algebraically, confluences require six equations in the six unknowns for a closed system. In a staggered grid this is done with a technique for the solution of a water surface compatibility and continuity condition in conjunction with the St. Venant equations across the main channel reach. By forcing a Q point at the branch termination, and intersecting the main channel at an h point, an algorithm can be developed for the linked solution of the St.Venant described channels. This provides six equations (2 Saint Venant momentum, 1 Saint Venant continuity with source, 1 junction continuity, 2 water surface compatibility) in six unknowns (Q at two locations on main branch, and one location on tributary, h at main branch (upstream and downstream of tributary and tributary endpoint), introducing only the momentum error of the tributary, and the dQ/dx error as it relates to the continuity at the junction. The prescription of a stage-discharge relationship at a single node presents a conceptual and algorithmic difficulty for a staggered scheme, and various solution techniques have been utilized (Khatibi, 1999). Additionally, the lack of detailed channel and floodplain geometry, the particular interpolation assumptions, and unstable initial conditions can combine to create uncontrolled oscillations. The degree of discretization required to resolve complex channel-floodplain interactions adds to the opportunity for the creation of these instabilities, as the number and locations of channel-floodplain connections may not be physically based at certain model scales.

The representation of the channel floodplain interactions at basin and subbasin scales is the key component of one-dimensional distributed hydraulic modeling. This classification is separate from the domain of multi-dimensional modeling, which commonly occupies the reach scale, and that of hydrologic modeling, which often maintains a much longer time scale than that required for tidal and short period wave resolution. Numerous techniques have been devised for the configuration of one-dimensional numeric models in a quasi-two-dimensional manner, with varying results depending on the particular details of the physical system and the requirements of the modeling application. The methods of quantifying the effect of floodplain storage and conveyance on the aggregate channel-floodplain system can be classified according to two basic criteria: the planform discretization of channels as a function of spatial scale and function; and the modification of the means of hydraulic communication between these discretized channels.

Under the first criteria, planform classification of discretization methods, the spatial scale employed in modeling will dictate the degree of realism required of the model network. A coarse representation of the overall network may provide useful answers to a downstream concern, while issues within the floodplain may require a more in depth description. The functional form of the first classification includes a distinction between the types of one-dimensional channels used in the model: lumped channel-floodplain studies are often employed for steady flow analyses, since a description of time lags for transport via channels and floodplains is not included in such studies. Separate channel and floodplain elements allow a varying lateral velocity, and storage and drainage periods.

The second classification of discretization methods involves a modification of the mathematical connection between types of channels. The default connectivity is of course the St. Venant equations, with variations employed for all tributary inflows, channel bifurcations, structures, and boundaries. At these locations, some additional knowledge is inserted in the form of a constitutive relationship, connecting the independent variables across the structure or channel discontinuity. Generally these equations follow the form of a Q-h or h-Q-h, or Q-t relationship (Danish Hydraulic Institute, 1997). Several variations of this methodology are employed for floodplain channel connections, including structures, link channels, which are essentially elongated structures employing a h-Q-h relationship, and modifications to the St. Venant system of equations through additional width and storage terms.

Presentation and examples of these various methods are described in numerous references , and have been employed for over forty years in varying degrees of accuracy, resolution, and physical justification. The increased capability of unsteady and multi-dimensional modeling has allowed more accurate and physically-based solutions to the runoff and routing of flood hydrographs. Concurrent advance in computing and numerical techniques have enabled the efficient solution of complex and highly resolved hydraulic systems, and provided an opportunity for the numerical investigation of not only channel processes, but also the links between river channels, their floodplains, and their termination within estuarine and coastal regimes.

Often the nature of such riverine systems lends itself to a one-dimensional description, with floodplains described within a one-dimensional framework, or as discrete sub-models with a multi-dimensional formulation. As such, the one-dimensional model remains a viable and necessary component of the computational gradient between basin and reach scales.

The utility of one-dimensional hydraulic modeling has been extended by integration of geographic information systems (GIS) and fully dynamic unsteady flow simulations. This most significantly allows the mapping of hydraulic simulation results onto a Digital Terrain Model (DTM), specifically a gridded Digital Elevation Model (DEM), through an interpolation of water surface elevations based on an estimate of the channel floodplain connectivity. As a result, time series of inundation and flood statistics can be determined anywhere within the modeling and hydro-domain. This is an example of a closely coupled Hydraulic-GIS approach, via an extension of the classification by Sui and Maggio to the field of hydraulic modeling (Sui and Maggio, 1999). Additional features of the linked GIS include area-elevation data extraction, cross section and profile determination, and DTM feature modification, to increase the accuracy of the water surface interpolations. It is noted, however, that the coupling of one-dimensional modeling with the core functionality of a GIS is merely a convenience and computational aid in extending the one-dimensional assumption to two dimensions, and does not provide an increased dimensionality to the solution.

<u>Definition of variables used in this section</u>

x	longitudinal stream direction
y	transverse stream direction
u	longitudinal stream velocity
Q	stream volumetric flow rate
t	time
ñ	fluid density
g	acceleration of gravity constant
b	stream width (y direction)
b_s	storage width
H	stream depth (z direction)
A	stream cross sectional area (in y-z plane)
F_W	driving force due to fluid weight
F_R	resultant force
I	stream bed slope
è	angle between stream bed with horizontal
S_f	resistance, or friction, slope

III METHODS

The development and application of the one-dimensional unsteady hydraulic model for the Cosumnes River, its tributaries, and the North Delta was performed using MIKE11. This program is the principle component of a comprehensive river modeling system developed by the Danish Hydrologic Institute, and has been used extensively for the simulation of hydraulics, water quality and sediment transport for branched and looped systems of channels and floodplains. The procedures employed in obtaining, processing, constructing, and operating the model are described in the following sections.

Boundary Condition Development

The amount of information on the inflows to the North Delta has increased in quantity, and improved in resolution and accuracy in recent years. The USGS operation of an ultrasonic velocity measurement (UVM) system on the Sacramento has recorded the inflows from the Sacramento River and its tributaries since 1987. The configuration of the system allows for a determination of the flows down Georgiana Slough, as well as the mainstem Sacramento, for periods when the Delta Cross Channel gates are closed. Numerous stage gauges within the delta, primarily operated by the California DWR, record water surface elevations at 15 minute increments, describing the pulsing of flood flows and the tidal response of the delta. The direct tributaries to the North Delta, namely the Mokelumne River, Cosumnes River, and Dry Creek have been gauged for nearly a century, providing a long-term record of flood patterns. The Cosumnes River has several gauges on the upper tributary forks operated by the USGS, as well as the gauge at Michigan Bar, approximately 55 river kilometers upstream of its confluence with the Mokelumne River. The Michigan Bar location was used for sediment monitoring in the 1950-60’s. The California DWR also operates the water surface elevation gauge on the Cosumnes River at McConnell (Highway 99), the crossing with State Route 99, formerly a USGS stage and flow gauge, as well as a sediment monitoring station in the 1950-60’s.

The EBMUD operates several gauges on the Mokelumne River, downstream of Comanche Dam. These locations are near the dam at Victor and at Woodbridge. The Woodbridge flow gauge is located downstream of the Woodbridge diversion dam, and so provides an indicator of delta inflow. Since the closure of Comanche Dam, the peak flows at this point have been limited to approximately 5000 cfs. A gauge of importance in the upper Mokelumne River basin is the flow gauge at Mokelumne Hill, which includes all of the major Mokelumne tributaries, and is located above the major storage projects, providing a long-term indication of the basin's runoff characteristics.

The Dry Creek at Galt gauge has been operated by the USGS from 1927 to the present. Currently it is only used for low flow measurements (Robert Meyer, personal communication), but as recently as 1996-1997 it was operated by the USGS for flood flows (period of record 7/12/1996 – 12/8/1997), recording the complete stage hydrograph of the near record stage occurring in January of 1997.

The County of Sacramento began the automated monitoring water surface elevations in the southern county streams in 1996, in order to provide a flood warning system. With increasing data recording, this has become an important source of information about tributary inflow to the delta, and fills some gaps in the monitoring efforts of other agencies. Significantly for the Cosumnes River system, Sacramento County records water surface elevations on Deer Creek (at Wilton Road and Scott Road), on the Cosumnes River (Wilton Road and Highway 99), and on Snodgrass Slough (at Lambert Road), along with several other locations.

