North Delta Sedimentation Study

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Prepared for:

California Department of Water Resources

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Contents

Section 1.0
Introduction

The nature, distribution, and transport of sediments in the Sacramento-San Joaquin Delta impacts many activities in the region including navigation, recreation, fisheries development, and flood control. The physical processes that initiate and control sediment transport in the Delta are sensitive to the hydrology and hydraulics of the system, and small changes in these variables have been found to initiate substantial responses sometimes with unforeseen results. Sedimentation analyses are, therefore, an essential part of any proposal that may affect local waterways.

1.1 Study Objectives

This report presents the findings of a sedimentation study performed by Northwest Hydraulic Consultants (**nhc**), in conjunction with North Delta Flood Control and Ecosystem Restoration Project proposed by the California Department of Water Resources (DWR). The study investigates the nature of sedimentation in the Delta using both historical and recently obtained data, and computer modeling techniques. The objectives of the study are to develop an appropriate tool for modeling sediment transport and channel morphology within the study area and to evaluate the effects of proposed project alternatives. The results of the study will be used to better understand the sedimentation characteristics of the region and to evaluate the impacts of proposed flood control and environmental enhancements, which include the re-establishment of aquatic habitat, subsidence reversal, and erosion control. The analyses presented herein are appropriate for the preliminary design phase of the North Delta Flood Control and Ecosystem Restoration Project. Additional sediment monitoring and analysis will be required in subsequent project design phases.

1.2 Project Area

Located in the North Delta, the project area encompasses McCormack-Williamson Tract, Dead Horse Island, Staten Island, and adjacent waterways. The extent of the project area is presented in Figure 1. Significant waterways include the Delta Cross Channel, Snodgrass Slough, and the Mokelumne River, which enters the Delta along the southern boundary of the McCormack-Williamson Tract. Within the project area, the Mokelumne River bifurcates into a North Fork and a South Fork, which surround Staten Island before rejoining again at the southern end. Snodgrass Slough borders the western edge of McCormack-Williamson Tract and Dead Horse Island and is connected to the Sacramento River via the Delta Cross Channel, an important contributor of fresh water to the Mokelumne River. The Delta Cross-Channel typically operates during low flow conditions in summer and diverts flows from the Sacramento River to the Mokelumne River.
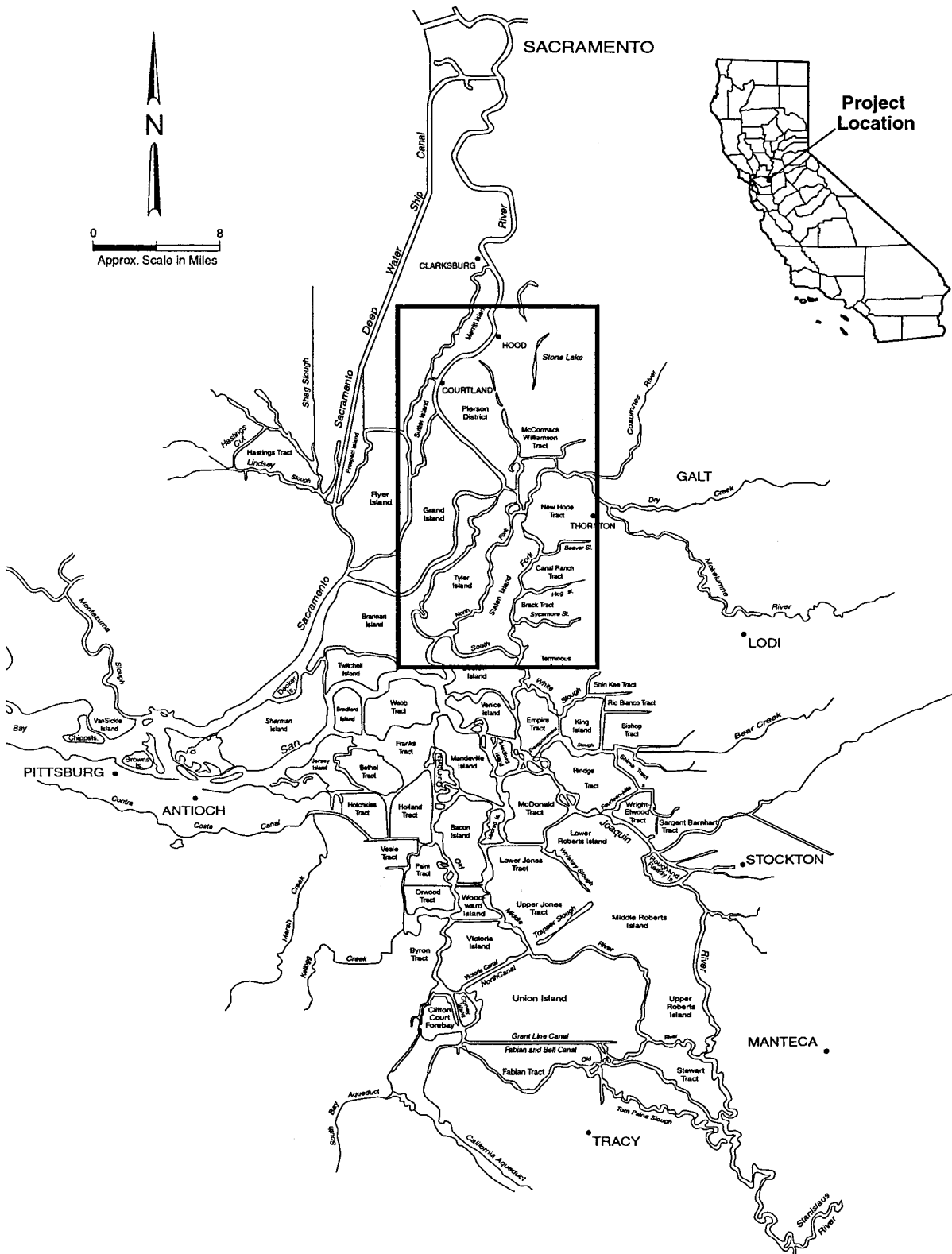
Figure 1. The Sacramento-San Joaquin Delta and general location of the project area

Section 2.0
Geology of the Delta

2.1 Geology

The Sacramento-San Joaquin Delta is located along the western margin of an immense sediment-filled structural trough that forms the Central Valley of California. In the vicinity of the Delta, these sedimentary deposits can be distinguished into discrete layers. Several kilometers beneath the Delta surface, basement rocks are composed of marine sedimentary rocks dating from the pre-Cretaceous Period (before 144 m.y.a., million years ago) to the early Tertiary Period (66.4 m.y.a. to about 40 m.y.a.) (USACE, 1974; DWR, 1986). Basement rocks are overlain by 5 km to 10 km of sedimentary deposits, most of which accumulated in marine environments between 175 m.y.a. and 25 m.y.a. (Atwater, 1982). These marine sediments are capped by late Tertiary (about 25 m.y.a. to 1.6 m.y.a.) and Quaternary (1.6 m.y.a. to present) non-marine sediments ranging from 720 m to 900 m in thickness (Burroughs, 1967; DWR, 1980a). Lastly, non-marine sediments are overlain by a layer of peat and peaty sediments between 0 and about 20 m feet thick interbedded with fluvial and tidal deposits of marine clay, silt, and sand. These sediments form the modern Delta and decrease in thickness with distance toward the Delta margins.

The Delta evolved as a result of millions of years of gradual infilling of the Sacramento Sea, an inland sea that once occupied a large part of Central California during the Oligocene Epoch (39 m.y.a.). During this time, the Sierra Nevada Mountains were much lower than they are today, as was the ancestral Coast Range. Over the next 35 million years an active subduction zone along the California coastline contributed to uplift of the Sierra Nevada and Coast Range and, as the mountains rose, eroded material gradually filled the Sacramento Sea. Prehistoric delta environments occupied large tracts of land along the vast inland shoreline that, as sedimentation progressed, migrated westward to converge in the vicinity of the modern Delta. By about 5 to 3 m.y.a., the Sacramento Sea had largely filled in with sediment, forming the Central Valley (Hickman, 1993).

The modern Delta is the most recent of several deltas that formed during a sequence of depositional and erosional cycles in the Quaternary Period, the period from 1.6 m.y.a. to present (Shlemon and Begg, 1975; Shlemon, 1971). These cycles resulted from fluctuations in climate and sea level related to the advance and retreat of glacial ice. The most recent cycle is one of deposition, resulting from a rise in sea level initiated by deglaciation following the height of the last (Tioga) glaciation approximately 20,000 years ago, a time when sea level was approximately 390 ft lower than it is today (USACE, 1974; Hickman, 1993). As glacial ice retreated, sea level rose more rapidly at first then slowed to a rate of about 0.04 to 0.08 inches per year, a rate that has persisted from about 6,000 years BP (Before Present) to the present time (Atwater et al., 1977).

Unlike most deltas, the modern Delta formed in the inland direction as rising sea levels intruded upstream and flooded a pre-Holocene valley, creating a broad tidal marsh. Rising sea levels gradually submerged the marsh over time, creating anaerobic conditions

that greatly reduced the rate of plant decomposition. As a result, the accumulation of decomposing plant material kept pace with rising sea levels over approximately 7,000 to 11,000 years, resulting in the formation of thick peat deposits (Prokopovich, 1988; Shlemon and Begg, 1975). These deposits are thickest in the west and central parts of the Delta and grade to thinner accumulations inland toward the Delta margins (DWR, 1995a).

2.2 Seismicity

The Delta borders the eastern margin of the San Francisco Bay area, a region characterized by several major faults and high seismic activity (Figure 2). There have been numerous large (M>5) earthquakes in the region during the historical period of record, many of which produced seismic shaking in the Delta (USACE, 1995). The Midland Fault Zone, the Tracy-Stockton Fault, the Antioch Fault, the Rio Vista-Sherman Island Fault, and the Montezuma Hills Fault are all located near or within the limits of the Delta (Atwater, 1982; Jennings, 1994; USACE, 1995). Of these five faults, several have shown historical activity since 1800. The proximity of the Delta to major active fault systems in the San Francisco Bay area, most notably the Calaveras Fault and the Hayward and San Andreas Fault Zones, make it susceptible to strong seismic shaking events.

Although the Delta has been subjected to moderate seismic shaking during historical earthquake events, there has been no recorded observation of levee failure directly caused by an earthquake (Kearney, 1980; USACE, 1995). Nevertheless, the risk of liquefaction of protection levees is present given the potential for strong earthquakes in the region and the poor geotechnical characteristics of the peat deposits on which most Delta levees are constructed.

2.3 Land Subsidence

Almost all islands and tracts in the Delta lie below sea level. Land elevations decrease toward the west and center of the Delta to as much as 25 ft below sea level (USGS, 2000). Land surface elevations have been declining throughout the Delta due to widespread land subsidence, initiated when land reclamation began in the middle 1800's. Land subsidence is due largely to the decomposition of organic carbon in the Delta's predominantly peat soils (Deverel and Rojstaczer, 1996). Prior to land reclamation, peat soils were saturated under anaerobic conditions and decomposed at a much slower rate, a rate exceeded by the rate of accumulation of dead organic matter. Exposure to aerobic conditions following land reclamation in the mid-1800s resulted in a dramatic increase in the rate of peat decomposition.
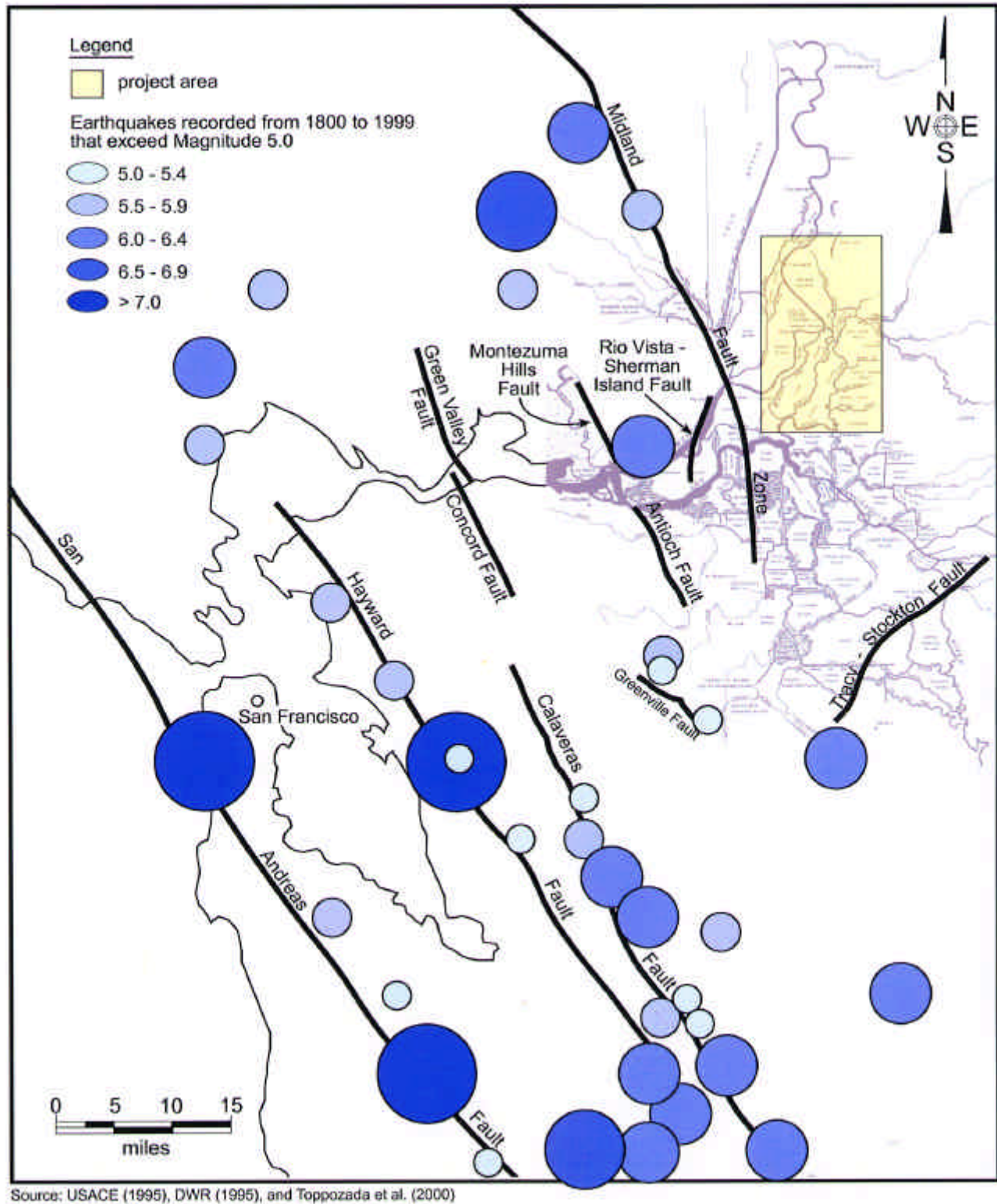
Figure 2. Historical earthquakes (magnitude > 5.0) in the San Francisco Bay region

Many studies have been conducted to accurately measure the rate and amount of land subsidence on Delta islands over time (Weir, 1950; Davis, 1963; Lao, 1965; Newmarch, 1980; DWR, 1986; Rojstaczer et al., 1991; Deverel and Rojstaczer, 1996; Deverel et al., 1998; Kerr and Leighton, 1999). These studies show that land subsidence is greatest in areas where peat deposits are thickest, namely the western and central parts of the Delta. In addition, land subsidence is typically greatest toward the center of islands and least along the levees around the island perimeter. Because the levees act as a protective cap, peat deposits underneath are not exposed to oxygen and therefore do not subside as rapidly as open areas of soil adjacent to levees (Davis, 1963).

Where long-term data are available, a gradual trend toward declining rates of land subsidence over time has been observed (DWR, 1986; Rojstaczer et al., 1991). Short-term data (1992-1994) also support this apparent trend (Deverel and Rojstaczer, 1996). The cause of this decline is attributed to a decrease in the proportion of organic carbon available for decomposition in the near surface (Galloway et al., 1999).

Historical land subsidence in the project area generally increases in a southwest direction. At McCormack-Williamson Tract, thicknesses of organic soils are negligible whereas organic soils are between 30 and 40 feet thick in the southwestern corner of Tyler Island (DWR, 1995a). For the most part, islands and tracts in the project area have experienced less than 10 feet of historical land subsidence, except Tyler and Staten Islands, where the extent of land subsidence may exceed 20 feet (DWR, 1980b).

Section 3.0
Geomorphology of the Delta

3.1 Geomorphic Setting

The Delta covers approximately 738,000 acres (1,153 mi^2) of land area, and forms a roughly triangular shape that broadens with distance inland. Most of the Delta is occupied by about 60 large islands or tracts separated by waterways (DWR, 1995a). Almost all of these areas have been reclaimed for agricultural purposes and lie at or below sea level. Islands and tracts are kept dry by approximately 1,100 miles of levees, and lift pumps are commonly used to lower the local ground water table to levels acceptable for farming. An overview of Delta geography is provided in the Delta Atlas (DWR, 1995a).

Rivers flowing into the Delta convey approximately 50% of the state's annual runoff (DWR, 1995a). The main rivers include the Sacramento, San Joaquin, Mokelumne, Cosumnes, and Calaveras Rivers. All the major rivers are regulated by dams, except for the Cosumnes River. The Sacramento River is the dominant source of fresh water and sediment to the Delta, accounting for approximately 80% of annual fresh water inflows (Anderson, 1994). The San Joaquin River is the second largest contributor, accounting for about 10% of annual fresh water inflows. Similarly, most of the sediment supplied to the Delta is carried by the Sacramento River, between 80% and 85% in an average year, whereas the San Joaquin River and the Mokelumne-Cosumnes River supply only about 10% and 4%, respectively (NHC, 2003). The remaining sediment enters the system from the Yolo Bypass and from several other smaller streams and sloughs. A detailed discussion of the Delta sediment budget, past and present, is provided by NHC (2003).

Water and sediment movement in the Delta involves a complex interaction between tidal fluctuations, inflowing river discharges, and topography. The Delta exhibits mixed semi-diurnal tides with two high and two low tides each day. Tidal fluctuations result in changes in water surface elevation and the direction and volume of water and sediment flow in the Delta (NHC, 2003). Tidal effects are most significant in low freshwater flow conditions whereas during floods, tidal fluctuations are largely washed out by inflowing freshwater discharges.

Rivers flowing into the Delta exhibit a decline in stream power due to the combination of decreasing slope and tidal effects. Historically, prior to agricultural development and levee construction, annual flooding would regularly overtop existing low-lying natural levees and flood vast areas of tidal marsh lands. This resulted in sediment deposition and general aggradation of the Delta surface over time. In some cases, flows would concentrate through natural levee breaks and scour new channels through the tidal marsh. This led to a cycle of ongoing change in the alignment and location of channel bifurcations in the Delta. Today, channel alignments are largely fixed by artificial levees and erosion control measures. Flooding, except when artificial levees break, no longer occurs on most islands and tracts. Instead, flow and sediment remain confined to the existing channel network.

3.2 Historical Geomorphology

The geomorphology of the North and South Forks of the Mokelumne River is characteristic of Delta waterways. Both channels are bordered by levees that protect agricultural land uses. Channel alignments are preserved by ongoing levee maintenance and instream dredging. The North Fork is generally deeper and has a higher flow capacity than the South Fork. Combined, the North and South Forks have a maximum flow capacity of approximately 40,000 cfs whereas the 100-year flood requires a capacity of approximately 90,000 cfs (DWR, 2004). As a result, islands and tracts in the region are susceptible to flooding during high flows.

This section summarizes key historical events that have affected geomorphology in the North Delta since land reclamation began in the 1850s. Historical events are divided into the following subject areas: land reclamation and dredging, water diversions, and historical flooding. Summaries of key historical events in the Delta relating to water resources and geomorphology are provided by Prokopovich (1985), Anderson (1994), and DWR (1995a). Historical information regarding early settlement in the Delta is provided by Thompson (1957).

3.2.1 Land Reclamation and Dredging

Before European settlement, the Delta was described as a low-lying area covered by tidal marshes, backwater sloughs, and meandering river courses bordered by natural levees (LTMS, 1996). Much of the land area was at or near mean sea level (MSL) with highest elevations 10 ft to 15 ft above MSL (LTMS, 1996). As a result, much of the area was flooded regularly during high tides and/or high river flows. Natural spring floods annually inundated about 70% of delta lands (USACE, 1982).

The first period of land reclamation, from 1852 to 1875, occurred prior to the use of dredges in the Delta. Levees during this period were constructed largely by Chinese laborers. Reclaimed areas were drained and leveled by filling in the many sloughs and backwater areas of the natural tidal marsh lands. Levees during this period typically ranged from 4 ft to 6 ft in height (Thompson, 1982). Because levees were built atop and from soils with a high organic content, they were prone to settling, dessication shrinkage, and cracking.

The first recorded use of dredged material for levee construction in the Delta was on Jersey Island in 1875 (Thompson, 1982). Early dredges were steam powered and used throughout the Delta to improve existing levees and construct new ones for land reclamation (LTMS, 1996). Once leveed, arable lands were cultivated for farming and irrigated using tide gates that allowed water to flow into the leveed tract at high tide and flow out of the tract at low tide (DWR, 1980c; Prokopovich, 1985). No pumps were needed until the 1880's when land subsidence had become too great for the gravity based tide gate system to function properly (Thompson, 1982).

