MOBILE BOUNDARY HYDRAULICS

sediment flow analysis in streams and rivers in one dimension

Walnut Creek Sedimentation Study

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Prepared for:

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INTRODUCTION

Purpose

The work for this task order is to support the USACE Sacramento District by participating in HEC-6T model construct, debugging, calibration and verification activities. The model was based on without-project conditions. USACE Sacramento District intends to use the model, in future studies, to evaluate the sedimentation effects on proposed flood control and/or ecosystem restoration alternatives.

Study Area

The study area is shown in Plate 1 and includes the Walnut Creek watershed. The focus area for this analysis is the downstream 7.7 miles of Walnut Creek and its tributaries. At the mouth of Walnut Creek, the watershed has an area of about 145.6 square miles. Elevations in the watershed range from sea level to nearly 3300 feet on the edge of Mount Diablo. In the flatter areas of the watershed near Walnut Creek, the study area is highly developed and includes a mix of residential, commercial, and open land. Near Suisun Bay, there is a large oil refinery located on the right overbank of the creek.

Study Approach

The study approach was to develop a numerical model using the one-dimensional HEC-6T model. This model has been applied successfully to evaluate long-term sedimentation responses to various engineering projects in a variety of flood control projects in the United States. These applications have included river responses to dredging, flow diversions, channel modification, and changes in water and sediment inflows.

The historical sedimentation data available for this study include channel surveys and dredging records from which deposition quantities were calculated. Measured sediment inflow data, collected during the period of measured deposition, is virtually non-existent. This makes it difficult to determine the effects of temporal changes in sediment inflow on deposition during the historical simulation. The model developed for this study can be used to make reliable assessments of the relative effects of proposed flood control and other geometric alternatives. However, there will be more uncertainty attached to absolute quantitative predictions of sediment deposition.

It is recognized that HEC-6T is designed to model riverine sedimentation processes and that the lower reaches of Walnut Creek are affected by tidal processes, which are not simulated in the HEC-6T model. In their paper on the conceptual design and modeling of restored coastal wetlands, Odell, Hall and Brooks, (2008) present an approach for designing tidal channels. Three significant parameters are tidal hydraulics forces, marsh accretion rates and supply channel dimensions. These are associated with normal hydrological events. The proposed use of HEC-6T at Walnut Creek is for the analysis of plans that will handle the low probability runoff events resulting from rainfall floods. In these cases, riverine forces dominate the processes. Project designs that are currently being envisioned include cross section geometries that include high berms on one or both sides of a low flow channel or on the side of tidal marshes. These are only flooded during the extremely rare flood runoff events. They do not affect the tidal prism. They will not change marsh accretion rates or volumes associated with normal hydrological events where riverine forces dominate tidal forces.

The consequences of tidal processes that may be significant with respect to sedimentation are: 1) formation of a low-flow channel in the tidal prism, and 2) deposition and re-distribution of fine sediment during the tide cycle. These are associated with normal hydrological events and are not expected to be changed by the plans envisioned for protecting against the low probability runoff events. Consequently, the low flow channel is not expected to change as the result of the high-berm plans for flood protection.

Computational sedimentation studies fall into two general categories: 1) computational model studies and 2) computational analysis studies (ASCE 2008). A study is considered to be a computational model study when sufficient data are available to calibrate the model according to a set of formal guidelines (USACE-HEC 1992). Often, available data are not sufficient to achieve a formal calibration, but computational modeling is still the best method for analyzing the problem. In these cases, model tests are devised and conducted to evaluate relative effects of various parameters so that engineering judgment can be used to make decisions about project designs. These are called computational analysis studies. Due to the scarcity of sediment data, the Walnut Creek numerical sedimentation study falls into the latter category.

Numerical Model Description

The HEC-6T one-dimensional numerical sedimentation model was used in this study. Mr. William A. Thomas initiated development of this computer program at the U.S. Army Engineer District, Little Rock, in 1967. Further development at the U.S. Army Engineer Hydrologic Engineering Center by Mr. Thomas produced the widely used HEC-6 generalized computer program for calculating scour and deposition in rivers and reservoirs. Additional modification and enhancement to the basic program by Mr. Thomas and his associates at the U.S. Army Engineer Research and Development Center (ERDC) led to the HEC-6W program. The HEC-6T program used in this study is the product of additional modification and enhancement conducted by Mr. Thomas at Mobile Boundary Hydraulics PLLC. Version nine of the HEC-6T code was used to make calculations in this study. The model is proprietary and can be obtained from Mobile Boundary Hydraulics.

The HEC-6T program produces a one-dimensional model that simulates the response of the riverbed profile to sediment inflow, bed-material gradation, and hydraulic parameters. The model simulates a series of steady-state discharge events, their effects on the sediment transport capacity at cross sections and the resulting degradation or aggradation. The program calculates hydraulic parameters using a standard-step backwater method.

HEC-6T is a state-of-the-art program for use in mobile bed channels. The numerical model computations account for all the basic processes of sedimentation: erosion, entrainment, transportation, deposition, and compaction of the bed for the range of particle sizes found in Walnut Creek. The model calculates aggradation and degradation of the streambed profile over the course of a hydrologic event and/or a long-term simulation. It does not adequately simulate bank erosion or natural adjustments in channel widths. When applied by experts using good engineering judgment, the HEC-6T program will provide good insight into the behavior of mobile bed rivers.

NUMERICAL MODEL

Geometry

The initial geometry used in the numerical model was developed from as-built drawings that extended from Suisun Bay to Grayson Creek (Stations 35 to 185+35) and from design channel dimensions thereafter. Cross section geometry for design conditions were obtained from the USACE Sacramento District (SPK) HEC_RAS model - *LWC As-Built Unstdy 03192010A.* The limits of the Walnut Creek HEC-RAS and HEC-6T models are shown on Plate 2.

In the HEC-RAS model, the Pacheco Creek geometry is based on design plans to Station 66+86 and on 2005 survey data upstream from that station.

The as-built cross sections between Suisun Bay and Grayson Creek had significant excavation below the design channel invert. The September 1965 surveyed cross section data were extracted from ten of the sedimentation transects shown in Plate 3 and in the document *DE-4-4-137.pdf*. The plotted data were converted to NAVD88 and into the correct XY locations corresponding to the cross sections in the SPK HEC-RAS model, which were subsequently converted into the HEC-6T model. The HEC-RAS geometry file containing the 1965 as-built geometry is *Sediment Transects.g05*. The invert elevations from transect 15+00 (RAS 1605.889) were used to obtain elevations for HEC-6T sections 0+35 and 7+59 since there was no way to interpolate the geometry to those sections. Similarly, the geometry for transect 184+00 (RAS 184+18.04) was used to obtain the invert geometry for HEC-6T section 185+35 since it is only located about 100 feet away from the transect (upstream).

Model Network

The downstream boundary of the numerical model is at Suisun Bay. The first cross section on Walnut Creek is at Station 0+35. The upstream boundary on Walnut Creek is at Station 405+89, 7.7 miles upstream and just downstream from Monument Boulevard. The HEC-6T model included 1.4 miles of Pacheco Creek, 3.0 miles of Grayson Creek, 0.8 miles of Clayton Valley Drain, and 0.9 miles of Pine Creek. The HEC-6T network schematic, which identifies the location of model segments and control points, is shown in Figure 1.

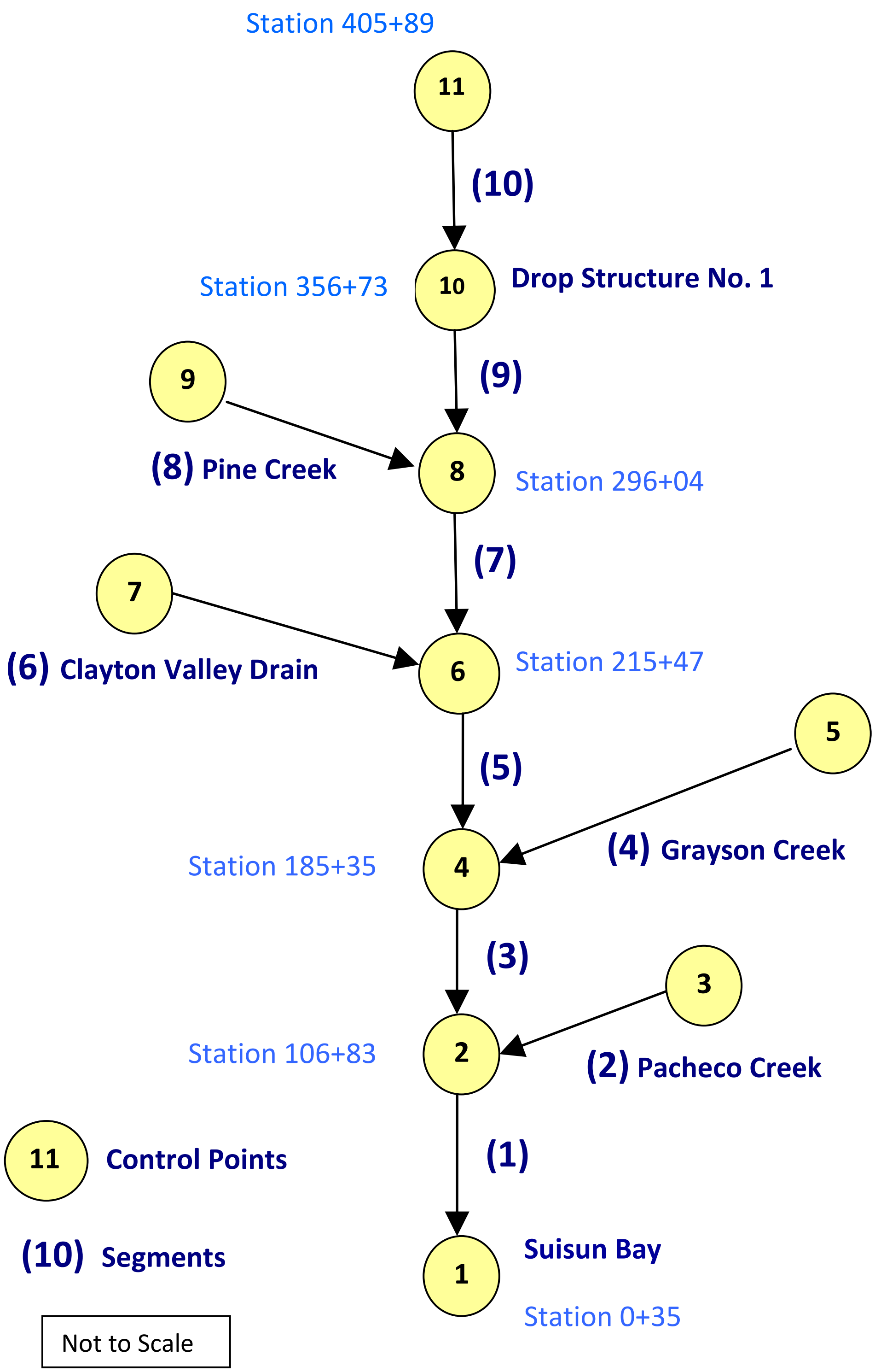

Figure 1. HEC-6T model schematic showing segments and control points.

Hydrographs

Discharges for the 1965-2005 historical simulation were provided by the USACE Sacramento District. Daily discharges were provided in DSS file *WC_Daily.DSS* and hourly discharges for 92 high flow periods were provided in DSS file *WC_Hourly.DSS*. Boundary discharges in the HEC-6T model came from the DSS locations: Walnut Creek at Concord (refer to Plate 2), Pine Creek at Mouth, Clayton Valley Drain at Mouth, Grayson Creek at Mouth, and Pacheco Creek at Mouth. The Walnut Creek at Concord gage is located about one-quarter mile upstream from the model boundary.

Two USACE approved models were used in tandem to calculate flows for the 1965-2005 simulation time period. These were the USDA-sponsored Soil Water Assessment Tool (SWAT) (Neitsch, Arnold, Kiniry and King, 2001a and 2001b) and HEC1L, a version of HEC1 (USACE, HEC, 1990) modified to allow long-term simulation. The choice to use two models provided the most efficient use of available resources for the project. An HEC1 model had been developed for the Walnut Creek watershed in previous studies for which single events had been the focus. It consistently showed the ability to mimic watershed response at sub-daily time steps for discrete events, but significant calibration has been required for each effort. Furthermore, little was known about the model's ability to reconstruct runoff for multi-year periods. The SWAT program was specifically developed for long-term simulation. It accounts for the entire mass of water as it progresses through the surface and groundwater systems. Therefore, it was decided that daily flow for the entire period of record would be calculated using SWAT, while HEC1 could give sub-daily definition to discrete events interspersed throughout the simulation period. By scaling the sub-daily hydrographs to match the total daily volume generated by SWAT, the results of the two models could then be brought into agreement.

The computations were made in two parts: 1) a SWAT model was developed for the entire period of record and 2) the HEC1 model was used for over 200 single flood events. More detail on development of the model hydrographs is provided in Appendix A.

Downstream water surface elevation

The downstream boundary of the HEC-6T model is located at Station 0+35 in the tidal flats just upstream from Suisun Bay. The water-surface elevation for each day during the numerical simulation was assigned based on data obtained from the nearest NOAA tide gage, which is located at Port Chicago (Station 9415144) (refer to Plate 1 for location). The historic tide data were taken from the NOAA web site: http://tidesandcurrents.noaa.gov/. Hourly tide elevations were reported in ft NAVD, at local time.

In the HEC-6T simulation, computational time steps between one-day and six minutes were used. One-hour time steps were used during periods of high flows. The historical hourly water-surface elevations at Port Chicago were used for one-hour computational time steps. Six-minute time steps were used when numerical instability issues arose during model calibration. The corresponding average hourly elevation was used for the six-minute time steps. An average daily stage of 3.66 ft was used in the model when mean daily discharges were used in the HEC-6T simulations

The average daily stage was determined from first averaging all the hourly data for each day and then averaging all the daily data for the year. This calculation was made for two five-year periods, 1965-1969 and 1990-1994. The average stage was 3.66 for all ten years. There was no indication of sea-level rise. Average monthly stages were then determined for the two five-year periods. Average monthly stages ranged between 3.47 and 3.85 ft. This difference is insignificant in terms of the numerical calculations and the average annual stage was used for all mean daily computational time steps. Calculations of average downstream stages are in EXCEL file *24hr1965-69R.xlsx*

Temperature

Water temperature data from the USGS water quality web site, for USGS gage 11183600, Walnut Creek at Concord, California, consisted of ten measurements. Four of these measurements were taken in 1970, one in 1977, and 5 in 1988. These data were insufficient to develop temperature data for the historical hydrograph.

A regional analysis was adopted to assign water temperature in the HEC-6T model. Data from Alameda Creek near Niles and the Napa River near Napa were used in the regional analysis. Daily temperatures for the entire simulation period were estimated from these USGS data. Daily data at the Niles gage was given priority because it was the most complete. Gaps in the daily data were filled using linear interpolation. Long periods of time without data were filled using average monthly temperatures from the Napa and Concord gages. Temperatures from the gage data are shown in Figure 2. Daily temperature data were available from the Alameda Creak near Niles gage for the following dates: October 1, 1964 – September 30, 1973; 1 Oct 75 – 12 Feb 79; 6 Nov 99 – 31 May 00 and; 18 Aug 00 – 30 Sep 09. Daily temperature data were available from the USGS gage 11458000 Napa River near Napa for the following dates: 1 Oct 76 – 14 Apr 77; 21 Nov 77 – 30 Sep 79; 20 Mar 80 – 13 May 80 and; 23 Sep 80 – 19 Oct 81. Between 1976 and 1979 there were many days when mean daily flow data were reported at both the Napa River and Alameda Creek gages. Correlation between the two gages is reasonable. It is also reasonable to assume that temperatures in Walnut Creek, which is located between the Niles and Napa gages, may be estimated using data from the regional analysis. Temperature data and calculations are contained in Excel file *Temperature.xlsx.*

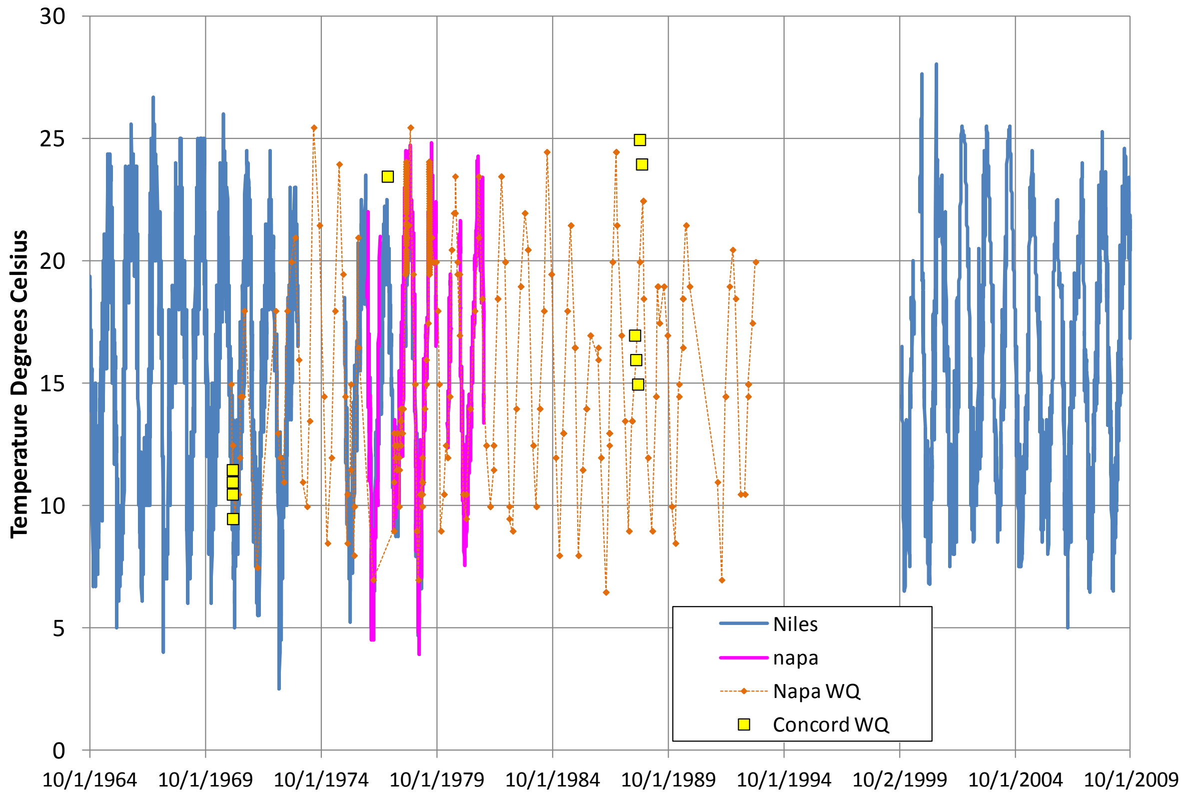

Figure 2. USGS reported water temperatures for Alameda Creek at Niles, Napa River at Napa, and Walnut Creek at Concord. Solid lines are daily data, points are individual measurements.

Sediment Removal Templates

Sediment removal was simulated in the numerical model five times during the 1965-2005 historical simulation. Removal was simulated instantaneously in September of 1973, 1986, 1989, 1993, and 1995. Removed sediment was assumed to be disposed of outside of the model limits. Sediment removal is simulated in HEC-6T by extracting channel sediment above a specified horizontal elevation, between specified lateral limits. Specified limits in the HEC-6T model were based on contract specifications not on actual sediment-removal surveys.

Sediment removal was simulated in the model between Suisun Bay and the BNSFRR Bridge (Stations 0+35 and 138+00) in September 1973. The design sediment removal template for 1973 was the original design invert elevation with one-foot of over-excavation between Stations 0+35 and 100+00. Between Stations 100+00 and 138+00 the over-excavation depth was 2.0 ft. The design invert elevation was horizontal. In the HEC-6T model, the horizontal invert was replaced with a sloping invert and a stepped channel between channel Stations 0+35 and 138+00. The elevations for the complex shape were set so that the average elevation was the same as the design elevation of the invert. This change allowed for a channel more similar to the channel that developed naturally over the 40-year simulation period. As it turned out, calculated deposition in this reach of Walnut Creek, over the remaining 32 years of simulation, continued to be relatively uniform over the movable bed width. This is attributed to the effect of the tide elevations which generally kept the entire movable bed wet.