Cross Section Attainment

The cross sections utilized in this study were assembled from a number of sources, and are listed in Appendix A. These data have been assembled in a spatial database. The data have been datum checked to correspond to the project datum National Geodetic Vertical Datum of 1929 (NGVD 29), and is detailed in the following descriptions.

The California DWR has compiled channel cross sections in the North Delta dating from the early 1900's, and is committed to continuing to acquiring up-to-date channel information in support of the Department's modeling efforts (http://www.iep.ca.gov). The DWR has developed a cross section display and output program (CSDP) written in JAVA, which is publicly available. In an effort to establish a common ground for study with developments in the North Delta, and facilitate the timely incorporation of new cross section information in the modeling database, this program has been used to export the required cross sections.

The second source of channel information is the USGS channel capacity report for the Mokelumne River (Simpson, 1972). This report details a hydraulic study to determine the backwater and post closure effects on the downstream hydraulics of Comanche Dam. This information is dated, but currently is the most recent available for the lower Mokelumne River. The cross sections were digitized from the original report, datum-corrected and converted to MIKE11 input format using a Matlab script. The report indicates a mean sea-level datum of 1929, incorporating the 1960 adjustment.

Additional channel information is available from the EBMUD for the Mokelumne River between Comanche Dam and the Woodbridge Diversion Dam. These data are in the form of two-foot contour interval topography for the land surface above a low flow water surface, approximately 200 cfs, and extends from Comanche Dam to a point 1.5 miles below Lower Sacramento Road. The data set is available from the Information Center for the Environment (http://www.ice.ucdavis.edu). This channel and floodplain information has not been incorporated into the hydraulic model at this time.

The Cosumnes River was extensively surveyed between Highway 99 at McConnell and Dillard Road USGS, resulting in 60 cross sections of the main and overflow channels of the Cosumnes, Deer Creek, and portions of their shared floodplain. The cross sections and the peak flows, water surfaces, and steady flood hydraulics are detailed in the USGS Open-File report 98-283 (Guay et al., 1998). The vertical datum used for the cross section information is mean sea level, described as the NGVD 29. These data have been incorporated into the modeling, using digitized coordinates and cross section data obtained from the USGS. The USGS also monitors the cross section at Michigan Bar in support of the flow calculations at the gauging station. A typical cross section has been obtained from the USGS field station and is utilized at the model boundary.

The existence of historic cross sections surveyed by the USACE on the Cosumnes River was documented in a report on the flood regime of the Cosumnes River (Vick et al., 1997). In 1957 the USACE surveyed 27 cross sections on the Cosumnes River between the Mokelumne River and a point upstream of Highway 16. Philip Williams and Associates (PWA) re-occupied eight of these locations in 1996, noting significant degradation of the channel profile since 1957, ranging from 2 to 10 feet and increasing upstream. PWA also surveyed two additional cross sections at bridge locations and an intervening location. These cross sections are available in the technical appendix (Vick et al., 1997) with the elevation datum of these sections reported as NGVD 29. These cross sections have been entered in from the HEC-2 model data sheets, and digitized when necessary.

Mitch Swanson and Associates surveyed six cross sections between Interstate 5 and Twin Cities Road (Swanson and Hart, 1994). The local benchmark for these sections was a foundation pad on a building near Twin Cities Road, and the cross sections were not field-monumented (Mitch Swanson, personal communication). These cross sections were reported to NGVD 29 datum in the PWA report (Vick et al., 1997), and input from this source.

Six channel cross sections were surveyed on the Cosumnes River, monumented, and tied into a National Geodetic Survey (NGS) benchmark located on Thornton Road, as part of a UC Davis, Department of Geology study of the river and floodplain geomorphology. These cross sections are located on the Cosumnes River Preserve and provide a basis for the detailed hydraulic modeling in this report.

Bridge cross sections have been obtained at relevant locations where channel and flood plain constriction plays a significant role in the overall system hydraulics, and as means of filling in gaps in cross section information. These cross sections originated from California Department of Transportation (Caltrans) bridge inspection surveys catalogued in the BIRIS system of the Structures and Maintenance Division, and from the original bridge plans archived at the Sacramento and San Joaquin County Transportation Departments. These sections were digitized and datum corrected to NGVD 29, where possible. Often a lack of datum information for the sources required the use of the existing assumption of local mean sea level as the datum.

Continuing work at UC Davis by the Department of Geology will provide additional cross sections between the Cosumnes River Preserve and Highway 99, and can be incorporated into this modeling effort when available. These locations are likely to be helpful, as model geometry is limited in the lower reaches of the Cosumnes River and its tributaries.

Within the focus areas, a refined grid was employed to check the calculations of the area–elevation curves, and to provide cross sections for hydraulic modeling. Data sources for this effort are the USGS 10 meter DEM, the Nation Oceanic Survey (NOS) Light Detection and Ranging (LIDAR) data (see Appendix C) for the upper mainstem Cosumnes floodplain, the USGS Open File Report 98-283 cross sections for the upper floodplain, cross sections surveyed by PWA, cross sections surveyed by UC Davis Department of Geology and the Center for Watershed Studies, and the floodplain topography located on the lower "triangular floodplain" and the floodplain between Woodduck Slough and the Cosumnes River, surveyed by Northwest Hydraulics, Inc. A subset of this data was used to create a three dimensional representation of the Cosumnes-Deer Creek floodplain, from which cross sections for the Cosumnes River, Deer Creek, Cosumnes Bypass Channel, Cosumnes Overflow Channel, and the various floodplain links were extracted. By using an automated technique for this task, a focus of effort could be given to the accurate discretization of the floodplain system.

Another approach to the surface model of this floodplain would be to obtain the Digital Line Graph (DLG) representation of the floodplain, and create a digital terrain model directly from this source, avoiding the re-sampling required for creation of the gridded DEM. This spatial information is not yet available through the

USGS, although third party providers may be a viable source. The DLG data can be used to create a 5-meter grid for the selected study area, with the available cross sections defining the course and elevation of the river channels, and break lines added to improve the interpolation performance. The 5-meter LIDAR grid can be easily superimposed on the composite 5-meter grid to incorporate the increased vertical resolution data available. Additionally, as higher resolution and accuracy data becomes available, it can be incrementally added to the surface model characterization of the floodplain. Portions of this work have been completed, as allowed by available topographic data, and are described in Appendix C.

A byproduct of this processing is that elevation data from a variety of sources are available for comparison to the LIDAR data, in order to assess its utility in floodplain modeling. This analysis is described further in Appendix C.

Model Discretization

The analysis of the unsteady floodplain inundation and conveyance on the Cosumnes River began with a simplistic description of the main tributaries and an approximation of a floodplain at the Cosumnes River Preserve. As expected the difficulties in modeling this system are found in describing the evolution in time of the channel–floodplain interactions. A variety of procedures have been attempted to make this description as accurate and efficient as possible with the data available. Due to the cellular configuration of the Cosumnes River floodplain in the vicinity of the Cosumnes River Preserve, the spatial scale of discretization is effectively fixed, in order to describe flows inundating and draining each of the cells. The selected method for numerical representation of the floodplains, providing a stable solution for a range of flows, is achieved through the use of link channels, which convey the water between conventional channels based on an h-Q-h relationship. Sensitivity to this relationship it constrained through successive approximations, to reproduce observed flow patterns on and off the floodplain.

The current flow patterns of the Cosumnes River Preserve floodplain is predominantly a function of the location of natural and artificial channels and sloughs, roadways, railways, and embankments crossing the historic floodplain, and the location of weirs and breaches. As such, compiling an accurate spatial representation of these elements is a critical step in properly developing a discretization of the system. The accompanying map [Figure 12] shows the locations of the major elements defining the floodplain. The net effect is to divide the floodplain into a series of cells, which fill and drain through intentional and natural breaches, and occasionally through overtopping, especially on the lower Preserve, where flood depths reach between 6 and 20 feet (Swanson and Hart, 1994). Also indicated are the primary mechanisms for the transfer of surface waters during a flood, as currently understood. This conceptualization is an initial attempt at understanding the system, and is likely to evolve as field observations, measurements, and modeling work continues.