Hydraulic mining for gold in the Sierra Nevada Mountains from 1853 to 1884 created vast changes in the Delta (Gilbert, 1917). Hydraulic mining reached its apex in the 1870's and early 1880's and introduced huge sediment loads that were transported down major rivers to the Delta, causing river aggradation and the partial infilling of San Pablo and Suisun Bays (Gilbert, 1917; Ogden Beeman & Associates and Ray B. Krone & Associates, 1992; Krone, 1996; Galloway et al., 1999). An estimated 600 million cubic meters of sediment was introduced into the Delta during the period of hydraulic mining (Prokopovich, 1985). Divided over the 32 years of hydraulic mining operation, this value equates to a fivefold to sixfold increase in average annual sediment load over current levels (Prokopovich, 1985; Ogden Beeman & Associates and Ray B. Krone & Associates, 1992). As a result, delta channels became clogged with sediment and aggraded as much as 15 ft, interfering with navigation and increasing the incidence of flooding (LTMS, 1996). Following litigation, hydraulic mining was banned in California in 1884 (DWR, 1980c). Although banned, hydraulic mining continued sporadically until around 1915 (Gilbert, 1917).

A new generation of dredges, called clamshell dredges, was applied to clear the accumulated sediments from Delta channels following the end of hydraulic mining in 1884 (Galloway et al., 1999). The same style of dredge remains in use today. Clamshell dredges were also instrumental in constructing new levees and in improving existing ones to offset the effects of land subsidence. Ongoing reclamation work continued and by 1900 about half of the Delta had been reclaimed for agricultural use. In 1911 a Reclamation Board was established to manage and regulate private levee construction (DWR, 1980c) and by 1916 almost the entire Delta had been reclaimed (DWR, 1980c; Thompson, 1982). In addition to levee construction and land reclamation, many existing sloughs were straightened and new cuts dug through islands and tracts in the Delta (DWR, 1995a). By the 1930's, reclamation of the Delta was largely completed and in the configuration currently observed today (Thompson, 1957; Prokopovich, 1985). Over the period from 1852 to 1930, land reclamation resulted in the loss of approximately 97% of the total original tidal marsh in the Delta (Atwater and Belknap, 1980).

As development in the Delta and the Central Valley continued, Congress authorized the Sacramento Flood Control Project in 1917, resulting in the construction of improved levees along the Sacramento River and its distributary channels in the northern Delta (DWR, 1995a). Completed in 1960, the levee system, referred to as project levees, includes Georgiana Slough just south of the Delta Cross-Channel. The remaining levees in the project area are locally funded non-project levees maintained by local reclamation districts with support from the State.

In 1933, the Stockton Deep Water Ship Channel (DWSC) was dredged along the San Joaquin River from Suisun Bay to the city of Stockton (USACE, 1934). The project included channel dredging as well as the excavation of cuts through a meandering portion of the San Joaquin River in the east Delta. In 1935, dredging work on the Sacramento River was also conducted to improve navigation (Anderson, 1994). In 1963 the Sacramento DWSC was constructed along the Sacramento River from Sherman Island to West Sacramento. In 1983, both the Stockton DWSC and Sacramento DWSC were

deepened to 35 ft to allow for the passage of larger ships (DWR, 1995a). Both the Sacramento DWSC and the Stockton DWSC fall under the jurisdiction of the Corps and are subject to maintenance dredging each year to maintain depths for ship passage (Valentine, 2000). Dredging in the Delta is also conducted by State agencies, reclamation boards and private companies for levee repair, marina maintenance, and other channel improvements.

Traditionally, the U.S. Army Corps of Engineers has been responsible for large dredging projects in the Delta for improving navigation. According to their records, the Corps has not been involved in any dredging projects along the Mokelumne River (Mirakomi, 2002). However, the river has been dredged in the past to supply local landowners and reclamation districts with material for levee construction and maintenance. A summary of recent dredging activities in the project area is provided by NHC (2002).

3.2.2 Water Diversions

California is home to the largest water distribution system in the world and its primary source of water is the Delta. In 1933, Congress authorized the Central Valley Project to distribute water from the Delta to the San Francisco Bay area, the San Joaquin Valley, and southern California (DWR, 1980c). The first component of the project, the Contra Costa Canal, was completed in 1940 and began exporting water from the Delta that same year. In 1951, the Delta Mendota Canal and the Delta Cross Channel were completed, greatly increasing the rate of annual water exports from the Delta. The final stage of the CVP was completed in 1973 when the California Aqueduct was constructed from the Delta to southern California.

Because fresh water was needed at the newly constructed pumping plants year round, dams were constructed in upper basins of the Delta watershed to regulate flow in winter and provide flow releases in summer, supplying adequate water for pumping and limiting the upstream transgression of saline sea water into the Delta. Today, all major rivers draining into the Delta, except the Cosumnes, are regulated by dams. Some of the most notable reservoirs are Lake Almanor on the North Fork of the Feather River completed in 1924, Millerton Lake on the San Joaquin River in 1942, Lake Shasta (1944) on the Sacramento River, Lake Oroville (1967) on the Feather River, Folsom Lake on the American River (1955), Lake Berryessa on Putah Creek (1956), Camanche Reservoir on the Mokelumne River (1963), Don Pedro Reservoir on the Tuolumne River (1970), and New Melones Reservoir on the Stanislaus River (1978).

As a result of these water projects, salinity intrusion in the Delta has been greatly diminished (DWR, 1993, 1995b). Historically, before Shasta Dam was completed, the maximum extent of salinity intrusion in dry years extended over more than 80% of the Delta. Today, salinity intrusion, even in very dry years, is limited to the area west of Oulton Point on Twitchell Island. In addition to changes in salinity intrusion, state and federal water projects also affected general flow patterns in the Delta. Historically, fresh water from the Sacramento River was once concentrated in a more westerly direction toward Sherman Island and Suisun Bay. Today, fresh water from the Sacramento River

flows in a more southerly direction, leaving the Sacramento River through the Delta Cross-Channel and flowing south toward the Tracy and Harvey Banks Pumping Plants that supply water to the Delta-Mendota Canal and California Aqueduct, respectively (DWR, 1995a).

3.2.3 Historical Flooding

Historically, major floods in the Delta occurred in the following water years: 1878, 1881, 1890, 1893, 1902, 1904, 1907, 1909, 1938, 1950, 1955, 1958, 1969, 1980, 1982, 1983, 1986, 1995, 1997, and 2004 (DWR, 1995; Thompson, 1996). In each water year, one or more large islands or tracts were flooded and required draining and levee repair. Although flooding in the Delta typically occurs during flood flows on either the Sacramento or San Joaquin River systems, levees have also failed during low flow summer or early fall conditions (DWR, 1995a). Delta levees are subject to wave erosion, seepage, overtopping by floods, and structural failure due to underlying soil type (DWR, 1980c, Thompson, 1982). In addition, as ongoing land subsidence continues, levees are subject to increasingly greater pressure as the difference between water surface and land surface elevation increases.

Levees on McCormack-Williamson Tract and Dead Horse Island have frequently been overtopped during large floods. Aside from frequent flooding in the late 1800s, McCormack-Williamson Tract experienced flooding in 1955, 1958, 1964, 1986, and 1997. Dead Horse Island has also experienced frequent flooding, in 1950, 1955, 1958, 1980, 1986, and in 1997. Staten Island has not flooded for almost 100 years, last flooding in 1904 and again in 1907.

3.3 Channel Morphology

3.3.1 Planform Comparison

Historical maps of the Walnut Grove area and vicinity are shown in Figure 3. Maps shown in Figure 3 date from the 1910-1916 period and the 1978-1993 period. Several significant changes during this time period are noted. First, the area of McCormack-Williamson Tract appears as marshland in 1910-1916 era maps with some small lakes bordering the tract. McCormack-Williamson Tract was one of the last remaining areas of marshland in the North Delta to be converted to agriculture. Also notable are the numerous sloughs that partially dissect many of the tracts and islands in the North Delta. Broad Slough, near the southern end of Tyler Island, is particularly extensive. A slough appears to connect Snodgrass Slough and Georgiana Slough at the west end of Deadhorse Island in 1910-16 mapping, but has been filled in by 1978-93. Construction of the Delta Cross-Channel in 1951 from the Sacramento River to Snodgrass Slough is also a notable change from 1910-16 to 1978-93.
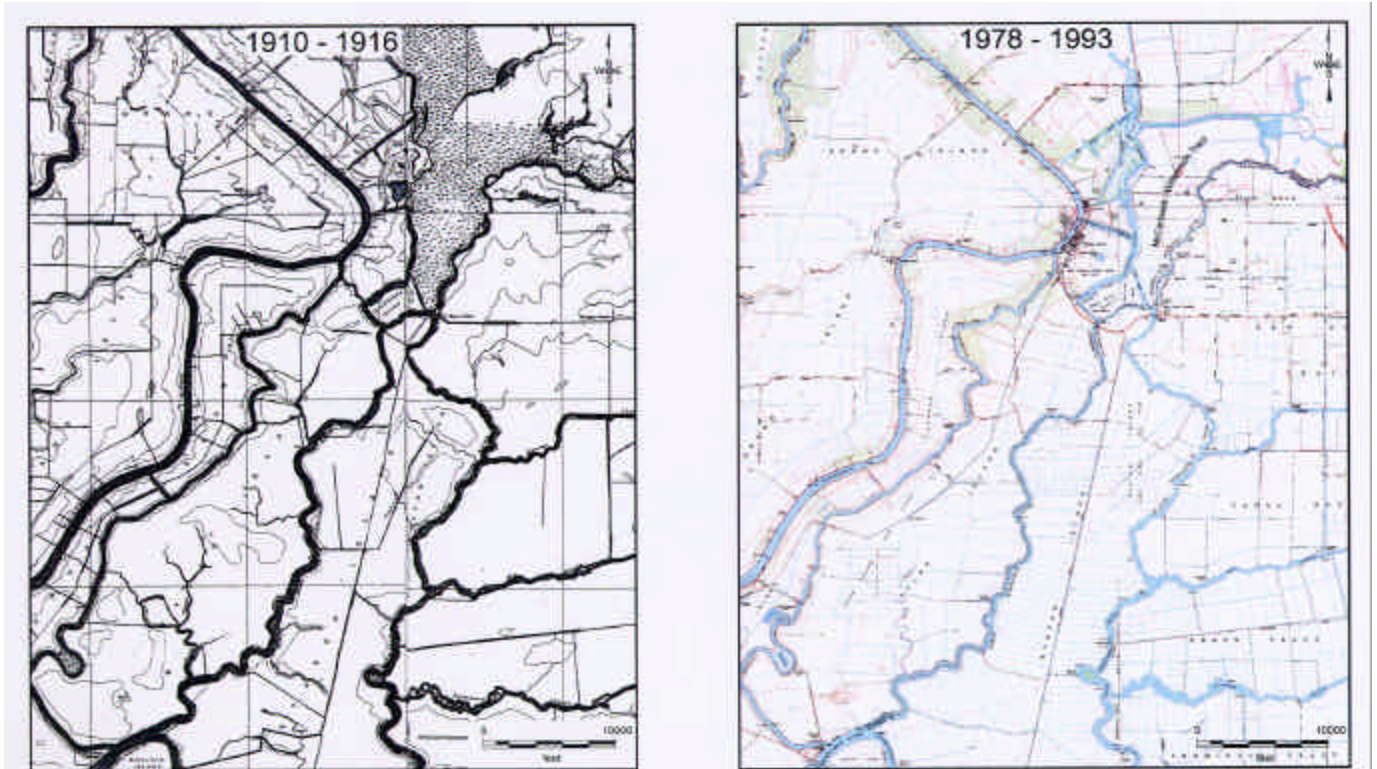
Figure 3. Historical map comparison of Walnut Grove and vicinity

In contrast to observed changes, much of the islands, tracts, and channel alignments in the North Delta still appear as they did in the early 1900s. Major river alignments have not changed significantly over the last several decades although levee heights have increased by several feet to improve flood control. The most significant changes to flow and sediment transport in North Delta waterways are not expressed in terms of channel alignments but rather in the land subsidence of islands, grading and filling of farm land, increases in levee heights and channel flow capacities, and water regulation by the State Water Project.

3.3.2 Cross-Section Comparison

Historical cross-section data for the North Delta were available from the State Department of Water Resources (DWR) for two time periods, namely: bathymetric data from 1934 and annual cross-section data from 1994 to 2001. Bathymetric data are available from the Cross Section Development Program (CSDP), a software application that develops stream cross-sections by drawing from bathymetric points upstream and downstream of the desired section line. The bathymetric data are not sufficiently dense to produce accurate cross-sections but do provide a general sense of channel morphology. In contrast, detailed annual cross-section data are available from the North Delta Scour Monitoring Program (DWR, 1998, 2000). Initiated in 1994, the program has collected cross-section data for the last 10 years, although released data are only available through 2001.

Cross-section data from 1994 through 2001 were available at 32 locations on waterways adjacent to McCormack-Williamson Tract, Dead Horse Island and Staten Island. Cross-section locations and a summary of historical changes at each site are shown in Figure 4 and discussed below. Where available, the channel invert from 1934 bathymetric data is also shown in the figure.
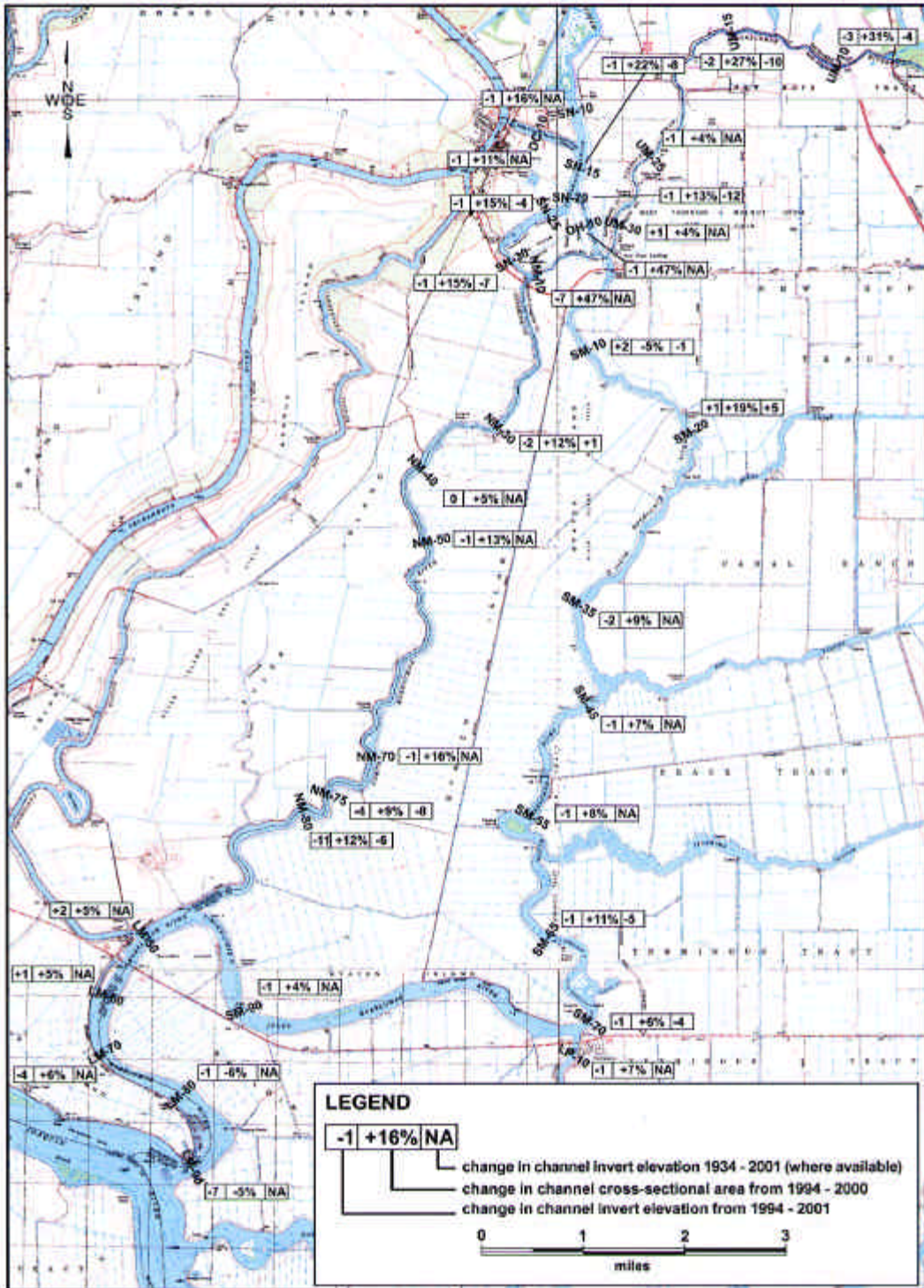

Figure 4. Summary of historical cross section changes (feet) in study area

At most locations in Figure 4, the 1934 – 2001 and 1994 – 2001 cross-section data show declines in channel invert elevation as well as increases in cross-section area for the 1994 – 2000 period. Note that, due to the lack of density of data points, estimates of the 1934 channel invert could be made at only 13 of the 32 cross-section locations and are estimated to be accurate to within +/- 5 feet. This made it impossible to identify long term changes in bed elevation with confidence; however, almost all the data (11 of 13 sites) show an apparent decline in invert elevation from 1934 to 2001. Only two sites indicate a possible channel invert rise, NM-30 (+1 feet) and SM-20 (+5 feet). The change at NM-30 is well within the range of error whereas the change at SM-20 is possibly significant and corroborates an observed trend of aggradation on some parts of the South Fork Mokelumne River in recent years (Fleenor, 2002).

A summary of historical cross-section data from 1994 – 2001 is shown by stream segment in (Table 1). Similar to the 1934 – 2001 data, a general decline in channel invert elevation is observed in the project area. In addition, the average cross-section area for each stream segment shows an increase for the period, reflecting an increase in channel capacity.

Table 1. 1994 - 2001 Cross section changes in North Delta project area

Stream Segment	Average Invert Change 1994 – 2001 (ft)	Average Cross-Section Area Change (1994 – 2000)
South Fork Mokelumne	-0.5 ft	+7%*
North Fork Mokelumne	-3 ft**	+16%*
Upper Mokelumne	-1 ft	+17%*
Lower Mokelumne	-2 ft	+1%
Snodgrass Slough	-1 ft	+16%
Dead Horse Slough	-1 ft	+47%*

* dredging occurred in this reach during the period of change
**excluding NM-80 where the invert lowered by 11 feet, this reach would have had an average
    invert change of -1.5 ft

Dredging was conducted between 1994 and 2001 on the North and South forks of the Mokelumne River, the Lower Mokelumne River and Dead Horse Slough (Darcie, 2002). Clearly, dredging has affected channel invert elevation and may have contributed to the observed net channel incision from 1994 to 2001. In addition to dredging, major floods in 1995 and 1997 may have scoured some channels in the North Delta (NHC, 2003). Due to incomplete records, the quantities and locations of historical dredging in the project area are not well documented. Thus, the extent to which dredging has contributed to the observed sediment loss in project area is not known.

3.4 Historical Trends

Historical changes in the North Delta that have affected channel morphology include land reclamation, levee construction, dredging, hydraulic mining, impoundment of water and sediment by upstream dams and other diversions, as well as the construction of water diversion facilities and consequent alteration of flow and sedimentation patterns in the Delta. The effects of these changes on channel morphology in the project area are summarized below:

- Waterways in the project area are largely confined by levees and able to convey significantly greater flow and sediment discharges than during historic times.

- Historical cross-section data indicate that the majority of waterways in the project area have experienced some channel incision over the several decades and may be experiencing a net sediment loss over time.

- Water regulation, diversions, and the impoundment of water and sediment by dams has resulted in a decline in the total annual water and sediment outflows to the Delta from the Central Valley, a trend that is expected to continue into the future (NHC, 2003).

- The construction of large water diversion facilities such as the Delta-Mendota Canal and Delta Cross Channel in 1951, and California Aqueduct in 1973 have altered the traditional flow patterns in the Delta that affect sedimentation. Water and sediment exhibit a more southerly flow in the Delta, somewhat reducing deposition of sediment in the North and Central Delta and increasing deposition of sediment in the South Delta (NHC, 2003).

- The combination of overgrazing, deforestation, floodplain reclamation, river channelization, and, most importantly, hydraulic mining for gold caused huge increases in sediment loads in the Delta system. The historic trend demonstrates a rapid decline of sediment loads in the Delta streams at the beginning of the 20th century, followed by a gradual steady reduction of sediment loads over the last half a century (NHC, 2003).

Section 4.0

Extensions and Modifications Made to the MIKE11 Hydraulic Model

4.1 Model Description

Northwest Hydraulic Consultants obtained a MIKE11 hydrodynamic model of the North Delta from the University of California at Davis (UCD). The model was developed at UCD to evaluate flooding scenarios in the project area and to assist in the design of flood control and ecological restoration alternatives. Figure 5 presents the domain of the model and significant boundary conditions.

A thorough review of the original MIKE11 model developed by UCD, as well as its documentation (Chris Hammersmark, MS Thesis, UCD, 2002) (Stephen Blake, MS Thesis, UCD, 2001), was undertaken. Sources for the geometry and input parameters were verified. An unsteady HEC-RAS model of the project area was also obtained from MBK engineering and used to extend the original MIKE11 boundaries and to evaluate its results. Both models were developed with respect to the NGVD 29 vertical datum, although the MIKE11 model used SI units and the MBK model English units.

Once acquired, the original MIKE11 hydrodynamic model was updated to extend the domain of the model and to improve the accuracy of the results. Important changes were made to both the model's channel geometry and boundary conditions.

4.2 Channel Geometry Improvements

As depicted in Figure 5, various geometric improvements and extensions were made to the channels in the MIKE11 hydrodynamic model. These included:

Cosumnes River and Deer Creek: Additional cross sections were added along the Cosumnes River and Deer Creek to improve their alignments and increase the overall length of the branches. The resulting total length was 56240 m (about 35 miles) for the Cosumnes River and 10108 m (about 6.3 miles) for Deer Creek. Existing maps and aerial photographs published by the U.S. Geological Survey (http://terraserver-usa.com) were used to during the process. Surveys provided by Candice Fehr from year the 2000 at 31 locations along the reaches were also integrated into the model.