Calculated cross section geometry at Station 16+06, at selected times during the historical simulation, are shown in Figure 3. The 1965 as-built channel bottom is slightly lower than the design geometry, which had a horizontal invert at elevation -4.4 ft. The figure shows deposition of about two feet by 1973. The sediment removal template used in HEC-6T is shown in Figure 3 as the orange line labeled “1973 After Removal.” Calculated erosion and deposition after the sediment removal are also shown in the figure. Note that there was slight erosion at this cross section between 1973 and 1982. A very large flood occurred in January 1982. Between 1982 and 1995 and between 1995 and 2005, deposition occurred.

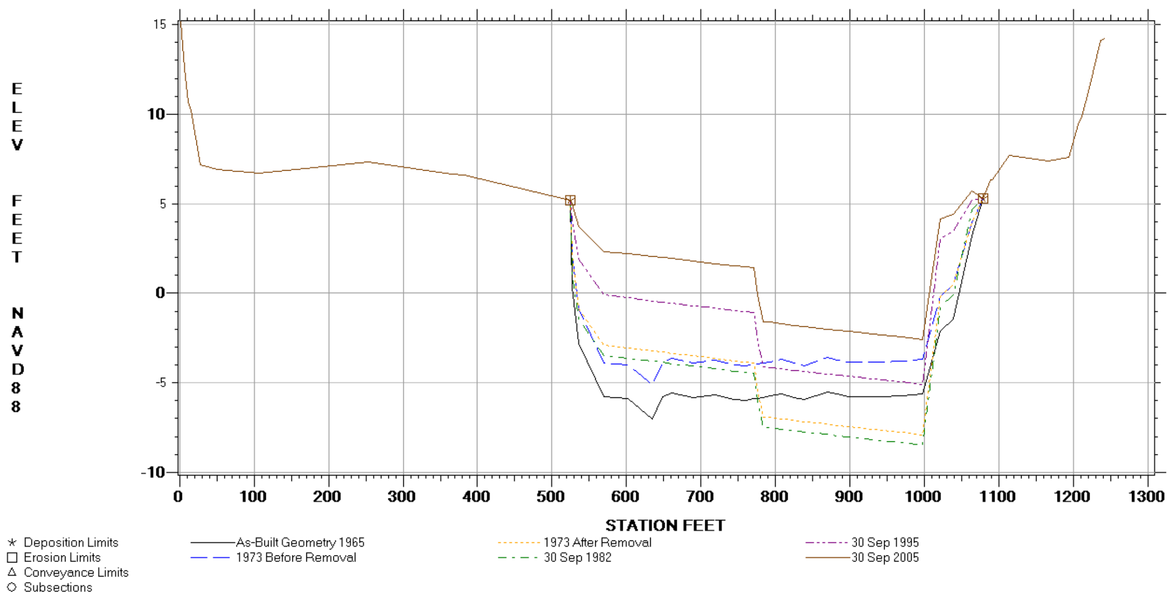

Figure 3. Calculated cross section changes at Station 16+00.

Sediment removal was simulated in Walnut Creek between Clayton Valley Drain and Drop Structure No. 1, Station 215+37 to Station 356+73, in September 1986 and September 1989. In 1986, sediment was removed only from the left side of the channel. Sediment was removed from the right side in 1989. The sediment-removal template extended down to the highest elevation of the design channel’s sloping invert at that cross section. This elevation corresponds to the bank toe. Calculated cross section geometry at Station 276+46, before and after dredging in 1986 and 1989, is shown in Figure 4. This is typical of the 33 cross sections modeling the channel in this removal site.

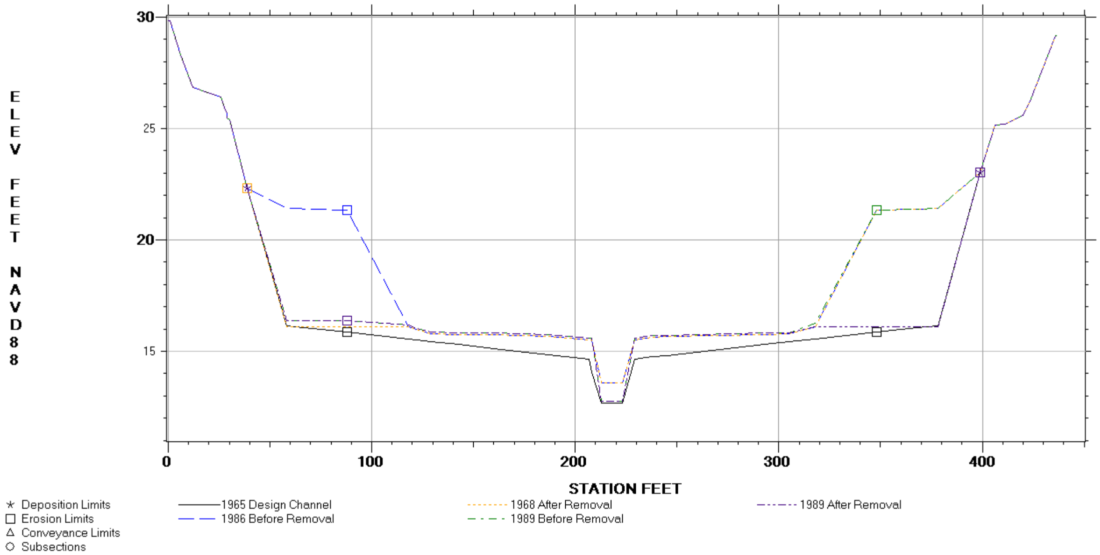

Figure 4. Calculated geometry before and after sediment removal in 1986 and 1989 at Station 276+46.

Sediment removal was simulated in the model between Pine Creek and Drop Structure No. 1, Station 296+04 to 356+73, in September 1993 and September 1995. In 1993, sediment was removed only from the right side of the channel. Sediment was removed from the left side in 1995. The sediment-removal template extended down to the lowest elevation of the design channel's sloping invert at that cross section. This elevation corresponds to the top elevation of the low flow channel. Calculated cross section geometry at Station 330+61, before and after dredging in 1993 and 1995, is shown in Figure 5. This is typical of the 17 cross sections modeling this removal site.

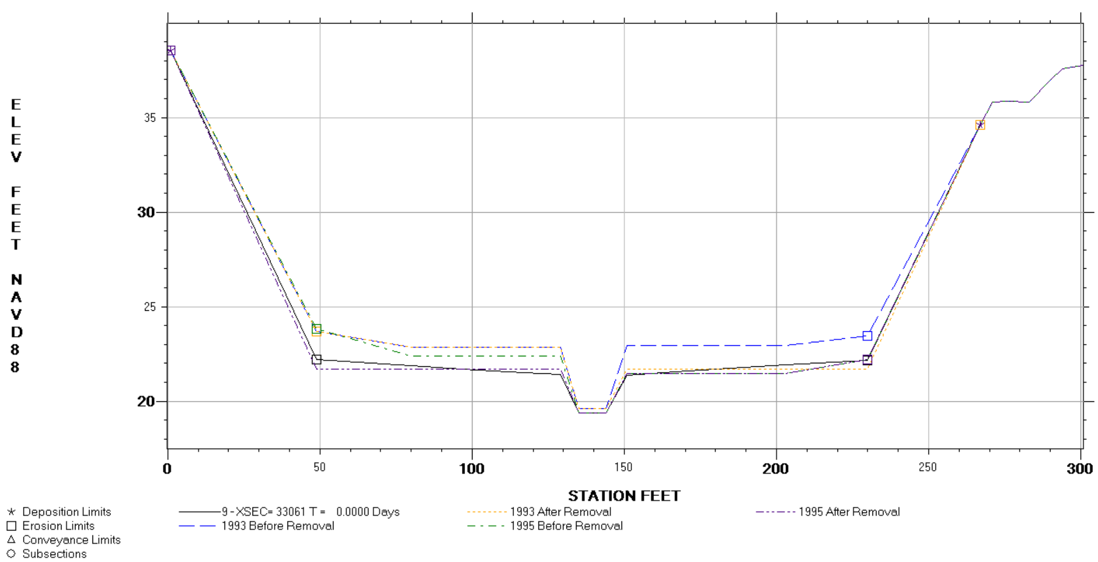

Figure 5. Calculated geometry before and after sediment removal in 1993 and 1995 at Station 330+61.

Sediment Data / Characteristics of Deposit

In 2009, two sampling efforts were conducted in Walnut Creek in order to identify the characteristics of the material which has deposited since construction of the Walnut Creek channel in 1964. The first effort included obtaining 30 vibra-core samples in the reach between Grayson Creek and Suisun Bay (refer to Plate 3). The second effort included obtaining 34 grab samples of the near-surface material from Walnut Creek and the tributary channels (refer to Plate 4). From these samples, average specific gravities and specific weights of deposited silt and clay were determined by Teeter in Appendix B. Clay was assigned a specific gravity of 2.53 and a deposited specific weight of 30 lbs/cu ft. Silt was assigned a specific gravity of 2.53 and a deposited specific weight of 82 lbs/cu ft. Sand was assigned a specific gravity of 2.65 and a deposited specific weight of 90 lbs/cu ft.

Sediment Data / Bed Material

Initial bed gradation data for the HEC-6T model were taken from sample data. Sample gradations were normalized to 0.008 mm in the HEC-6T model. This is the size class that separates the wash load from the bed-material load in this model. The actual bed material samples collected in Segment 1 (Suisun Bay to Pacheco Creek) are shown in Figure 6. The normalized gradations used as initial conditions in the HEC-6T model are shown in Figures 7 through 9.

The initial bed gradation does not significantly affect calculated results because deposition is the dominate process in Walnut Creek and composition of the bed is determined primarily by the composition and quantity of the sediment inflow. Initially, the initial bed sediment reservoir was set near zero at most cross sections in the HEC-6T model. This is reasonable because most of the constructed channel has parent material on the original bed and is relatively resistant to erosion. During model calibration, the depth of the bed sediment reservoir was increased to two feet in reaches where sediment removal was calculated. This became necessary to reduce numerical instabilities associated with the numerical algorithm at low discharges.

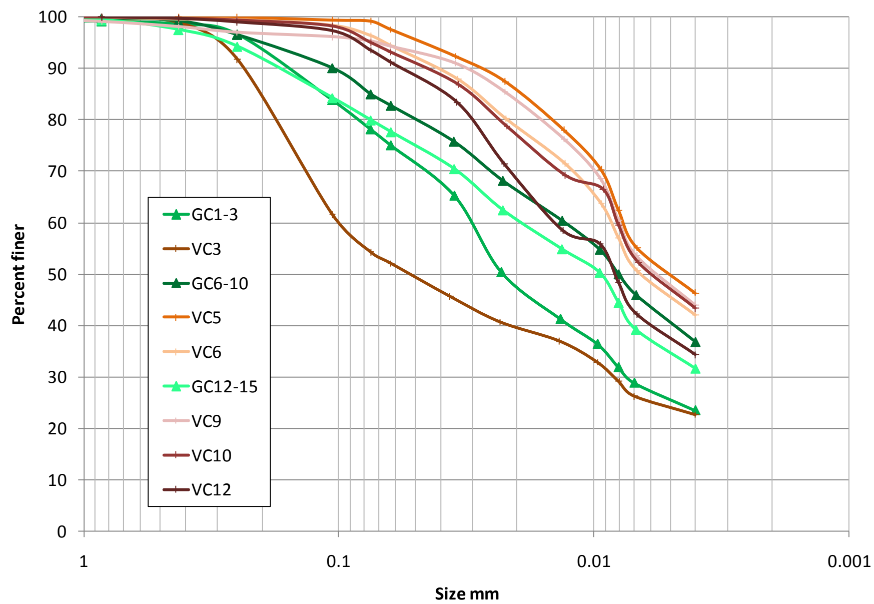

Figure 6. 2009 Bed material gradations between Suisun Bay and Pacheco Creek.

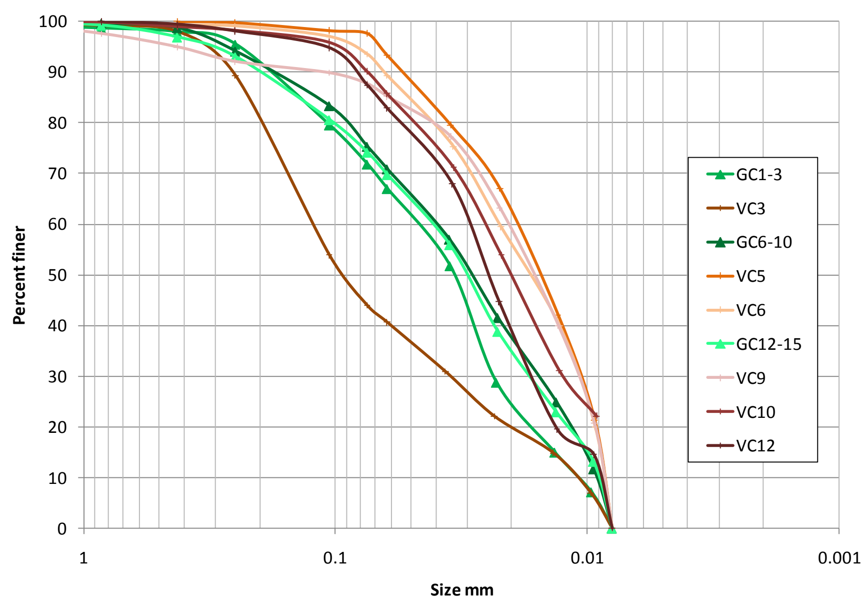

Figure 7. Initial bed material gradations used in HEC-6T model between Suisun Bay and Pacheco Creek normalized to 0.008mm.

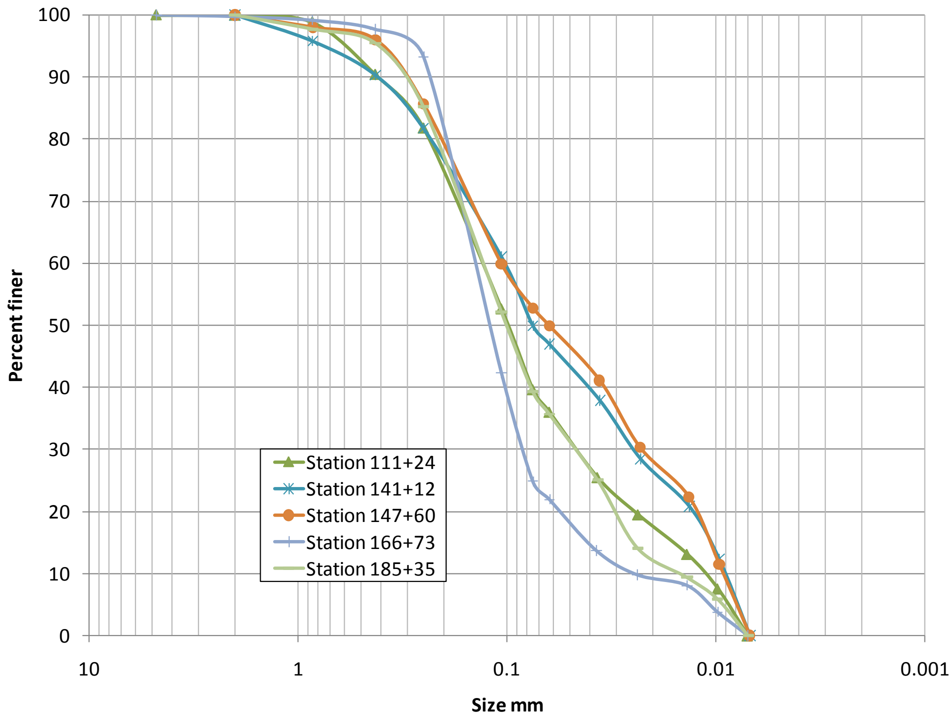

Figure 8. Initial bed material gradations used in HEC-6T model between Pacheco Creek and Grayson Creek normalized to 0.008mm.

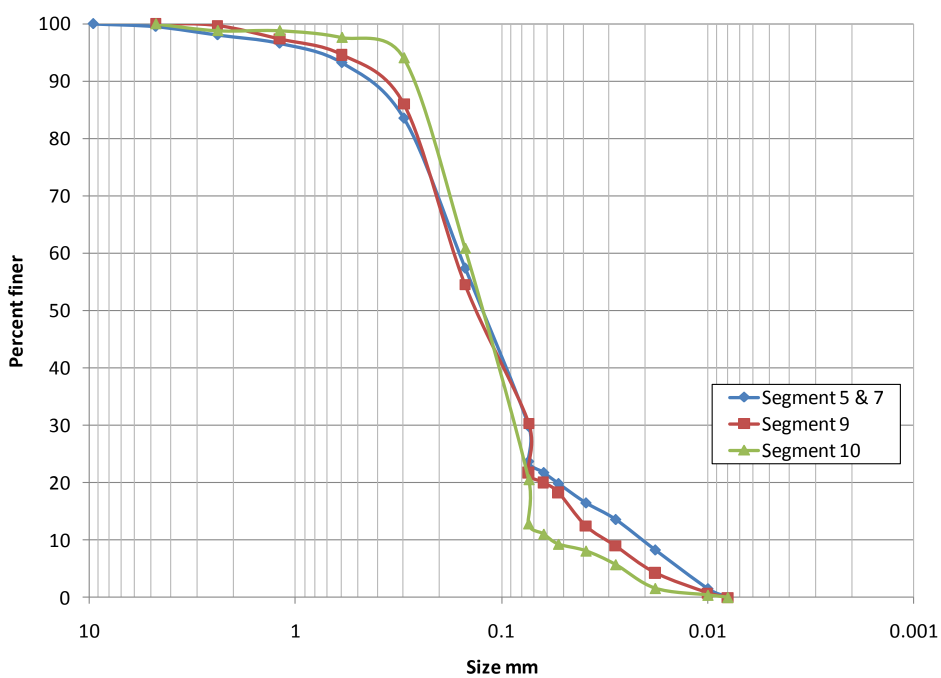

Figure 9. Initial bed material gradations used in HEC-6T model upstream from Grayson Creek normalized to 0.008mm.

Bed-Material Transport Function

The bed-material transport function in HEC-6T calculates sediment transport as a function of the percentage of each size class in the bed sediment reservoir. The composition of the bed sediment reservoir at each cross-section control volume is continuously re-calculated during the course of the numerical simulation as a function of the composition of the sediment inflow and sediment outflow. In most cases the bed sediment reservoir consists of the sand and gravel size classes. However, in Walnut Creek, the bed deposits contain significant percentages of the silt size classes. The only sediment transport function in HEC-6T that allows for transport of silt as bed-material load in the Laursen-Copeland function. This is the function employed in this study to calculate sediment transport of fine silt through very coarse gravel.

The Laursen-Copeland function is a modification of the Laursen (1958) sediment transport function. The Laursen-Copeland function incorporates more river and flume data in its development to extend the applicability beyond the original Laursen equation, and it changes the fundamental equation for boundary shear from total shear to grain shear. The additional data extends the range of particle size classes to include both gravel and fine silt. Sediment transport is calculated using the following equations:

$$C_s = 0.01\,\gamma \sum_{i=1}^{N} f_i \left(\frac{d_i}{D}\right)^{7/6} \left[\frac{\tau'}{\tau_{ci}} - 1\right] f\left(\frac{u'_*}{\omega_i}\right)$$

$$\tau' = \frac{\rho\, V^2}{58}\left(\frac{d50}{Rb'}\right)^{\frac{1}{3}}$$

$$\tau_{ci} = \theta_{ci}\,(\gamma_s - \gamma)\, d_i$$

where:

C_s = the concentration in weight per unit volume
γ = the unit weight of water
f_i = the fraction of grain size class i in the bed
N = the number of grain sizes
d_i = the median size of size class i
D = the mean water depth
τ' = the grain shear stress
τ_{ci} = the critical shear stress for particle size i
u_*' = the grain shear velocity = $\sqrt{\frac{\gamma R_b' S}{\rho}}$
ω_i = the fall velocity of particle size i

$f(u_*' / \omega_i)$ = a function derived from a large set of measured flume and river data
S = Slope
ρ = the water density
V = the average velocity
$d50$ = the median grain size
R_b' = the hydraulic radius due to grain roughness, which is calculated using the Limerinos equation
ϑ_{ci} = the critical Shields parameter for grain size i and varies between 0.039 and 0.020
γ_s i= the specific weight of sediment.