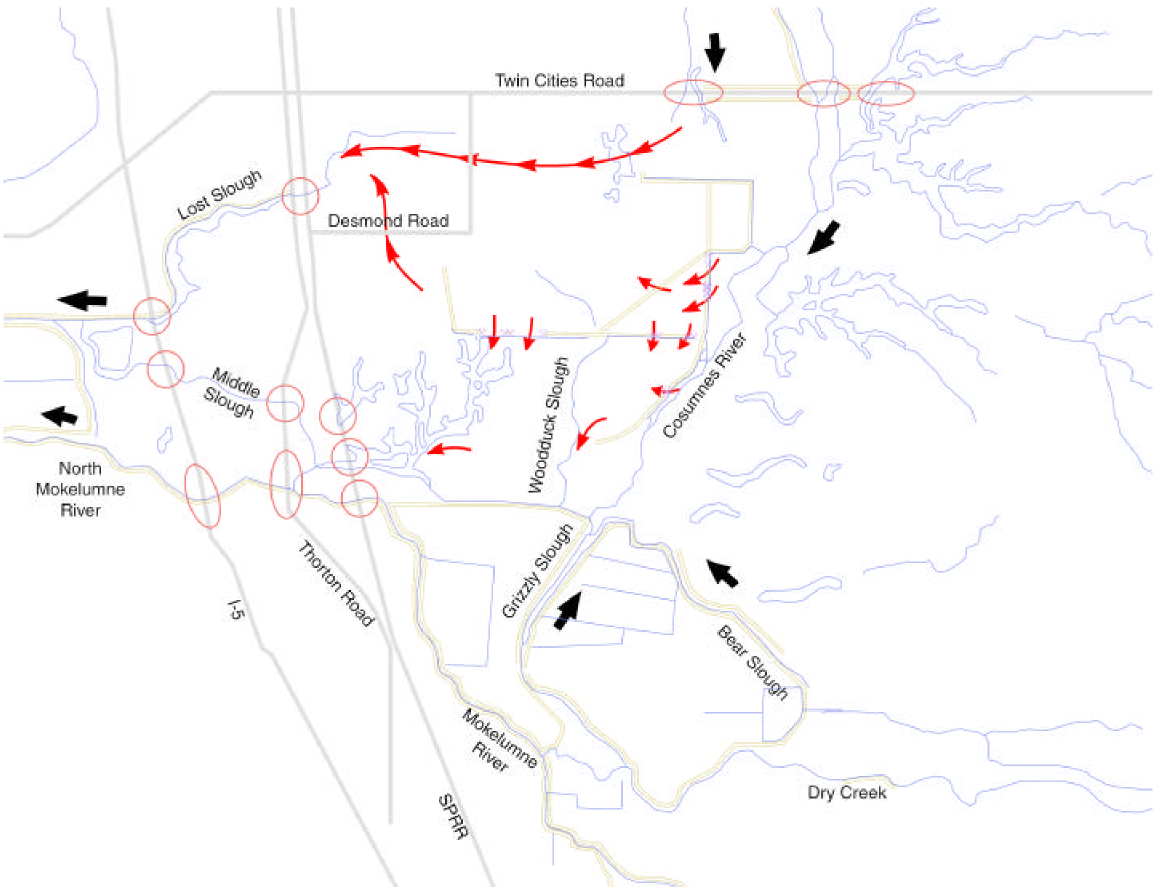


Figure 12. Floodplain Features and Observed Flow Mechanisms on the Cosumnes River Preserve
Heavy arrows indicate significant channel flows, light arrows show possible location of flooding and draining mechanisms, and circles represent locations with openings in flow confining structures, such as bridges and embankments.

The pattern of floodplain cells on a portion of the Cosumnes River Preserve is shown in Figure 13. The available floodplain geometry for much of the modeling domain is limited to the 10 meter DEM. For this reason, and to describe the function of the lower floodplains as level pool systems, an area-elevation description is used for these areas. These descriptions have been extracted from the DEM using an automated script for this purpose, and is included in Appendix A for reference.

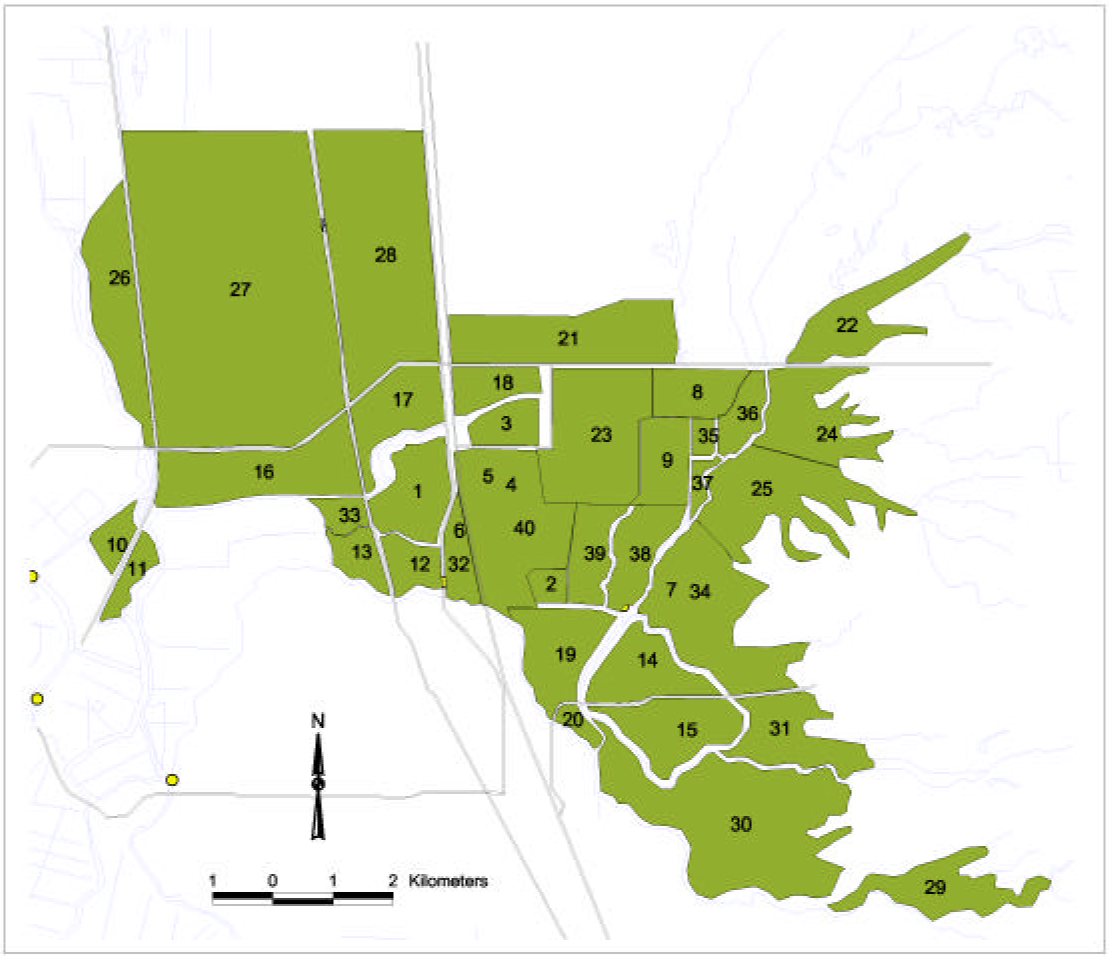


Figure 13. Location of Floodplain Cells Near the Cosumnes River Preserve
Map follows locations of roads, embankment and levees, and extends up to the limits of the 1986 and 1997 delta specific flooding, as obtained from the California Department of Water Resources digital maps.

The major North Delta tributaries included in the model along with the Cosumnes River are the Mokelumne River and Dry Creek. Although the Dry Creek boundary is not available for hydrodynamic modeling at this time, the tributary has been included for sensitivity testing and simulation. Flow boundaries are located at Michigan Bar on the Cosumnes River, Woodbridge on the Mokelumne River, Galt on Deer Creek, and the Sacramento Ultrasonic Velocity Meter (UVM) at the upstream location at the Delta Cross Channel. Upstream stage boundaries are employed at Deer Creek at Wilton Road and the Lambert Road at Snodgrass Slough. Downstream boundaries are located at the Mokelumne River at Georgiana Slough, Little Potato Slough, and the downstream UVM on the Sacramento River at the Delta Cross Channel. These locations allow the flow subtraction at the USGS UVM gauges to be used to force Georgiana Slough, and hence provide a realistic southern boundary at the Mokelumne, incorporating flows from both forks of the Mokelumne, Georgiana Slough, and Little Potato Slough. Other tributaries and dead end sloughs are included for accurate tidal exchange representation, and to represent the expected backwater effect during floods. These representations are accomplished by inserting a zero flow boundary condition at the minor tributaries' upper limit.