Dry Creek, Grizzly Slough, and Bear Slough: The original cross-sections along Dry Creek, Grizzly Slough, and Bear Sloughs in the original MIKE11 model were somewhat inconsistent. Therefore, they were replaced with those from the HEC-RAS model. Raw cross-section data was converted from HEC-RAS format into MIKE11 format by UCD. The HEC-RAS cross-sections did not extend as far upstream as the present Dry Creek branch in the MIKE11 model. Therefore, the upstream most section was duplicated multiple times to extend the total reach length. Although most cross-sections along Grizzly and Bear Sloughs compare more favorably between the models, the HEC-
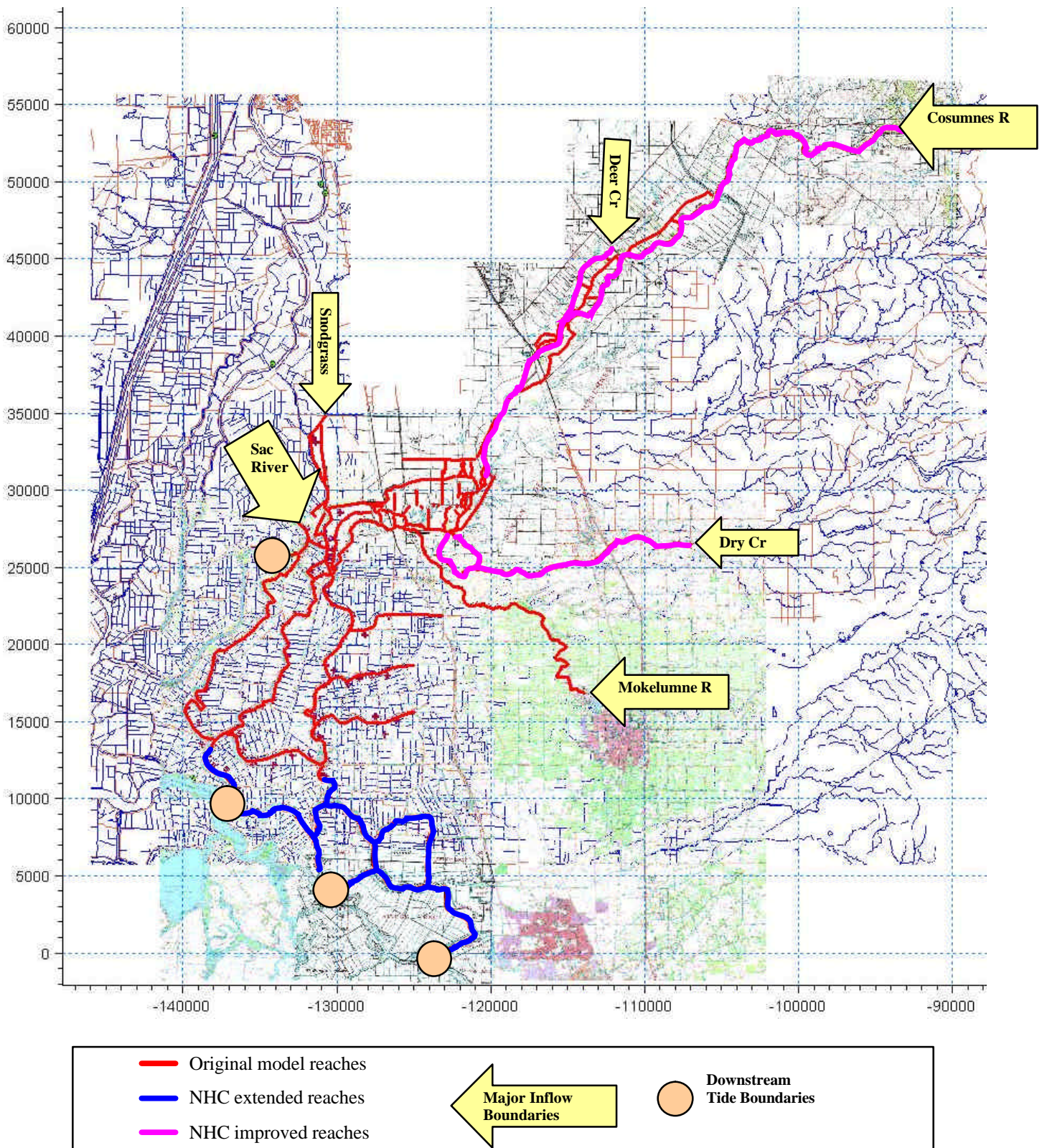
Figure 5. Modeling domain and branch layout for MIKE11 model of the North Delta

RAS sections for the Cosumnes tended to be higher than those originally in the MIKE11 model.

Lower Mokelumne and Sloughs: In parallel to NHC's work, UCD continued to make its own improvements to the MIKE11 model, which have also been integrated into the present model. UCD updated channel geometries in the region below Benson's Ferry near the McCormack-Williamson Tract using recent cross-sections obtained from the North Delta Scour Monitoring Program and by redigitizing existing branches to elongate and improve channel alignments. This helped capture actual channel sinuosity and improved model representations of tidal oscillations. Additional improvements implemented by UCD include:

- *Channel Redigitization*. Branches for the following streams were redigitized and lengthened, with cross-sections repositioned as necessary to represent proper location based upon their coordinates: Middle Mokelumne (below Cosumnes), South Mokelumne, North Mokelumne, Lower Mokelumne (above Georgiana), Georgiana Slough, Hog Slough, Sycamore Slough, Beaver Slough, Snodgrass Slough, Dead Horse Cut, Delta Cross Channel, Meadow Slough, Lambert Slough, and Middle Slough.

- *Cross-sections Additions*. Cross-sections were added to the following branches using data from the North Delta Scour Monitoring (NDSM) 2000 survey: Middle Mokelumne (below Cosumnes), South Mokelumne, North Mokelumne, Lower Mokelumne (above Georgiana Slough), Little Potato Slough (north of White Slough), Hog Slough, Sycamore Slough, Beaver Slough, Snodgrass Slough, Dead Horse Cut, and Delta Cross Channel.

- *Branch Additions*. The North of Twin Cities Road (NofTCR) floodplain branch was added to the current model, improving the performance of the model at the Twin Cities Road bridges under high flows.

Bridge Crossings: Except for the Highway 99 bridge over the Cosumnes River, no other bridges were initially incorporated into the UCD MIKE11 model. To remedy this, NHC attempted to add bridge structures to the model at the following locations: Wilton Road on Deer Creek and Cosumnes River, Dillard Road on Cosumnes, Highway 99 on Cosumnes, Twin Cities Road on Cosumnes and overflow branch, Thornton/Franklin Road (J8) on Mokelumne River, and New Hope Bridges (J11) on the North and South Mokelumne. Unfortunately, results were generally quite unsatisfactory, as to the model overestimated headloss under a variety of hydraulic conditions. The bridges were subsequently removed and replaced by simple pier structures in the channel. Bridges at the Twin Cities Road on the Cosumnes, Thornton/Franklin Road (J8) on the Mokelumne, and the New Hope Bridges (J11) on both the North and South Mokelumne Rivers were added to the model in this manner. After analyzing the results of several model runs, it was evident that the Twin Cities Road Bridge could become submerged during a large flood event. Under this scenario, the model might not accurately predict local flow conditions since the deck of the bridge is not included in the model geometry.

4.3 Downstream Boundary Improvements

The downstream boundaries in the original MIKE11 model consisted of the Lower Mokelumne River just below its confluence with Georgiana Slough and Little Potato Slough at the confluence with White Slough, approximately 2 miles downstream of Highway 12. These were extended by NHC to the San Joaquin River using channel geometry data from the HEC-RAS model. Likewise, Little Potato Slough was extended downstream past White Slough about 1.5 miles. At this point, Little Potato Slough joins with Connection Slough, which splits off the San Joaquin, to become Potato Slough and then rejoins the San Joaquin. Connection, Potato, and White Sloughs were all added to the model, along with Honker Cut, Bishop Cut, Disappointment Slough, and Fourteenmile Slough.

The resulting extended model has five downstream boundaries, all along the San Joaquin River. Stage data for the boundaries was readily available through the California Department of Water Resources and the Interagency Ecological Program. The data sets include (1) Rindge Pump at the confluence between the San Joaquin Riverand Fourteen Mile Slough, (2) Venice Island at the outlet of Disappointment Slough, and (3) San Andreas Landing located on the San Joaquin River just downstream of the confluence with the Mokelumne.

4.4 Upstream Boundary Improvements

For the simulation events modeled by MBK, in 1995 and 1997, in most cases the upstream boundary data used for the MIKE11 model were chosen to match the HEC-RAS modeling. For both the Dry Creek and Cosumnes River inflow boundaries, adjustments had been made by MBK to fill in missing data and account for rating curve shifts. In order to allow direct comparison with the MBK results, these adjusted data were also used in the MIKE11 model. Laguna Creek was also added to the MIKE11 model as a lateral inflow to the Cosumnes, using the MBK inflow data. For Deer Creek at Wilton Road and Stone Lake outlet at Lambert Road (Snodgrass Slough), these are exterior stage boundary conditions in the MIKE11 model. However, these locations are interior within the MBK model. Therefore, HEC-RAS stage output was extracted from the model for the 1995 and 1997 floods, and used as the MIKE11 boundary conditions at these two locations. Realtime (www.sacflood.org) and historic data are also available at these locations from Sacramento County.

4.5 Model Verification and Results

The UCD MIKE11 model was extensively reviewed, and determined to be appropriately developed and applied. Details of the model calibration and setup can be found in a UCD Master's Thesis (Hammersmark, 2002). The model appears to have been reasonably well-calibrated to historical events in 1998 and 2000, and remains well-calibrated with the nhc-modified model (as described herein) – although the results are somewhat

different, in most cases improved. Simulations were also carried out and comparisons made for events in 1995 and 1997 that were simulated by MBK with HEC-RAS.

2000 results: The latest 2000 MIKE11 model compares closely to the original 2000 UCD model, prior to all the improvements. Those bridges with significant piers were modeled by modifying the cross-section geometries, and yield reasonable results. In the area of Cosumnes River at Twin Cities Road, the new results are significantly lower due to the addition of new flow paths by UCD from their 1986 model. These should be more accurate. The Dry Creek branch profile is significantly different due to the new cross-sections which replace the sparse cross-section definition of the previous MIKE11 model. At Benson's Ferry and New Hope Landing, where stage gages are maintained (Figure 6), the calibration is still good if not even better. At Benson's Ferry, particular improvement is noted during the lower stages of the event, while the peak results remain about the same (Figure 7). At New Hope Landing, the previous model tended to over predict water levels. The new model very closely captures the high tide levels and also more closely captures the lower tide (although still too high), resulting in an overall more accurate tidal fluctuation (Figure 8).

1999 results: At the time of the analysis, we had yet to obtain data for the Rindge Pump downstream boundary (Fourteenmile Slough). This data may now be available from the IEP or other website. Boundary conditions elsewhere have been set up for 1999, and the model is otherwise ready to simulate that event.

1998 results: The trends and conclusions for the 1998 simulation are similar to 2000, although the improvement is even more pronounced. At Benson's Ferry, with a few exceptions, the refined model more closely replicates the measured data throughout the simulation (Figure 9). At New Hope Landing, the previous model over predicted water levels by up to more than a meter. The refined model both lowers the computed water levels and also increases the tidal fluctuation, resulting in a very close prediction to the measured levels (Figure 10). Some of the improvement here can be attributed to Chris Hammersmark's recent improvements to the lower part of the model, as discussed previously.

1997 results: The model has been set up and even run for the 1997 flood event, with all the appropriate boundary conditions. However, none of the numerous levee breaches have yet to be added to the MIKE11 model, so the results are not valid for replicating historic 1997 conditions or for comparing with the MBK HEC-RAS model.

1995 results: The MIKE11 and HEC-RAS results generally compare reasonably well. One exception seems to be in the area of the lower Cosumnes, around Twin Cities Road and downstream to Grizzly and Bear Sloughs and the adjacent. MIKE11 results are as much as 2.5m higher (Cosumnes at Grizzly/Bear) than HEC-RAS. The HEC-RAS model, outside of the main channels, consists of many inter-connected storage areas, whereas the MIKE11 model includes more linked branches but is missing some floodplain areas that do become inundated. Measured data is lacking within this area, although adding these missing floodplains to the MIKE11 model would add storage (and

possibly conveyance) and likely lower the predicted water levels somewhat closer to the HEC-RAS results. There was also one levee breach simulated in the HEC-RAS model along Grizzly Slough, which was not included in the MIKE11 simulation. From this area continuing downstream towards the west and south, however, the results improve. At Benson's Ferry as well as New Hope Landing, both models replicate the measured data reasonably well, with the HEC-RAS model slightly under predicting the stage and the MIKE11 model slightly over predicting (Figures 11 and 12). Continuing downstream the results between the two models compare even better.
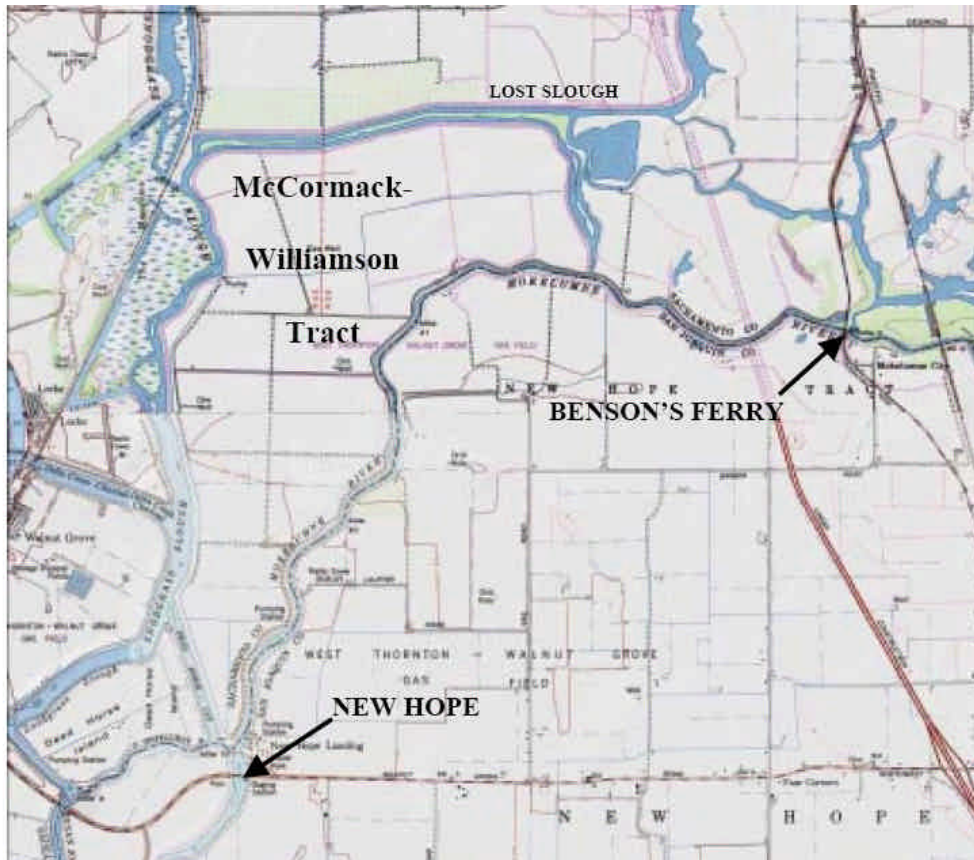

Figure 6. Water surface elevation gage locations within the project area
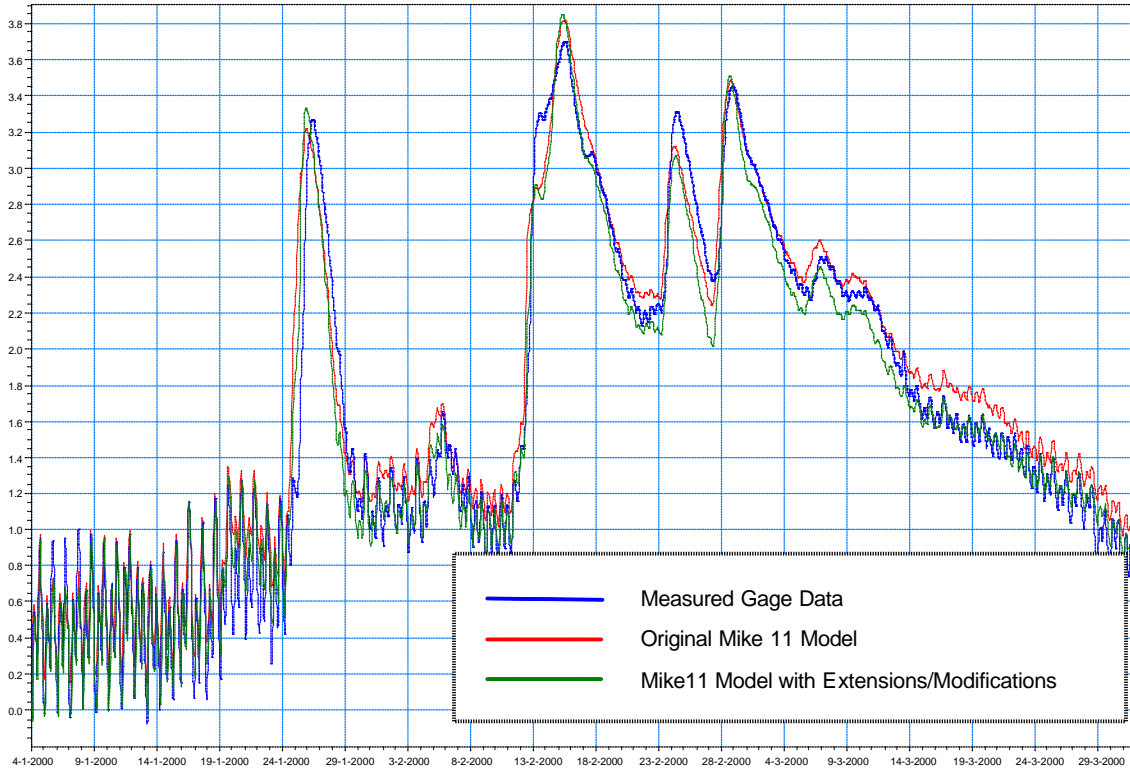
Figure 7. Benson's Ferry water level comparisons (meters NGVD29) for Jan-Mar 2000.

Figure 8. New Hope Landing water level comparisons (meters NGVD29) for Jan-Mar 2000.