The function, $f(u_*' / \omega_i)$, is defined by the following equations within the specified limits:

$$\frac{u'_*}{\omega_i} < 0.05 : f\left(\frac{u'_*}{\omega_i}\right) = 0.0$$

$$0.05 < \frac{u'_*}{\omega_i} < 0.225 : f\left(\frac{u'_*}{\omega_i}\right) = 7.04E15 * \left(\frac{u'_*}{\omega_i}\right)^{22.99}$$

$$0.225 < \frac{u'_*}{\omega_i} < 1.0 : f\left(\frac{u'_*}{\omega_i}\right) = 40 * \left(\frac{u'_*}{\omega_i}\right)$$

$$1.0 < \frac{u'_*}{\omega_i} < 30 : f\left(\frac{u'_*}{\omega_i}\right) = 40 * \left(\frac{u'_*}{\omega_i}\right)^{1.843}$$

$$30 < \frac{u'_*}{\omega_i} : f\left(\frac{u'_*}{\omega_i}\right) = 10165 * \left(\frac{u'_*}{\omega_i}\right)^{0.1990}$$

Silt and Clay Transport Functions

The equation for silt and clay deposition used in HEC-6T is the Krone (1962) equation. The required calibration coefficient is the critical bed shear stress below which deposition occurs. In HEC-6T this coefficient has a variable name *DTCL* for clay and *SLDTSL* for silt.

$$\frac{C}{C_o} = e^{-k't}$$

$$k' = \frac{\omega\left(1 - \tau_b / \tau_d\right)}{2.3D}$$

where:

C = concentration at end of time step

C_o = concentration at beginning of time step
t = time = reach length / flow velocity
ω = settling velocity of sediment particle
τ_b = bed shear stress
τ_d = critical bed shear stress for deposition (*DTCL* and *SLDTSL*)
D = water depth

Erosion in HEC-6T is calculated using the Parthenaides (1965) equation. It is the cohesive properties of the clay that determine the erosion thresholds. For this reason, the same erosion coefficients are used for silt and clay in HEC-6T. Particle erosion is determined by:

$$C = \frac{M_1 S_a}{Q \gamma}\left[\frac{\tau_b}{\tau_s} - 1\right] + C_o$$

where:

M_1 = erosion rate for particle scour *(STME – STCD) / ERME*
S_a = surface area exposed to scour
Q = water discharge
τ_s = critical bed shear stress for particle scour *(STCD)*
γ = specific weight of water

As the bed shear stress increases, particle erosion gives way to mass erosion and the erosion rate increases. Because the mass erosion can theoretically be infinite, a characteristic time, T_c, is used. With a computation time interval of Δt, the mass erosion becomes:

$$C = \frac{M_2 S_a}{Q \gamma}\frac{T_c}{\Delta t} + C_o$$

where:

M_2 = erosion rate for mass erosion ($ERMC + ER2 \{\tau_b - STME\}) \Delta t / T_c$)
T_c = characteristic time of erosion
Δt = duration of time step

The relationships of erosion and deposition coefficients are shown in Figure 10 and Figure 11.

Silt and clay coefficients used in the numerical model were determined by Teeter (2010) (Appendix B) using previous laboratory studies of dredged material from the San Francisco Bay area (Teeter 1987). Composites of maintenance dredged material from the bay area were tested at the WES Hydraulics Laboratory and by the University of Florida. Those tests, taken together, indicated a two-phase particle erosion where erosion is first initiated at a low level of shear stress and then increases more sharply at higher shear stress. Threshold shear stresses for deposition are from Krone's tests on bay sediments. In the Walnut Creek model, the Parthenaides and Krone equations were only used for sediments smaller than 0.008 mm (clay and very-fine silt). Parameters used for cohesive material in the HEC-6T model are shown in Table 1.

Table 1. Silt and Clay Coefficients for Parthenaides and Krone Equations

Coefficient	**Variable Name in HEC-6T**	**Value in HEC-6T**	**Units**
Shear threshold for clay deposition	DTCL	.00125	lbs/ft^2
Shear threshold for silt deposition	DTSL	.00167	lbs/ft^2
Shear threshold for erosion of silt and clay particles	STCD	.0209	lbs/ft^2
Shear threshold for mass erosion	STME	0.2089	lbs/ft^2
Erosion rate at STME	ERME	17.7	$lbs/ft^2/hr$
Slope of the erosion rate curve for mass erosion	ER2	60	1/hr

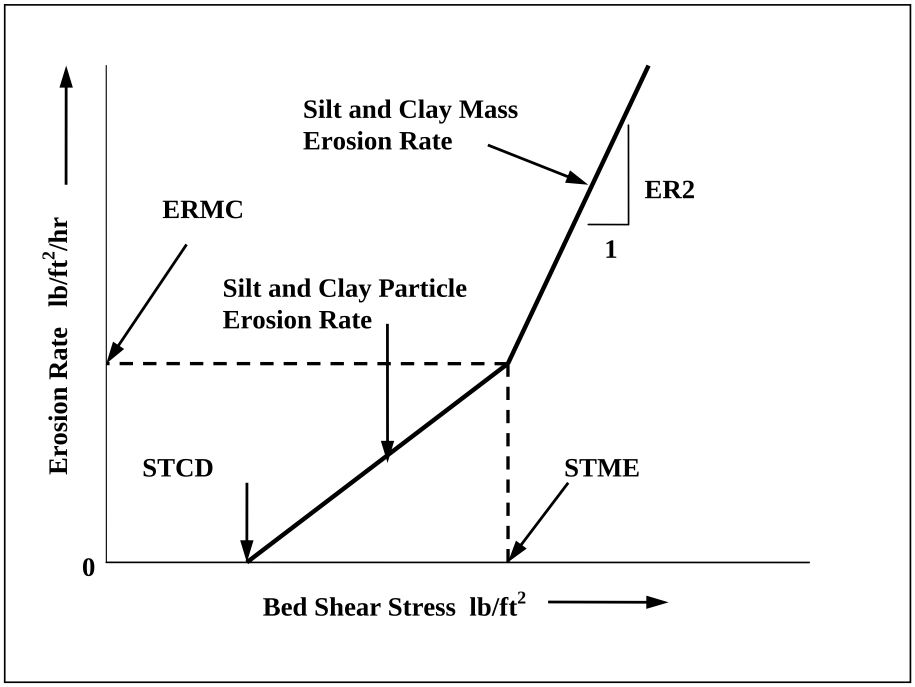

Figure 10: Erosion Rate Characteristics

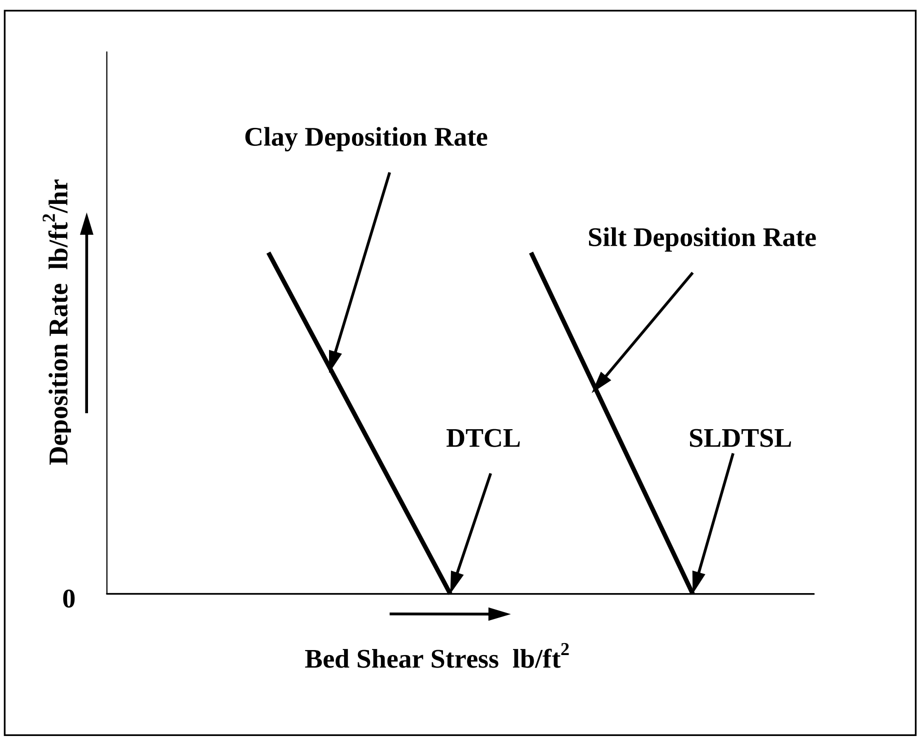

Figure 11: Deposition rate characteristics

Sediment Data / Inflow

Suspended sediment data were collected during the 1957-62 water years at the Walnut Creek at Walnut Creek, California gage. The gage was located at the Southern Pacific railroad bridge, 0.7 mile downstream from the confluence of San Ramon and Las Trampas Creeks. Sediment samples were collected for a discharge range between 1.0 and 2180 cfs. Samples were collected infrequently during periods of low flow and frequently during periods of medium and high flow. Particle-size distributions were determined for nine selected samples to determine the percentage of sand, silt, and clay transported by Walnut Creek. A sediment-transport rating curve was developed from these data and is presented in a USGS report (Porterfield 1972). The sediment- transport rating curve was not considered well defined because samples were collected on an infrequent basis were insufficient to establish the relationship between sediment concentration and streamflow for the entire range of streamflow. Sediment discharge was assumed, however, to be a reasonable estimate.

During November and December of 1970, four samples of suspended sediment were collected at the Walnut Creek at Concord gage (3.8 miles downstream from the confluence of San Ramon and Las Trampas Creeks). These data were collected at discharges ranging between 200 and 500 cfs. The 1970 data indicated that sediment concentrations, at least in the 200 to 500 cfs discharge range, were only 30 to 40 percent of the average concentrations between 1957 and 1962. Porterfield concluded that the 1970 data do not prove that a significant change in sediment yield occurred because (1) four samples are insufficient to be conclusive and (2) the data fall within the limits of the random variation of concentrations sampled during the 1957- 1962. However, he stated that the possibility should be considered that a change in sediment yield has occurred, and that additional data should be obtained.

Porterfield noted that bank stabilization, flood control measures, and land-use changes in the Walnut Creek watershed, after 1962, may have affected the relationship between stream flow and sediment discharge.

Disregarding Porterfield's recommendation for more sediment measurements, no additional data were collected. This lack of basic field data places the present study in the category of a "computational analysis" rather than a "computational model study." In a computational analysis model calibration is based more on circumstantial evidence and engineering judgment more than it is on field measurement. A computational analysis is more dependable for comparing alternatives than it is for predicting volumes of sediment.

Sediment inflow to the numerical model was determined using the 1957-62 Porterfield data as a base, but attempts to obtain the actual Porterfield measurements from the USGS were not successful. Sediment rating curves were scaled from Figure 2 in the Porterfield report and are shown in Figure 12 in this report. Both the fine and sand sediment inflow curves for the HEC-6T model were developed from two power regression equations; one for discharges less than 500 cfs and one for discharges greater than 500 cfs. Although the maximum sediment measurement was made at a discharge of 2,180 cfs, Porterfield extrapolated his sediment discharge curves to 5,000 cfs. In this HEC-6T model, the curves were extrapolated even further - to a discharge of 20,000 cfs. The size class distribution of the sediment inflow was based on size class percentages in the Porterfield report. The size class data were collected in 1958-1962. There were nine samples taken with a discharge range between 242 and 2,180 cfs. The data were insufficient to determine a trend with discharge so a straight average of size class percentage was calculated from the nine samples and used for the entire discharge range in the HEC-6T model.

Standardized sediment samplers typically are not capable of measuring the total sediment-load. There is always a fraction of the load that travels at an elevation below the sampler nozzle. Porterfield estimated the unmeasured sand load using the Modified Einstein equation and estimated it to be 23.5 percent of the measured sand load. Porterfield does not specify whether or not the sand rating curve in his report includes the correction for unmeasured load - but based on the method he used to calculate sediment yield later in the report, we assume that it does not. Therefore, the sand sediment inflow curves in HEC-6T were increased by 23.5 percent to account for unmeasured load. This constant correction was made for all sand size classes at all discharges.

Be aware that there is considerable uncertainty associated with assigned sediment inflow in this study. There is the uncertainty associated with using data collected during a five-year time period that occurred five years before the 40-year simulation period. There is the uncertainty associated with extrapolating the existing data beyond the range of the collected data. There is uncertainty associated with how accurate the sampling equipment and sampling methodology duplicates the true sediment load. For these reasons, sediment inflow is used as the primary calibration parameter in this numerical model.

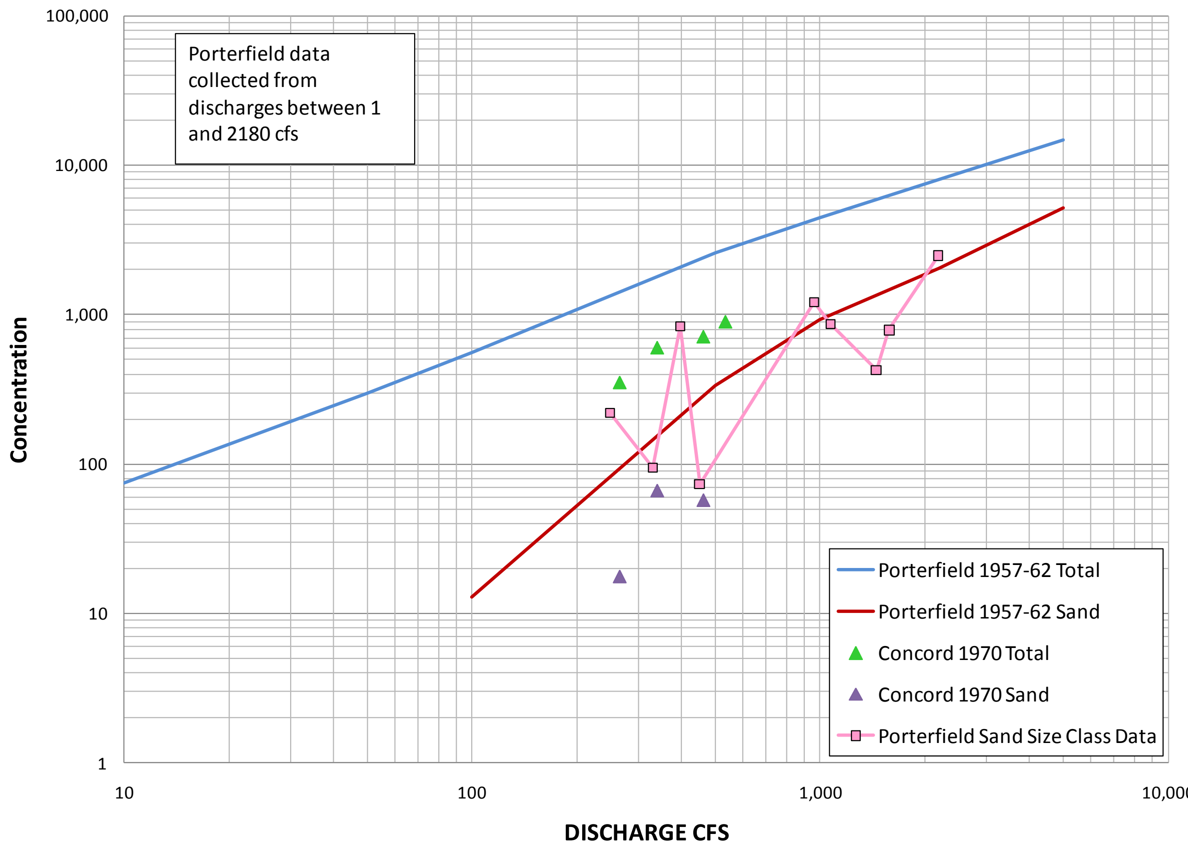

Figure 12. Sediment inflow on Walnut Creek from Porterfield 1972 report. Total and sand load curves were scaled from report. Sand size class data and Concord 1970 data are reported measurements.

Sediment Inflow / Tributaries

There were no available sediment measurements from the tributaries of Walnut Creek. Sand inflow could not be estimated by calculation, because no fully-alluvial supply reaches could be identified on the tributaries. Consequently, the sediment inflow curves determined for Walnut Creek were also used as the base for the tributaries.

Porterfield assumed that the sediment yield, adjusted for drainage area, from tributary streams draining the foothills and higher elevations were equal to that determined for Walnut Creek. This assumption does not account for the fact that the tributary watersheds are typically steeper than Walnut Creek at the Walnut Creek gage. Drainage areas for Walnut Creek and its tributaries are shown in Table 2.

Table 2. Drainage Areas	
Concentration Point	Drainage Area – Square Miles
Walnut Creek at Concord	85.6
Pine Creek at Mouth	31.1
Clayton Valley Drain at Mouth	5.6
Grayson Creek	18.1
Pacheco Creek	4.0
Walnut Creek at Suisun Bay	144.1

Tributary inflows in the HEC-6T model were adjusted to account for the expected increase in sediment concentration with discharge. This was accomplished using output from the SWAT model. Daily sediment yields for Walnut Creek at Concord and the four tributaries were calculated for the 1965-2005 historical period using the SWAT model. The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) to calculate sediment yield. The input variables for MUSLE were already available in the SWAT input data. The MUSLE equation is:

$$Y = 95(Qq)^{0.56}\, K\, LS\, C\, P$$

where:

Y = single storm sediment yield in tons
Q = storm runoff volume in acre-ft
q = peak discharge in cfs
K = soil-erodibility factor
LS = slope steepness and length factor
C = cover management factor
P = conservation practice factor

Power regression curves were developed in EXCEL for Walnut Creek at Concord and for each tributary using calculated sediment concentrations from the SWAT model. Using the regression curves, ratios of tributary concentrations to Walnut Creek at Concord concentrations, for specific discharges, were calculated and then used to adjust the sediment inflow curves from Walnut Creek to each tributary. Ratios calculated at the maximum discharges in the SWAT model were held constant for discharges in the sediment rating table outside the range of the SWAT data. Assigned ratios are listed in Table 3.

Table 3. Ratio of Tributary Sediment Inflow Concentration to Walnut Creek at Concord Concentration								
Discharge CFS	10	50	100	500	1,000	2,200	5,000	10,000
Pacheco	2.30	2.30	1.24	0.78	0.78	0.78	0.78	0.78
Grayson	4.08	3.70	3.44	2.05	1.40	1.40	1.40	1.40
Clayton Valley	2.54	2.38	2.27	2.01	1.73	1.73	1.73	1.73
Pine	2.54	2.38	2.27	2.01	1.73	1.73	1.73	1.73

MODEL CALIBRATION

Available data were not sufficient to certify this as a computational model. However, it is very useful for computational analysis. A computational analysis is made to compare one alternative versus another because it will show trends in the parameters that were used in the confirmation. One cannot be confident in the computed quantities of deposition or erosion.

Sediment Inflow – USGS Sediment Load Curve

Initially, HEC-6T was run with sediment inflow rating curves based on Porterfield's (1972) rating curves and the 1965-1970 water discharge hydrograph in an attempt to duplicate the measured volume of sediment deposits in Walnut Creek downstream from the Grayson Creek confluence. The Porterfield rating curves were extrapolated beyond the measured data using a power regression relationship. Extrapolation was deemed more appropriate than arbitrarily assigning lower concentrations at higher discharges because the extrapolated curve provided more sediment, which was needed to duplicate measured sediment deposition in Walnut Creek. The Porterfield rating curves were adjusted to account for unmeasured load. Porterfield had used the Modified Einstein equation to estimate the unmeasured load, but did not include this adjustment in his published sediment rating curves. Annual sediment inflow quantities varied significantly as a function of the annual hydrograph as shown in Figure 13. Years with the highest sediment inflow were 1982, 1983 and 1986.

The volume of deposits in Walnut Creek downstream from Grayson Creek was calculated by USACE Sacramento District using available channel surveys. As-built cross sections of this reach were surveyed in 1965. The reach was resurveyed in April 1969, in April 1970, and in April 1972. Additional surveys were taken in 1995 and 2005. Deposition depths between 1965 and 1995, and between 1995 and 2005, calculated from these surveys, are shown in Plate 5. The survey transects are shown in Plates 6-10

Bed material samples were also collected in April 1970 and published in the Porterfield report. These bed material samples and the calculated volume of deposits between 1965 and 1970 were used by Porterfield to determine the composition of the deposited material in Lower Walnut Creek.