For the simulation of historic hydrology, from 1996-2000, data are generally available for 1996, 1998, 1999, and 2000, as described in Appendix B. Specific limitations include the lack of Snodgrass Slough and Deer Creek boundaries for 1996, and the Sacramento River boundaries for 2000, which were not yet publicly available from the USGS UVM program. The 1997 flood year was not attempted due to the lack of boundary data, as well as the extent of flooding from the record flows on Cosumnes River at many locations. The effect of dynamic breeches during the flood, and the importance of non-channel conveyance (for example, Twin Cities Road under I-5 (U.S. Army Corps of Engineers, 1999)), present a number of difficulties for an accurate flood description.

The accuracy and stability of the numerical model is defined by the spatial and temporal discretization of its components. This observation in practice conflicts somewhat with the linear stability analysis that prescribes unconditional stability, and is likely caused by the non-linearities that develop in the solution due to channel looping and inadequate or inaccurate topographic discretization. These instabilities constrain the model to operate at timesteps below that of the CFL condition. Similarly, the cross section spacing required to describe the channel complexity and channel-floodplain connectivity is also lower than would be necessary for a description of tidal or flood wave profiles on the Cosumnes River. Specifically, cross sections must be located at every channel begin and end, and at both ends of a channel intersection, in order to provide a smooth interpolation of cross section properties. This includes locations where floodplains are discretized to exit and re-enter the main channel. For this reason, cross-sections have been interpolated from nearby locations to represent geometries at these critical connection points. Representative timesteps used in the model are 10 to 30 seconds, with a maximum cross section spacing of 500 to 1000 meters.

The channel-floodplain connections in the MIKE11 model have been constructed as link channels, with a geometry equivalent to the surveyed or estimated breach opening. This has been selected as an accurate and convenient method to describe the flow through the managed, cellular floodplain. Additionally, interior cells without significant through conveyance have been included as circular loops, connected to throughflow conveying channels with one or more link channels. This seems to reproduce the filling and draining cycles observed on the floodplain, and is capable of accurately simulating the volume of the floodplain through the use of the storage elevation tables, whose extraction is described above. The resulting flow network is shown in Figure 14a, with a close up of the Preserve as Figure 14b. The depicted network utilizes over 70 branches (channels, floodplains, and links), which are catalogued in Appendix D, with length, type, and connectivity information. The network and cross sections used are similar for each simulation year, excepting 1996, which does not include the discretization of the “Corps” breach on the Cosumnes River Preserve, formed in 1997.

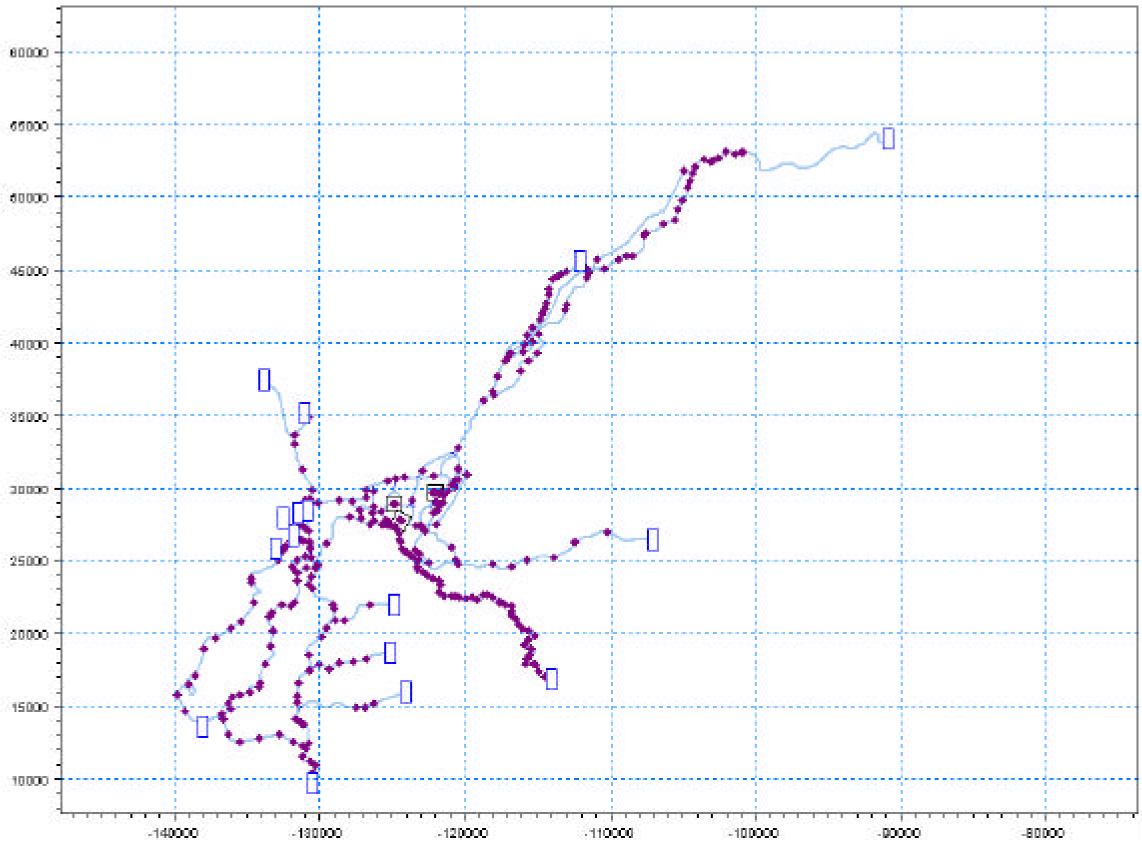


Figure 14a. Complete Model Network

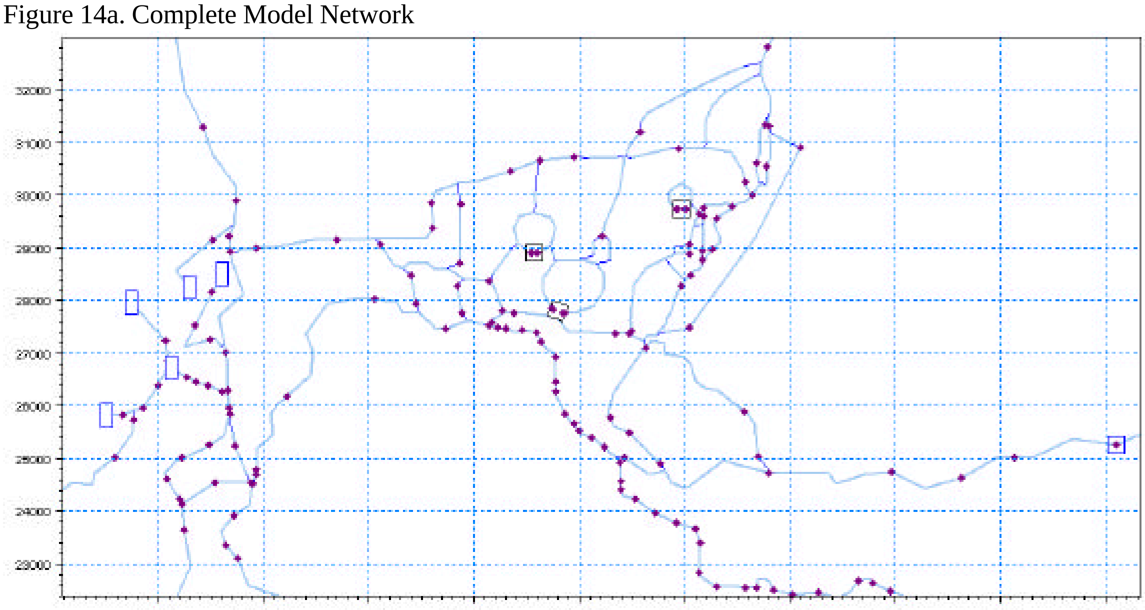


Figure 14b. Model Network Detail

Figure 14a shows the Cosumnes-North Delta model in its entirety, with channels shown as solid lines, boundaries as upright rectangles, cross sections as diamonds, and structures as squares. Figure 14b, using similar notation, shows the model in the vicinity of the Cosumnes River Preserve. Grid coordinates are in the Teale Albers projection, units of meters.