Figure 9. Benson's Ferry water level comparisons (meters NGVD29) for Jan-Apr 1998

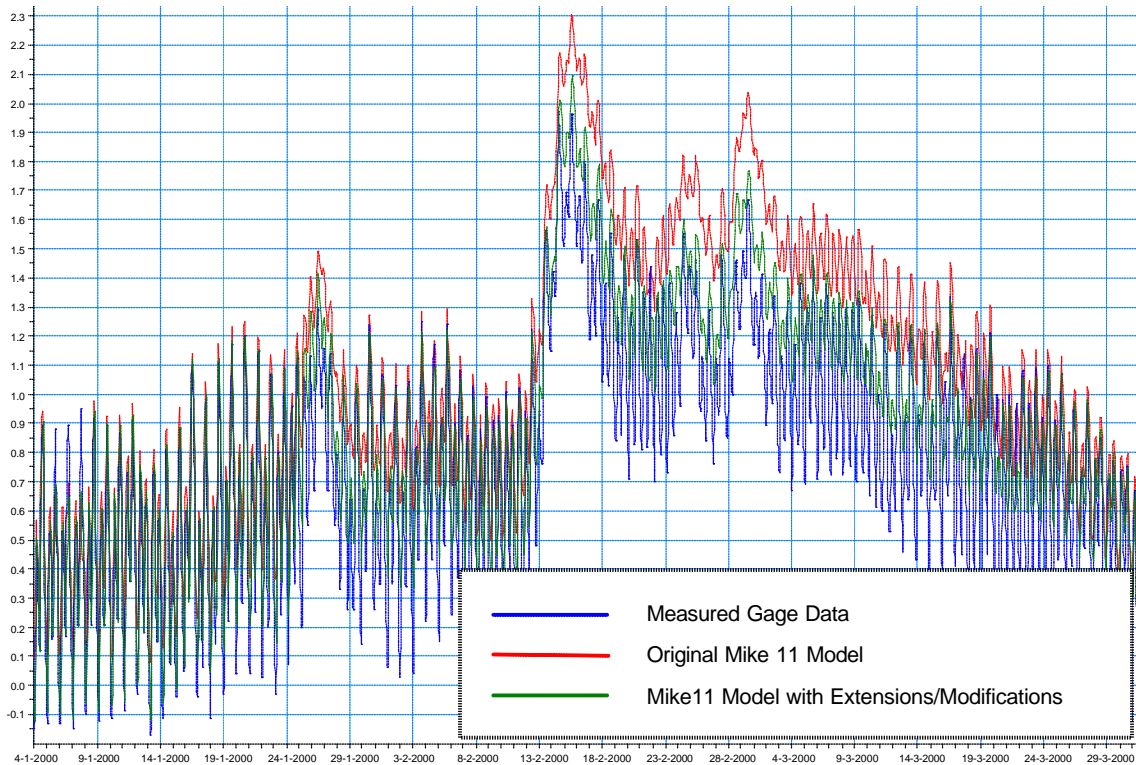**Figure 10.** New Hope Landing water level comparisons (meters NGVD29) for Jan-Apr 1998
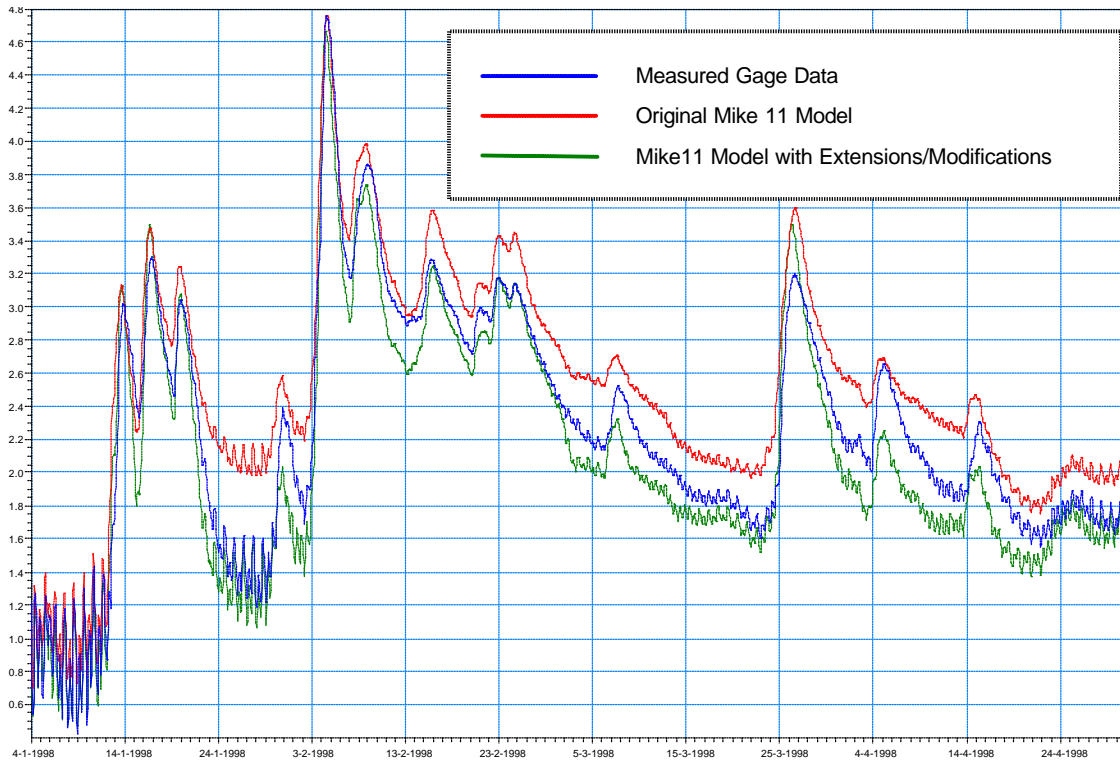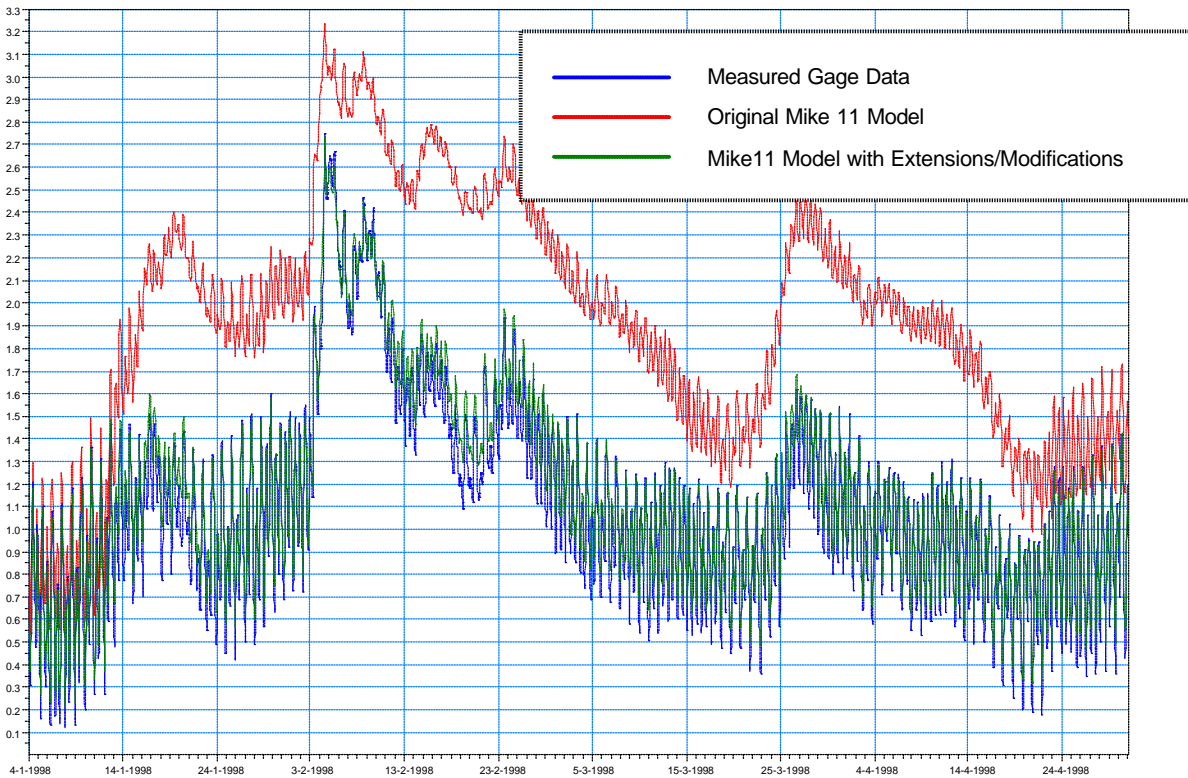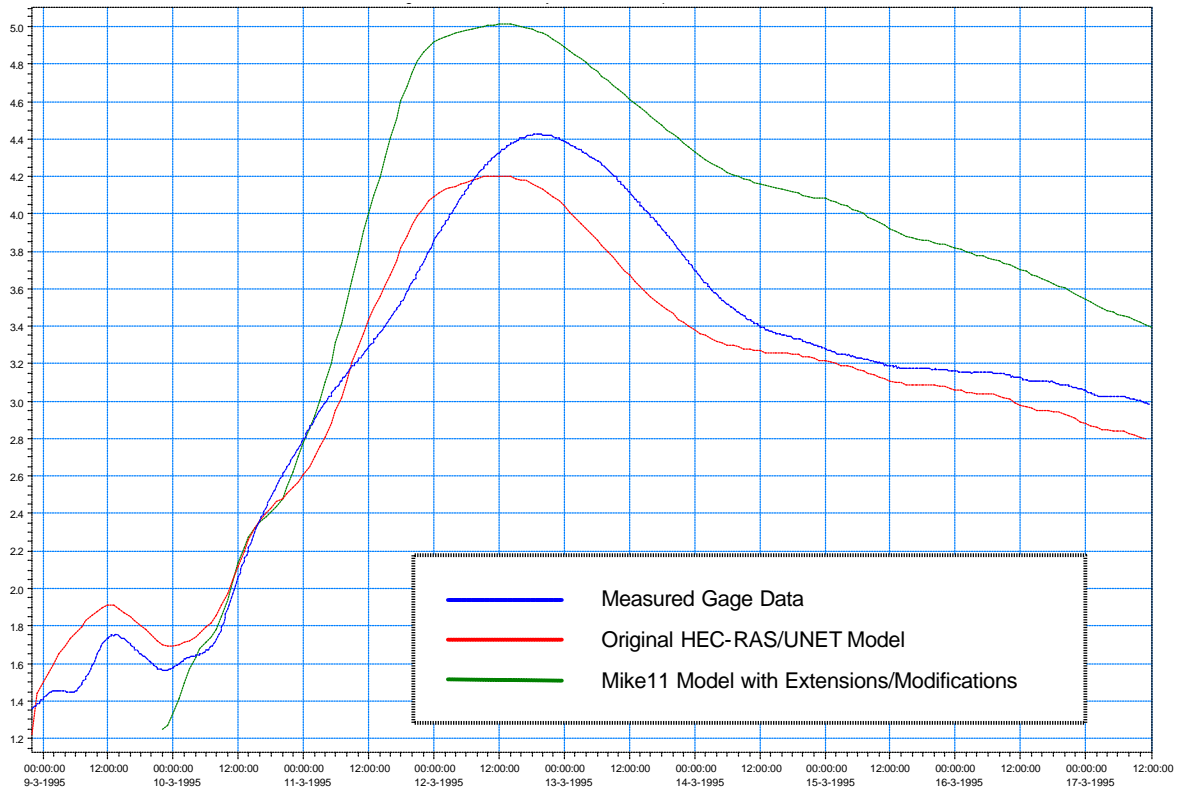
Figure 11. Benson's Ferry water level comparisons (meters NGVD29) for Mar 1995
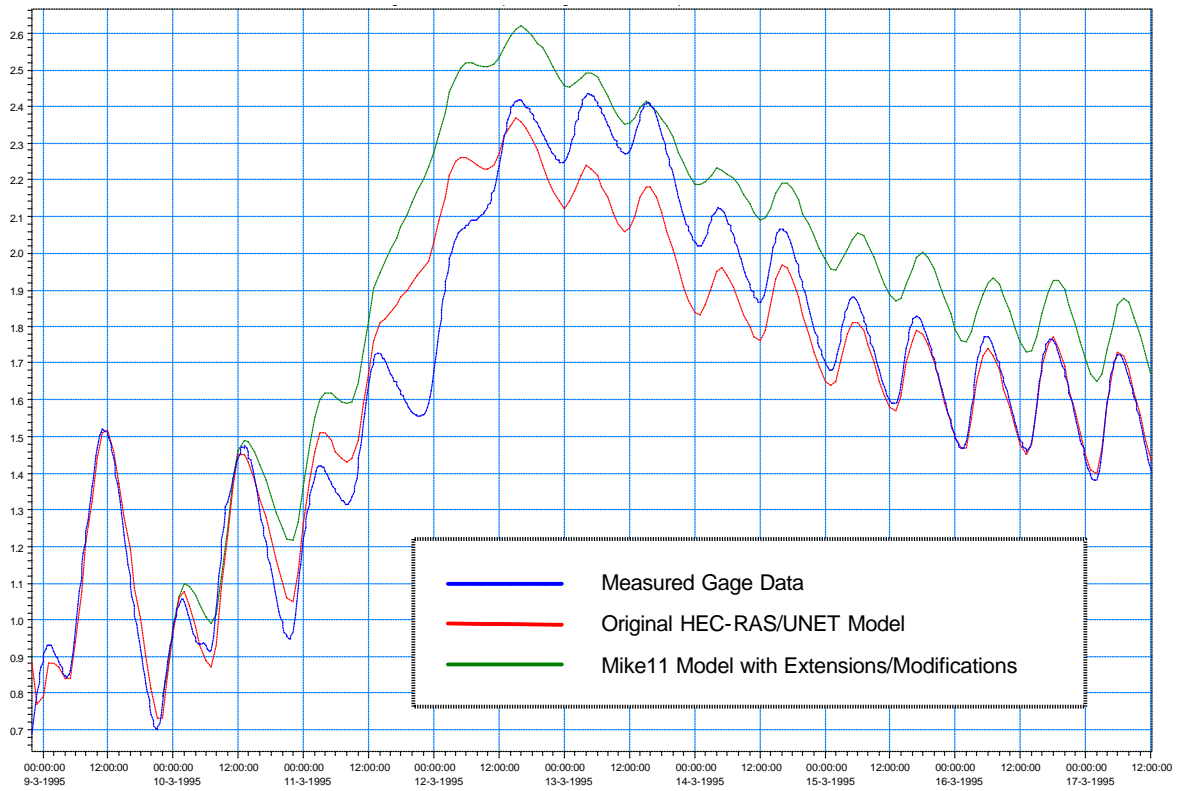

Figure 12. New Hope Landing water level comparisons (meters NGVD29) for Mar 1995

Section 5.0
North Delta Data Collection

Bed samples and flow measurements were taken from the North Delta study area prior to the development of the sediment transport model to verify the existing data set and to fill-in data gaps. The following section describes the nature of the data collected and summarizes its implications with respect to calibration of the transport model.

5.1 Existing Sediment Data

Bed material samples had been collected previously near the study area by the USGS (2002) and the University of California, Davis (Constantine, 2001). According to the results of this sampling, the bed material in the Sacramento River near Sacramento consisted of fine to coarse sand with small amounts of fine gravel. The bed material of the lower Cosumnes River was composed of fine to medium gravels. The grain size distributions for the Sacramento and Cosumnes Rivers are presented in Figure 13.

Systematic measurements of suspended load at selected locations on streams tributary to the Sacramento-San Joaquin Delta was initiated by the USGS in the late 1950's. Daily suspended load data are available for the Sacramento River at Sacramento (1956-1979) and at Freeport (1979-2000), Yolo Bypass near Woodland (1979-1980), San Joaquin River near Vernalis (1959-2000), and Cosumnes River at Michigan Bar (1962-1970). Episodic measurements of suspended load are available for Yolo Bypass near Woodland (1957-1961), Cosumnes River at McConnell (1965-1967), and Mokelumne River at Woodbridge (1974-1994). Suspended sediment composition data found for the Sacramento and Cosumnes Rivers are presented in Figure 14. As is apparent from the figure, suspended sediments in the Delta streams are mostly composed of clay, silt, and fine sand.
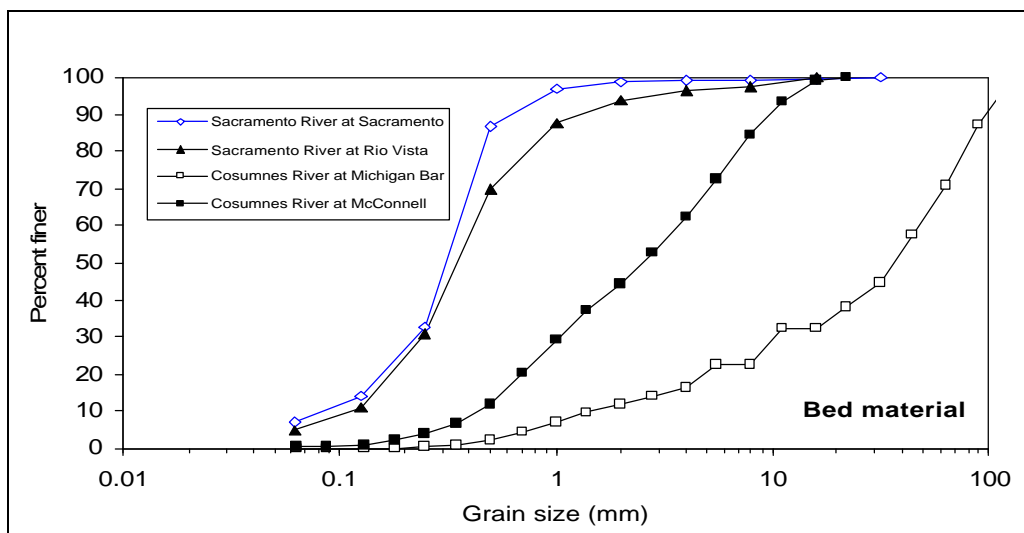

Figure 13. Grain size distribution of bed material from the Sacramento and Cosumnes Rivers
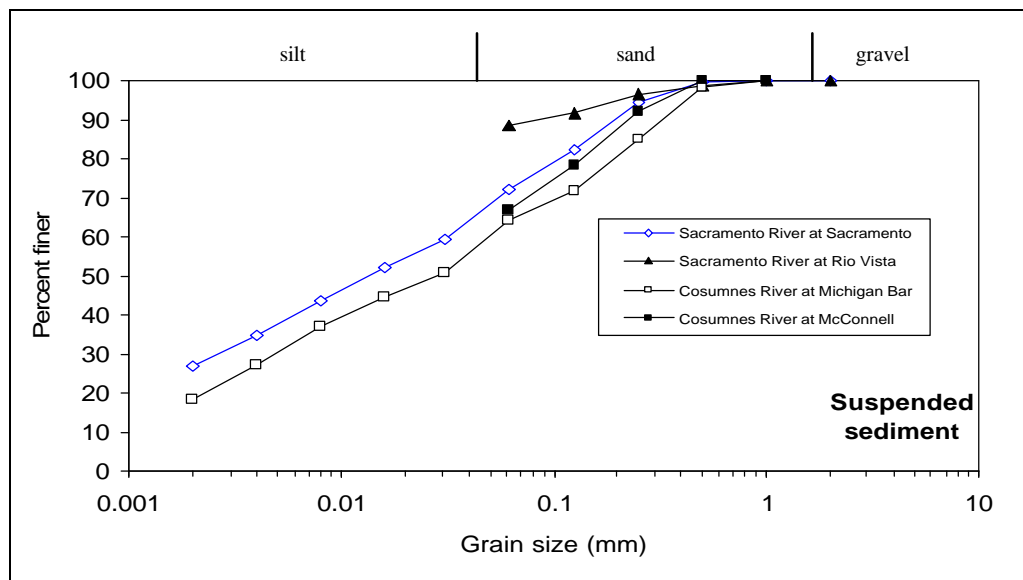
Figure 14. Grain size distribution of suspended sediment from the Sacramento and Cosumnes Rivers

5.2 Sediment Sampling by NHC

Northwest Hydraulic Consultants collected bed material samples from within the study
area in October of 2003 and September of 2004. The material collected during 2003 was
taken from the network of channels surrounding Dead Horse Island north of Staten
Island. Analysis of the sediment was performed by Raney Geotechnical in order to
develop grain size distribution curves. The samples collected in 2004 were not quantified
by sizing, but rather evaluated qualitatively in the field. The main goal of this sampling
was to determine the general composition of the sediments in the North and South Forks
of the Mokelumne.

5.2.1 2003 Sediment Sampling

NHC collected bed material samples in the North Delta near Dead Horse Island for sieve
analysis in 2003. The locations of sampling sites are presented in Figure 15, and the
resulting cumulative grading curves of the analyses are presented in Figure 16. As shown
in the figure, the bed material samples consisted mainly of medium to fine sands with silt
and organic material deposited in low energy areas, such as Dead Horse Cut, portions of
Snodgrass Slough, and the North Mokelumne River above Snodgrass Slough. No
sediment samples were taken from Snodgrass Slough at North Mokelumne River due to a
thick layer of cockle-shells that exists there.

5.2.2 2004 Sediment Sampling

Bed samples were collected in the lower reaches of Georgiana Slough and from the North
and South Forks of the Mokelumne River in 2004 to determine the general composition
of the sediments in those regions. The sampling indicated that the lower ends of these
rivers contain mostly silt with a little fine sand that formed a foamy mud on the bottom of
the rivers. Samples taken just downstream of the Walnut Grove Road Bridge from the

North and South Forks of the Mokelumne, however, consisted of medium and fine sands with a little silt, indicating that a significant sediment interface exists in these reaches. The transition zone occurred approximately 1.5 miles south of the bridge on the North Mokelumne and near Beaver Slough on the South Mokelumne.