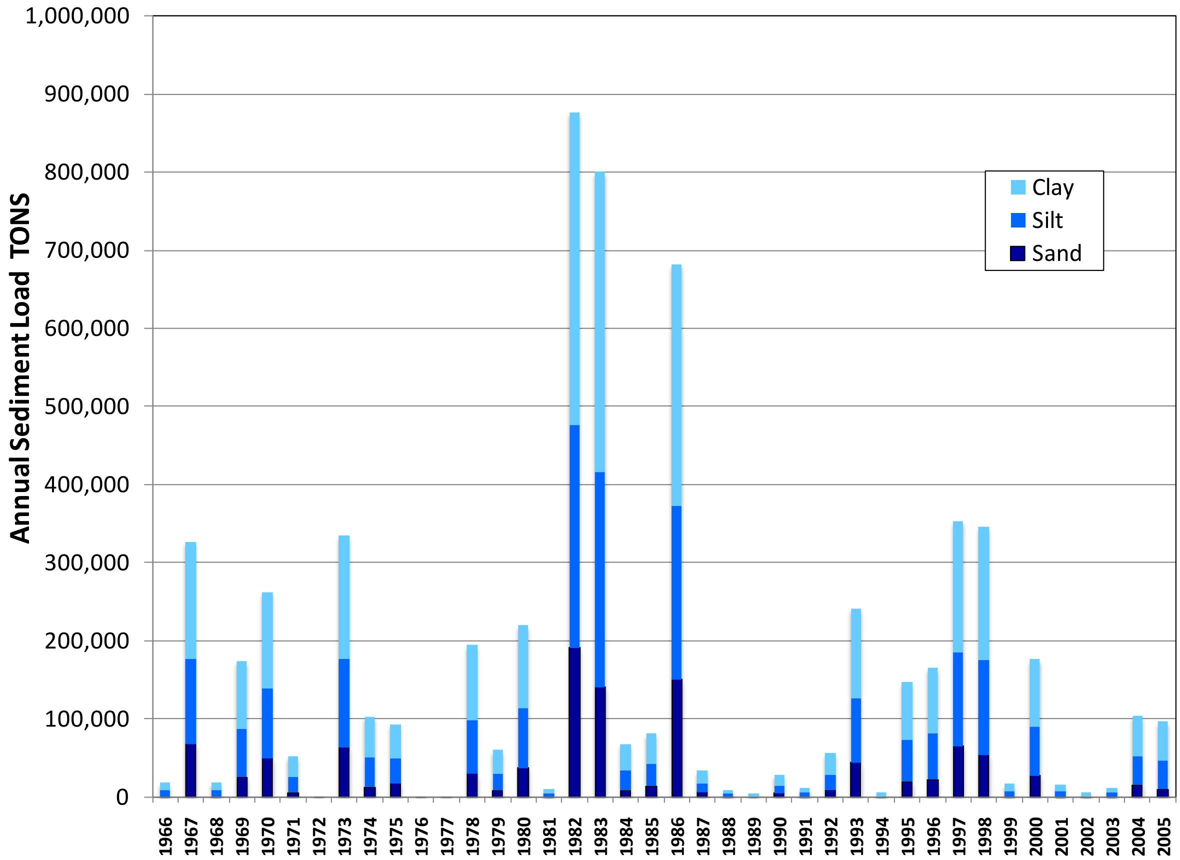

Figure13. Annual sediment Inflow calculated using HEC-6T sediment inflow curve and 1965-2005 hydrograph at Concord.

The deposition calculated from the surveys is compared to the deposition calculated by HEC-6T, in Table 4. Also shown in the table is the calculated runoff during the same time period. For practical purposes, August 1965 through November 1967 constitutes one water year, November 1967 through April 1969 constitutes two water years, April 1969 through April 1970 constitutes one water year, and April 1970 through April 1972 constitutes two water years. Table 5 compares the 1970 composition of the deposited material in the test reach, as reported by Porterfield, with the composition calculated by HEC-6T.

Table 4. Calculated Deposition and Runoff in Lower Walnut Creek downstream from Grayson Creek HEC-6T Calculations using USGS Sediment Inflow Rating-Curve 1965-1972			
	Deposition Cubic Yards Calculated from Surveys	Deposition Cubic Yards Calculated from HEC-6T	Runoff Acre-Feet From HEC-6T Output
Aug 65 – Nov 67	660,000	138,500	65,200
Nov 67 – Apr 69	275,000	84,400	63,300
Apr 69 - Apr 70	125,000	88,500	43,700
Apr 70 – Apr 72	70,000	36,000	31,600

Table 5. Calculated Size Class Percentages of Deposition in Lower Walnut Creek, April 1970			
	Sand	Silt	Clay
Calculated Size Class Percentages from USGS Data			
Pacheco Creek to Grayson Creek	69	14	18
Bay to Pacheco Creek	36	39	25
Calculated Size Class Percentages from HEC-6T			
Pacheco Creek to Grayson Creek	78	20	2
Bay to Pacheco Creek	31	62	7

The calculations provide three surprises: 1) the observed deposition calculated from the August 1965 and November 1967 survey data is much greater than the observed deposition determined for subsequent time periods, 2) the HEC-6T calculated deposition is much less than the observed deposition, and 3) the percentage of clay deposition in the calculated deposit is less than the observed percentage.

The under-prediction of deposition by the model is directly related to the sediment inflow rating curve. Using the Porterfield sediment inflow curves, adjusted to include unmeasured load, HEC-6T calculates about 30 percent of the observed deposition through 1972. The discontinuity between observed deposition and sediment yield from measured sediment inflow concentrations was identified in Porterfield (1972) report. Even employing assumptions that tended to provide more sediment for deposition in Lower Walnut Creek, Porterfield’s calculated sediment deposition came up short for sand. Porterfield assumed that the contribution of sediment from the tributaries, primarily Pine Creek, would be proportional to their drainage areas when compared to the Walnut Creek drainage area above the Concord gage. The result of this assumption was that 72% of the sediment load came from Walnut Creek, 22% from Pine Creek, 4% from Grayson Creek, and 2% from Pacheco Creek. In the Porterfield sediment budget, this resulted in increasing the sediment inflow to the reach below the Grayson Creek confluence by 39 percent. Porterfield further assumed that all the sediment passing the gage at Walnut

Creek and all of the sediment contributed by Pine Creek was transported to the deposition zone downstream from Grayson Creek. The sediment inflow of all size classes, calculated by Porterfield, was 828,000 tons, and the calculated deposition from surveys in the test reach was 750,100 tons. If the entire volume of deposited sediment were supplied by the watershed, the trapping efficiency would be 90 percent. The calculated weight of deposited sand was 333,150 tons, which is 44 percent of the total deposit. Using the Porterfield sediment rating curve, with the adjustment for unmeasured load, and including contributions from the tributaries, only 263,960 tons of sand inflow is provided by the watershed. Thus, even by increasing the sediment discharge at Concord by 39 percent to account for tributary inflow, and by 23 percent to account for the unmeasured load, the inflowing sand load was still less than the measured sand in the deposits.

The hydrologic data from SWAT and HEC-1 analyses and the sediment budget calculated at the boundaries in HEC-6T demonstrated that the contributions from tributaries are over-estimated in the Porterfield (1972) report. According to the hydrologic model, conducted by USACE Sacramento District for this study, 75 percent of the water yield is supplied by the watershed upstream from the Concord gage. Pine Creek supplies 17 percent, Clayton Valley Drain 1 percent, Grayson Creek 7 percent and less than one-percent is supplied from Pacheco Creek. Sediment yield calculated by HEC-6T indicates that 84 percent of the total sediment yield and 91 percent of the sand yield is supplied by the watershed upstream from the Concord gage. Pine Creek supplies 12 percent of the total sediment yield and 7 percent of the sand yield. Grayson Creek supplies 4 percent of the total sediment yield and 1 percent of the sand yield. Less than one-percent of the sediment yields are supplied from Clayton Valley Drain and Pacheco Creek.

Calculations in HEC-6T and historical evidence both indicate that deposition occurs in Walnut Creek between the Concord gage and Grayson Creek. The assumption of 100 percent sediment delivery to the Grayson Creek confluence, used in the Porterfield sediment budget, is an over simplification.

Ninety percent trap efficiency for all sediment sizes supplied to Lower Walnut Creek is unreasonable. HEC-6T calculates trap efficiency based on the physical properties of individual size classes and hydraulic conditions in the river. HEC-6T calculated an average trap efficiency of 42 percent for all the supplied sediment. Trap efficiency for sand was 100 percent, silt 57 percent and clay 4 percent. HEC-6T does not adequately account for flocculation of cohesive sediments in the salt water environment, the trap efficiency calculated by HEC-6T for clay may be too low.

There are several possible explanations for a larger than average deposition during the first year after channel construction.

1) It is expected that more sediment will be transported into the deposition reach during years of higher runoff. The August 1965 to November 1967 time period is the period with the highest runoff. However, even though sediment transport and runoff are not directly correlated, it is surprising that the sediment deposition differential is so much greater than the runoff differential. HEC-6T calculations account for the higher sediment transport rates at higher discharges, and these calculations do not support the percent change in sediment deposition after November 1967.

2) It is expected that deposition rates will be higher immediately after construction because the excavated channel has created a natural sink for sediment. However, the magnitude of the difference in deposition is unexpected. HEC-6T calculations account for the lower sediment transport potential in the excavated channel, and these calculations do not support the percent change in sediment deposition after November 1967.

3) Channel excavation was occurring in upstream reaches of Walnut Creek between 1965 and 1971. The contract schedules are shown in Table 6. It is likely that these construction activities provided considerable sediment to downstream reaches and the construction was downstream from the sediment gage. This conclusion was documented by the Corps of Engineers in "Letter Supplement to the Design Memorandum" (USACE Sacramento District 1973). It states, *"The removal of 498,000 cubic yards is considered to be extraordinary maintenance due to construction activities by the Corp's contractors in the stream channel and due in part to extensive urbanization in the tributary areas."* This third explanation is the most reasonable and was accounted for in the HEC-6T sediment inflow assignment at the upstream boundary.

HEC-6T under-predicts clay deposition, as shown in Table 5. In the numerical model, clay deposition is determined by the fall velocity of the clay particles and by the shear stress provided by the riverine stream discharge. There are few times steps during the historical simulation when the combination of clay concentration and riverine shear stresses are favorable for deposition. It can be concluded that clay deposition in the lower reaches of Walnut Creek takes place primarily as a result of the rising and falling tides. Clay deposition also will occur on the falling limb of hydrographs when water depth on the channel berms becomes shallow and shear stresses are reduced. The one-dimensional HEC-6T model uses only the channel hydraulic parameters to determine sediment transport potential and therefore does not simulate deposition due to shallow flow over the berms. Once this clay is deposited on the prototype channel berm, it is difficult to re-entrain due to cohesive properties and the protection afforded by the grass cover and root mass. In order for HEC-6T to reproduce measured deposition, sand inflow must be increased to account for the model's inability to simulate clay deposition.

Table 6. Construction Contracts for Walnut Creek and Pine Creek Provided by Contra Costa County		
Creek	Limits	Year Built
Walnut Creek	Suisun Bay (Sta. 0+00) to Grayson Creek (Sta. 187+50)	1964
Walnut Creek	Grayson Creek (Sta. 187+00) to Drop Structure #1 (Sta. 354+90)	1965
Walnut Creek	Drop Structure #1 (Sta. 353+90) to Drop Structure #2 (Sta. 460+70)	1966
Walnut Creek	Drop Structure #2 (Sta. 459+25) to Geary Rd. (Sta. 497+70)	1967
Walnut Creek	Waterfront Rd. (Sta. 66+30) to Grayson Creek (Sta. 187+50)	1967
Walnut Creek	Treat Blvd. (Sta. 490+88) to School Foot Bridge (Sta. 562+80)	1968
Walnut Creek	School Foot Bridge (Sta.562+80) to SPRR Bridge (Sta. 585+00)	1970
Walnut Creek	Mt. Diablo Blvd. (Sta. 4+27) to Capwells Culvert (Sta. 18+50)	1971
Pine Creek	Existing concrete lining to Walnut Creek	1978
Pine Creek	Market St. (Sta. 36+00) to Monument Blvd. (Sta. 88+95)	1981
Pine Creek	Monument Blvd. (Sta. 88+95) to Detroit Ave. (Sta. 135+71)	1982
Galindo Creek	Detroit Ave. (Sta. 8+53) to Albert Ln. (Sta. 45+00)	1982
Upper Pine	BART (Sta. 134+90) to Oak Grove Rd.(Sta. 279+30)	1989
Upper Pine	Perada Dr. (Sta. 289+62) to Detention Basin (Sta. 305+62)	1990
San Ramon Creek	Bypass	1985-1992

Sediment Inflow – Adjusted Rating Curve

The Porterfield sediment inflow rating curves, adjusted for unmeasured sand load, and extrapolated beyond the measured data using power regression relationships, were further adjusted to account for under-prediction of clay deposition. The sediment inflow of the sand size classes was increased by 25 percent. In addition, to partially account for the increase in sediment yield due to channel construction on Walnut Creek, sediment inflow rates of all size classes were increased by a factor of 2.2 between August 1965 and September 1970. Numerical instabilities occurred in the model when a factor of 2.3 was used. After September 1970, sediment inflow rates of all size classes were reduced by 50 percent, so that the sediment inflow ratio was 1.1. The 25-percent increase in sand inflow was applied to the tributaries, but not the factor to account for construction. Calculated deposition and dredging are compared to deposition calculated from historical surveys and reported dredging in Table 7. Calculated results shown in Table 7 are from computer runs that included channel erosion and deposition adjustments discussed in the following paragraphs.

Table 7. Comparison of Surveyed and Calculated Deposition and Sediment Removal 1965-2005			
Segment - Reach	Estimated from surveys	Calculated with original USGS inflow	Calculated with Adjusted Inflow
Deposition –Cubic Yards			
10 – Drop 1 to Station 405+89	72,300	26,500	52,100
9 – Pine to Drop 1	151,000	122,700	158,200
7- CVD to Pine	123,000	148,900	133,900
5 - Grayson to CVD	22,000	9,900	55,700
1&3 - Bay to Grayson			
Aug 65 – Nov 67	660,000	138,500	302,800
Nov 67 – Apr 69	275,000	84,400	189,400
Apr 69 Apr 70	125,000	88,500	238,300
Apr 70 – Apr 72	70,000	36,000	47,300
1973 - 1995	1,034,000	869,000	1,097,100
1995 - 2005	28,500	483,700	450,900
Sediment Removal – Cubic Yards			
1973 – Bay to BNSFRR	750,000	220,100	545,500
1986 – CVD to Drop 1	138,000	135,800	143,900
1989 – CVD to Drop 1	138,000	125,900	140,600
1993 – Pine to Drop 1	38,000	30,800	38,000
1995 – Pine to Drop 1	38,000	24,300	26,500

Notes:

1. Results are from computer runs that include channel erosion and deposition adjustments.
2. Clayton Valley Drain (CVD)

Deposition and Erosion Limits

Appropriate replication of deposition and sediment removal quantities could not be obtained by adjustment of sediment inflow alone. Adjustment of the model deposition and erosion limits was also required.

HEC-6T is not a geomorphic model. Neither does the one-dimensional, steady state HEC-6T model simulate the unsteady tidal effects directly. The model also uses average hydraulic parameters to determine uniform depths of erosion and deposition in cross sections. The model can calculate either erosion or deposition at the same cross section at different time steps as a function of the current hydraulic and sediment conditions at that time step. However, prototype conditions where both deposition and erosion are occurring simultaneously at the same time step at an individual cross section cannot be modeled.

The HEC-6T model does allow for differential change in cross section shape during a simulation. One method for this change to occur is when sediment deposits at high flows and erodes at low flows. Under these conditions, at high flow when the water surface elevation is high, sediment deposits uniformly across the movable channel bed. At lower flows, when erosion is occurring, some of the cross-section points are not submerged and therefore do not have a decrease in elevation. Over a long period of time, a berm may develop in the cross section. This natural process is simulated well by HEC-6T. It allows for channel narrowing as shown by the example cross section in Figure 14. This cross section is located on Segment 10 between Drop 1 and Station 405+89.

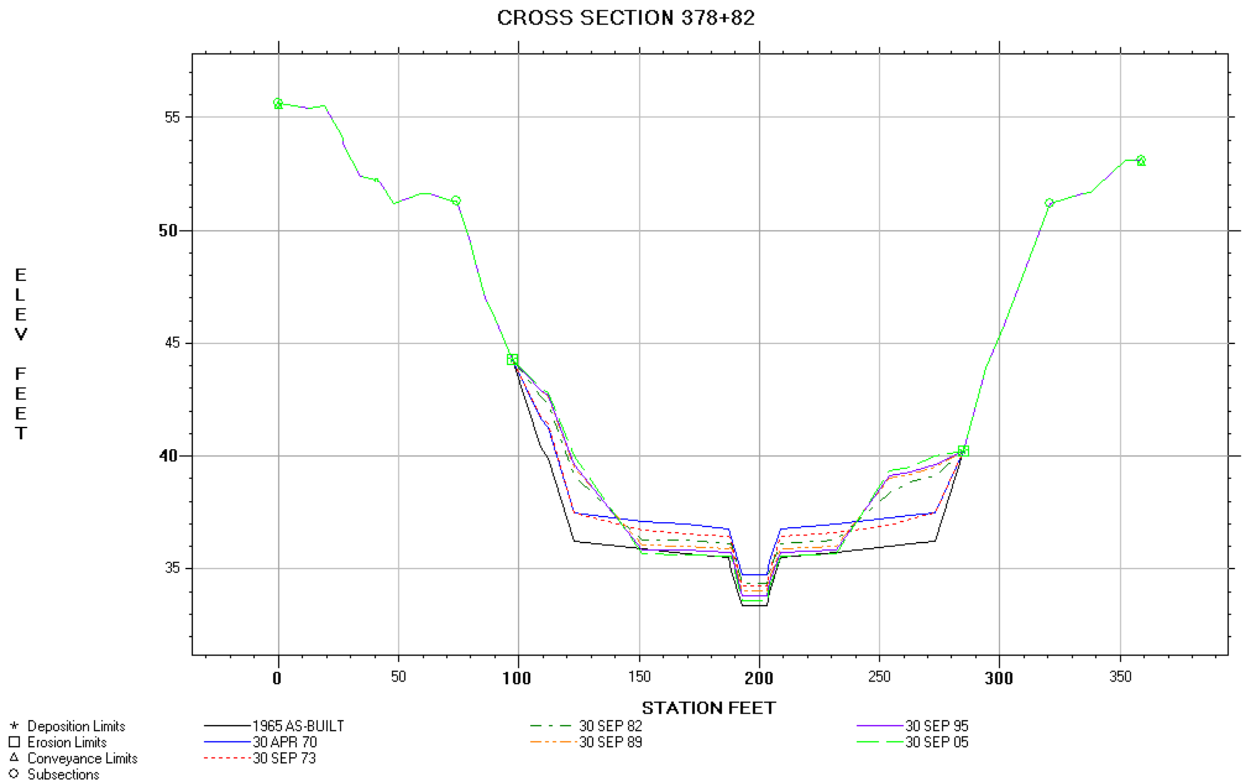

Figure 14. Calculated Change in cross section shape at Station 378+82 during 40-year simulation.

The natural process where erosion and deposition are occurring simultaneously at a cross section due to significantly different hydraulic parameters occurring in different parts of the cross section cannot be simulated by the model. However, the process can be approximated by restricting erosion to a specified portion of the channel width. By specifying a limited erosion width, deposition is allowed to occur in a portion of the channel without ever being reduced in elevation. This is not an unreasonable assignment in a channel where the berms are somewhat stabilized by a significant fraction of cohesive material and are frequently covered by vegetation and its accompanying root mass. The assigned erosion width is determined during the calibration of the model to historical data. In the Walnut Creek model this assignment was only used in Segments 7 and 9, which are between Clayton Valley Drain and Drop Structure 1, Figure 1. Sediment removal records and the 2005 survey allowed for temporal checks to the deposition quantities during the 1965-2005 simulation time period. An example cross section is shown in Figure 15.