Model Operation, Calibration, and Sensitivity

The operation of the Cosumnes–North Delta hydraulic model followed an extensive period of trial and error, with regard to channel and floodplain discretization, temporal and spatial dimensions, and initial conditions. This effort has been documented to the extent possible here and in Appendix E, but several controlling factors are described here for clarity in interpreting the model results.

Controlling the interpolation procedure for interior cross sections is a critical step in providing an adequate representation of the actual channel structure. For this reason, cross sections must be placed at the endpoints of all branches, to avoid unintended extrapolation. To achieve this, the chainages at all channel endpoints should be specified as fixed, user defined chainages. This also disallows the "wandering" of boundary conditions, as interior elements of the branch are adjusted or relocated. Similarly, cross sections can be placed at the intersections of all branches, if possible, so that mismatched bed elevations can be anticipated. The current version of MIKE11 allows a forced interpolation of input cross sections at selected locations, and thus provides the modeler with a degree of control over the interpolation at channel junctions.

The method of initializing the model run is one of the most important for achieving productivity for a particular discretization. Methods of starting the simulation include hot start files, steady flow simulations, and initial condition specification. Due to the complexity and spatial extent of the model, the procedure for the determination of a starting water level can be quite complex. It was found that the use of a very small timestep obscured instabilities that were not necessarily related to initial conditions, and therefore did not lead to useful simulations after the startup period. Steady flow simulations were not found to converge, probably due to the complexity of the floodplain discretization and its solution during periods of low water. The selected approach was to allow for a linearly varying water level in the larger tributaries, for a range specified separately for each branch. A global water level for all deltaic and floodplain branches was set on the low side, to allow a filling of the channels. Fluctuations due to large water surface gradients must be avoided in order to allow the model to "feel" the boundaries, before a realistic solution is achieved. This period can be observed in some of the reported results, as an uncharacteristically high or low water surface elevation. Additional sensitivity at the boundary can be partially controlled by locating boundaries a sufficient distance from tributaries, and especially from floodplain features. The use of additional roughness at the initial cross section can also be in controlling numerical boundary-related oscillations.

The primary parameter that is required for the operation of a one-dimensional hydraulic model is the bed roughness. This parameter is commonly used as a coefficient of calibration to achieve a reasonable fit to the observed hydrograph and water surface elevations. However it is possible to obscure the effects of channel interaction and two-dimensional floodplain effects on the flow with the over utilization of the roughness parameter. Recent attempts at calibration of the California DWR Delta model (DSM2) by the Interagency Ecological Program have relied on an alternative approach. The delta and it surrounding environments have been classified into several physiographic regions, for which a uniform roughness coefficient is prescribed. Calibration follows with the variation of the roughness coefficient for the region as a whole, so that a link between a qualitative channel description and its roughness coefficient is preserved. This approach has been applied to the North Delta tributary model, as the calibration of roughness at and above the reach scale is required. Additionally, work done by the USGS on the roughness characterization of tidal sloughs in the south delta has been reviewed as a significant source for the range of roughness behaviors expected of similar channels during tidal periods. Little, however, has been done on the assessment or calibration of unsteady flow roughness factors for the vicinity during times of flood. Generally a range of Manning’s M (= 1/n) of 20-28 has been used for the channels, with higher values for floodplain roughness.

Further descriptions are possible within the selected numeric model. These would allow for depth-varying descriptions of channel roughness (a likely function for vegetated riparian zones), flow-indexed roughness to incorporate bed morphology and flood dynamics, as well as additional analysis of the relationship between channel and floodplain resistance functions. Significant advances in understanding could be chieved with the use of a detailed field-based flood study, incorporating a variety of resistance formulations.

For this work, a brief sensitivity analysis has been performed on the floodplain roughness coefficients at two key locations: on the Cosumnes River Preserve, and on the lower Cosumnes floodplain between Wilton Road and Highway 99. This analysis has not been performed to reveal interactions between factors other than bed roughness, and modeling judgment must be used for extension to general scenarios where roughness may be more or less important. Care has been taken to vary only one parameter at a time from the base case, so as to provide useful results.

The most sensitive element of the modeling of complex channel floodplain systems is likely to be the reliance on a particular schema for representing the floodplain, and for connecting the floodplain and channels. Included in this sensitivity are the floodplain volumes, link channel geometries and h-Q-h relationship, and the weir elevations used to represent locations of levee overflow. Several scenarios have been used to test this sensitivity. The elevation controls for overbank flooding have been modified within the sensitivity analysis, specifically at the locations of floodplain links, as have flood cell volumes on the Cosumnes River Preserve. This analysis will be useful in assessing the need for further topographic, bathymetric, and levee profile information, and its relative spatial importance.

IV RESULTS AND ANALYSIS

Simulation Results

A list of the simulations and corresponding information is included in Appendix E, detailing the type of run, the flood year of simulation, the maximum flow for that period, and the result files. Observation and application of the numerical results can be performed in four basic manners: observation of time series at a point, observation of animations of planform and longitudinal profiles of flow and water surface elevation for any combination of channels, observation of cross section animations of water surface elevation, and distributed flood mapping of water elevation, transcribed to depth. Several typical profiles have been included to indicate the maximum and minimum water surface elevation, and a specific value during flood for the major branches. Flood mapping has been done for a selected set of representative runs to help characterize the aggregate effect on the floodplain for the simulation years, using the most accurate results. While all of this information is useful in understanding the function of the model, an emphasis is placed on the time series information for this report. A systemic approach has been used to extract information, in order to facilitate comparison. These results are compiled in Appendix E for the selected runs.

Computational results have been cumulated at a number of key locations, which can be used to compare the performance of the model between hydrology of various years and scenarios. These locations are first the stations designated as interior boundary conditions, where the solution can be checked against measured data, namely at the Cosumnes River at McConnell (Highway 99), the Mokelumne River at Bensons Ferry, just below the Cosumnes inflow, and the South Fork of the Mokelumne River at New Hope Bridge (also known as New Hope Landing), located on the south end of Dead Horse Island (see Appendix B for map of locations).

Secondary stations for time series extraction provide information about the regional flows surrounding the preserve. These locations are the Cosumnes River channels at Twin Cities Road, Lost Slough and Middle Slough at I-5, Mokelumne River at Bensons Ferry (discharge), and the location of the historic and cut channel bends on the Cosumnes River. This last location indicates the relative splitting of flows that occur upstream of the preserve, and hence dictates the availability of water for floodplain inundation on the Cosumnes River Preserve. The next series of results extraction is used to describe the flows through specific breaches at the preserve. These are displayed as exterior breaches (including the “Corps” breach, the “triangular floodplain” breach, and the “accidental breach”) and interior breaches (namely the 4 breaches in the east-west levee of the “triangular floodplain”, also known as the “up-and down road”). See Figure 7 for breach locations and naming conventions.

An important distinction between the 1996 simulation and subsequent years is the evolution of breaching activity during 1996 and 1997, as described earlier. The model network used for the 1996 breaches assumes that the “Corps” breach has not been opened, and that the triangle breach, just to the south has also not formed. This second breach seems to have formed via levee failure at an unknown time. This allows a convenient representation of the effect of these breaches, by comparing results for 1996 with and without the breaches.

The model results for a several low flow periods of the study years 1996-2000 have been compiled for New Hope and Bensons Ferry, for comparison to the gauge data at these locations. This was done to indicate errors in boundary conditions, datums, and timing, as well as to assess the model performance without floodplain flows. The tidal flows around the Preserve exhibit ranges of 0 to 3 feet, with significant tidal fluctuations propagating up the Mokelumne River, and through Lost Slough . Reversing flows are limited to the tidal channels of the Delta, with the North and South Mokelumne showing reverse tidal flows below New Hope. The larger flows of the Sacramento do not reverse direction within the model domain, as expected, and their effect on Georgiana Slough is to force tidally-varying, non-reversing flows of between 50 to 400 m^3/s through this channel. This effect is maximized during flood scenarios, when the Delta Cross Channel gates are closed.