5.3 Flow Measurement Sampling

Discharge measurements were taken at ten locations within the North Delta study area on June 9th and 10th, 2004. Flowrates in each channel reach were measured using an acoustic doppler channel profiler (ADCP) attached to the bow of a small boat. Most measurements of flow into a junction were taken within a few minutes of each other, so that tidal effects were minimized. The locations of the flow sampling sites are also presented in Figure 15. The results of the discharges measurements at the four junctions
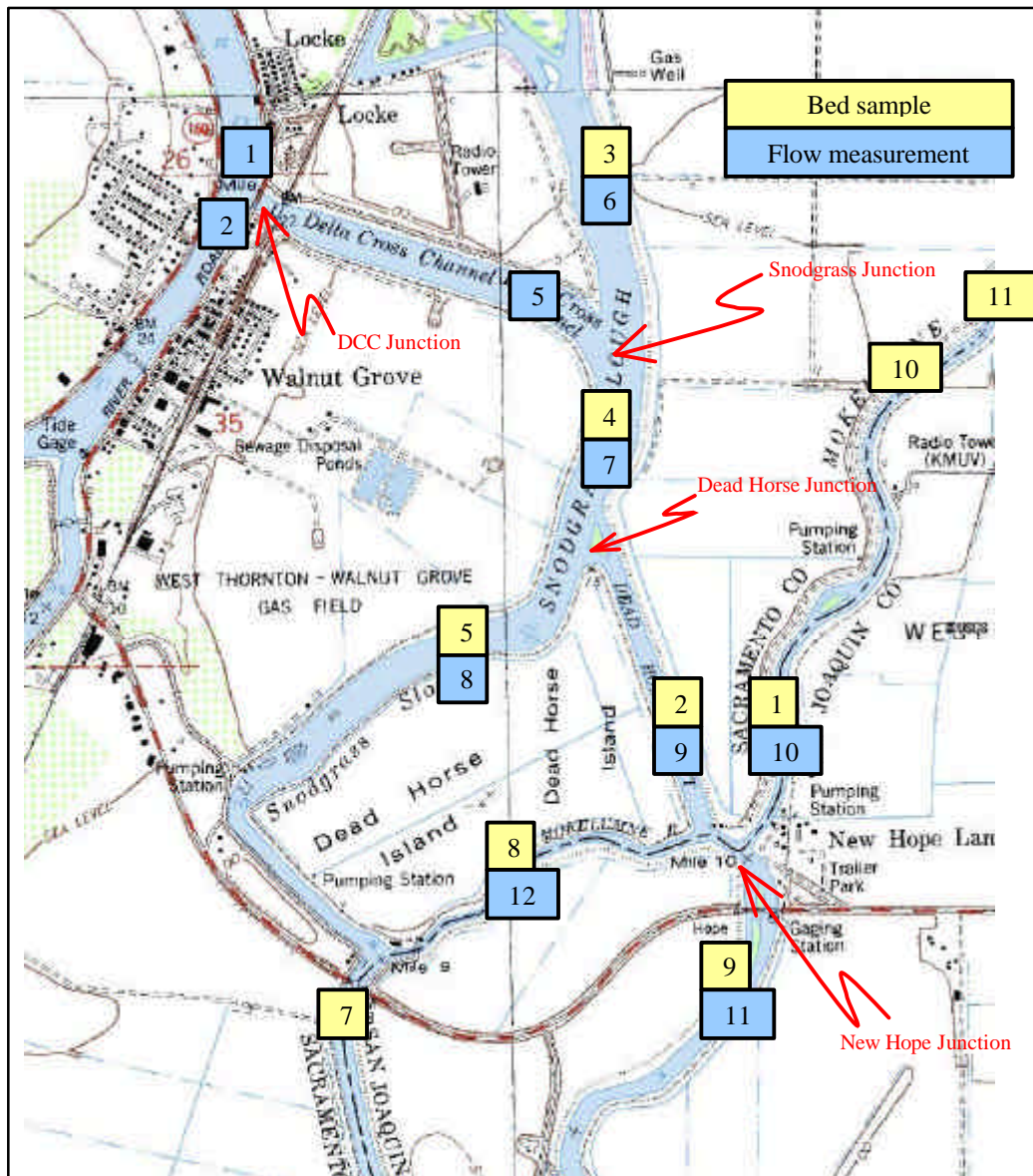

Figure 15. Location of bed material (10/03) and flow discharge (06/04) sampling sites in project area
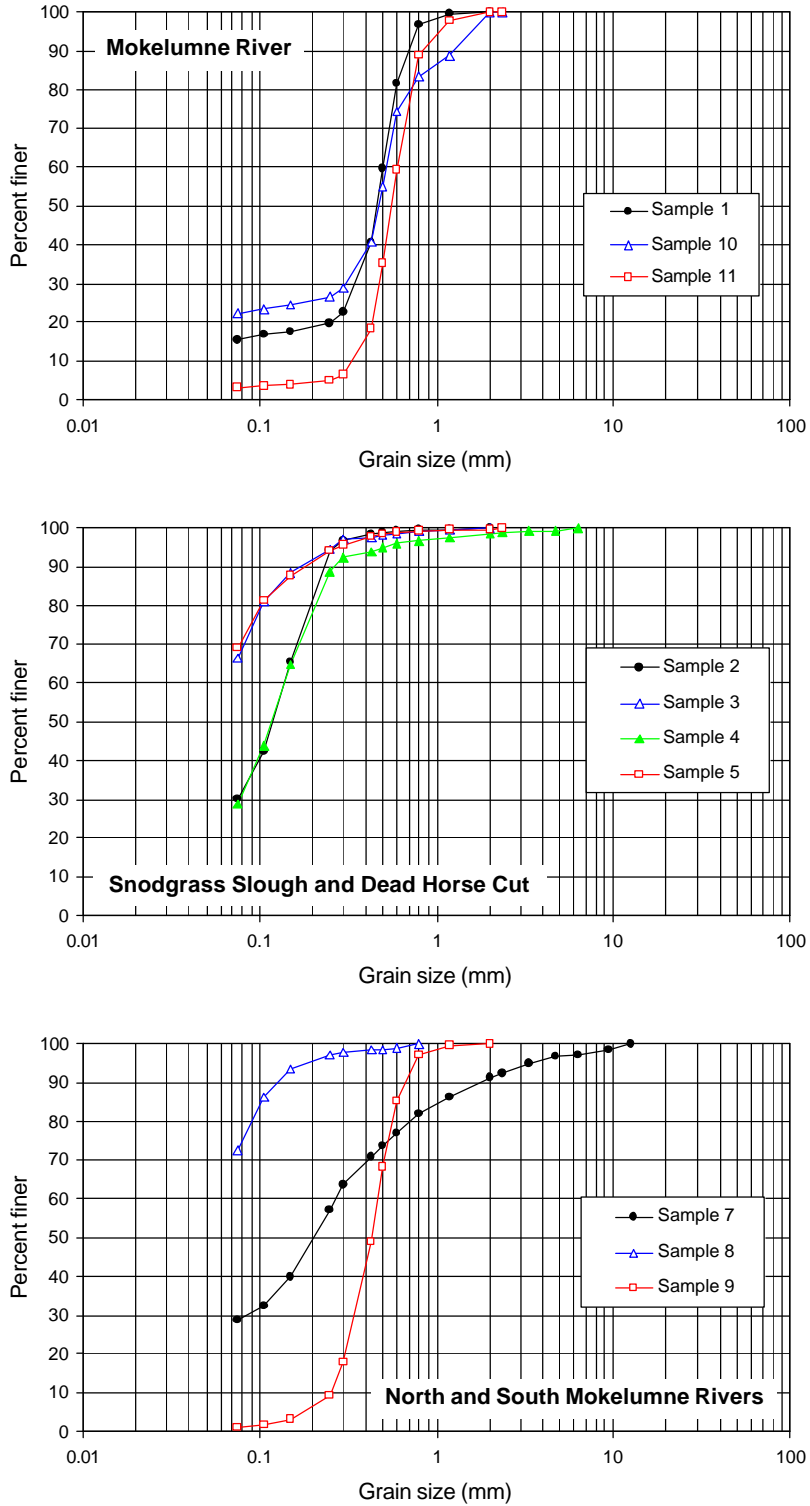
Figure 16. Bed material composition from North Delta sites shown in previously in Figure 15

are presented in Tables 2a through 2d. The column *diff Q* in the tables represents the net sum of flow into and out of a junction. This residual flow is due mainly to tidal fluctuations in the Delta that strongly affected both stage and discharge at each junction. Additional differences may also be attributed to instrument precision.

Table 2a. Measured discharges near the Delta Cross Channel Junction[†]

Junction: **Delta Cross Channel**				
Day	Sampling Time	Reach 1 (cfs)	Reach 2 (cfs)	Reach 5 (cfs)	diff Q (cfs)
Jun 09	11:13-11:36	9500	-	-3900	-
Jun 10	11:06-11:24	8400	-1400	-7300	-300
Jun 10	13:02-13:28	10700	-8800	-3100	-1200
Jun 10	15:17-15:55	13500	-11500	-2200	-200

Table 2b. Measured discharges at Snodgrass Slough Junction[†]

Junction: **Snodgrass**				
Day	Sampling Time	Reach 5 (cfs)	Reach 6 (cfs)	Reach 7 (cfs)	diff Q (cfs)
Jun 09	12:09-12:48	1200	2200	-3000	400
Jun 10	11:06-11:57	7300	-2600	-4600	100
Jun 10	12:24-13:07	3100	-800	-3100	-800
Jun 10	15:12-15:37	2200	2100	-4300	0

Table 2c. Measured discharges at near Dead Horse Island[†]

Junction: **Dead Horse**				
Day	Sampling Time	Reach 7 (cfs)	Reach 8 (cfs)	Reach 9 (cfs)	diff Q (cfs)
Jun 09	10:08-10:40	3300	-2300	-1200	-200
Jun 10	10:29-10:48	4600	-3000	-1600	0
Jun 10	12:04-12:29	3300	-2500	-1200	-400
Jun 10	14:52-15:15	4300	-3400	-1000	-100

Table 2d. Measured discharges at near New Hope Landing[†]

Junction: **New Hope Landing**					
Day	Sampling Time	Reach 9 (cfs)	Reach 10 (cfs)	Reach 11 (cfs)	Reach 12 (cfs)	diff Q (cfs)
Jun 09	9:31-10:12	1200	-1100	-500	200	-200
Jun 10	10:01-10:31	1600	-1000	-1000	300	-100
Jun 10	11:38-12:07	1200	-600	-700	-40	-140
Jun 10	14:29-14:54	1000	1000	-1300	-600	100

[†]*Measured discharges at channel junctions presented in Figure 15 (positive signifies flow into junction)*

Section 6.0
Sediment Budget of the Delta

A preliminary sediment budget for the Sacramento-San Joaquin Delta was estimated by Northwest Hydraulic Consultants using available sediment data, rating curves, and established sediment transport equations. Annual suspended sediment loads were determined using USGS suspended sediment data collected in 1998 (high-flow year) and 1999 (average-flow year) from the Sacramento, San Joaquin, Mokelumne, and Cosumnes Rivers, and from the Yolo Bypass, Delta-Mendota Canal, and Suisun Bay. Annual bed loads were established indirectly using the *Levi* sediment transport equation.

It is worthwhile noting that the estimation of a sediment budget for a system as large and complex as the Delta is subject to high degrees of uncertainty, and the results presented here should be viewed accordingly.

6.1 Suspended Sediment

The annual suspended sediment contribution of the Sacramento River was calculated using daily time series data collected at the Freeport sediment gauge. Annual suspended sediment yields in the San Joaquin River were calculated using daily data available from the Vernalis gauge. Suspended loads passing through the Sacramento Weir to the Yolo Bypass were calculated using daily flow data for the weir and daily suspended sediment concentrations from the Sacramento and Freeport gauges. Suspended sediment concentration at the weir was assumed to be 0.78 of the concentrations at Sacramento and Freeport (Porterfield, 1980).

Annual suspended loads in Yolo Bypass near Woodland, Cosumnes River at Michigan Bar, Mokelumne River at Woodbridge, and Delta-Mendota Canal near Tracy were estimated using daily flow time series data and sediment rating curves developed from episodic measurements of suspended load. Suspended sediment outflow from the Delta to the Clifton Court Forebay and further to the California Aqueduct was estimated using daily flow data for the Banks Delta Pumping Plant and a suspended load rating curve obtained for the Delta-Mendota Canal. It was assumed that the suspended sediment concentration at the water intakes was the same for both water export facilities.

6.2 Bed Load

The bed load data collected by the USGS in the Sacramento River and in Threemile Slough (Dinehart, 2000) are limited in volume and range, which prevents accurate estimation of the bed load yield using the measured data alone. However, these data provide a useful basis for selection of a bed load transport formula most appropriate for the conditions of Delta streams. Since hydraulic data from Delta streams usually contains both flow and stage information at a station, and due to the complex and highly sensitive flow behaviors exhibited in the tidally influenced Delta, six bed load transport formulas based on the flow-velocity concept were considered. Of the six, the Levi (1957) formula

proved to be most accurate at predicting the bed load of the Sacramento River at Freeport. Using metric units, the formula can be expressed by:

$$q_b = 2\left(\frac{V}{\sqrt{g\,D}}\right)^3 D\left(V - V_c\right)\left(\frac{D}{h}\right)^{0.25} \tag{1}$$

where q_b is the bed load transport rate per unit channel width (kg/s/m); V is the average flow velocity (m/s); V_c is the critical average flow velocity at which bed load transport begins (m/s), defined as

$$V_c = 1.4\sqrt{g\,D}\,\log\frac{12h}{D_{90}}\left(\frac{D}{D_{max}}\right)^{0.1} \text{ for } \frac{h}{D_{90}} > 60 \text{, and}$$

$$V_c = 1.4\sqrt{g\,D}\left(0.8 + 0.67\log\frac{10h}{D_{90}}\left(\frac{D}{D_{max}}\right)^{0.1}\right) \text{ for } 10 \le \frac{h}{D_{90}} \le 60 \tag{2}$$

where g is gravitational acceleration (9.81 m/s^2); D is the median grain size (m); D_{max} is the maximum grain size (usually D_{95}) of the bed material (m); D_{90} and D_{95} are the grain sizes for which 90 and 95% of sediment is finer (m); and h is the flow depth (m).

Equation (1) was used together with flow and stage data downloaded from the USGS and DWR databases, and bathymetry data from NOAA, USCOE, USGS, and DWR. Discrete bed load volumes were calculated at 15-minute to 24-hour intervals, depending on the resolution of the available flow and stage data, and then summed together to obtain annual yields.

6.3 Annual Sediment Budget Estimate

Figure 17 presents the results of the sediment budget estimate developed for various discrete locations in the Sacramento-San Joaquin Delta. The figure demonstrates that the Sacramento River system including the Yolo bypass is the primary supplier of sediment to the Delta. The average annual sediment inflow from the Sacramento River system is
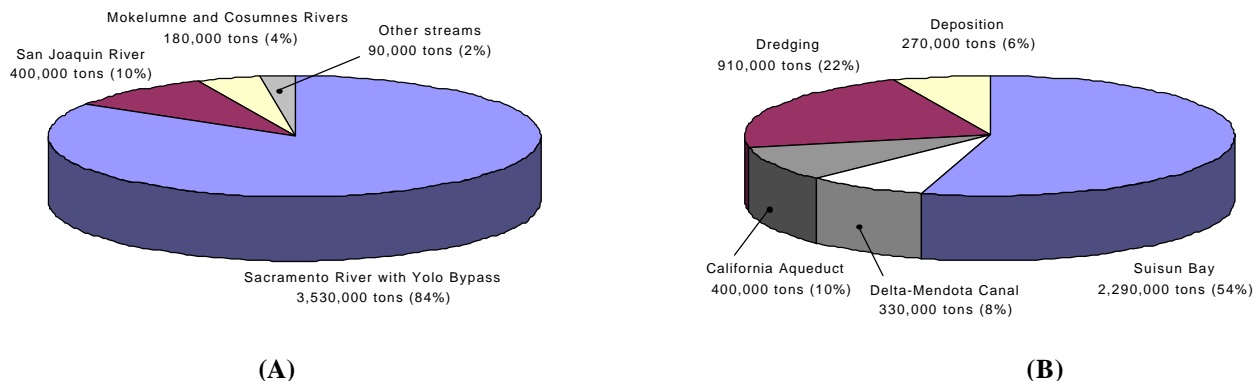

(A)   **(B)**
Figure 17. Average annual inflow (A) and outflow/dredging (B) of sediments in Delta

about 3,530,000 tons, or 84% of the total sediment inflow to the Delta. The San Joaquin River system supplies about 400,000 tons of sediment and the Mokelumne River system supplies 180,000 tons of sediment. An allowance of 90,000 tons per year was added for other streams and creeks not covered by the present analysis (Porterfield, 1980). Bed load supply is 151,000 tons for the Sacramento River, 79,000 tons for the San Joaquin River, and about 8,000 tons for the Mokelumne River. For these calculations, bed load outflow through the Delta-Mendota Canal and California Aqueduct was ignored. Although bed load constitutes only 4% to 20% of the total sediment load in the Sacramento, San Joaquin, Mokelumne, and Cosumnes Rivers, bed load transport is believed to be the main factor determining channel evolution (fill and scour of the channel bed) in the Delta.

On average, an estimated 2,290,000 tons (54%) of the average annual sediment supply to the Delta is transported to Suisun Bay and 730,000 tons (18%) is exported through water export facilities to Delta-Mendota Canal and California Aqueduct. An estimated 1,180,000 tons (28%) of the sediment supplied is deposited in the Delta each year. About 910,000 tons (22%) is dredged for navigation and levee maintenance purposes. Figure 18 presents the findings geographically.

Using the estimates above, a remainder of approximately 270,000 tons (6%) of sediment per year on average would be deposited in the Delta. Based on analyses of cross sections and data published in DWR's Scour Monitoring Programs (DWR, 1993 and DWR, 2000), it appears that the majority of this deposition is occurring in the South Delta rather than in the north. However, additional analysis and data collection are necessary to confirm this apparent trend.
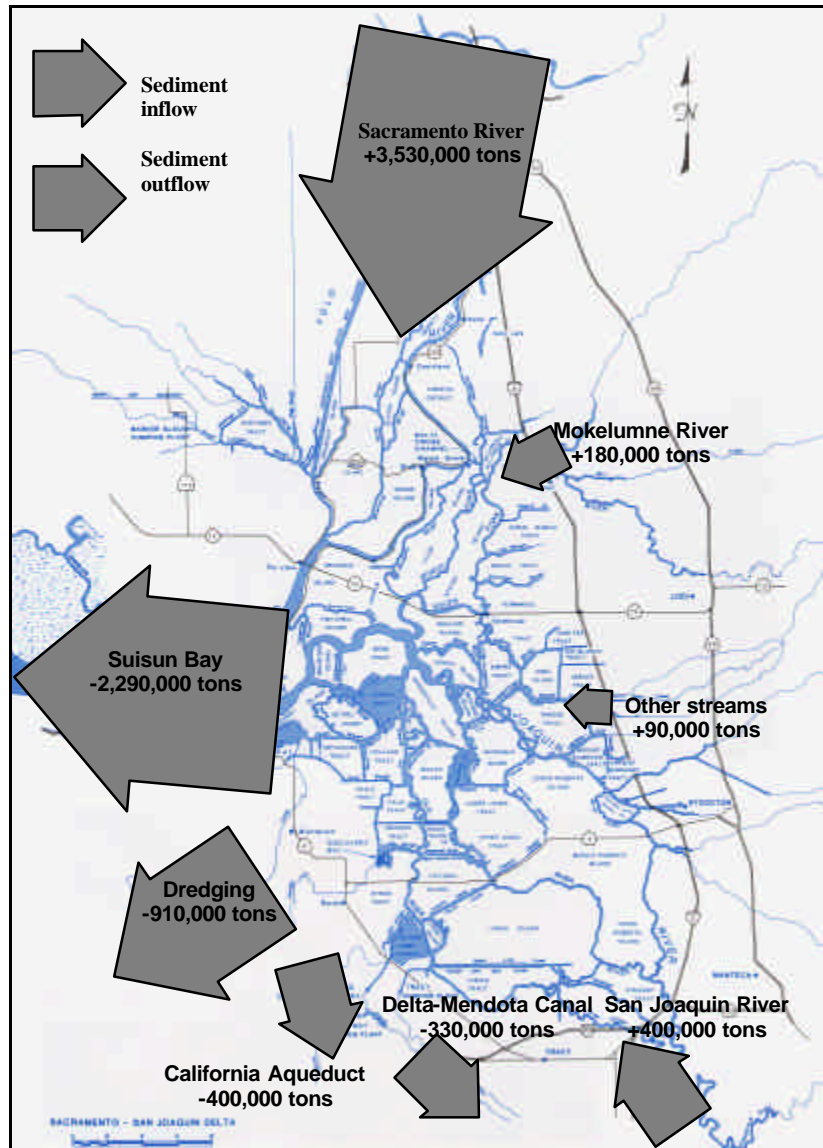
Figure 18. Estimated annual sediment budget for Sacramento-San Joaquin Delta

Section 7.0
Sediment Assessment for 1995 and 1997 Floods

The sediment assessment conducted for streams and sloughs within the North Delta Improvement Project study area was performed as a part of the Task 2 "Sediment Assessment." The work included initial estimation of sediment transport capacities of the channels comprising the NDIP area under a range of flow conditions, using results from the existing conditions HEC-RAS model of the North Delta developed and provided by MBK Engineers.

7.1 Background

The study area for which sediment assessment was conducted is shown in Figure 19. Sediment transport was calculated for two flood events lasting from 8 March 1995 to 17 March 1995 and from 29 December 1996 to 9 January 1997. Calculations were performed for selected representative cross sections of the streams comprising the study area including the Mokelumne River, North Mokelumne River, South Mokelumne River, Dead Horse Cut, Snodgrass Slough, Lost Slough, and Georgiana Slough. The cross sections at which sediment transport was calculated were selected on straight river reaches in the vicinity of the main stream junctions. A few additional cross sections were selected on the streams upstream and downstream of the study area to estimate sediment transport variability along the streams. Cross section geometry and flow hydraulic data were obtained from the HEC-RAS model.

7.2 Assumptions

The transport calculations were performed using the Ackers-White (1973) transport function as modified by Ackers (1993). This transport function predicts total sediment load, which includes sediment transported both in suspension and as bed load. The function is based on a large set of experimental data and is often used for calculation of sand material transport. A mean sediment grain size of $D_{50}=0.5$mm was established using Bed Sample 1 (see Figure 16) to represent the parent bed material and section-average hydraulic parameters were used in the calculations to estimate sediment transport capacity of different channels.