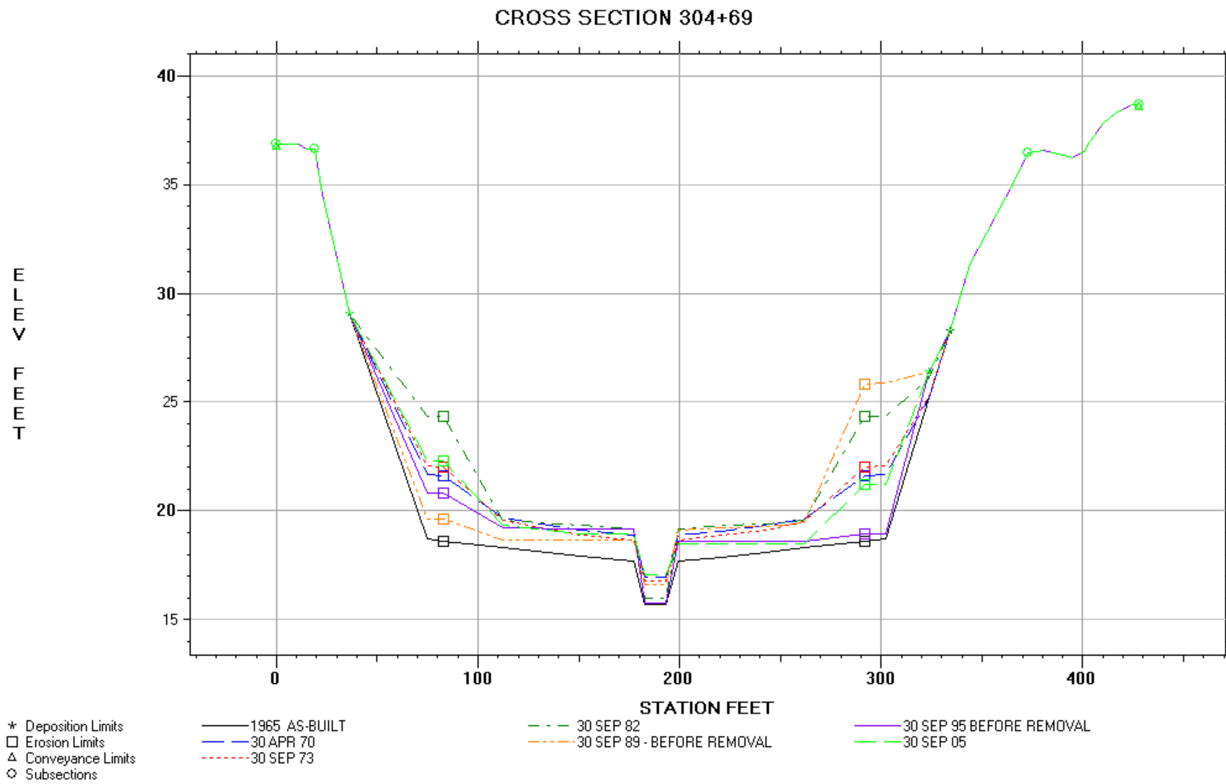

Figure 15. Calculated Change in cross section shape at Station 304+69 during 40-year simulation.

Erosion and deposition limits were adjusted only in Segments 7 and 9. This is the reach where sediment was removed in 1986, 1989, 1993 and 1995. With these adjustments the final calibrated "base test" was developed. Calculated and measured volumes of deposition and removal are compared in Table 8. Calculated and sampled bed material gradations are compared in Table 9.

This modeling technique was used to move the pattern of cross section adjustments toward the patterns observed in the surveyed cross sections of the prototype. It is coded into the water discharge hydrograph that was used for calibration. Therefore, it is important for that code to remain a part of the testing hydrograph that will be used to compare plans of development for Walnut Creek.

Table 8. Comparison of Measured and Calculated Deposition and Dredging for Base Test 1965-2005		
Deposition		
Segment - Reach	Measured Cubic Yards	Calculated Cubic Yards
10 – Drop 1 to Station 405+89	72,300	52,100
9 – Pine to Drop 1	151,000	158,200
7- CVD to Pine	123,000	133,900
5 - Grayson to CVD	22,000	55,700
1&3 - Bay to Grayson		
Aug 65 – Nov 67	660,000	302,800
Nov 67 – Apr 69	275,000	189,400
Apr 69 Apr 70	125,000	238,300
Apr 70 – Apr 72	70,000	47,300
1973 - 1995	1,034,000	1,097,100
1995 - 2005	28,500	450,900
Sediment Removal		
1973 – Bay to BNSFRR	750,000	545,500
1986 – CVD to Drop 1	138,000	143,900
1989 – CVD to Drop 1	138,000	140,600
1993 – Pine to Drop 1	38,000	38,000
1995 – Pine to Drop 1	38,000	26,500

Table 9. Calculated Composition of Deposited Sediment after 1965-2005 Simulation (Percent by weight)				
Segment	Walnut Creek Reach Description	Percent Sand	Percent Silt	Percent Clay
10	Drop 1 to Walnut Creek Station 405+89	96	4	
9	Pine Creek to Drop 1	87	13	
7	Clayton Valley Drain to Pine Creek	77	23	
5	Grayson Creek to Clayton Valley Drain	100	0	
3	Pacheco Creek to Grayson Creek	94	6	
1	Bay to Pacheco Creek	74	23	3
Reach Averaged Bed Material Gradations from 2009 Samples				
10	Drop 1 to Walnut Creek Station 405+89	75	11	14
9	Pine Creek to Drop 1	69	21	10
7	Clayton Valley Drain to Pine Creek	54	20	26
5	Grayson Creek to Clayton Valley Drain			
3	Pacheco Creek to Grayson Creek	48	31	21
1	Bay to Pacheco Creek	22	48	30
USGS Average Bed Material Gradations 1970				
3	Pacheco Creek to Grayson Creek	69	14	18
1	Bay to Pacheco Creek	36	39	25

Cross sections at Stations 0+35 and 7+59, which are located at the downstream end of the model, initially were assigned movable bed widths within the design channel width. The design channel width is about 450 feet. The two cross-sections included wide overbanks that represent the tidal flats adjacent to the channel as it flows into Suisun Bay. These wide overbanks allow flood flows to occupy the tidal flats, reducing the flow in the channel. When the channel flow is reduced, sediment transport potential is reduced inducing deposition. It is uncertain how much of the deposition would actually deposit in the channel and how much would deposit in the tidal flats. There were no survey data available to make this determination. During the initial calibration simulations the channel completely filled with sediment during the 1982 flood event. In order to prevent this unreasonable outcome, the movable bed limits at the two downstream cross sections were extended to include the entire tidal flat width during the peak of the flood on January 4 and 5, 1982. This change in movable bed limits was effective for 48 hours. With this model adjustment about one foot of deposition occurred on the overbanks at both cross sections. The overbank width at Station 0+35 was about 2700 feet and at Station 7+59 it was about 800 feet. This adjustment produced reasonable, but unverifiable, amounts of deposition in both the channel and overbanks.

Future predictive studies that include major flood events should also include the expanded movable-bed width adjustment at stations 0+35 and 7+59. In this study, the February 1982 flood had a peak discharge of 28,600 cfs and required the adjustment. The next highest peak discharge was 12,900 cfs, which occurred in March 1998, and the adjustment was not required. Whether or not the adjustment is required for future floods can be identified when channel deposition completely fills the designated channel.

Initially, during the 1965-2005 historic simulation, the channel at the downstream cross section was full by 1992. In order to prevent numerical instabilities, a transmissive boundary condition was inserted after October 1992. This prevented any further deposition at cross section 0+35. Future predictive studies that use a surveyed cross section at the downstream boundary with significant deposition above the design channel elevations should include a transmissive downstream boundary assignment.

Sensitivity of Input Parameters

Computer runs were conducted to test the sensitivity of key model input parameters. Tested were the effect of adjusting the erodible bed limits, the effect of removing the low flow channel set by the project design, and the effect of changing the sediment inflow. Comparisons of calculated and measured deposition and sediment removal are shown in Table 10. The base test column represents the final calibration values discussed in the previous paragraphs. Calculated results in the other columns were obtained from the base test model with only the specified difference included. The column entitled *"wide erosion limits"* contains results from a model where the deposition and erosion limits were the same. The column entitled *"remove low flow channel"* contains calculated results for the condition where the low flow channel was removed from all the cross sections in Walnut Creek. This change was included because, with the design low flow channel, erosion was calculated along the channel invert at some cross sections even though the bed sediment reservoir depth was assigned a depth of 0.01 ft. The model assumes that the minimum elevation in the channel is the bottom of the bed sediment reservoir so that elevations higher than the minimum elevation are subject to erosion.

The effect of decreasing the sediment inflow at the upstream boundary of Walnut Creek by 20 percent and increasing the sediment inflow at the upstream boundary by 10 percent are shown in Table 10, also. The upstream sediment inflow could not be increased by 20 percent because it induced numerical instabilities.

Table 10 Sensitivity of Input Parameters,1965-2005					
Deposition – Cubic Yards					
Segment - Reach	Base Test	Wide Erosion Limits	Remove Low Flow Channel	Decrease Concord Inflow 20%	Increase Concord Inflow 10%
10 – Drop 1 to Sta 405+89	52,100	52,300	18,800	36,300	57,000
9 – Pine to Drop 1	158,200	14,100	192,300	139,500	116,000
7- CVD to Pine	133,900	120,500	195,200	111,000	150,000
5 - Grayson to CVD	55,700	76,500	48,000	34,300	70,200
1&3 - Bay to Grayson					
Aug 65 – Nov 67	302,800	363,600	297,400	250,800	327,700
Nov 67 – Apr 69	189,400	193,900	177,200	154,400	207,300
Apr 69 - Apr 70	238,300	249,700	222,100	194,900	264,900
Apr 70 – Apr 72	47,300	47,200	48,200	40,500	50,000
1973 - 1995	1,097,100	1,110,600	1,143,200	979,100	1,153,500
1995 - 2005	450,900	478,300	453,500	426,200	467,200
Dredging – Cubic Yards					
1973 – Bay to BNSFRR	545,500	603,600	521,100	422,200	605,900
1986 – CVD to Drop 1	143,900	42,900	203,000	113,200	147,200
1989 – CVD to Drop 1	140,600	46,000	192,900	111,400	149,500
1993 – Pine to Drop 1	38,000	19,700	19,900	34,900	26,500
1995 – Pine to Drop 1	26,500	14,700	16,600	27,600	21,200

DISCUSSION AND CONCLUSIONS

Available data were not sufficient to certify the HEC-6T model developed during this study as a *computational model*. However, it is very useful for *computational analysis*. A *computational analysis* is made to compare one alternative versus another because it will show trends in the parameters that were used in the confirmation. However, one cannot be confident in the computed volumes of deposition or erosion.

Channel Stability

A comparison of Walnut Creek's design cross sections with recent surveys showed that the design cross sections were not geomorphologically stable. Deposition rates were much more rapid immediately after construction and after sediment removal. This occurs because the original channel design is not as efficient, with respect to sediment delivery, as the smaller channel created by natural deposition. During the time period between 1965 and 2005 the Walnut Creek channel has been adjusting itself to better maintain sediment continuity through the study reach. However, it is improbable that a state of equilibrium, in which all the sediment supplied from the watershed is delivered to Suisun Bay, will be ever be reached - at least in engineering time. Deposition and delta building are on-going natural processes that are expected to continue where rivers and streams flow into bays.

In the upstream reaches of the Walnut Creek study area, sediment has been depositing on both sides of the design channel, forming berms, while retaining a smaller low-flow channel in the center. In contrast, sediment deposited relatively uniformly across the channel invert in the downstream reaches during the early years of channel evolution (1965-1972). More recent surveys in the downstream reaches (1995 and 2005) show a well developed low flow channel with berms on both sides with little additional deposition. This suggests that tidal processes have become dominant, in the downstream reaches, and that the existing channel is much closer to a stable channel than the original project design. Future project designs should recognize this condition and avoid making significant changes to the cross-section shape in the tidal reaches of Walnut Creek.

Model Performance

The adjusted HEC-6T model was relatively successful in simulating 1965-2005 reported deposition upstream from Grayson Creek, but not as successful in simulating reported deposition downstream from Grayson Creek. Between August 1965 and November 1967, the volume of deposits, downstream of Grayson Creek, calculated by HEC-6T, was less than the reported volumes. Between 1967 and 1995, the computed and reported volumes downstream from Grayson Creek agreed reasonably well. Between 1995 and 2005, HEC-6T over-predicted deposition downstream from Grayson Creek.

The reported volume of deposition downstream from Grayson Creek, between August 1965 and November 1967, was significantly higher than in subsequent years. This was the time period when the Walnut Creek channel was being excavated between Grayson Creek and the USGS gage. It is likely that the source of a considerable quantity of the deposited sediment was from that construction. In fact, HEC-6T calculations indicated that Walnut Creek cannot deliver a sufficient quantity of sand from the watershed to the deposition area to create the reported volume of deposition. The upstream channel would become clogged with sand deposits.

Between 1967 and 1995, the numerical model results and reported deposition determined from surveys was reasonably consistent. The channel geometry in the tidal marsh was becoming more stable during this time. Sedimentation processes were the result of both tidal and riverine hydrodynamics, but it is speculated that riverine processes were dominant.

After 1995, surveys suggest a relatively stable channel in the reach downstream from Grayson Creek, whereas the HEC-6T model results show a deposition rate consistent with previous years. It is likely that tidal sedimentation processes have become dominant and have successfully maintained a channel that is in dynamic equilibrium, whereas HEC-6T, which models only the riverine hydrodynamics, continues to compute a deposition rate that is consistent with the earlier years.

Boundary Condition Issues

Difficulties in matching historical observations are attributed to uncertainties related to boundary conditions and to failure to account for tidal processes in the downstream reaches. The boundary conditions affecting calculated deposition volumes include estimated sediment inflow, selection of channel bed erosion limits, and the sediment removal template.

There is considerable uncertainty associated with predicting precise quantities of deposition because of the serious deficit in sediment inflow information. Available sediment inflow data are sparse and date back to 1957-62. Data for discharges above 2,200 cfs are completely lacking. There is no accounting for changes in the watershed's sediment producing characteristics nor of channel improvements that may have reduced sediment input from bank erosion. The adopted sediment inflow for the HEC-6T model represents an average estimate that produced a reasonable simulation of historical deposition in the study reach.

The selection of channel bed erosion limits and sediment removal templates were based on reported historical data. Erosion limits and sediment removal template elevations were adjusted until the computed volumes of sediment removal matched the reported volumes in the reaches of Walnut Creek above Grayson Creek. In these reaches, the adjusted model was relatively successful in reproducing the volume of sediment deposits as well as the volumes of sediment removal. However, it is uncertain if the model, as adjusted for calibration, will adequately predict future long-term sedimentation patterns. When the model deposition limits are wider than the erosion limits, there is no erosion of sediment outside the erosion limits. Over a long period of time it is possible that computed berm heights will reach unreasonable elevations. When this model is used to project future deposition, calculated results need to be carefully evaluated for reasonableness. It is recommended that the initial channel geometry in the HEC-6T model be replaced with current cross section geometry to make future predictions. With this change at the downstream boundary, a transmissive boundary condition should be assigned.

Movable bed limits at the downstream two cross sections (0+35 and 7+59) were adjusted to include the overbank tidal widths during the 1982 flood. When this model is used to simulated future extreme flood events the erosion limits should be treated similarly.

Because of the uncertainty associated with these boundary conditions, using the model to make long-term predictions of sediment deposition volumes in the upstream reaches is limited. In the tidal reach, the model's long-term predictive capability is very limited due to the failure to account for tidal processes. However, the model can be used to make reliable, relative comparisons between different plans, especially during flood events.

Model Application

It is recognized that HEC-6T is designed to model riverine sedimentation processes and that the lower reaches of Walnut Creek are affected by tidal processes, which are not simulated in the HEC-6T model. In their paper on the conceptual design and modeling of restored coastal wetlands, Odell, Hall and Brooks, (2008) present an approach for designing tidal channels. Three significant parameters are tidal hydraulics forces, marsh accretion rates and supply channel dimensions. These are associated with normal hydrological events. The proposed use of HEC-6T at Walnut Creek is for the analysis of plans that will handle the low probability runoff events resulting from rainfall floods. In these events, riverine forces dominate the processes. Project designs that are currently envisioned utilize high berms on one or both sides of a low flow channel or on the side of tidal marshes. These are only flooded during the extremely rare flood runoff events. They do not affect the tidal prism. They will not change marsh accretion rates or volumes associated with normal hydrological events where riverine forces dominate tidal forces.

The consequences of tidal processes that may be significant with respect to sedimentation are: 1) formation of a low-flow channel in the tidal prism, and 2) deposition and re-distribution of fine sediment during the tide cycle. These are associated with daily tidal flows and are not expected to be changed by the plans envisioned for protecting against the low probability runoff events. Consequently, the low flow channel is not expected to change as the result of the high-berm plans for flood protection. This HEC-6T model can be used reliably to compare one such design with another. The long term hydrology and tidal hydraulics forces that created the dimensions of the existing low flow channel are not expected to change in the future. Therefore, the model need not predict development of a low flow channel.

Recommendations for Additional Data and Modeling

This model study demonstrates the need for additional sediment data. It is clear that, without additional measurements of sediment inflow, projected sedimentation patterns in Walnut Creek cannot be reliably quantified with HEC-6T (or any other model). Since 1962, the Walnut Creek watershed has experienced extensive urbanization and considerable channel stabilization work has been constructed. It is recommended that a suspended sediment data collection program be reinstated at the Concord gage. Equipment and gaging methodology should be adequate to obtain samples at high discharges. Sediment size class percentages should be determined in the laboratory analysis. Data should be collected bi-monthly with additional samples collected during floods. The data collection program should continue for at least ten years (assuming that several flood events occur and are measured).

It is important that geometric data be collected in the deposition reaches in conjunction with the sediment data. Surveyed cross-section geometry before and after major flood events is especially critical. This includes measurements in the tidal flats adjacent to the channel at the creek's mouth. LIDAR data can be used for most of the cross section elevations, but it is important that these data be supplemented by hydrographic survey data. These data will confirm the relative importance of riverine processes in the deposition and erosion cycle.

Tidal hydrodynamics and sediment processes are best simulated with a 2-dimensional model. It is not required that a long-term hydrograph be simulated or even a flood hydrograph. Tidal effects on channel geometry are the result of the twice daily ebb and flood tides occurring over and over again. It is also possible that increased sediment concentrations in Suisun Bay from floods on the Sacramento and San Joaquin Rivers significantly affect deposition in Walnut Creek. Short-term simulations with a two dimensional model should be sufficient to determine normal rates of sediment deposition and erosion. The modeling effort would necessarily include more than one set of geometry conditions in Walnut Creek as deposition and erosion rates are expected to change as the delta elevations increase.

The additional sediment and geometric data described in the preceding paragraphs are required to move the HEC-6T study from a *computational analysis* to a *computational model.* Additional calibration work would be required to account for the effects of tidal processes. Once the tidal deposition/erosion rates are known, sediment removal rates and erosion limits can be set in the one-dimensional model. This calibrated HEC-6T model would be considerably more reliable than the present one for predicting future long-term maintenance.

APPENDIX A: HYDROLOGY

Hydrographs for the 1965-2005 historical simulation were developed by Brian Walker of the USACE Sacramento District and provided to Mobile Boundary Hydraulics as DSS files. Daily discharges were provided in DSS file *WC_Daily.DSS* and hourly discharges for 92 high flow periods were provided in DSS file *WC_Hourly.DSS*. This appendix, which describes the hydrologic study, was written by Brain Walker.

Two USACE approved models were used in tandem to calculate flows for the 1965-2005 simulation time period. These were the USDA-sponsored Soil Water Assessment Tool (SWAT) (Neitsch, Arnold, Kiniry and King, 2001a and 2001b) and HEC1L, a version of HEC1 (USACE, HEC, 1990) modified to allow long-term simulation. The choice to use two models provided the most efficient use of available resources for the project. An HEC1 model had been developed for the Walnut Creek watershed in previous studies for which single events had been the focus. It consistently showed the ability to mimic watershed response at sub-daily time steps for discrete events, but significant calibration has been required for each effort. Furthermore, little was known about the model's ability to reconstruct runoff for multi-year periods. The SWAT program was specifically developed for long-term simulation. It accounts for the entire mass of water as it progresses through the surface and groundwater systems. Therefore, it was decided that daily flow for the entire period of record would be calculated using SWAT, while HEC1 could give sub-daily definition to discrete events interspersed throughout the simulation period. By scaling the sub-daily hydrographs to match the total daily volume generated by SWAT, the results of the two models could then be brought into agreement.

The computations were made in two parts: 1) a SWAT model was developed for the entire period of record and 2) the HEC1 model was used for over 200 single flood events, some of which were grouped together so that there were 92 different time periods. For each part of the effort, a slightly different methodology was used for the period when Walnut Creek data were available (1965-1992) and afterwards (1992-2009).