Improvement in the low flow performance of the model could likely be enabled with a calibration of resistance and bed configurations in the three principal North Delta channels. These channels, namely Georgiana Slough and the North and South Forks of the Mokelumne River, exhibit a wide range of flow conditions, often following a distinct pattern. Significant flows are seen in Georgiana Slough from the Sacramento River, while the North Fork of the Mokelumne River carries a bulk of the Cosumnes River flood flows, and more dynamic tidal flows. The South Fork of the Mokelumne River has a longer flow path and exhibits suppressed tidal range and flows, and does not carry reverse flows as strong as the North Fork and Georgiana Slough. This pattern has implications for sediment transport, the resulting channel bedforms, and the effective flow resistance.

The base runs for flood years 1996, 1998, 1999, and 2000 can be used to assess the performance of the model at the interior boundary locations. The floods of 1996 are distinct from the more recent flood seasons due to the fact that this was the first year of the re-opening of the “accidental breach”, and because the “Corps” breach was not formed at this time. Regarding the results from the 1996 model simulation, the boundary at Snodgrass Slough was derived from the record for the 1998 Lambert Road gauge for this year, as the Sacramento County data were not recorded at a sufficient frequency for dynamic modeling. The 1996 simulation also employs the 1998 Deer Creek signal at Wilton Road, representing a fraction of the total Cosumnes River inflow, and therefore a direct comparison to the gauge record is expected to show some deviation. Similarly, the 2000 results include the Sacramento River boundary from 1999.

<u>1996 Analysis</u>

The flood peak predictions at these locations, specifically at Bensons Ferry, show a slightly accelerated flood peak, with regard to timing, and over prediction of total peak height and associated over-steep falling limb. This effect is likely due to an under prediction of the effect of the floodplain in attenuating the peaks. The results show the boundary’s effect at New Hope and Bensons Ferry. These locations are seen as sensitive to this boundary, due to its proximity, and indicate the likely importance of northern delta flows from the Morrison Creek watershed during times of low flow from the Cosumnes River.

The simulations from 1996, for a peak flow with an approximate two-year return period (300 m^3/s), show an interesting effect when a negligible flow is used for the Dry Creek branch. The flat channels of Bear and Grizzly Sloughs exhibit reverse flows driven by the high water surface gradient between the Cosumnes River and Dry Creek, as shown in Appendix E. The peak upstream flows are of the order of approximately 50 m^3/s, and effectively drive a peak flow of 100 m^3/s from the Cosumnes River, through the sloughs to Dry Creek (actually dry, at this point), and then into the Mokelumne River (note Figure E1, *Dry Creek Mokelumne Interaction*). This phenomena significantly impacts the accuracy of the model prediction, as shown by the comparison plot at Bensons Ferry. By way of comparison, a flow equal to 40% of the Cosumnes River flow at Michigan Bar was assumed at the Dry Creek boundary at Galt, and the model run for the same simulation as the previously described 1996 analysis. Although some improvement is seen, the particular geometry of these two sloughs (Grizzly Slough and Bear Slough) has not been effectively captured by the two bridge cross sections available. With this information, as well as a visual inspection of the highly vegetated channels, additional roughness has been incorporated, and an improved simulation has resulted. This effect is prevalent for other model years, and therefore the revised channel description has been incorporated throughout. See additional sensitivity runs for a discussion of Dry Creek's connectivity with the Mokelumne River.

Comparison at Highway 99 shows an under representation of the flow volume, indicating a likely source from Deer Creek that is not represented in the 1998 boundary condition. Comparisons with the observed data at this location reveal a great deal about the flood attenuation and local hydraulics, and should continue to be helpful for further studies. Flows using this boundary indicate significant flows on Deer Creek, but of course do not coincide in timing with the actual flows for that year on the Cosumnes River. Some minor instabilities in the solution for Deer Creek may point to an inadequate representation for this channel, that may not take into account the complex channel and floodplain connectivity at this level of discretization. Additional impacts at this gauge station are the backwater effects previously discussed. The flows in the Cosumnes River overflow channel reached a peak of 70 m^3/s representing a redirection of a third of the Cosumnes flow at this point. This channel is accessible to flows greater than 5000 cfs in the Cosumnes mainstem, according to the recent USGS flood study (Guay et al., 1998).

Lost Slough and Middle Slough show marked differences in tidal response during periods of flood flow, with Lost Slough showing a tidal range of nearly 0.5 meters, largely absent from Middle Slough. This is due to a persistent water level difference between the channels. Both channels carry flows of 0 to 50 m^3/s, with Lost Slough at times exhibiting a small tidal flood. This effect is also represented in the other simulation years.

Flow peaks of the Cosumnes River above the preserve were limited to 250 m^3/s, approximately 80% of the peak at Michigan Bar. The 1996 flows generated a very small degree of flow splitting at the Twin Cities Road channels. This is possibly a realistic description for the two-year flows, but additional geometry obtained for this vicinity may show a more subtle interaction between the mainstem Cosumnes and the upper reaches of the Cosumnes River Preserve.

The 1996 simulation shows an approximate 60/40 percent split between the cut Cosumnes channel and the historic channel. In this simulation, no breach was modeled to provide floodplain access to the area known now as the “triangular floodplain”. A small flow was represented through the newly reformed “accidental breach”, and successive runs indicated that the flows through the breach were very sensitive to the establishment of a weir elevation. An analysis was done to reveal the impact of flows through the more recent breaches with 1996 hydrology (Figure E1).

1998 Analysis

The 1998 model runs were done for two separate storm periods, corresponding to approximately 2 and 10-year flood events. These flows on the Cosumnes River were augmented by a peak flow on Deer Creek of 250 m^3/s. This flow approaches the expected 100-year flow on this stem (as estimated by Guay et al., 1998), and indicates that a more detailed description of Deer Creek may be necessary. Possibilities include the extension of the branch to Scott Road (and the existing Sacramento County gauge), with the use of the Wilton Road gauge as an interior control on model behavior.

Results comparison at Bensons Ferry do not indicate a solid representation of flood attenuation for the ten year event, or even the smaller magnitude flood for this simulation period. This may be due to an under-representation of the floodplain storage along the middle Cosumnes which is accessible to storm flows of this magnitude. Peaks above the preserve are approximately 350 m^3/s for storm 1, and 850 m^3/s for storm 2, which represent 85% and 90%, respectively, of the maximum flow at Michigan Bar (409 and 928 m^3/s, respectively). The second storm shows a high degree of flow access for the other Twin Cities Road channels, contributing a peak flow of 300 m^3/s. Significantly, these peaks are reduced to 250 and 450 m^3/s at Bensons Ferry, indicating the marked effect the preserve breaches and floodplains (as well as direction through Lost and Middle Sloughs) have on flows to the delta.

The 1998 10-year flows access the three exterior Cosumnes River Preserve breaches with some intensity, directing peak flows of 250 m^3/s from the Cosumnes cut channel. The interior flows on the Preserve are very large as well, with peaks of over 250 m^3/s being delivered from the “triangular floodplain” to the “accidental floodplain”. This mechanism may include drainage paths which are not discretized at this level, including direct paths to Woodduck Slough. The western drainage of the preserve, facilitated by flow through Lost and Middle Sloughs, shows more active drainage for the 10-year flows. Peaks on lost slough reach over 100 m^3/s during this simulation period.

1999 Analysis

The largest storm of 1999, generating a flow peak of 624 m^3/s at Michigan Bar, was coupled with a modeled flow of 100 m^3/s in Deer Creek, based on the stage record boundary at Wilton Road. The Cosumnes River overflow channel captured approximately half of this peak flow, redirecting it through its own channel, and redistributing the flows across the floodplain above Highway 99. This mechanism may be exaggerated in the model, and indicates the need for accurate side channel and floodplain topography at the near-bridge location. The degree of connectivity between the multiple channels and floodplains as a function of elevation will be an important element in future refinements of the hydraulic bridge description.

Agreement of the model results for 1999 at New Hope is remarkably good, with the exception of an under-represented peak lasting about a day, presumably from an un-gauged tributary or isolated event. The tidal representation is adequate, though some damping at ebb tide is observed.