7.3 Results

Calculated sediment yields for the 1995 and 1997 flood events are also summarized in Figure 19. Cross section geometry, maximum water surface elevations during the two flood events, and calculated relationships between sediment load and flow velocity are shown in Figure 5. According to the calculations, net sediment transport capacities in the tidally affected North Delta channels varied from practically zero (Dead Horse Cut) to 25,000 metric tons (Georgiana Slough) during the 1995 flood and up to 56,000 metric tons (North Mokelumne River) during the 1997 flood. Transport capacities vary
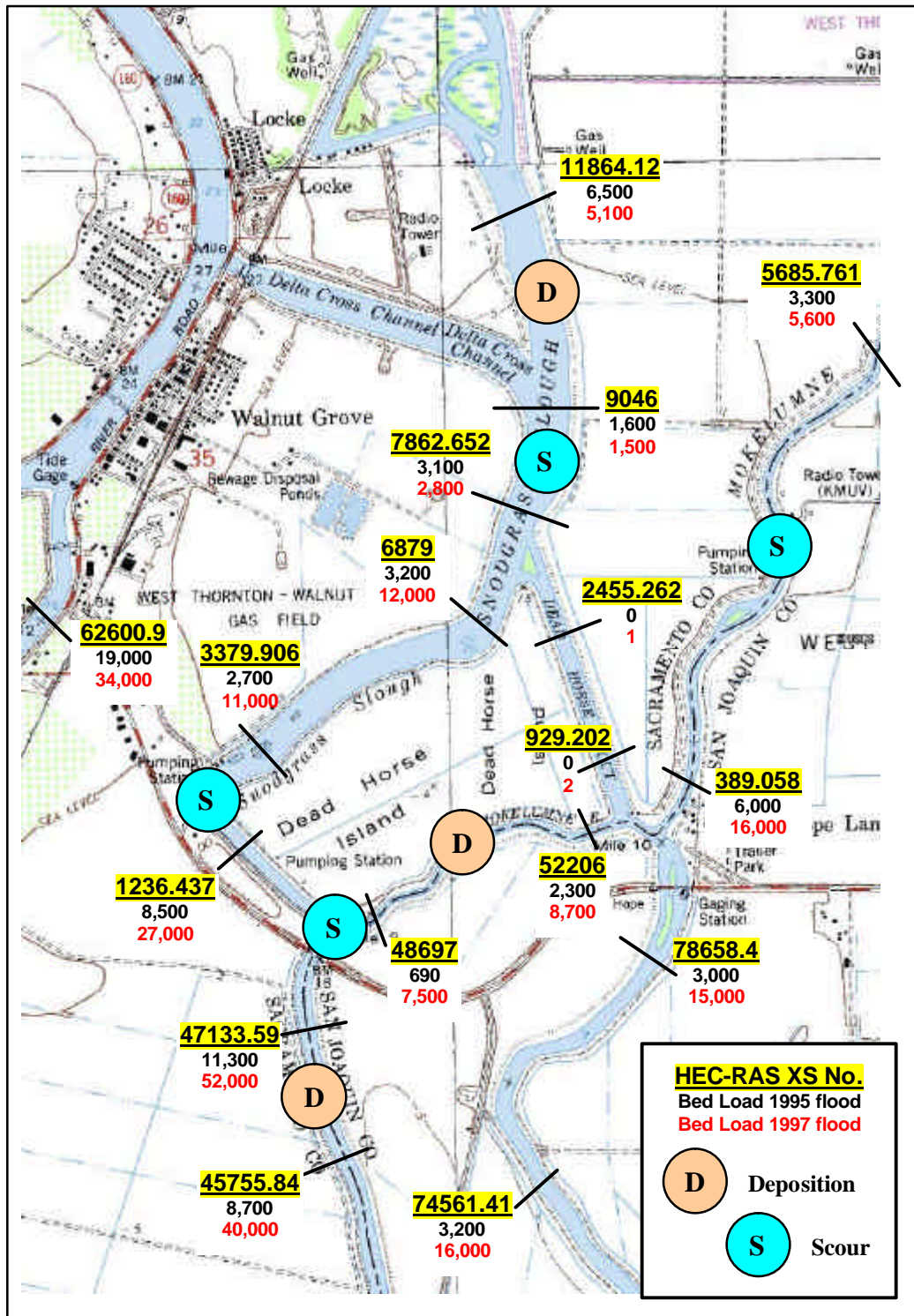
Figure 19. Calculated potential sediment yields (in metric tons) during 1995 and 1997 flood events, including reach tendencies to deposit or scour sediment

significantly along the streams, depending on local channel conditions and tributaries supplying or diverting water and sediment. In the Mokelumne River, sediment transport capacity generally increases in the downstream direction. In the North Mokelumne River, transport capacity increases abruptly below Snodgrass Slough. Fairly uniform longitudinal distribution of transport capacity is obtained for the South Mokelumne River and Georgiana Slough. Although some sediment can be transported by tidal flows up and down Dead Horse Cut, net sediment transport here is practically zero. In Snodgrass Slough, transport capacity reduces in the vicinity of Dead Horse Cut and increased at North Mokelumne River. Variable capacity is obtained along Lost Slough.

In most of the channels higher transport capacities are obtained for the extremely high 1997 flood. During this flood levees were overtopped in some reaches, which resulted in significant volumes of water entering inside areas of islands and tracts. Filling and draining of the floodplain storage areas resulted in complex, atypical streamflow and sediment transport conditions through the North Delta channel network during the 1997 flood event. Therefore, the 1997 flood data are not suitable for sediment budget assessment within some of the North Delta channels. The sediment transport data calculated for the 1995 flood, which was conveyed within the channel boundaries, were primarily used here to identify reaches where significant scour or deposition during high flow events is likely. Potentially depositional/scour reaches of the North Delta are shown in Figure 19. Potential streambed scour is obtained for the lower Mokelumne River at New Hope Landing, Snodgrass Slough between Delta Cross Channel and Dead Horse Cut, narrow channel of Snodgrass Slough at North Mokelumne River, and at confluence of Snodgrass Slough and North Mokelumne River. Potential sediment deposition is obtained for Snodgrass Slough above Delta Cross Channel, North Mokelumne River between Dead Horse Cut and confluence with Snodgrass Slough, and North Mokelumne River below Snodgrass Slough.

Section 8.0
Long-Term Sediment Transport and
Channel Morphology Modeling

Sedimentation in the streams and channels of the North Delta is controlled by a complex sequence of events and physical processes that occur over vast distances and on a wide range of time scales. Modeling such a system over the long-term, in a deterministic sense with confidence, is simply not possible. However, it is possible to develop a simplified model of sediment transport in the Delta by identifying and quantifying some of the significant variables affecting sedimentation, so that trends can be revealed and ultimately predicted.

Northwest Hydraulic Consultants investigated the long-term sediment dynamics of the study area associated with the North Delta Flood Control and Ecosystem Restoration Project to better understand the existing system conditions and to evaluate the effects of proposed flood control and restoration alternatives. The analyses were performed using an enhanced MIKE11 model originally developed by researchers at the University of California, Davis. The sediment transport modeling capability was added to the MIKE11 model using DHI's ST module. The goal of the investigation was to develop a sediment transport model extending from upper MWT to the San Joaquin River that could identify sedimentation rates and changes to those rates due to proposed flood control and restoration alternatives for the region. All modeling described in this report was performed using the 2003 version of DHI's MIKE11 model.

8.1 Sediment Transport Modeling Background

Engineering analysis of erosion and sedimentation is based on Newtonian mechanics applied to moving fluids and sediment particles. Non-cohesive sediment transport assumes that the sediment in a channel is made up of individual particles or grains that do not interact chemically or electromagnetically. Only mechanical forces are assumed to affect the particles, which include the force of moving water, particle collisions, and gravity.

Sediment transport of non-cohesive particles is often categorized using three transport modes: bed load, suspended load, and wash load. The bed load is that portion of sediment transported by bumping and rolling along the bed of the channel. This typically includes coarser sands, rocks, and gravels. Suspended load is transported within the mean flow above the bed and is usually made up of finer sands and silts. Wash load is the term used to describe the fraction of the suspended load that is made up of very fine material, such as fine silts and clays. This sediment is so fine that it tends not to settle out even under low flow conditions, and it usually transported all the way through the system. Each of these sediment loads and their relative position within the water column are depicted in Figure 20.
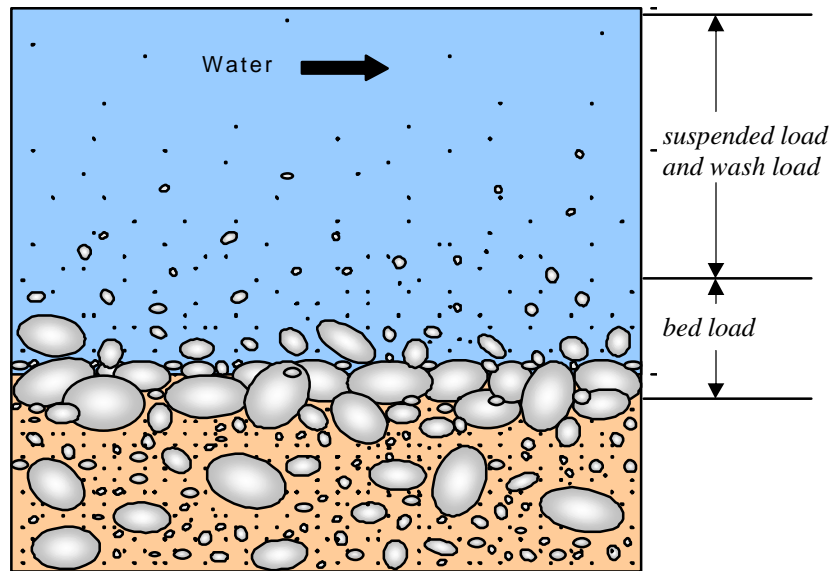
Figure 20. Non-cohesive sediment transport classification

Sediment transport in rivers is modeled using a variety of equations, techniques, and rules of thumb that have been proposed by various researchers over the years. Due to the extremely complex nature of sediment transport, commercially available software packages typically employ simplified empirical and semi-empirical formulas to estimate transport rate based on grain size and local flow conditions. Specific inputs and levels of sophistication vary among the methods, but the output is generally sediment flow rate at a station, with units such as tons per day or liters per second. Because most sediment transport equations provide a deterministic answer to a chaotic and probabilistic event, it is always important to ruthlessly review the results and make sure that the solution makes physical sense.

8.2 MIKE11 Model Setup

The MIKE11 modeling package includes a non-cohesive sediment transport module (ST) which tracks the movement, erosion, and deposition of sediment in river channels. The program allows the user to choose from several standard sediment transport equations that estimate the local rate of scour/deposition based on sediment properties and other hydraulic parameters. The ST module also includes a morphological component that updates the geometry of local cross sections at each time step to simulate deposition and erosion within the system. Sediment transport at a station can be calculated either separately as bed load and suspended load, or together as total load. The model also allows the definition of multiple grain sizes within a reach, to better describe grain-size distributions and to more accurately model mobilization of the bed. The ST module of MIKE11 is appropriate for tracking bed material loads consisting of fine sands and larger particles. Wash load transport and deposition rates were, therefore, calculated separately as described in Section 9 of this report.

8.2.1 North Delta Model Description and Limitations

The North Delta sediment transport model was developed to identify and evaluate changes in sedimentation due to proposed flood control and habitat restoration alternatives. It was operated as an add-on to the existing MIKE11 hydraulic model of the North Delta, which contained all of the channel geometry and network connections for the system. Due to the sheer size of the modeling domain, the resolution of the geometry in the original hydraulic model was rather coarse, especially for sediment transport modeling. However, since the primary goal of the investigation was to evaluate relative differences between alternatives and not to predict exact sediment transport quantities, the resolution was deemed sufficient.

8.2.2 Modeling Domain

The modeling domain of the North Delta sediment transport model is smaller than that of the MIKE11 hydrodynamic model (see Figure 21). It was reduced because of numerous numerical problems that arose in the upstream sections near bridges and around link channels commonly used in MIKE11 to simulate levee breaches and levee overtoppings. Due to a programming flaw, MIKE11 sometimes assumes a cross sectional area of $1m^2$ for link channels when calculating sediment flow splits at a junction. This forces most of the sediment to flow directly past the link channel and to be deposited immediately downstream due to a decrease in flowrate. The sediment deposits quickly grow to unreasonable heights and eventually cause the model to crash. Since it was noted that the link channels were an integral part of the North Delta hydraulic model developed by
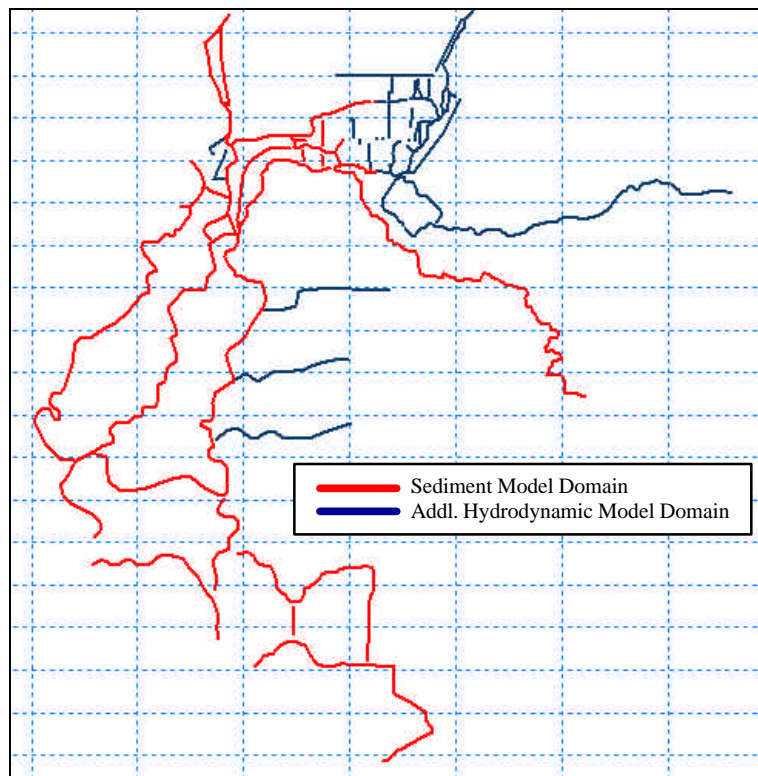

Figure 21. Domain of sediment transport and hydrodynamic models (upper Cosumnes reaches not shown)

UCD and could not be simply removed, the domain of the sediment transport model was reduced instead by excluding some channels near and to the east of Highway 5.

8.2.3 Representative Grain Sizes

Due to the size of the study area and the resolution of the model, it was deemed practical to use a single sediment grain size per channel to represent the local bed material for the base model. However, a multiple grain size model which used three grain sizes per channel was also developed. The multiple grain size model proved to be highly unstable and cumbersome to operate, and the results did not differ substantially from those of the single grain model.

Figure 16 in Section 5 presented the grain size distributions of bed samples taken by NHC around the project area. Different representative grain sizes were used in the model, depending on the location of a particular reach. A relatively large grain size of D_{50}=100mm was used on all the Cosumnes reaches upstream of Grizzly Slough to avoid numerical instabilities that commonly occurred in these steeper sections. Preliminary modeling results demonstrated that the exclusion of the upstream channels from the sediment calculations did not significantly affect the transport rates calculated around MWT and below. The Mokelumne and Sacramento Rivers were modeled using a medium sand of D_{50}=0.4mm. Snodgrass Slough and Dead Horse Cut were modeled using D_{50}=0.25mm, and all other channels downstream and to the west of MWT were modeled using a finer sand of D_{50}=0.1mm. The standard deviations of the grain size distributions in each channel were assumed to be equal to the grain sizes themselves.

8.2.4 Transport Equations

The ST module in MIKE11 provides the user with the option to calculate bed load and suspended load separately, or together as total load using a single equation. Due to the size and hydraulic complexity of the North Delta model, a single total load approach was used. The Ackers and White transport formula was used in the calculations due to its applicability to sand bed rivers. The sensitivity of model to the Ackers and White equation was evaluated by also running the model using Engelund and Hansen's formula.

8.2.5 Passive channels

Many of the channels that were defined as having over-sized bed material (D_{50}=100mm) were defined as passive channels within the model. This sped up the calculation process and reduced total run times. According to MIKE11 literature, this setting essentially causes the channel to be eliminated from sediment transport calculations. Sediment is allowed to enter the reach, but disappears and never reenters the system. Passive channels may be though of as sediment traps. However, despite the insistence by Danish Hydraulic Institute representatives that this option functions normally in the most recent model version, sediment was observed to be transporting through and exiting out of passive reaches in the North Delta model. However, the fact that the passive channel

option did not appear to be functioning properly did not affect the general results of the model.

8.2.6 Boundary Conditions

The sediment transport module of MIKE11 requires sediment boundary conditions at all flow boundaries. Since all of the model's hydraulic inflow boundaries are far from the sediment transport model's area of interest, it was deemed acceptable to define each sediment boundary as flowing at the channel's full sediment transport capacity. For the Cosumnes River, Deer Creek, and Dry Creek, this implied an input of almost zero since the bed material was defined as very large to avoid sediment transport calculations there. The Mokelumne and Sacramento Rivers, however, do exhibit sediment transport at their inflow boundaries.

8.2.7 Hydrodynamics

The principal objective of the sediment transport modeling was to investigate existing conditions in the project area and to compare differences in sedimentation due to the implementation of the proposed project alternatives. It was, therefore, necessary to develop a model that could evaluate the sedimentation patterns and geometric evolution of the project area over the long-term. To achieve this, synthetic flow hydrographs were developed for each of the five major hydraulic inputs into the North Delta: the Sacramento, Cosumnes, and Mokelumne Rivers, and Deer and Dry Creeks. The representative synthetic hydrographs were created from flow duration curves that used daily mean flow data collected by the U.S. Geological Survey. Table 3 presents the various periods of record used to develop the flow duration curves and associated representative synthetic hydrographs, which are shown in Figure 22.

In order to be sure that the representative synthetic hydrographs adequately described flow conditions for sediment transport modeling purposes, a comparison was performed of the sediment transport rate predicted by the model using actual annual hydrographs verses using the synthetic hydrographs based on the same data. The actual hydrographs were developed using hourly flow and stage data obtained from websites operated by the California Department of Water Resources. Hydrographs that best represented a typical water year were arbitrarily chosen for each upstream boundary, such that the water years of inflows do not necessarily match. Data from the same water year (1999) was used to model all of the downstream tide boundary conditions. Table 4 presents the data used for each boundary in the model. Figure 23 presents each real hydrograph together with the associated synthetic hydrograph developed using the same data set.

Table 3. USGS stage data used to develop flow duration curve hydrographs for long-term modeling

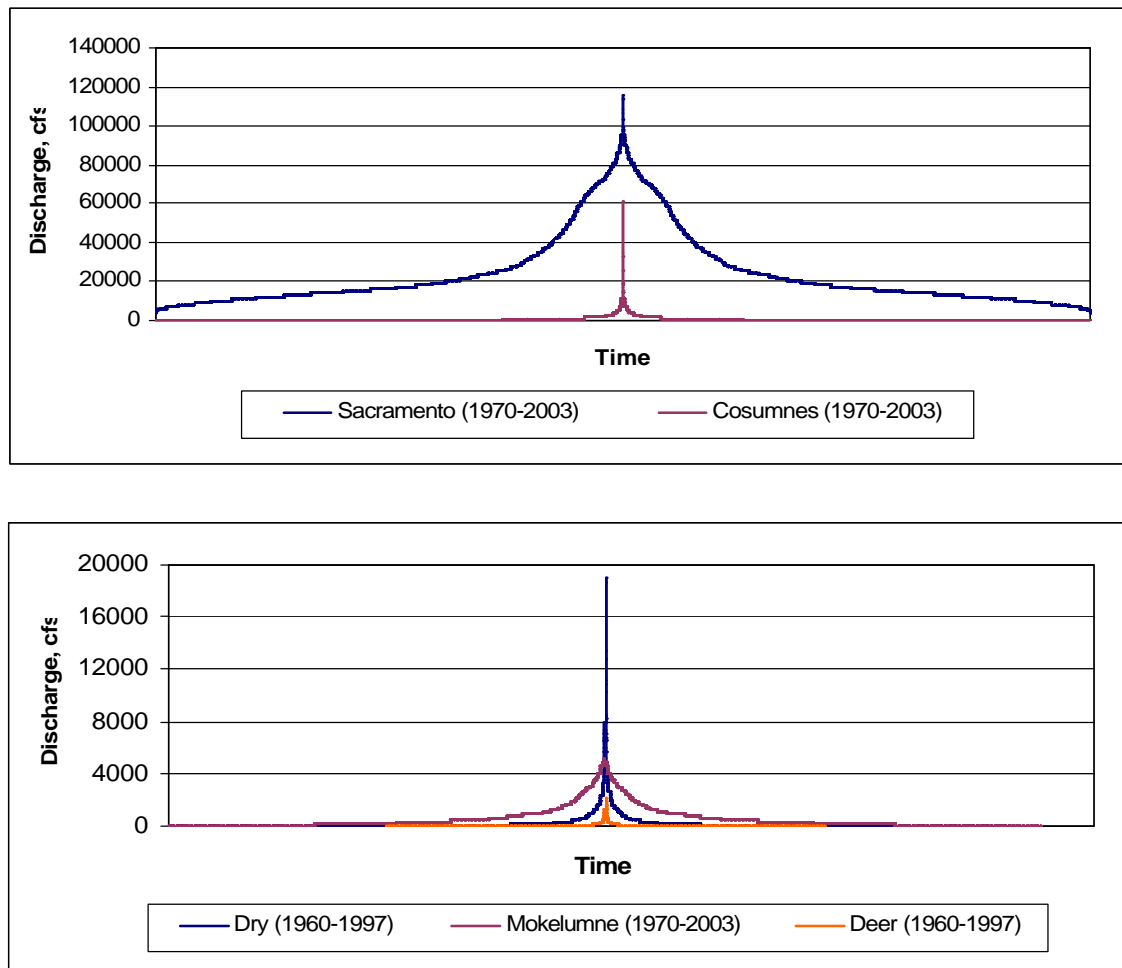| Upstream Boundary	USGS Station No.	Period of Record
Sacramento River at Freeport	11447650	1970-2003
Cosumnes River at Michigan Bar	11335000	1970-2003
Mokelumne River at Woodbridge	11325500	1970-2003
Dry Creek near Galt	11329500	1960-1997
Deer Creek near Sloughhouse	11335700	1960-1977

Figure 22. Representative synthetic hydrographs developed for Dry Creek, Mokelumne River, and Deer Creek using data from the period of record specified

Table 4. One-year flow and stage data sets used to validate similarity of sediment transport predictions between modeling based on actual hydrographs and representative synthetic flow hydrographs