Daily Hydrologic Analysis

The SWAT model was selected to simulate daily flows based on its extensive use in watersheds for which little observed data is available (Borah and Bera, 2003). SWAT is a process-based, semi-distributed model specifically designed with the intent of simulating the effects of land management decisions for continuous, multi-year periods at a daily time step (Arnold et al., 1998). SWAT simulates watershed hydrology with a mass balance representation of the water cycle, as expressed in Equation A1.

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad \text{Eq. A1}$$

where SW_t is the soil water content at the end of time step t, SW_0 is the soil water content at the beginning of time-step t, R_{day} is the precipitation for the day, Q_{surf} is the surface runoff on day i, E_a is the total water lost to evapotranspiration processes on day i, w_{seep} is the flow from the shallow aquifer into the overlying unsaturated zone, and Q_{gw} is the groundwater flow.

GIS-based processing with user-defined thresholds defines a watershed at three spatial levels (in order of decreasing size): the overall basin, the sub-basin (here, subdivision of the basin that contributes to a single stream segment), and the hydrological response unit, a unique combination of land use and soil type within each sub-basin. A digital elevation map (DEM) provides the primary means of delineating the watershed and creating the surface water stream network in SWAT. The user then selects the minimum area contributing to each segment of the stream network. The sub-basin structure can have as few as one or as many as 200 sub-basins. For this study the maximum sub-basin area was limited to 42 ha, which resulted in the identification of 100 sub-basins in the SWAT model.

Runoff generation begins at the hydrological response unit (HRU). Each subbasin is composed of multiple hydrological response units (HRU). An HRU is a unique combination of land use and soil type. Unlike subbasins, HRUs don't have a physical location associated with them; an HRU is purely the percentage of total subbasin area dedicated to a combination of land use and soil type. The user may exclude HRUs that do not encompass a minimum percentage of the watershed area. For instance, a threshold of 5% in a 20 ha subbasin would exclude all HRUs of less than 1 ha. For this model, the threshold was set to 0%. Hence, all 1610 HRUs were used in calculating the watershed runoff.

A two-stage procedure routes runoff first overland and then through the stream network. For this study, the SCS curve number (CN) method was chosen to route overland flow. For each HRU, SWAT determines a CN value based on the land cover, the hydraulic properties of the soil, and the antecedent moisture condition. Since CN values are dynamically updated based on watershed conditions at the time of the event, the CN value in this case may be utilized for multiple-day events. The total generated runoff is summed for the sub-watershed and is then routed overland using a kinematic-wave model and a modified Manning's equation to determine the time required for the entire sub-basin to be contributing runoff. The total volume is then routed through the single stream segment in each sub-basin. Infiltrated water is tracked in the groundwater and shallow aquifer calculations and may reenter the stream or exit the basin through evapotranspiration.

Model Inputs: SWAT required four basic inputs. Three of these were GIS layers used by SWAT to derive physical parameters for the watershed: a digital elevation map (DEM), a map of land use, and a digitized soil map. Furthermore, a digitized stream network was imported into the model, which was used to artificially decrease the elevations of the stream beds relative to the original DEM. The lowered elevations increase the likelihood of reproducing the actual stream network and properly delineating the subbasins. During simulations the model required precipitation and temperature data, both of which it read from separate text files. A description of each of these model inputs follows:

1. Digital Elevation Map: The representation of the watershed was derived from a 7.5 minute USGS 30 m resolution DEM (Gesch et al., 2002: Gesch, 2007).
2. Land use and land cover: The 1992 National Land Cover Dataset (NLCD) of the entire United States prepared by the USGS provided information on land use (Vogelmann et al., 2001).
3. STATSGO: For consistency with the land use map from 1992, the State Soil Geographic (STATSGO) data set published in 1994 by the National Cooperative Soil Survey was used (Soil Survey Staff, 2009).
4. Digital Stream Network: The high resolution National Hydrography Dataset (NHD) is the product of a cooperative effort between the USEPA and the USGS to produce a feature-based representation of the surface water network in the United States. The NHD for Contra Costa County was imported and digitized within the model to lower local elevations near streams in order to aid SWAT in predicting the natural stream network (USGS, 2009).
5. Daily Precipitation and Temperature Data: The National Climate Data Center provided daily rainfall and temperature values for three sites within the watershed, which are shown in Table A1.

Table A1. Daily rainfall and temperature available for NOAA

		Precipitation		Temperature	
Gauge Name	COOP ID	**Start**	**End**	**Start**	**End**
Martinez Waste Treatment Plant	045378	11/1/1945	3/31/2009	2/1/1970	3/31/2009
Mt. Diablo Junction	045915	4/1/1952	3/31/2009	4/1/1952	3/31/2009
St. Mary's College	047661	12/1/1942	6/30/2005	12/1/1942	7/31/1981

Sub-daily Hydrologic Analysis

The HEC1 (USACE, HEC 1990) model used for the 2005 Walnut Creek Feasibility Study provided the basic structure for which unique event parameters (precipitation and starting baseflow) were then altered. For the 2005 study, the delineation of sub-basins and computation of their watershed parameters for contemporary land use conditions was performed using GIS data and the HEC-GeoHMS computer program (USACE, HEC 2006). The HEC1 model developed for the Grayson and Murderer's Creeks Feasibility Study (USACE, SPK 2005) was used for the Grayson-Murderer's Creeks component of this study. Run prior to the Walnut Creek model, the Grayson-Murderer's model output was then read as input at its confluence with Walnut Creek for each event.

Basic unit hydrograph procedures developed by the U.S. Army Corps of Engineers, Los Angeles District, were used for computing the sub-basin unit hydrographs (USACE SPL, 1962). In both models, the exponential loss rate was used to model storm losses. The exponential loss rate is an empirical method which relates loss rate to rainfall intensity and accumulated losses. Accumulated losses are representative of the soil moisture storage. Estimates of the parameters of the exponential loss function can be obtained by employing the HEC1 parameter optimization option.

Routing parameters for two detention basins, located in the upper reaches of Pine Creek basin, were included in the HEC1 model. Pine Creek Dam, the more upstream of the two structures, was built in 1955 and therefore had an impact for the entire period of study. The lower structure Pine Creek Detention Dam was completed by the SCS in 1981; however, results indicate that routing through the lower detention basin had no major difference with results from models for which no detention basin was in place for the same event. For ease of assembling the 92 separate models, the decision was made to keep both structures in place, as both were included in the 2005 model.

Selection of individual events for sub-daily modeling was made by screening the daily results for events that produced a minimum of 2,000 cfs at the watershed outlet. This criterion resulted in the need for modeling 211 events. When the lag between some events was not long enough to allow for a return to baseflow conditions, the events were combined into a single simulation period. Combination of events created 92 separate simulations and models. There were 60 events that took place during the gauged period (before WY 1993) and 32 after.

APPENDIX B: Sediment Data Analysis and Suggested Sediment Model Parameters

Allen Teeter, CHT 15 August 2010

Project Setting

The Walnut Creek basin drains an area of 146 square miles in California and empties into Suisun Bay. The flood control project at the downstream end of the Walnut Creek was constructed in 1965. By 1970, the downstream 3.5 miles had filled in with approximately 1,060,000 yd^3 of fine-grained sediment. Although the operation and maintenance manual required the project sponsor, CCCFC&WCD, to remove excess sediments from this reach of the channel, the Corps conducted a one-time dredge of the lower 2.7 miles of the newly constructed channel in 1973. Since the 1973 dredging, the local sponsor has not been able to secure the necessary environmental approvals to conduct additional dredging operations to maintain the advertised capacity of the channel.

As part of the general re-design of the project, thirty sediment cores were collected in October 2009 and analyzed to characterized the sediment material which has deposited in the project and to provide information for a model study. The data developed from those sediment cores are summarized here, analyzed, and sediment model parameters suggested.

Walnut Creek empties into Suisun Bay which causes the lower reach to be a sub-estuary of the San Francisco Bay system. Water samples from Sept and Oct 2007 confirmed elevated salinity (specific conductance) values at some downstream locations. Appreciable estuarine sedimentation can occur as the result of sediment transport from seaward, gravitational circulation, and asymmetric tidal transport. Estuarine areas are also generally efficient traps for fine sediments entering from upland.

The magnitude of the suspended load of Walnut Creek is large and may account for the bulk of the shoaling in the project. However, even without a riverine sediment source, appreciable shoaling would occur in the lower reach of this project setting as the result of estuarine sedimentation. Therefore, some background on local estuarine sedimentation is provided below.

Estuarine Aspects of the System

The following paragraphs describe local estuarine and sedimentation conditions. [1]Suisun Bay is located in northern San Francisco Bay, where freshwater from the Sacramento - San Joaquin Delta meets saline water from the Pacific Ocean. Suisun Bay is the furthest landward sub-embayment of San

[1] Ganju, N.K., Schoellhamer, D.H., and Younis, B.A. (2006). "Development of a decadal-scale estuarine geomorphic model for Suisun Bay, California: calibration, validation, and idealized time-stepping," Univ. of Cal. Water Resources Center, Techn. Completion Report, Univ. of California.

Francisco Bay, and is therefore most responsive to freshwater flow. Most probably, recent water withdrawals from the Delta have caused salinities to increase. Channels in Suisun Bay are about 9-11 m deep. Carquinez Strait is a narrow channel about 18 m deep that connects Suisun Bay to San Pablo Bay, to the rest of San Francisco Bay, and to the Pacific Ocean. Tides are mixed diurnal and semidiurnal and the tidal range varies from about 0.6 m during the weakest neap tides to 1.8 m during the strongest spring tides. Freshwater inflow typically first encounters saltwater in the lower rivers, Suisun Bay, and Carquinez Strait. The salinity range in this area is about 0-25 ppt and depends on freshwater inflow. Suisun Bay consists of two smaller sub-embayments, Grizzly and Honker Bays. See Figure B-1.

Suspended and bed sediment in Suisun Bay is predominately fine and cohesive, except for sandy bed sediment in some of the deeper channels. The typical suspended-sediment concentration (SSC) range in northern San Francisco Bay is about 10-300 mg/L and sometimes up to about 1,000 mg/L in an estuarine turbidity maximum (ETM). In Suisun Bay, ETMs are located near sills and sometimes near a salinity of 2 ppt, depending on tidal phase and the spring/neap tidal cycle.

An annual cycle of sediment delivery and redistribution begins with large influx of sediment during winter (delivery), primarily from the Central Valley. Much of this new sediment deposits in San Pablo and Suisun Bays. Stronger westerly winds during spring and summer cause wind-wave resuspension of bottom sediment in these shallow waters and increase SSC. The ability of wind to increase SSC is greatest early in the spring, when unconsolidated fine sediments can easily be resuspended. As the fine sediments are winnowed from the bed, however, the remaining sediments become progressively coarser and less erodible. Thus, tides and wind redistribute the annual pulse of new sediment throughout the Bay. Since 1850, alterations in the watershed and estuary have changed the bathymetry of Suisun Bay (see Figure B-2).

Recently-deposited sediment beds have been described for Suisun Bay.[2] Gravity cores obtained in 1990-1991 and 1999 were analyzed to delineate depositional environments and sedimentation patterns in Suisun Bay. Major depositional environments include: tidal channel (sub-tidal), tidal channel banks (sub-tidal), tidal flat (intertidal to sub-tidal), and bay mouth (sub-tidal). The tidal channel environment includes both large and small channels in Suisun Bay as well as the tidal sloughs Suisun and Montezuma Sloughs. The coarsest sediment, usually sand or muddy sand, characterize this environment and water depths range from 2 to 11 m.

Thin (1-2 mm) and discontinuous silt and clay laminae are common. Suisun and Montezuma Sloughs are the exception to this pattern in that they consist of massive, intensely bioturbated muds. Tidal channel banks (both "cut" and "accretionary" channel margins), particularly accretionary banks, are characterized by low-to-moderate bioturbation and sandy mud to muddy sand lithology. Typically alternating sand and mud beds (1-6 cm thick) are present; both types of beds consist of 1 mm to 1 cm thick sub-horizontal to inclined laminae. Laminae composed of organic detritus are also present. Where this environment is transitional with the tidal flat environment water depths range from 2-8 m. Tidal flat environments include the "sand" shoals present on bathymetry charts, and are typically a bioturbated

[2] Chin, J.L., Orzech, K., Anima, R., and Jaffe, B. (2002)."Modern Estuarine Sedimentation in Suisun Bay, California", American Geophsical Union, Fall Meeting 2002, abstract.

muddy sand to sandy mud. Sand and mud beds, 1-3 cm thick, are often characterized by very fine 1-2 mm thick silt and mud laminae. Water depths range from 2 to 4.5 m where these laminated tidal flat sediments occur.

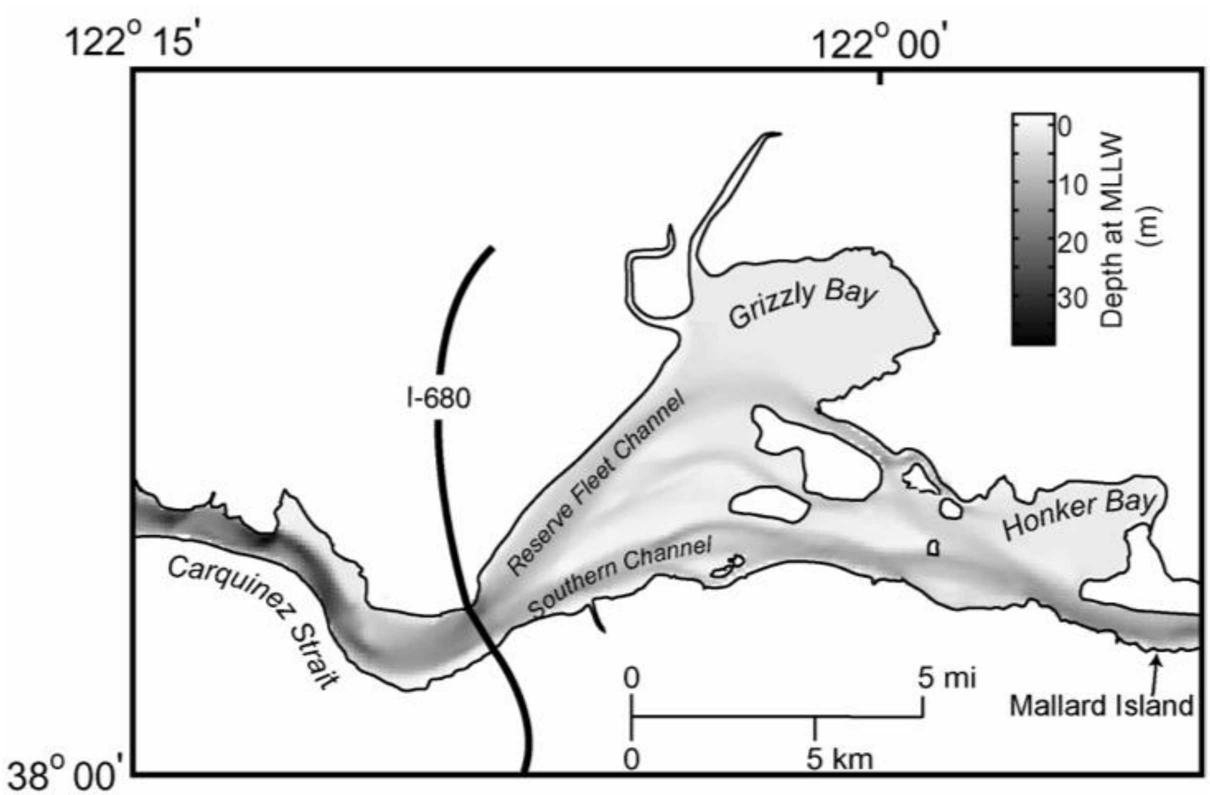

Figure B-1. Bathymetry of Suisun Bay (Walnut Creek enters near the “Southern Channel” label).

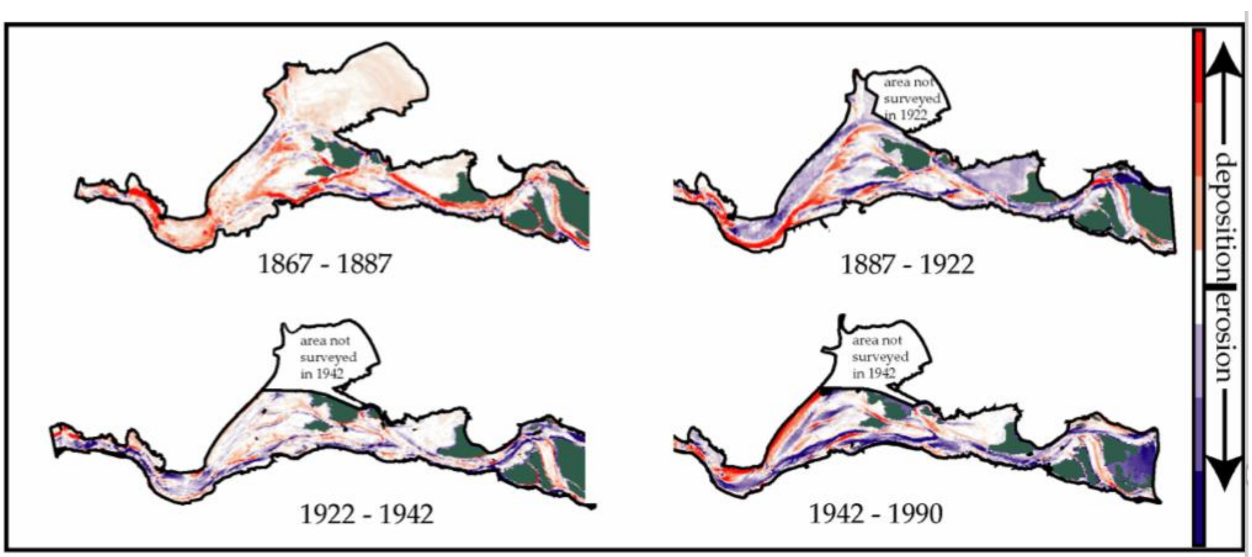

Figure B-2. Historical sedimentation patterns in Suisun Bay.

Bay mouth environments occur only in the distal portions of Grizzly and Honker Bays, sub-embayments of Suisun Bay proper. This environment is transitional with both tidal channel bank and tidal flat environments and shares characteristics with each. Massive to interbedded mud is the most common lithology, although sandy mud to muddy sand also occurs. Centimeters thick sand and mud beds typically alternate vertically. Bioturbation is low to moderate. Water depths over this environment range from 2 to 3 m.

Depositional environments present in Suisun Bay are the result of a full range of tidal and fluvial processes as shown by the lithologies and alternating sediment stratigraphic patterns observed in cores. Very thin beds and intense bioturbation evidence intervals of very slow to negligible sedimentation. Rapid deposition and/or resuspension are evidenced by thick sediment intervals and by laminae that are continuous and apparently unbioturbated.

USGS researchers summarized Suisun Bay historical sedimentation patterns as follows[3]:

- Between 1867 and 1887, approximately 115 million cubic meters of sediment was deposited in the Suisun Bay area. This is equivalent to about 2.5 cm/yr accumulation over all of Suisun Bay. Almost two-thirds of Suisun Bay was depositional during this period. Most of this is debris from hydraulic gold mining in the Sierra Nevada, and is likely contaminated with mercury which was used to extract gold from tailings.
- Hydraulic mining ceased in 1884, while water distribution and flood control projects increased during the 20th century. These factors decreased the input of sediment to the Bay, and from 1887 to 1990 Suisun Bay was erosional.
- On average, Suisun Bay deepened during the study period. From 1867 to 1990, Suisun Bay lost more than 100 million cubic meters of sediment. This is equivalent to a loss of 74 cm over the entire Suisun Bay area.
- Changes in sedimentation in Suisun Bay affected its ecosystem in many ways. For example, the area of tidal flat, rich habitat, and sources of sediment to the wetlands increased by approximately 10 square km from 1867 to 1887 due to the input of hydraulic mining debris. From 1887 to 1990, however, tidal flat area decreased from 52 square km to 12 square km.

There are numerous tidal creeks near the local project area in Suisun Bay which drain tidal marshes. These tidal creeks are expected to be stable with inlet areas balanced by tidal prisms. If this local relationship were known it might be used to make some simple estimates of estuarine shoaling in systems where the inlet is initially larger than the stable size.

[3] Cappiella, K., Malzone, C., Smith, R.E., and Jaffe, B.E. (1999.) "Historical bathymetric change in Suisun Bay 1867 - 1990," USGS Open-file Report 99-563.