As mentioned earlier, the effect of an obviously low Dry Creek boundary has had a large impact on the model predictability, for 1999 as well. Water surface plots at Bensons Ferry are significantly lower than observations (up to a 1meter discrepancy), due in part to the capture and redirection of water through the Dry Creek Sloughs, as well as the missing flows from Dry Creek. Plots have been included to isolate this effect (Figure E4. *Cosumnes River above and below Grizzly Slough*), with a peak flow of over 150 m^3/s out of the Cosumnes River, and into the Dry Creek Slough system. Other factors which likely impact this result are the drainage mechanisms from the Cosumnes River Preserve and surrounding floodplains. Also, a revised network and assumed boundary condition have been used to illustrate an alternative flow description within the sensitivity analysis.

Significant flows above the Preserve, at Twin Cities Road, continue to stay within the primary channels, with 400 m^3/s in the main channel, and a composite of 150 m^3/s in the adjacent channels (a net attenuation of 88% from Michigan Bar). Flows at the Preserve are split less evenly between the historic and cut channel for the 1999 simulation, as higher peaks are effectively captured by the new channel, resulting in a difference in flows between the two of over 150 m^3/s. The flows by the Preserve are then directed through the breaches, with an affinity for the “accidental breach”, which captures a peak of 100 m^3/s, compared to approximately 40 m^3/s for the “triangle” and “Corps” breaches.

Modeled flows on the Preserve for 1999 show a large pulse traveling through the east and west breaches on the up and down road (80 and 50 m^3/s, respectively), with smaller flows of 20 to 30 m^3/s, occurring in the more eastward interior breaches. The smaller flows into Woodduck Slough and its associated floodplain, providing a peak of 40 m^3/s (Figure E4), were augmented by flows through the "accidental breach", peaking at 140 m^3/s towards the Cosumnes River.

Flows in Lost Slough are vigorously tidal, with a directionally varying 40 m^3/s flow commonly represented for the simulation period (Figure E4). Middle Slough shows some evidence of tidal fluctuations superimposed on a solitary flow peak of 20 m^3/s (Figure E4).

<u>2000 Analysis</u>

The peak Cosumnes River flow for 2000, recorded at Michigan Bar, reached over 300 m^3/s twice, with Deer Creek potentially adding flows of 120 m^3/s, and several lower peaks at 80 m^3/s based on model results. The Cosumnes overflow channel redirected peaks of approximately 100 m^3/s on two separate occasions during the simulation. The simulation provides an adequate comparison at New Hope, whereas the Bensons Ferry gauge comparison indicates a under representation of channel flow and floodplain drainage, for reasons mentioned previously.

Features of the lower floodplain for the 2000 flood simulation show agreement with the earlier simulations, with a reduction in the flows on the Cosumnes River Preserve floodplain commensurate with the reduced flows at Michigan Bar. Flows through the exterior breaches peak at 120 m^3/s, total, compared to 180 m^3/s the previous year. Interior Cosumnes River Preserve peak flows cluster around 15 to 20 m^3/s for each of the four modeled breaches.

Drainage from the Preserve was limited through Middle Slough, as lower water levels in the Mokelumne River, coupled with higher levels in Lost Slough prevented the development of a significant gradient. A correction of the Dry Creek capture effect is expected to alter this phenomena, which was still present with the assumed hydrograph on Dry Creek, due to re-circulation noted in prior year simulations.

The flow calculated at Bensons Ferry does not show as much attenuation for this magnitude of flood, with peaks of approximately 250 m^3/s recorded three times, corresponding to peaks of 330 m^3/s at Michigan Bar.

Sensitivity Results

The model results for the sensitivity analysis are included in Appendix E. Significant variability was achieved with the variation of a number of parameters, including the type and configuration of floodplain connections. The presence of levee breaches introduces a great degree of variability in the modeling domain, as location, sill elevation and lateral extent of each breach may vary substantially from year to year. This information is likely to be some of the most important to obtain for future modeling of the evolving Cosumnes floodplain.

Channel and floodplain roughness was varied on the Preserve to gauge its effect on the flow through breaches. This component of the resistance is the most likely to vary significantly with planned and natural changes to floodplain configuration and vegetation.

Floodplain access has been demonstrated as a key component in calibration of the one-dimensional channel-floodplain model. Several access weirs, or link channels have been lowered to allow more rapid access to the floodplain. The lowering of sill elevations was undertaken at the Preserve, at the Cosumnes River above Wilton Road and along the Cosumnes above Twin Cities Road. Floodplain volume was manipulated to represent the effect of levee setback issues along the Cosumnes River above Wilton Road and for Cosumnes above Twin Cities Road. These two parameters together account for the net effect of the floodplain connection to the river channel, and the comparison of model results with and without the enhanced floodplain connection can be used to gauge the likely effects of levee manipulation on flood flows.

An effect noted during several simulations was the effect of a significant volume of water remaining perched on floodplain after high water in the channels has receded. Floodplain drainage seems to be under represented at times, in part due to the high degree of floodplain connectivity and seepage that is not represented in the model. Time series of water surface elevations on the floodplain during the recession hydrograph will help to understand the time evolution of this mechanism. Spatial patterns in drainage can be assessed and roughly measured with GPS drogues, as described in Appendix D. Model performance may be improved with the use of several artificial drainage channels that allow for a one-direction flow, in effect draining the floodplain after the channel flows have passed. This method is often used as a surrogate for small scale drainage processes not represented in the model.

The inclusion of Dry Creek flow boundary, using an estimate of 40% of the Cosumnes at Michigan Bar flow, allowed a simulation hydrograph to generate flows along Dry Creek, and enabled study of the impact on the slough dynamics near the Preserve. For each year analyzed, Dry Creek flows were channeled through Bear Slough, but flow into the Cosumnes River was still controlled by a backflow situation on Grizzly Slough, which directed water from Bear Slough towards the Mokelumne River. Very little geometry is available in this area for slough or floodplain representation. The cutoff of Dry Creek from the Mokelumne River, as well as floodplain dynamics, may play a significant role in any backwater created by Dry Creek, south of the Preserve. These results are included in Appendix E for 1998, 1999, and 2000.
As an extension of this analysis, the discretization of Dry Creek as it enters the Sloughs was altered to get a sense of the importance of the slough channel geometry in the area. This alleviated Mokelumne River interaction and significantly increased water surface elevation along the lower Preserve.

Floodplain Mapping

The extraction of time series data and conversion to a flood map product was done for the Cosumnes River Preserve to characterize flooding likely to occur for certain return periods. This information is directly dependent on the accuracy of the input topographic data, first as hydraulic information, and second as a spatially variable datum for interpreting the calculated water surface. Two levels of analysis were done for the floodplain mapping: 1) with model results from the phase II analysis and the 30 meter DEM, and 2) with the current model results and the 10 meter DEM. Depth–duration maps for this area, for both levels of analysis, are included in Appendix E.

V CONCLUSIONS

The application of the unsteady flow model to the channel and floodplain environments of the Cosumnes River, and its receiving waters has extended the knowledge base of the geometries and fluvial forcing of the hydraulic system. This information is deemed critical to the quantification of the current trends in floodplain morphology, and to the establishment of procedures for directing this morphology, as necessary.

Specific questions which this work has helped to answer are:

1. Is a dynamic description of this system possible within the limitations of a one-dimensional numerical model?
2. Is sufficient information available to provide a realistic description of flood events for this system?
3. What are the descriptive characteristics of floods of specific return intervals within the Cosumnes River Preserve?
4. What elements of the system control the flood regime of the Cosumnes River Preserve and warrant a more detailed description and further study?
5. What recommendations for the management of a natural flood regime within a rural, and increasingly urban landscape, can be extracted from this work?
6. What future issues and problem-solving tasks can be addressed using the model developed herein; and what recommendation will enable this application?

Question 1: A one-dimensional model?

The role of a one-dimensional model in the study of distributed phenomena over a large spatial extent is well established. However, the application of this type of model to a system with the natural complexity of the Cosumnes River, the quasi-controlled nature of the modern floodplain, and the estuarine dynamics of the North Delta, presents a significant challenge. It has been demonstrated that additional understanding of channel flows and floodplain inundation has been developed which did not previously exist, which will help to define the role of the major tributaries for site-specific studies of channel, floodplain, and habitat interactions. This understanding should be coupled with a recognition of the limitations of a one-dimensional surface water model in describing the subtle interplay of surface and groundwater hydrology, more nearly two-dimensional flows on the floodplain, and fully three-dimensional flows at channel confluences, bends, and constrictions. Given development in available numerical models, a nested two-dimensional component within the one-dimensional model may provide a more detailed simulation of the study area.