Boundary Name	B.C. Type	Source	Name	Data Year
Sacramento R. u.s. of Delta CC	u.s.	IEP[†] (DWR)	RSAC128	1999
Cosumnes R. at Michigan Bar	u.s.	CDEC[‡] (DWR)	MHB	2000
Mokelumne R. at Woodbridge	u.s.	USGS[*]	11325500	2000
Dry Creek near Galt	u.s.	USGS[*]	11329500	1980
Deer Creek at Highway 32	u.s.	CDEC[‡] (DWR)	DCH	1970
Sacramento d.s. of Georgiana Sl.	d.s.	IEP[†] (DWR)	RSAC123	1999
San Joaquin at Rindge Pump	d.s.	IEP[†] (DWR)	RSAN052	1999
San Joaquin River at Venice Island	d.s.	IEP[†] (DWR)	RSAN043	1999
San Joaquin R. at San Andreas	d.s.	IEP[†] (DWR)	RSAN032	1999

[†]Interagency Ecological Program, http://iep.water.ca.gov
[‡]California Data Exchange Center, http://cdec.water.ca.gov/
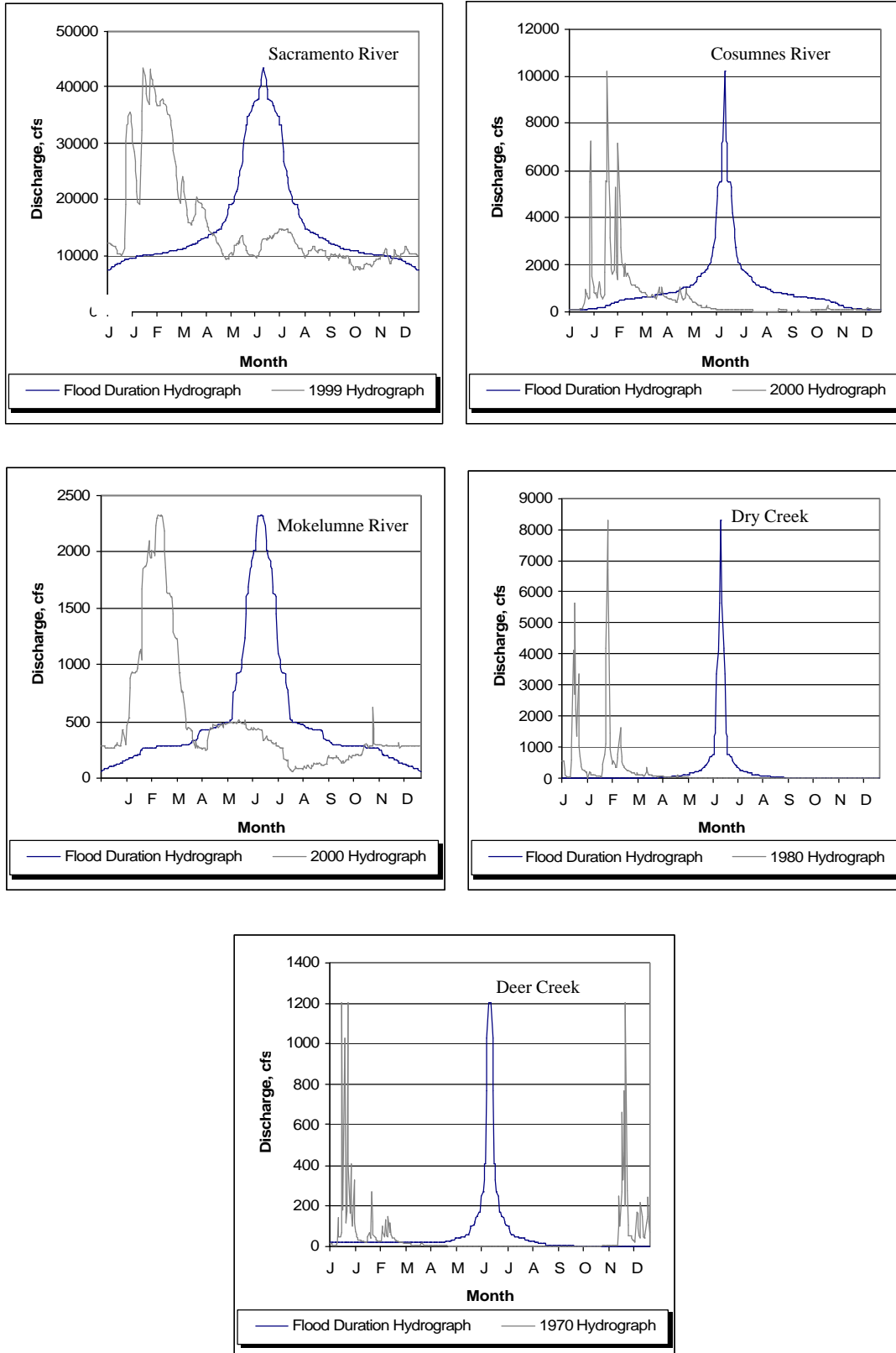[*]U.S. Geological Survey, http://water.usgs.gov/

Figure 23. Comparison of actual annual hydrographs and representative synthetic hydrographs used to validate the simplification of inflow hydrology in MIKE11 sediment models

A direct comparison of the sediment transport results obtained using the actual hydrographs for the North Delta and the representative synthetic hydrographs revealed only minor differences. In addition, since nearly all the sediment transport occurred during the top 10% of annual discharges, the results indicated that it would be necessary to model just the peak 10% of the flood duration curve to obtain the effective transport results.

8.2.8 Specific Geometry Changes Made to MIKE11

Several specific changes were made to the North Delta geometry files to make the MIKE11 model better suited for sedimentation modeling. Due to problems that MIKE11 had when routing sediment past bridges, all bridge structures were removed from the model. Although this affects the local hydraulics of the flow in the model, such minor alterations in geometry should not have a wide-ranging effect on general reach averaged sedimentation patterns over the long-term simulations completed for this analysis.

Additionally, since sediment transport was shown to occur almost entirely in the highest 10% of annual discharges, it was deduced that the Delta Cross Channel gates would be closed during all sediment modeling scenarios.

8.3 Baseline Model and Initial Results

A baseline sediment transport model was originally developed to test the sensitivity of the model setup and to verify the model's results against observed data. A ten-year time interval was chosen as a simulation period for the baseline model so that the length of its results would be of the same order of magnitude as the seven years of cross section scour data available through DWR. Because the period of record for the DWR scour data is short, it can not be used to define long-term erosion or accurately describe depositional trends in the system. However, a reasonable qualitative assessment of the model's performance was made by comparing its predictions to the observed data set. Because the model must calculate sediment transport in the system over a period of years, the run time was shortened considerably by ignoring the lower 90% of flows from the flood duration curve hydrographs since these flows were shown to have little or no effect on sediment transport in the MIKE11 model.

Figures 24a and 24b present the mean elevations of specific scour cross sections surveyed by DWR from 1994 to 2001 combined with the mean channel elevations predicted by the model for 2002 to 2012. The location of each cross section in the North Delta study area can be found in Figure 4 (Section 3). The figures demonstrate the reasonable agreement that exists between the observed data and elevations predicted by MIKE11 for channel reaches to the west of Highway 5. Sediment transport in the channels east of Highway 5 was not evaluated due to instabilities in the model.

Examination of the figures reveals a rapid initial change in bed elevation in some cross sections at the beginning of the simulation. This is mainly due start up instabilities in the sedimentation routine as the model establishes an equilibrium state. Near junctions, these

exaggerations can be profound, sometimes resulting in large sediment deposits or deep scour holes. However, over time, these initial shocks generally subside.
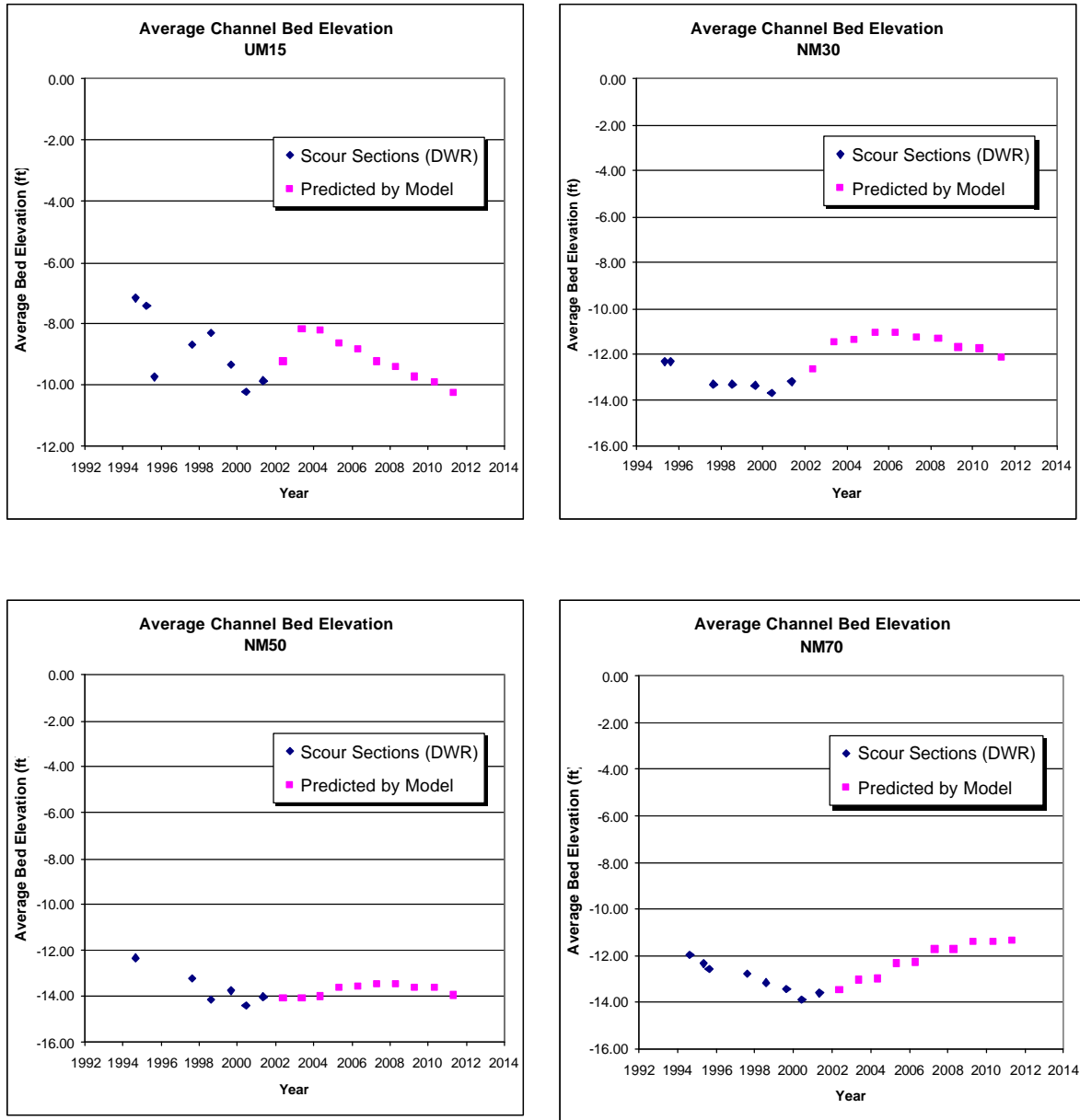

Figure 24a. Historical mean elevations of channels (DWR) combined with elevations predicted by model (cross section locations shown in Figure 4)
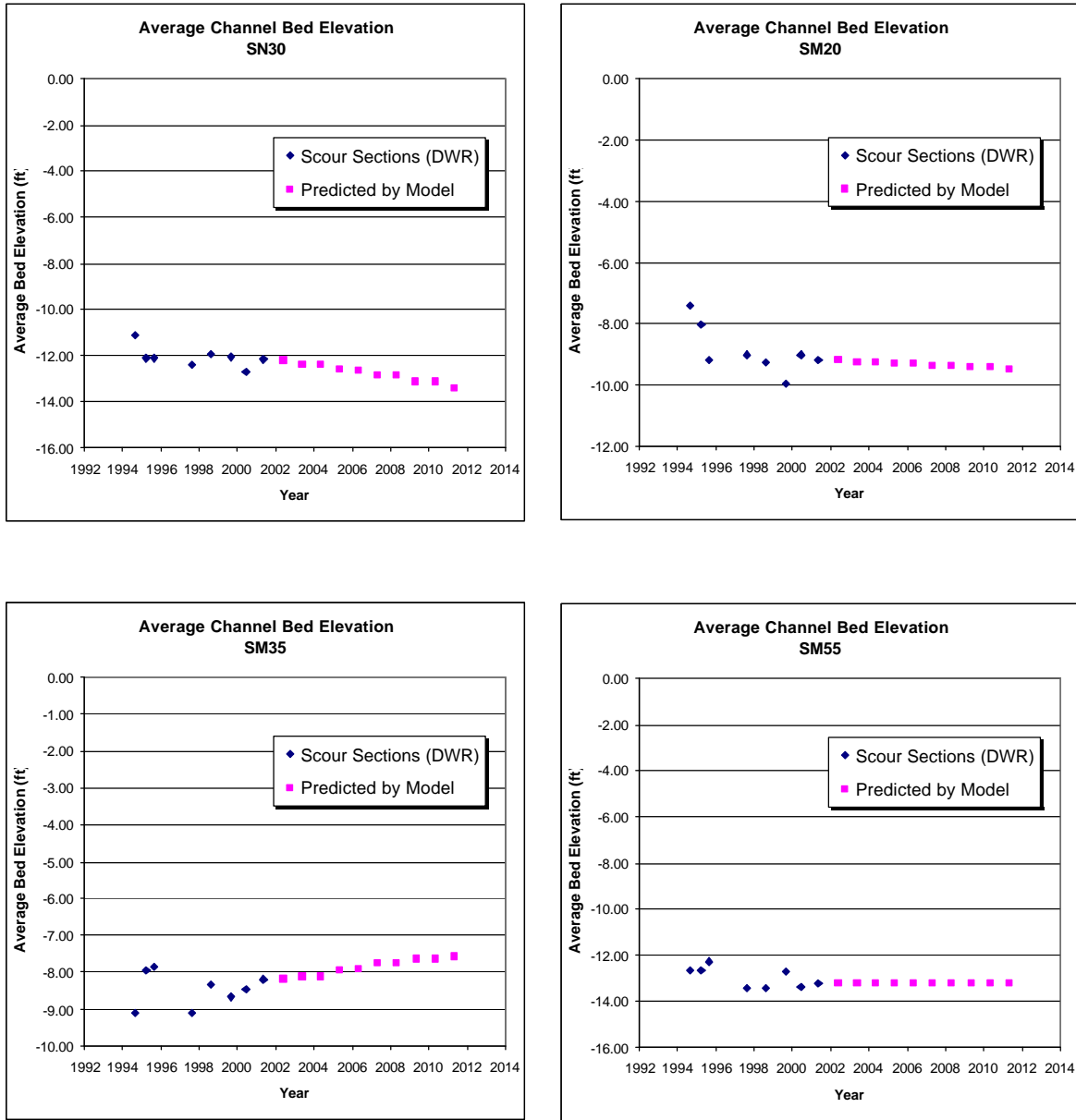
Figure 24b. Historical mean elevations of channels (DWR) combined with elevations predicted by model (cross section locations shown in Figure 4)

8.4 Sensitivity Runs for Baseline Model

To evaluate the sensitivity of the baseline model to various parameters, additional model runs were conducted. These included runs designed to determine the model's sensitivity to particle size per reach, the use of multiple grain sizes, and the application of different transport equations. Additional runs were also conducted using the highest 5% and 20% of the representative flood duration curve hydrographs to confirm that sediment transport in the MIKE11 model occurred only within the upper 10% of flows recorded in the historical record. Table 5 lists some of the sensitivity runs performed and comments on the differences noted when comparing the results to the baseline model.

Table 5. Summary of sensitivity runs for sediment transport modeling

Modeling Scenario	*Sensitivity Parameter Invesigated*	*Major Differences Noted*	*General Comments*
Base model 10-yr simulation using top 10% of historical flows	n/a	n/a	n/a
10-yr simulation using top 20% of historical flows	Effect of applying lower flows on sediment transport predictions	none	Exact same sediment transport results as base model
10-yr simulation using top 5% of historical flows	Effect of only using very high flows on sediment transport predictions	negligible	Very similar sediment transport results as base model
50-yr simulation using top 10% of historical flows	Long-term modeling	Some development of scour holes; additional sediment movement through system evident	System continues to evolve dynamically and tends toward a more stable geometric configuration
Increase of channel bed material	Doubling of grain size in every reach	Large decrease in transport everywhere	Model is very sensitive to grain size, though relative transport between reaches observed to be similar
Use of multiple grain sizes in reaches	More accurate representation of bed using three representative grain sizes	Lower sediment transport, especially in upper N and S forks	General sedimentation patterns similar though magnitudes are different; model is very unstable
Use of Engelund and Hansen's transport formula in model	Ackers and White's Total load equation	Slightly lower transport volumes predicted (between 10-50%)	Model is sensitive to equation choice

8.5 Sediment Transport Modeling of North Delta Project Alternatives

Sediment transport models were developed for five different flood control and ecosystem restoration alternatives proposed by DWR for the North Delta. Each of the models was created by altering the geometry of the baseline model to reflect changes proposed by a particular project option. The goal of the modeling was to identify large-scale and long-term sedimentation trends in the study area under existing conditions and to note significant changes in these trends due to implementation of each proposed alternative.

8.5.1 Description of Project Alternatives

Table 6 presents a brief description of the proposed North Delta alternatives included in the scope of this analysis. The first two alternatives, Eco-Options 1 and 2, involve modifications to the levee system around MWT. Flood Control Options 2 and 3 propose the establishment of channel setbacks and a large flood detention pond on Staten Island. The final alternative, Flood Control Option 4, proposes significant dredging of the channels around MWT and Staten Island, as well as plans to lay back channel banks and levee slopes.

Table 6. Summary of project alternatives considered and modeled in the sedimentation study.

Project Alternative	Description
Baseline	• No change condition of existing North Delta system
Eco-Option 1 (EO1)	• Installation of a weir set at 8.5' NGVD on the upstream northwestern side of MWT to capture high flows and reduce flood peaks. • Degradation of downstream levee along Dead Horse Cut to -2.5' NGVD allowing tidal exchange into island. • 300' notch cut into levee on the upstream end of the island to allow water from the Mokelumne to pass onto the island
Eco-Option 2 (EO2)	• Installation of a weir set at 8.5' NGVD on the upstream northwestern side of MWT to capture high flows and reduce flood peaks. • Degradation of downstream levee along Dead Horse Cut to 5.5' NGVD • Installation of multiple box culverts on downstream end to facilitate draining of the island after flooding
Flood Control Option 2 (FO2)	• Widening of North Fork of the Mokelumne by setting back levees on Staten Island • Construction of a flood detention pond with inlet weir set at 9' NGVD on Staten Island to capture peak flood flows
Flood Control Option 3 (FO3)	• Widening of South Fork of the Mokelumne by setting back levees on Staten Island • Construction of a flood detention pond with inlet weir set at 9' NGVD on Staten Island to capture peak flood flows
Flood Control Option 4 (FO4)	• Dredging of channels around MWT and in the South Fork of the Mokelumne by Staten Island • Channel bank set backs and reduction of levee side slopes to 1:5

8.5.2 Model Setups

The original baseline MIKE11 sediment transport model was updated using revised network and geometry files created by UCD in mid 2005. Special attention was paid to changes made to channel reaches near the study area, which included the Mid Mokelumne, Snodgrass Slough, Dead Horse Cut, and the North and South Forks of the Mokelumne. Once a stable baseline model had been created and tested, it was used as a basis for developing the sediment transport models of the five alternative project configurations. Changes to the baseline model that reflected the proposed alternative geometries were copied from UCD's MIKE11 files.

The same boundary conditions and upstream hydrology were applied to each sediment transport model. A 20-year simulation period was adopted using a representative flood duration curve as described in Section 8.2 of this report. The resulting synthetic inflow hydrograph had 10 peaks distributed over a two-year run time period, using only the highest 10% of recorded mean daily flows. The downstream boundaries were modeled using a repeating annual tide series. A 15-second time step was used for hydraulic and sediment transport calculations, with output recorded every six hours model time.

8.5.3 Reach-Averaged Analysis of Sedimentation Results

The results from the sediment transport simulations were analyzed at a reach-wide level by defining eleven study reaches (Figure 25) near MWT, Dead Horse Island, and Staten Island. The sediment volume captured in a study reach was calculated by subtracting the
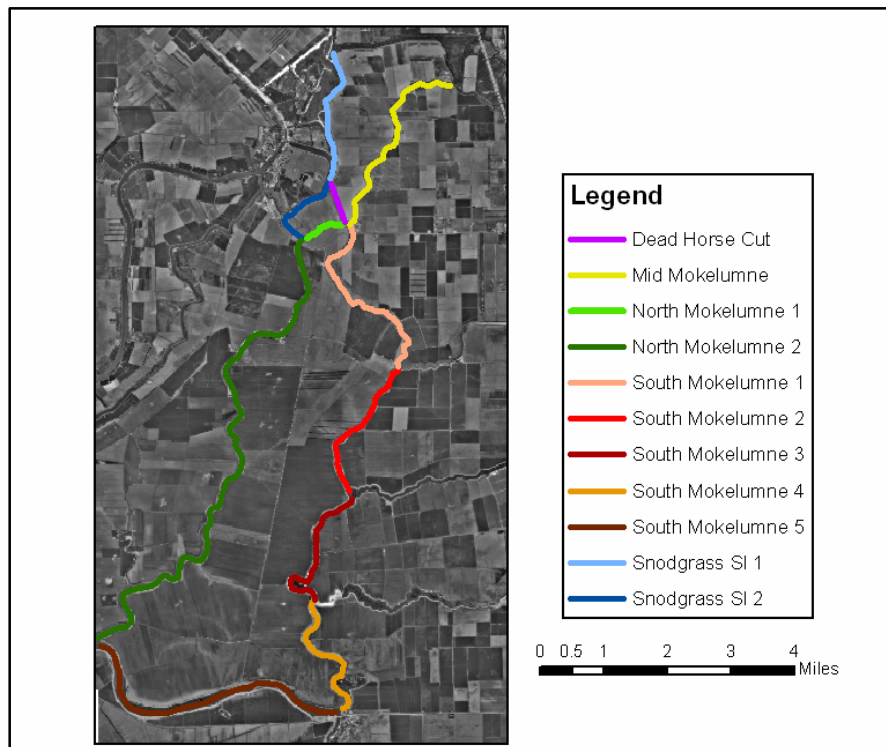

Figure 25. Location of study reaches used to calculate changes in sediment volume.