There are constructed canals on the south side of Suisun Bay at Port Chicago (or Bay Point?) east of the arsenal. These might provide case studies of the extent of estuarine shoaling. CCCFC&WMD conducted surveys in Lower Walnut Creek but only typical sections were plotted in COE drawing DE-4-137. Water years 1966 and 1968 were low-flow and very low sediment yield years on Walnut Creek. If more detailed survey information were available, an estimate of estuarine shoaling might be made using volume differences between 1967 and 1968 or 1965 and 1966 surveys.

Selenium is a waste product from numerous refineries along Suisun Bay and Carquinez Strait. Most Se attaches to fine sediment particles and to their organic coatings. About 90 percent of selenium directly input to a constructed wetland was trapped.[4] Subsequently, about 10 to 30 percent was found to be volatilized by wetland plants. The vertical distributions of elevated Se in wetland sediments at Martinez Regional and Benicia State Parks were determined to be fairly uniform by Zawislanski et al.[5] It might be possible to use Se as a tracer to determine the extent of estuarine shoaling in Lower Walnut Creek if no refinery effluent was input there at least since 1965, and if the magnitude of dissolved Se flux to sediments could be determined.

Some Field Observations

Allen Teeter accompanied the field crew on 20 and 21 October 2009 as they collected most of the recent core samples. Both Kinnetic Laboratory and Hultgren-Tillis Engineers personnel were well experienced and efficient at this work. Few if any fine laminae were observed in the cores at the sampling sites. Some relatively fine inter-bedding was observed near the bottoms of cores VC14 and VC15 that resembled bottom sets. These cores had beds as thin as about 0.1 ft.

Active wetland sedimentation was observed on marsh surface in the lower reach. On the west side of the Lower Walnut Creek reach from Suisun Bay to Waterfront Road (lower-Lower Walnut Creek) fringing marsh about 1000 ft wide is present. This marsh appears to tidally flood and ebb through lower-Lower Walnut Creek. Perhaps this is responsible for the higher deposition along the fringing marsh as compared to the east side of the channel. Riverine-looking channel bars were observed in the middle reach between Waterfront Road and the A. T. & S. F. Railroad bridge.

Hydrocarbon smells and color were evident in some lower-reach cores. Jerrold Hanson indicated that some large spills had occurred in the past and had been used to mark and date core layers in some cases.

It appeared that the recently excavated area in the upper reach (near VC20) had been overlain with 0.25 to 0.75 ft of fine-grained deposits. Some gravel-sized material was observed in this area which

[4] Hansen, D., Duda, P.J., Zayed, A., and Terry, N. (1998.) "Selenium removal by constructed wetlands: role of biological volatilization," *Environ. Sci. Technol.* , 32, pp. 591-597

[5] Zawislanski, P.T., Mountford, H.S., Gabet, E.J., McGrath, A.E., and Wong, H.C. (2001.) "Selenium distribution and fluxes in intertidal wetlands, San Francisco Bay, California," *J. of Environ. Qual.*, 30, pp. 1080-1091.

was very angular and appeared un-weathered. It was suggested that a local aggregate plant might be the source of this material.

Summary of Core Sediment Data

Kinnetic Laboratories collected 30 cores along Lower Walnut Creek, Hultgren-Tillis Engineers (HTE) logged and sub-sampled the cores[6] and sent selected samples to Soil Control Lab for analyses. Eighty sub-samples were collected in the field and forty samples were analyzed. Results are summarized in Table B-2.

Sediment Size Classifications

A combination of sieve and hydrometer was used to determine the complete grain size distributions of the samples. A triangular graph of the sand, silt , and clay fractions of samples is presented in Figure B-3. Color-coded points represent lower, middle and upper Lower Walnut Creek reaches as defined on the figure title. As can be seen, all three reaches are represented across the dimensions of the figure. Only sand was well sorted and clay and silt occurred in roughly equivalent proportions. When plotted as individual distributions, as in Figure B-4, silt and clay contents are normally distributed while sand content is log-normally distributed. (This might suggest that silt and clay occur randomly together and sand occurs as the result of hydrodynamic processes or other processes that result in log-normal distributions.)

Twenty percent of the samples analyzed had sand content greater than 50 percent. However, these were not truly random samples as some were selected as representative of certain observed bed classifications. Peats were not selected for analysis because of the difficulties they bring to analyses. The lower reach was sampled much more than the others. Statistics on core sample sand content by project reach is included in Table B-5.

A description of the size distribution statistics is presented later.

Sand and Peat Extent in Core Logs

Some 179.4 ft of length in 30 cores were visually classified in the field. Those classified as sand or peat beds are summarized in Table B-1 by length in the core logs. Statistical distributions (all log-normal) of all, sand and peat beds are presented in Figure B-5. The trend is that sand content increases from downstream to upstream - as supported by the sample data.

Atterberg Limits

Results of these twenty four analyses covered the same range as recorded in the visual classifications: lean to fat clays. Most samples were lean clays with liquid limits below 50 percent. Scatter plots of Atterberg limits and clay content are presented in Figure B-6. As can be seen, clay content correlates well with these parameters. Plasticity index and liquid limit are also plotted in Figure B-7 in the geotechnical manner suggested by Casagrande and others. These data indicate a comparatively high resistance to erosion (medium to high plasticity). Liquid limit and plasticity index correlate well to clay content (Figure B-6) but no spatial difference suggesting a difference in clay type could be detected in the data.

Derived Sediment Concentration Parameters

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[6] Hultgren-Tillis Engineers. (Nov 2009.) “Sediment core sampling Lower Walnut Creek Channel Contra Costa County, California,” Letter Report to CCCPWFC&WCD, Martinez, California.

Various sediment parameters were measured on forty core sub-samples. These data were used to derive other parameters as described in this section.

The sample bulk wet density *BWD*(w/v) = $Cv\ p_S + (1 - Cv)\ p_l$ where p_l is the liquid density (w/v), Cv is volume concentration (v/v), and p_S is the particle density (w/v). Other concentration measures are concentration by weight Cw and unit dry weight (or dry density or dry solids content) Cs. Conversions between parameters include the following:

$$Cv = Cs /\ p_S \text{ and } Cw =\ p_S\ Cv / BWD.$$

The average particle density was estimated for a mixture of organic and mineral grains as

$$\frac{1}{\rho_s} = \frac{O_f}{1050} + \frac{(1 - O_f)}{2650}$$

where O_f is the organic fraction and 1050 and 2650 kg/cu m are the assumed organic and particle densities, respectively. Sample organic fraction varied between 0.6 and 4.1 percent (median of 3.05 percent). Average particle densities varied accordingly between 2494 and 2626 kg/cu m (median 2532 kg/cu m).

Pore fluid densities were estimated using the method of Knudsen (1901) assuming that the determinations of pore fluid total dissolved solids (w/v) were equivalent to salinity (w/w). This assumption and since carbonate, bromine and iodine were not separately determined, introduced a small error on the order of 0.1 ppt. Knudsen's method assumes that the salinity-to-chlorinity ratio is 1.80655 and the method is third order in chlorinity and temperature. A temperature of 22 degrees was assumed. Pore fluid total dissolved solids *TDS* varied between 4.4 and 19.0 g/l (median of 12.0 g/l) and estimated pore fluid density ranged from 1001.2 to 1012.2 kg/cu m (median of 1006.9 kg/cu m).

Sample *Cw* was estimated by Soil Control Lab from moisture content *w* determinations. Since *w = (Wsat - Ws) / Ws* (where *Wsat* is the saturated weight and *Ws* is solids weight in the sample), *Cw = 1 / (w+1)*. The *BWD = ps pl / (ps - Cw (ps - pl))* using the parameters calculated earlier. Then *Cs = Cw BWD*.

Core data was used to estimate representative values of unit dry weights for sand *Sa*, silt *Sl*, and clay *Ca* such that *1 / Cs(total) = Ca(w/w) / Cs(ca) + Sl(w/w) / Cs(sl) + Sa(w/w) / Cs(sa)* where *w/w* is the weight fraction and *Cs(ca,sl,sa)* are the components of total unit dry weight *Cs(total)*. General linear model and least squares fits were attempted but finally an end-member/trial and error method was used to fit the data. (Problems arouse apparently because clay and silt unit weights were inversely related to their percentage values while sand was directly related to it.) The result is presented in Figure B-8 suggesting representative dry unit weights for clay *Ca* = 484, silt *Sl* = 1314, and sand *Sa* = 1811 kg/cu m. A Pearson's correlation coefficient between total unit dry weights and an estimates of total unit dry weight based on the combination of clay, silt, and sand unit dry weights was 0.90. The regression forced through 0.0-0.0 yielded an $R^2 = 0.98$ and a standard error of estimate of about 2.2 percent.

Table B-2 presents a summary of measured and derived parameters. Scatter plots of concentration parameters and clay, silt, and sand contents are presented in Figures B-9 and B-10.

Sediment Size Distributions

Cumulative grain size distributions on 40 samples were determined by Soil Control Lab, as previously described, and presented in graphical form. Those plots were digitized at the 16, 31, 50, 69, and 84 percentiles less-than as phi values (-log2(diameter, mm)). Then statistical methods similar to those of Folk (but generalized to include five points instead of three) were used to estimate mean, sorting (standard deviation), and skewness of distributions. Basing statistics on phi values makes these statistics similar to geometric statistics of mean, etc. On many digitized curves, the 16th percentile lay below the measured points. In most cases the necessary extrapolation was a relatively short interval and was facilitated by the last three measured values. In a couple of cases, extrapolation was more appreciable, almost to the end of the plotted size range.

Size distribution statistics are presented in Figure B-11 plotted against channels station. Mean sizes there were converted from phi units back to millimeters. Positive skewness is toward the fine end of the distribution. Over Lower Walnut Creek, sediments in the reach between the mouth (channel station 0+00 or 0.0 in the plot) and 100 (100+00 ft or ft/100) were finer than the remainder of the samples (95% confidence level, p-value = 0.026, and means of 7.5 and 22.6 µm, respectively). Differences in sorting and skewness were small and not significant.

Within the sediment cores, size distribution means (mm) decreased with depth into the sediment (p-value = 0.119), more significantly decreased with water depth at the sampling site (p-value = 0.025) and most significantly with depth in sediment plus water depth (p-value = 0.007). This could indicate that sediments are upward coarsening with respect to the sediment column and the constructed project base (since cores were designed to cover the sediment thickness to the constructed base). This could also reflect that the (coarser) sediments sampled upstream are at a higher elevation (often water depth = 0.0 ft) than the downstream sediments. Scatter plots are presented in Figure B-12.

Though there is a clear upstream coarsening, there is also considerable variability in the grain size statistics among the three reaches bounded by Waterfront Road and the A.T. & S. F. Railroad bridge. All three reaches contain some coarse, well sorted, positively skewed samples. See Figure B-13. Likewise they also contain fine, poorly-sorted, and more negatively skewed sediments. The former are lag deposits and at channel station 0+00 likely originated from wind-wave transport along the Suisun Bay shoreline.

There are eight combinations of mean, sorting, and skewness when each is considered to either increase or decrease (2*2*2). Of these eight, two combinations have been used to infer transport paths in directions of deposition and erosion. To apply this method, many surficial bed samples are usually collected along lines from material that is or recently has been in transport at the sediment surface. In the case of the Lower Walnut Creek samples, trend in statistics were examined along channel stations. Sediments in the lower reach appear to fine in the upstream direction although the trend is weak (p-value = 0.29). If the three coarsest (and well-sorted and positively skewed) samples are omitted from the analysis, the upstream fining trend improves (p-value = 0.18) and upstream sorting improves (decreases) (p-value = 0.32) and upstream skewness is more negative (p-value = 0.09).

Upstream estuarine transport might be indicated for the lower-Lower Walnut Creek but, as indicated, the trends in sediment statistics are somewhat weak (about 80% confidence level). Statistics and trends are plotted in Figure B-14 and an example hypothetical series of differential grain size distributions with the same trend is presented in Figure B-15.

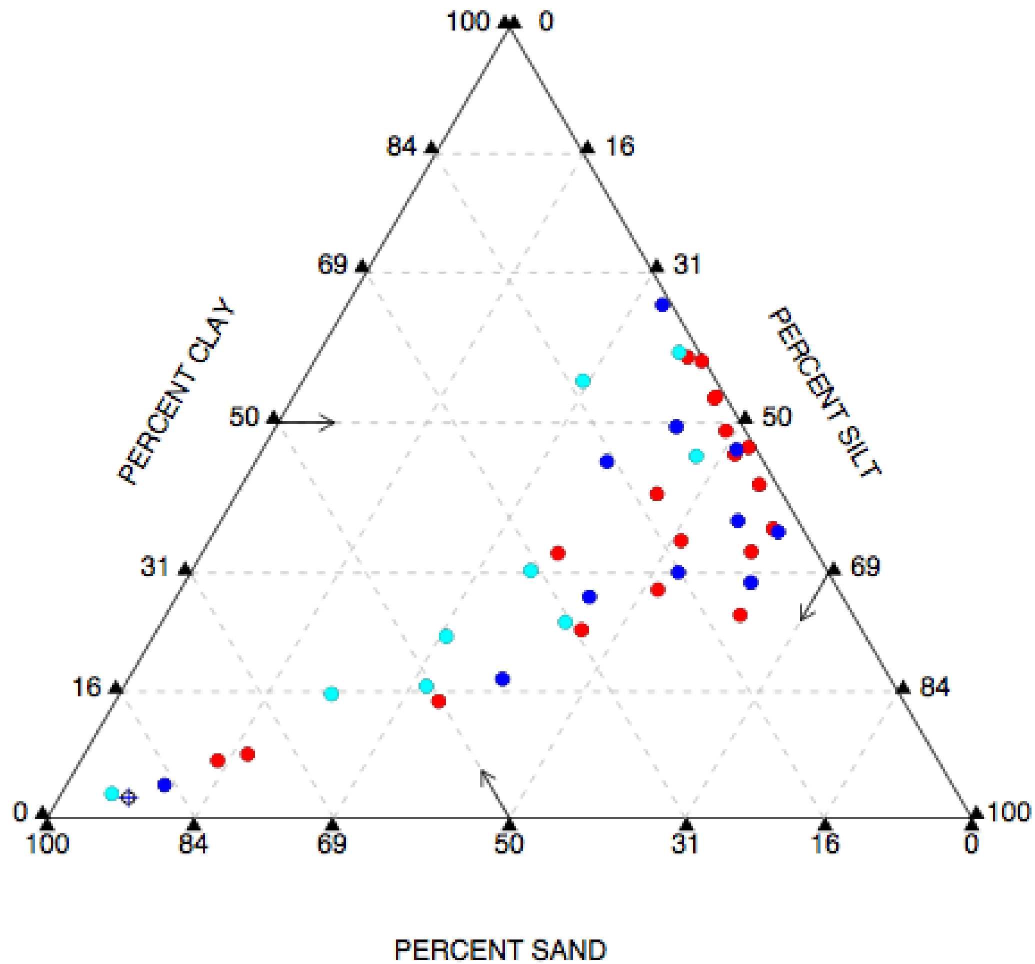


Figure B-3. Triangular graph of sand, silt and clay content of Walnut Creek core sub-samples.

Note: Read percentages 30 degrees to left of normals to axes as indicated by arrows. Red dots are from below Waterfront Road (HTE, Plate 1), blue dots are between Waterfront Road and A.T. & S. F. Railroad Bridge, and light blue dots are from above the bridge (blue circle with cross in the bottom left corner had gravel content added to sand content).

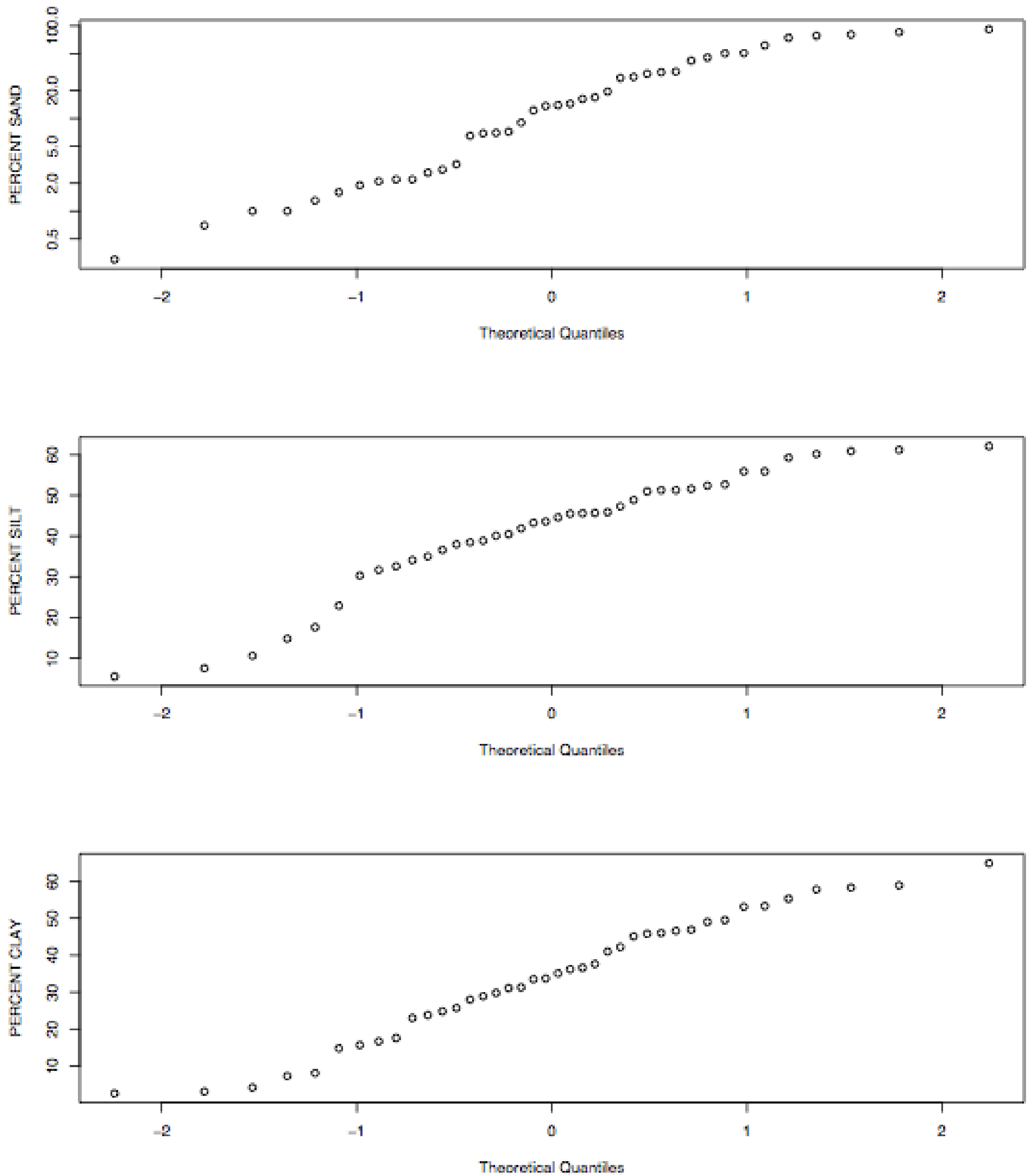


Figure B-4. Cumulative frequency distributions (by quantiles of standard deviation or standard normals about the median) for sand, silt, and clay.

Note that only the Percent-Sand ordinate is log scale and implies the sand distribution is log-normal while silt and clay distributions are normal (gaussian).