Question 2: Are existing observations sufficient?

The scale of the Cosumnes River floodplain, and the complicated nature of the various tributary interactions with the North Delta provides a hydrologic environment with many opportunities for flood management and restoration. This same complexity presents a number of challenges to the understanding of flood flows, their effects on the channel and floodplain environments, and effective flood management. Complexity and the linkage of floodplain effects extends throughout the lower Cosumnes system. Useful predictions and statistics of stages and flows at the Cosumnes River preserve are predicated on an accurate description of the upper floodplain, from Michigan Bar to Highway 99 at McConnell, and furthermore down to Twin Cities Road.

Specifically there is a need for a more detailed description of shared Deer Creek–Cosumnes River floodplain above Wilton Road, and refined representation of the lower floodplain down to Highway 99. Flows to this area are affected by the bridge backwater on the three effective channels at this point, which will control the flows to downstream reaches of the Cosumnes River and North Delta. This section of the river will require an extension of the surface modeling work done to date, to incorporate existing river cross sections, with an accurate method for extracting cross sections along the two main channels, and the numerous overflows, bypass, and floodplain channels. Combined with the geometric description, the model boundary can be moved to the Sacramento County gauge at Scott Road, to allow for a more realistic prediction of flows on steeper terrain, without backwater complications.

Continuing below Highway 99, a lack of both channel and floodplain information limits the successful description of channel-floodplain hydraulics, and must be overcome in order to predict flows along the length of the Cosumnes River Preserve, with any further accuracy. The river travels approximately 3.5 km between cross sections at this point, and relatively little is known about floodplain interaction in this zone. For these reasons, increasing knowledge of the geometry, and observed flows and water surface elevations above and near Twin Cities Road would provide an interior check on the model function, as well as indicate the timing and location of the distributed flows as they approach the Preserve.

The analysis of existing data, and the simulations performed with the hydraulic model suggest that Dry Creek can be an integral element of flooding on the Cosumnes River in the most common flood years, as a creator of an additional backwater effect which may force and sustain inundation on the lower floodplain reaches of the Cosumnes River, Woodduck Slough, and other local sloughs. Further study of Dry Creek may help to define this effect and could begin with the re-establishment of the flood gauging station at Galt, or other suitable location further upstream. A modest effort in surveying cross sections on Dry Creek and the sloughs which connect it to the larger delta tributaries would rapidly increase the hydraulic knowledge of the complete system. The information gained here would be helpful in defining the role of Dry Creek in particular, and the likely combined importance of other low elevation tributaries such as Laguna and Badger Creek, in establishing floodplain processes and habitat in an distributed manner.

The extension of the existing 10 meter DEM into the Delta and the Dry Creek and Mokelumne River would be an advantage for routine flood mapping for the Cosumnes River Preserve and its surroundings. For this detailed region, a floating-point representation would be reasonable. Eventual acquisitions in floodplain topography could be incorporated to make this a useful, accurate data product for decision making.

In general, topographic data needs, drive the extent of the predictability and utility of the model results. These data are of three types: channel cross sections, floodplain maps, and levee profiles, down to the breach scale. The requisite scales needed for these three types of information, and the recognition that they are in fact time series operating with independent periods of variation, will require an increased level of cooperation between agencies, operators, landowners, and each of the interests along the Cosumnes River, in order to adequately describe the existing topography. This could be facilitated by the broad-based interest in the Cosumnes River environment, and would provide a baseline for future work in developing a sustainable Cosumnes River system.

This topographic information will be most useful in conjunction with the established hydraulic model, which will serve to extend the expanded information over the complete model domain. In this manner, refined floodplain information in the middle reaches of the Cosumnes River can be helpful in understanding flows to the near-delta Cosumnes and its floodplain. In order to use this topographic data effectively, a field monitoring program of water surface elevations and flows at the main constriction points, during periods of high flows, should be used to describe, calibrate, and validate the refined model.

Question 3: Characterization of flood years and return frequencies

The impact observed hydrology has had on the lower Cosumnes floodplain has been assessed with the composite mapping of the 1996, 1998, 1999, and 2000 flood seasons. This index into the 2 to 10 year return interval floods provides a suitable benchmark for the development of floodplain management strategies for the floods in this category. Significantly larger events will warrant study for the analysis of impacts from extreme events, and will require more extensive topographic information. A suitable goal may be the calibration of the 1997 storm to typify the floodplain interactions due to an extreme event. For this work, extensive use of available aerial photography will be required to calibrate and validate the floodplain discretization. Specific use can be made of the Mokelumne River aerials from the 1986 flood, which were flown from Comanche Dam to the Delta, encapsulating the combined Dry Creek floodplain and the lower Cosumnes River.

Question 4: What controls the hydraulic system?

The remaining flood generators for the North Delta system are the Cosumnes River, Dry Creek, and Comanche Dam. Each of these elements should be included in an assessment of possible controls on flooding along the lower Cosumnes River, and into the North Delta. Understanding their interaction is a key element in successfully managed floods for the Cosumnes River Preserve.

Topography, and bridge and levee constriction play a fundamental role in the function of the floodplain. These elements, their current condition, and proposed changes should be addressed within the framework of a suitable hydrodynamic model, so that the effect of modifications can be assessed prior to detrimental impacts to the ecology and flood protection of the near-delta region.

The role of vegetation has not been explicitly addressed in this study, and continues to present a challenging issue of scale for further study at the Preserve. The current patterns of channel, riparian floodplain vegetation exert a strong influence on hydrodynamics of the channel-floodplain interaction. The active management of such vegetation can play a significant role in the evolution of the Cosumnes riparian zone for the foreseeable future. These issues should include the role of wood in channel processes, the effect of developing floodplain forests on flood hydrodynamics, and the concept of managed roughness as an approach to flood control.

A degree of understanding has been gained concerning the predictability which can be expected for flooding and draining mechanisms. Floodplain access events for which the location is known are generally reproducible with regard to timing, duration and magnitude. The drainage mechanisms are generally more subtle and dispersed than flows through breaches and overtopping levees, and hence more difficult to represent physically. This may be particularly true in the managed, breached environment of a restored floodplain, and attention should be paid to the pathways and mechanisms that control drainage and by extension, control the inundation period.

Questions 5 and 6: Recommendation for Future Directions

The application of the information learned in this study, as well as the further development of the hydraulic model as a tool for the evaluation of management alternatives, should readily follow the increasing availability of channel and floodplain geometry, and the observation of flow and sediment exchange between the channel and floodplain. Several concepts should be included in this evaluation.

First, the time varying elements of flooding, habitat provision and its restoration should be implicitly considered when decisions are made affecting the floodplain. This can occur principally by mapping the planform extent of various flood intervals, and directly accounting for the duration of flooding. This time component serves to evaluate the sustained access of the floodplain , while incorporating the uncertainty in discrete numeric predictions. The type of decisions which could incorporate this information range from development plans for infrastructure within the floodplain and levee protection issues, to urban and agricultural zoning, to the development of habitat restoration priorities, which should all incorporate a knowledge of the cycle of floodplain inundation to be expected. As developments within the Delta for agriculture, water supply, and habitat restoration proceed, the capability for mapping floodplains on seasonal and tidal scales should advance concurrently.

Second, the establishment of a priority schedule for further topographic data collection, as well as a system for the observation (both human and automated) of flood behavior, will help to groundtruth the model results, and provide some indication of the means toward accurate, quantified descriptions of the complexities not yet resolved in the model, such as bridge constrictions and dynamic levee breachings. The sensitivity results of the numerical modeling presently accomplished can be used to direct this collection effort. Implicit in this task is a generation of flood mechanism maps for the Cosumnes River from Michigan Bar to the delta (similar to that represented in Figure 12) This information should be a benefit to a broad consortium of groups and individuals interested in the future of the Cosumnes River, and as such could be made available through the web-accessible GIS managed by the Information Center for the Environment, at UC Davis.

Finally, the use of the flood-based hydraulic knowledge of the floodplain for flood management and riparian restoration should be accomplished in parallel with a recognition of the physical, biologic, and ecologic phenomena which drive a functional Cosumnes floodplain. Much of the advancement required for successful management and restoration of the floodplain remains in the linkage of these phenomena across conventionally accepted scientific boundaries.

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The Cosumnes Research Group http://www.ice.ucdavis.edu/cosumnes

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