Table 7. Net changes in study reach sediment volumes over 20-year simulation period.

Reach	*Net sediment volume (cubic meters)*					
	Baseline	*EO1*	*EO2*	*FO2*	*FO3*	*FO4*
DH Cut	45,841	-49,610	49,511	77,731	74,036	28,925
Mid Mok	-72,522	205,474	-123,468	-130,555	-134,561	-28,277
North Mok 1	13,389	-14,888	8,173	8,801	14,516	58,123
North Mok 2	51,120	43,983	50,195	-21,713	50,148	47,923
South Mok 1	61,558	-1,341	79,620	103,141	125,669	183,991
South Mok 2	2,289	-20,846	-2,624	13,681	-50,398	-22,352
South Mok 3	20,497	49,333	25,152	11,932	62,408	41,040
South Mok 4	1,192	1,679	1,244	894	2,207	9,747
South Mok 5	9	9	7	6	4	-1
Snodgrass Sl 1	102,235	5	181	72,232	77,250	56,961
Snodgrass Sl 2	-52,467	-31,864	-41,380	-56,249	-46,281	-9,342

volume of sediment leaving a reach during the simulation from the total volume entering. A positive result indicated a net increase in sediment volume (deposition) within the reach, while a negative result indicated a net export of sediment volume (scour). This approach is useful for assessing sedimentation impacts of project alternatives and provides a measure of quantifying the change in sedimentation patterns and the potential requirements for dredging and/or scour protection measures. The reach averaged analysis is also preferred over the analysis of bed level changes at individual cross sections since sedimentation trends in the sub-reaches are more likely to stand out and are less likely to be affected by local instabilities and minor disturbances which may occur at individual cross sections in a sedimentation model.

Table 7 presents the raw data from the results of the numerical simulations. Each of the reaches shown in Figure 25 is listed in the first column of the table. The table describes the total volume of sediment captured in a reach over the 20-year simulation period for the baseline conditions model and the five project alternatives. Although the results presented in Table 7 may appear definitive and accurate, it is important to bear in mind that sediment transport is an extremely complex phenomenon that is not easily quantified. Therefore, the raw data results should be used only to identify general trends in the system and for comparative purposes between project alternatives. Individual results should not be taken out of context nor accepted as a true prediction of future sedimentation.

8.5.4 Verification of Baseline Results

The results from the baseline sediment transport simulation can be qualitatively verified by comparing the model predictions outlined in Table 7 to the potential sediment yield calculations described in Section 7 and presented in Figure 19 of this report. In general, the two approaches for estimating reach-wide sedimentation agree. Both predict deposition in Snodgrass 1, North Mokelumne 1, and North Mokelumne 2. Both also predict scour in Snodgrass 2 and Mid Mokelumne. The two reaches showing dissimilarity between the techniques are Dead Horse Cut and South Mokelumne 1. In both cases, the MIKE11 model predicted deposition in these reaches, while the results from the sediment yield calculations predicted no significant sedimentation at all.

8.5.5 Analysis of Simulation Results

The results presented in Table 7 were compared and analyzed to identify changes in trends between the baseline model and the five alternative project configurations proposed by DWR. In general, a change in a channel's sedimentation pattern was perceived as significant if it increased or decreased the net sediment volume of a specific reach changed by a factor of two from existing conditions. The following subsections discuss the results of the simulations and describe observed sediment transport trends associated with each project alternative.

Baseline Condition
The results from baseline model predict a general trend of sediment deposition near Staten Island, especially in the upper reaches of the North and South Forks of the Mokelumne. Deposition is also predicted in upper Snodgrass Slough and in Dead Horse Cut. The model shows general scour in the Mid Mokelumne reach adjacent to MWT and in lower Snodgrass Slough around Dead Horse Island. These sedimentation trends seem reasonable, with erosion occurring in the Mid Mokelumne reach until the channel trifurcates, increasing the conveyance and encouraging deposition mainly in the South Fork of the Mokelumne. Farther downstream, in South Mokelumne 4 and 5, sediment transport is very small, and net sediment storage is minor.

Eco-Option 1
Eco-Option 1 calls for substantial modifications to the flood control system around MWT. The lowering of the northeastern levee allows flood flows to spill onto the island and reduces the peak flow in Lost Slough and Snodgrass Slough by one half. The reduction of flow in Lost Slough causes most sediment to drop out early and reduces the deposition predicted to occur in Snodgrass Slough. The levee cut at the upstream end of the Mid Mokelumne also encourages a substantial amount of flow to leave the channel and enter the island. The resulting reduction in velocity in the Mid Mokelumne causes most of the sediment load to drop out in the channel before it reaches the trifurcation. Flow exits the MWT Island through Dead Horse Cut, which experiences a great increase in scour. The upper sections of both the North Fork and South Fork of the Mokelumne also show increased scour as sediment-starved water from the island reenters the channel system and velocities increase. In the case of the South Fork, the increase in scour continues south through Canal Ranch. Some of this additional sediment load is then deposited in the Brack Tract reach of the Mokelumne. Figure 26 presents a schematic representation of the changes in sedimentation trends due to implementation of Eco-Option 1. Sediment transport onto MWT was not evaluated in this study because sedimentation there would be very small and consist of wash load deposits and some suspended sediments rather than bed load.

Eco-Option 2
The sedimentation trends associated with Eco-Option 2 were fairly similar to those observed in the baseline model. Because this option would merely capture a portion of the hydrograph peak during very large flood events, the hydraulics of the system would not be significantly altered. The notable exception is the reduction of sediment
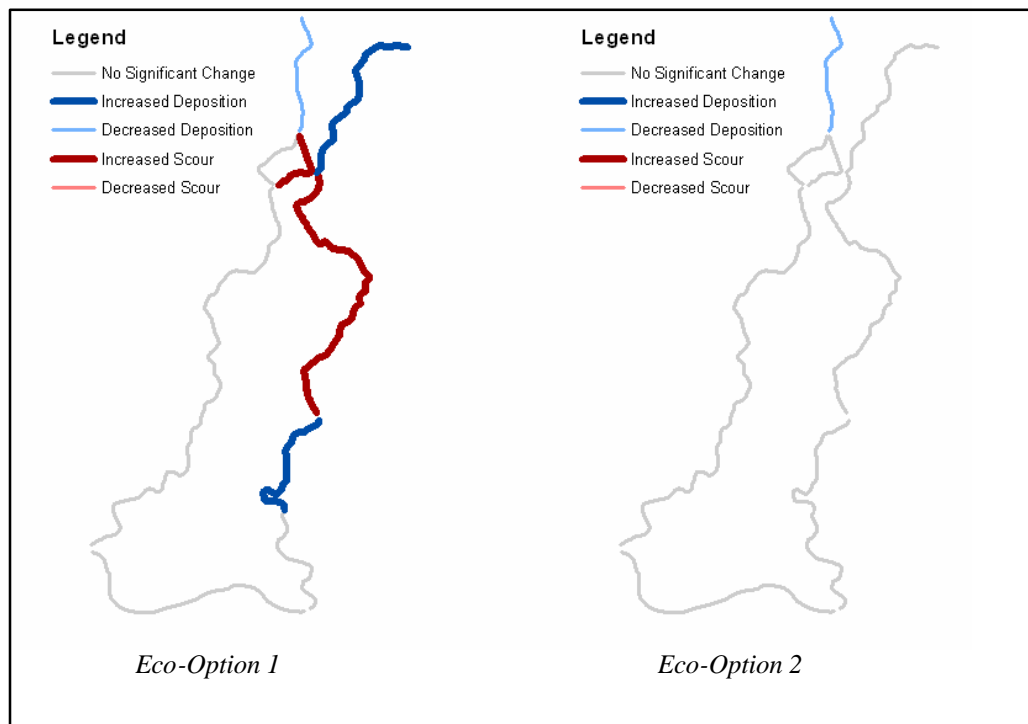
Figure 26. Changes in sedimentation trends between baseline conditions and Eco-Options 1 and 2.

deposition observed in upper Snodgrass Slough (Figure 26). This is due to increased sediment capture in Lost Slough upstream of Snodgrass Slough as a portion of the peak discharges are routed through MWT and slough velocities are reduced.

Flood Option 2
Proposed levee setbacks in Flood Option 2 would increase flood flows in the North Fork of the Mokelumne by widening the upstream section of the channel. The model predicts that, in general, the North Fork would experience additional scour from this increased in flow (Figure 27). Conversely, the reduction of flow into the South Fork would encourage additional deposition in its upper reaches. Water levels in the North Fork did not reach the elevation of the inlet weir of the flood detention pond, so its effects on sedimentation could not be evaluated.

Flood Option 3
In Flood Option 3, levee setbacks proposed on Staten Island across from New Hope Tract would encourage additional flow to pass through the South Fork of the Mokelumne. The levee setbacks would decrease local channel velocities near New Hope enough to increase deposition in the upper reach (Figure 27). However, downstream of the setbacks, the increased flows and sediment-starved water would encourage scour of the Canal Ranch reach. The additional sediment load picked up along Canal Ranch would then be deposited near Brack Tract as the river velocities decreased with increasing channel area. Similar to Flood Option 2, the Flood Option 3 simulation did not predict significant flooding of the flood detention pond, and its effects on sedimentation could not be evaluated.

Flood Option 4

In Flood Option 4, dredging is proposed for lower Snodgrass Slough, Dead Horse Cut, Mid Mokelumne, the upper reach of the North Fork of the Mokelumne near Dead Horse Island, and the upper and mid reaches of the South Fork. It is expected, therefore, that the general trend in these areas would be an increase in deposition or a decrease in scour due to lower velocities. This is exactly what the model predicted (Figure 27). Lower Snodgrass and the Mid Mokelumne reaches show significant reductions in scour over the baseline model. An increase in deposition follows downstream in the upstream reaches of the North and South Forks of the Mokelumne. However, the downstream reach of the South Fork along Canal Ranch shows a significant increase in scour. This is mainly due to the depositional trend observed upstream, which is responsible for sediment-starved water entering the reach and picking up material. The sediment load collected near Canal Ranch is then deposited just downstream near Brack Tract.

8.6 Summary and Conclusions

All of the proposed alternatives affect the sediment storage and export characteristics of the North Delta project area. In general, with the exception of the Mid-Mokelumne adjacent to the MWT, the region is a zone of sediment storage, which is to be expected given the reduction of stream gradient from the upper Mokelumne and Cosumnes River systems to the North Delta project area. The term "Delta" in the region's place name implies a zone of deposition. All of the many procedures utilized to understand sediment dynamics in this study all indicate net sediment storage within the region.

At first glance, the sediment modeling results may appear to contradict observed channel changes based on the CSDP scour surveys. However, it should be kept in mind that historical data, including the CSDP sections, show an extremely high level of data scatter when considering trends of aggradation or scour in North Delta reaches. Many cross sectional area and invert elevation trends can be reversed by choosing years other than 1994 and 2000 to compare. The CSDP record is not long enough to demonstrate long-term trends, only what was observed between 1994-2001. The sediment transport modeling, on the other hand, uses current cross section data and the entire historical discharge record to reveal future trends in the system based on relative channel morphology. Generally speaking, it should not be directly applied to predict absolute changes in particular cross sections based on one system configuration. It should also be noted that any dredging that may have occurred in the study area would be reflected in the scour surveys only and not in the sediment modeling results.

The computed changes in reach-averaged sediment characteristics for each alternative is an expected response of the river system's sediment balance. If an alternative results in sediment deposition within a reach, in general the adjacent downstream reach then adjusts to the lower inflowing sediment load through decreased deposition, or potentially scour, occurring in the downstream reach. Conversely, if an alternative results in scour within a reach, in general the adjacent downstream reach then adjusts to the increased inflowing sediment load through decreased scour, or potentially deposition, occurring in the downstream reach.
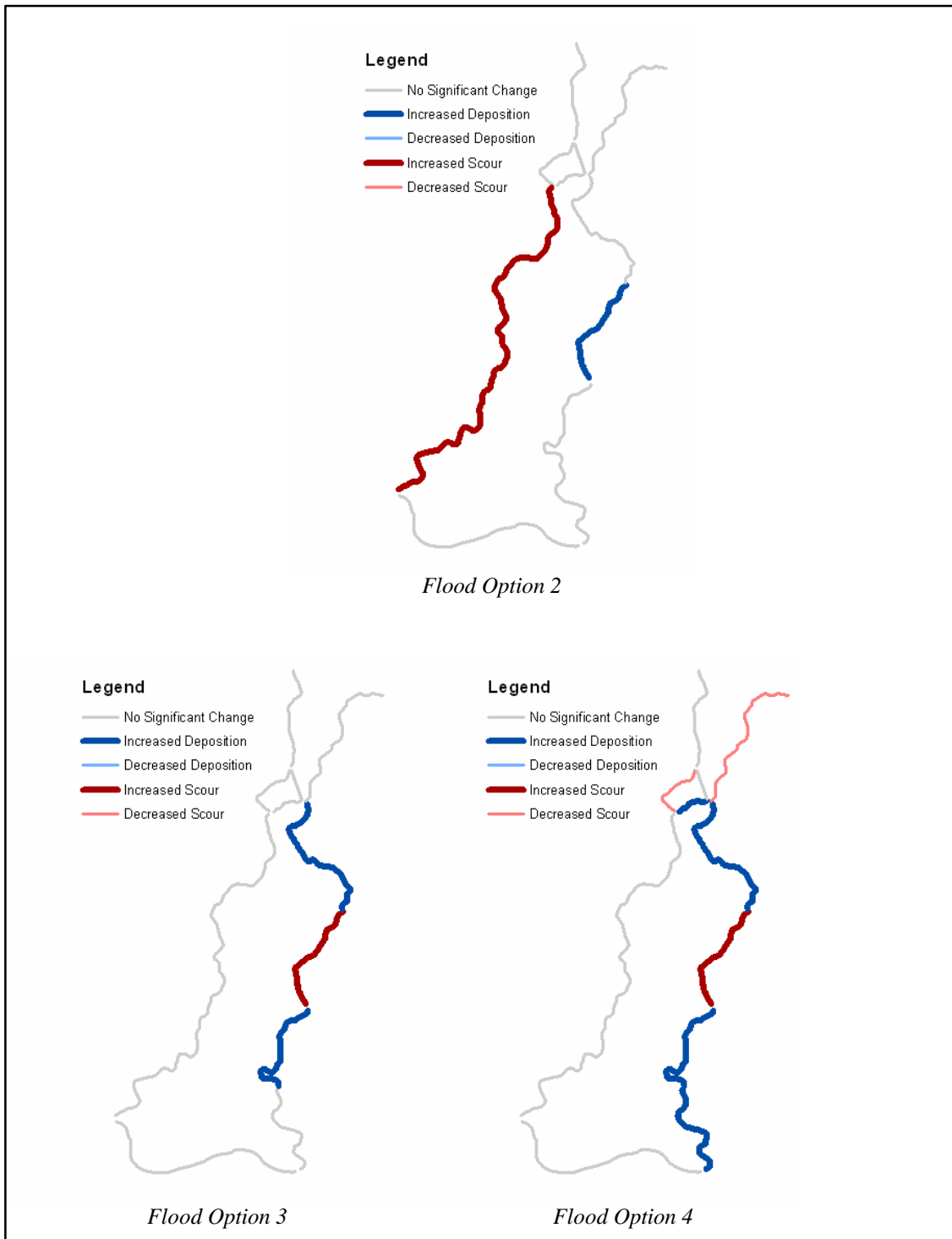
Figure 27. Changes in sedimentation trends between baseline conditions and Flood Options 2, 3 and 4.

Eco-Option 2 has the least impact on changes to the sediment regime of any of the project alternatives. This alternative has the least impact on the hydrodynamics of flood conditions, and hence the least impact on the resultant sedimentation dynamics. The other 4 alternatives entail a greater degree of channel and floodplain modification, and thus change to a greater extent the flood and sedimentation characteristics of the project reaches. None of the proposed alternatives are projected to drastically change the sediment characteristics of the project area to the point that management activities beyond those already implemented in the region would require significant modification. Site specific bank erosion control activities will likely be required in the future in response to continuing bank and bed scour. Limited dredging activity has been reported on some of the reaches in the project area, and such activity would likely continue in response to continued sediment deposition within the area.

Section 9.0
Long-Term Fine Sediment Deposition Rates in MWT

In addition to the modeling of bed material load transport and delta channel morphology using MIKE11, fine suspended sediment deposition rates in McCormack-Williamson Tract were estimated based on the proposed levee reconfigurations outlined in *Ecosystem Restoration Option 1* by the DWR. This particular configuration calls for the degradation of the southern-most levee to restore tidal action to the island, as well as the establishment of a 300-foot breach at the upper end of the island along the Mokelumne River to provide an inlet for river flow. In addition, the northwestern levee would be degraded to an elevation of 8.5 feet NGVD to capture flood peaks on the island during high flows in the Mokelumne. As described in Section 8, MIKE11 is not an appropriate tool for estimating fine sediment deposition rates in the Delta because they consist mainly of wash load. Therefore, the results presented here were developed from a spreadsheet model that utilized the hydrodynamic output from the MIKE11 model.

9.1 Description of Approach

Fine suspended sediment deposition rates on MWT were estimated by tracking the mass of sediment particles entering and leaving the island over time and calculating the deposition flux based on average sediment concentrations. Flow rates into and out of the island were established from hydraulic modeling results developed by **nhc** for DWR's *Ecosystem Restoration Option 1*. Inflow boundary conditions for the hydraulic model were based on synthetic hydrographs developed from flow-duration curves for the Sacramento, Cosumnes, and Mokelumne rivers.

Sediment calculations on MWT were performed at six-hour intervals using the results from the hydraulic model. Suspended sediment concentrations in the Mokelumne River near MWT were assumed equal to concentrations calculated for both the Cosumnes River and the Sacramento River during each time step. Suspended sediment concentrations in these rivers were determined by fitting a power-function regression curve to suspended sediment discharge and flow rate data collected by the USGS and **nhc** (see Table 8). The regression curve relationships developed for this study are described by:

$$\text{Cosumnes River:} \qquad Qs_{cms} = 1.64 \times 10^{-7} \left(Q_{cms} \right)^{2.31} \qquad\qquad (3)$$

$$\text{Sacramento River:} \qquad Qs_{cms} = 1.10 \times 10^{-8} \left(Q_{cms} \right)^{2.11} \qquad\qquad (4)$$

where Qs is suspended sediment discharge and Q is flow rate in SI units of m^3/s. Equations (3) and (4) predict total suspended sediment discharge throughout the water column, including fine sands that are transported in suspension during high flows. Therefore, the sediment discharges estimated by Equations (3) and (4) were adjusted to account for only the silt and clay fraction transported in the flow based on sediment grading analyses of suspended sediment samples taken at various flow rates on the Cosumnes River (Jones and Stokes, 2003).

Table 8. Suspended sediment data sets for the Sacramento River and Cosumnes River.

Station Location	Data Start Date	Data End Date	Data Collected by
Sacramento R at Freeport	Oct 1979	Sep 1989	USGS
Sacramento R at Freeport	Oct 1991	Sep 1992	USGS
Sacramento R at Freeport	Oct 1993	Sep 1994	USGS
Cosumnes River at Michigan Bar	Nov 1965	Sep 1974	USGS
Cosumnes River at Michigan Bar	Feb 2003	May 2003	**nhc**
Cosumnes River at McConnell	Nov 1965	Aug 1967	USGS
Cosumnes River at Plymouth	Aug 1957	Apr 1960	USGS

Suspended sediment concentration and deposition rates were calculated in MWT during each six hour time step. A sediment mass balance was developed by adding incremental water and sediment inflow volumes from the Mokelumne River and subtracting sediment deposition volumes. The rate of sediment deposition in the island was calculated using a fine sediment deposition and marsh plain accretion model developed by Krone (1987) at the University of California, Davis. Krone's model is widely used for estimating fine sediment deposition within the Sacramento-San Joaquin Delta and San Francisco Bay Estuary.

9.2 Summary and Conclusions

The results of the sediment deposition simulations are summarized in Table 9. Average accretion rates of 0.1 and 0.2 cm per year were calculated in MWT assuming sediment concentrations in the Mokelumne were equal to those estimated for the Sacramento River and Cosumnes River, respectively. In reality, suspended sediment concentrations near MWT would be lower than those used in the study due to inflows from the upper Mokelumne River and other local drainages that contain lower concentrations of suspended sediment. The accretion rates for MWT presented in Table 9 show reasonable agreement with suspended sediment deposition rates both observed and estimated around the Sacramento-San Joaquin Delta by **nhc** (2003), Reed (2002), and DWR (1984). These observed and estimated rates, which are all based on total suspended sediment deposition, vary between the orders of 0.1 and 1 cm/year.

Table 9. Fine suspended sediment deposition and accreting rates calculated for MWT based on concentrations developed from the Cosumnes River and Sacramento River.

Sediment Concentration Source	Average Sediment Entering Island (m³/yr)	Average Sediment Deposition (m³/yr)	Average Accretion Rate (cm/yr)
Cosumnes River	18,000	12,000	0.2
Sacramento River	10,000	4,000	0.1

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