TABLE B-1. Sand and Peat Bed Extent Based on Core Logs and Sand Content of Core Sub-Samples

	Lower Walnut Creek Reach			
	All	Lower	Middle	Upper
Percent Sand Beds	8.3	6.7	8.1	21.3
Percent Peat Beds	10.5	7.1	29.1	3.6
Other	81.2	86.2	62.8	75.1
Total Core Length, ft	179.4	131.6	31	16.9
Number of Sub-Samples	40	21	10	9
Percent w/ > 50% Sand	20	14.3	20	33.3
Mean Sand in Samples	24.3	16.7	28.7	37.3
Median Sand Sampled	13.8	7	16.6	32

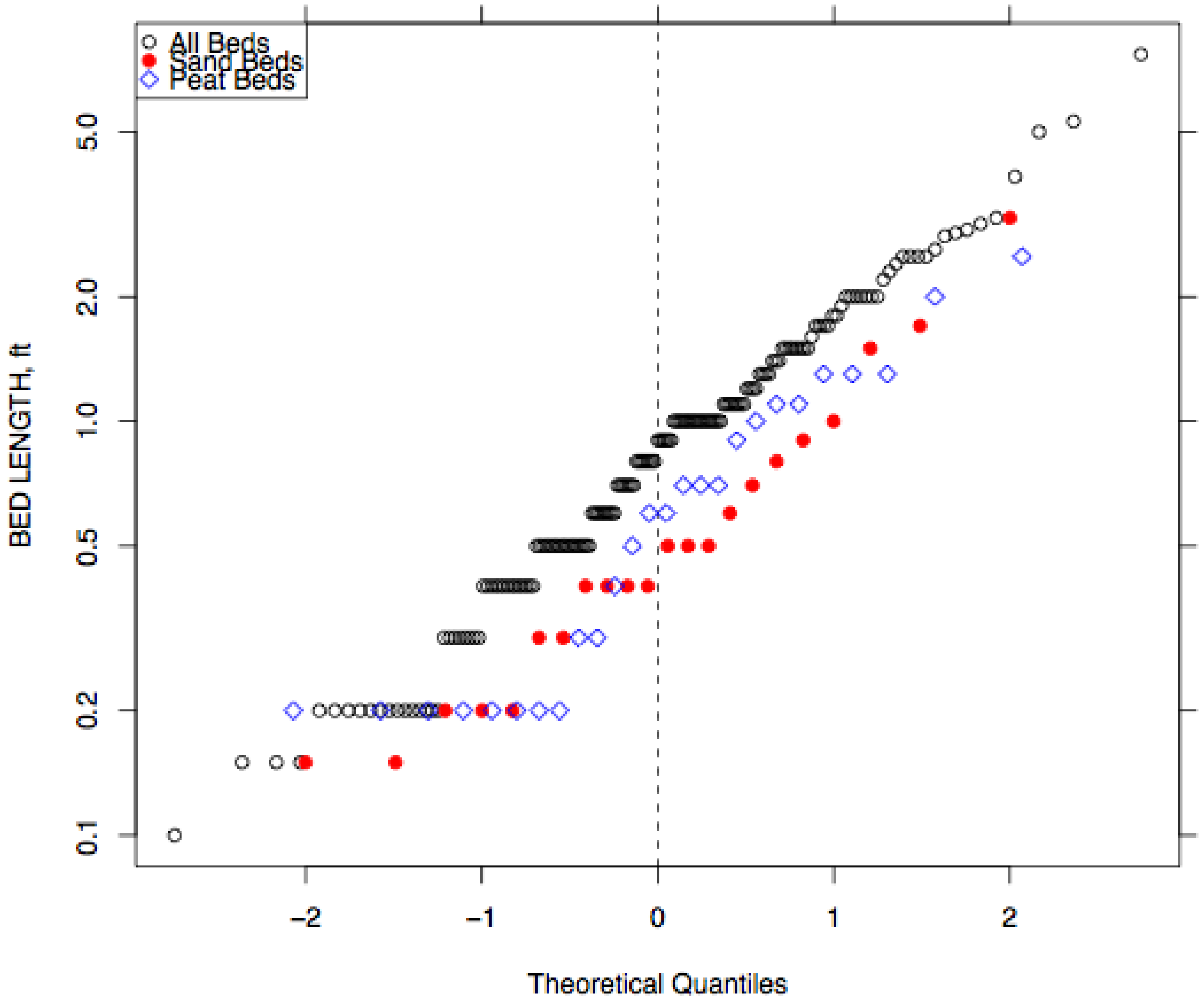


Figure B-5. Distribution of all, sand, and peat bed lengths in sediment cores.

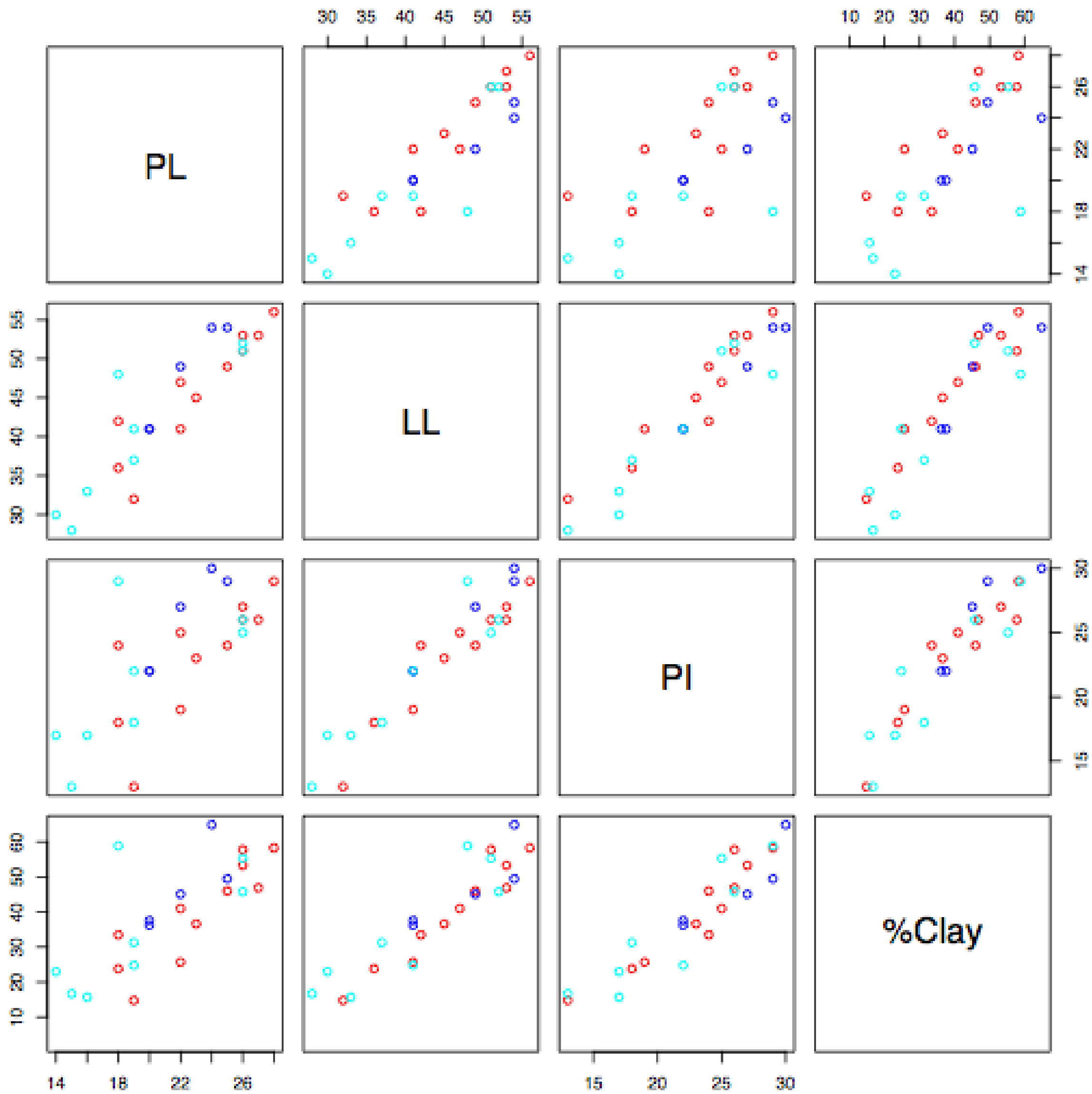


Figure B-6. Scatter plots of Atterberg liquid limit (LL), plastic limit (PL) and plasticity index (PI, LL - PL) parameters, and clay fraction.

Note: Color coding is by sub-reach as described in Figure B-1.

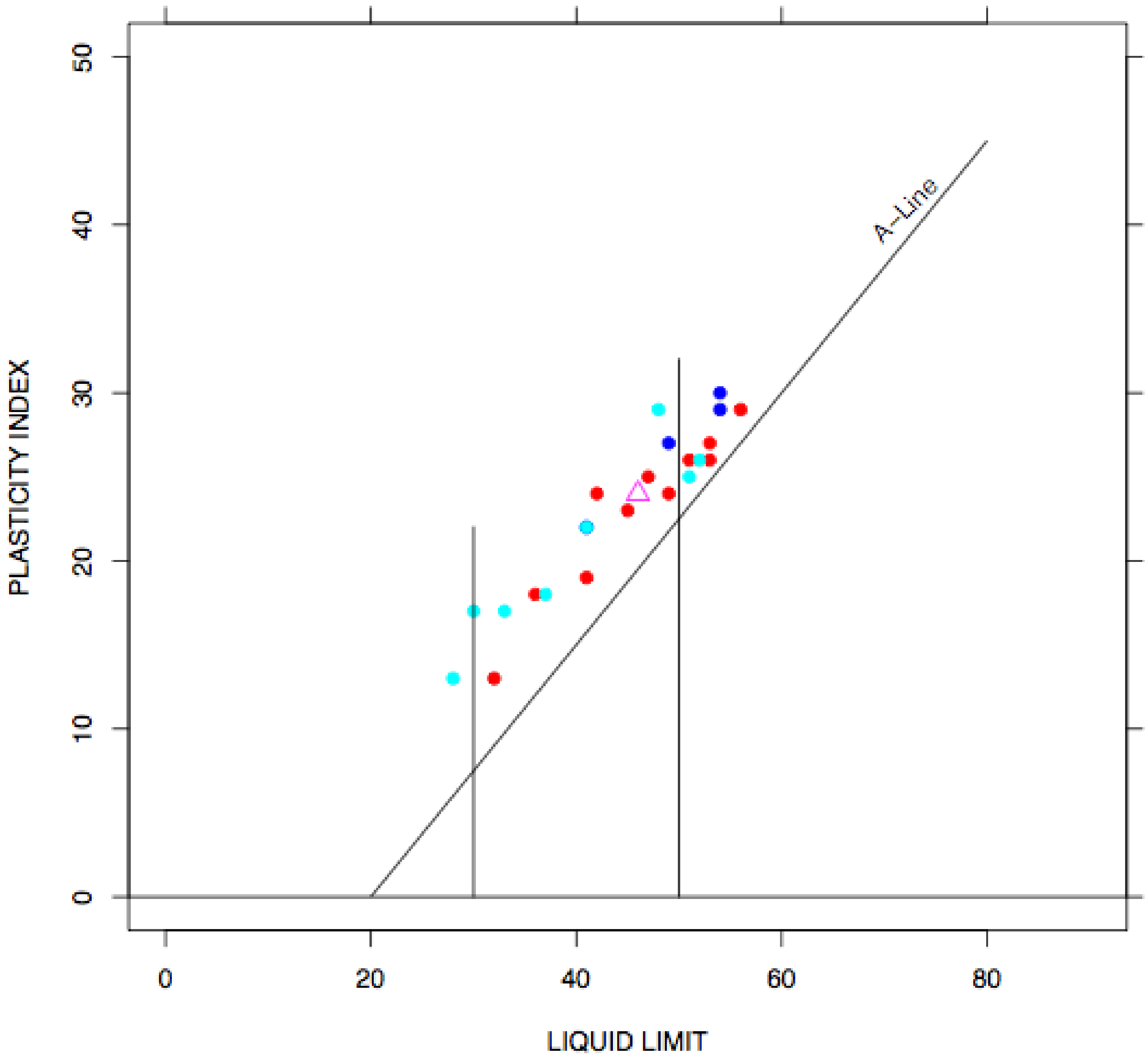


Figure B-7. Plasticity graph of Atterberg data (dots) and dataset median values (maroon diamond) in relation with Casagrande's A-line indicating high resistance to erosion.

Note: Color coding of dots is by channel sub-reach as described in Figure B1.

TABLE B-2. Summary of Measured and Derived Sediment Parameters				
Parameter	Mean	Median	16th Percentile	84th Percentile
Cw, %	57.4	56	49	69
Of, %	2.9	3	2.3	3.6
PI, %	23	24	17.7	27.6
PL, %	21.6	22	18	26
LL, %	44.3	46	35	53
TDS, g/l	12.1	12	9.9	14.8
Clay, %	34.1	34.4	15.9	52.2
Silt, %	41.3	44.1	30.6	55.1
Sand, %	24.4	13.8	1.9	50.5
Gravel, %	0.25	0	0	0
Median D, µm	15.9	10.8	4.6	76.5
Mean D, µm	11.7	7.7	3.1	50.6
Sorting, µm	0.141	0.14	0.09	0.185
Skewness	-0.233	-0.23	-0.013	-0.362
BWD, kg/cu m	1556.6	1517.6	1426.6	1729.3
Cs, kg/cu m	910.1	849.9	699.1	1194.3
Moisture *w*, %	79.2	78.6	44.9	104.1

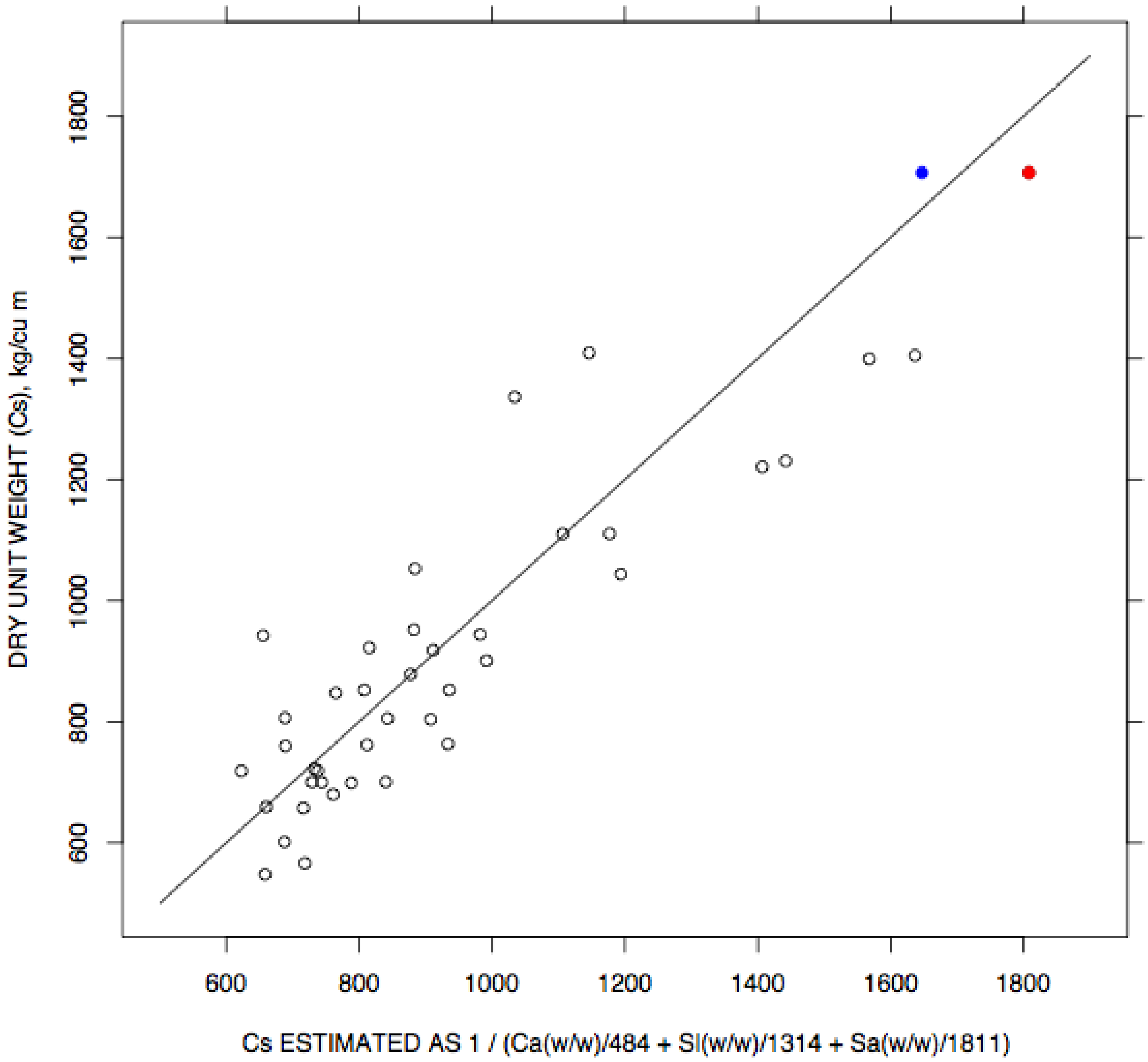


Figure B-8. Unit dry weight measurements and estimates from clay Ca, silt Sl, and sand Sa grain mixes.

Note that the red point in top right corner was computed from raw sand content while the blue point is the same sample computed by adding the gravel content (about 10 percent) to the sand.

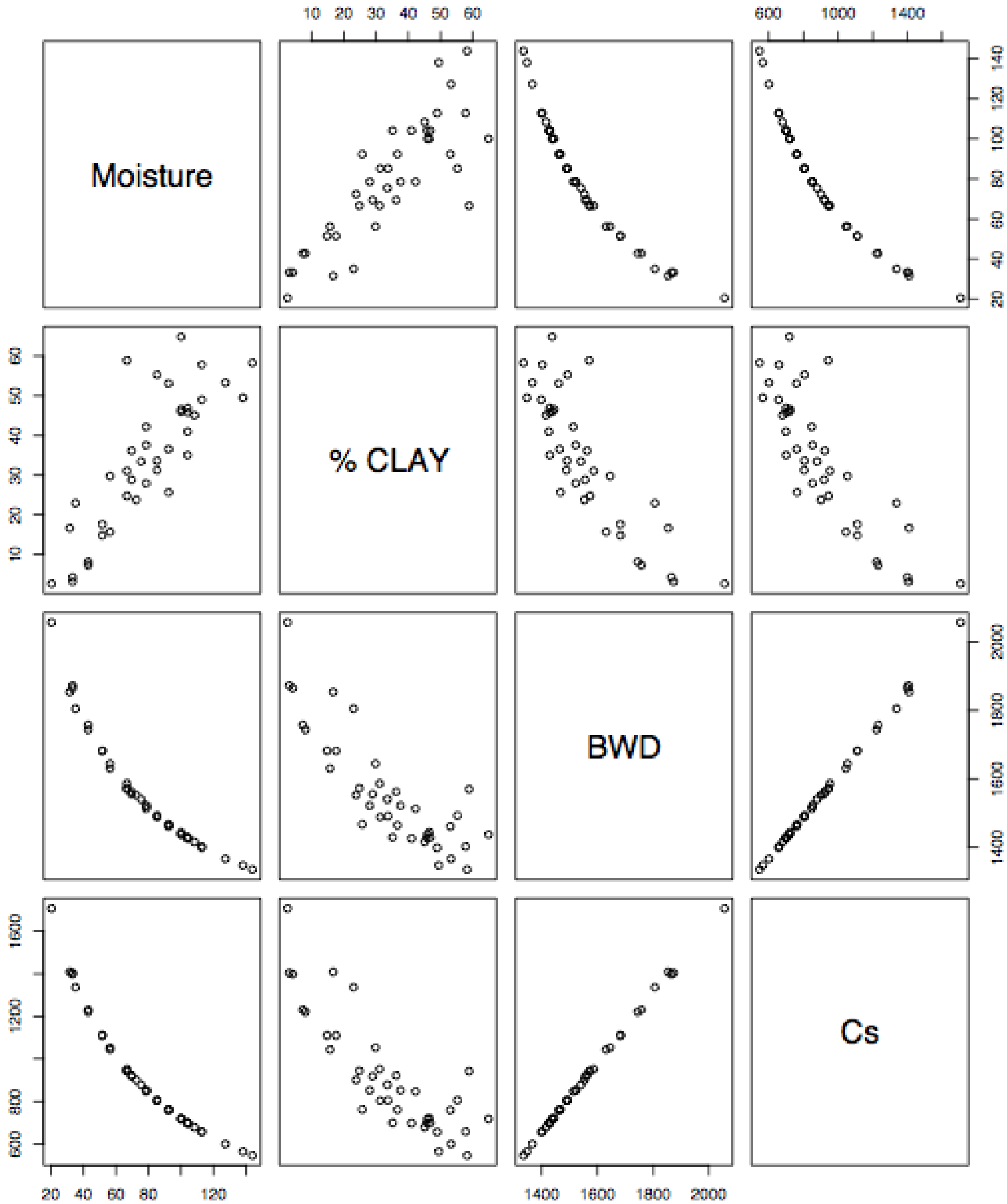


Figure B-9. Scatter plots of concentration parameters and clay fraction.

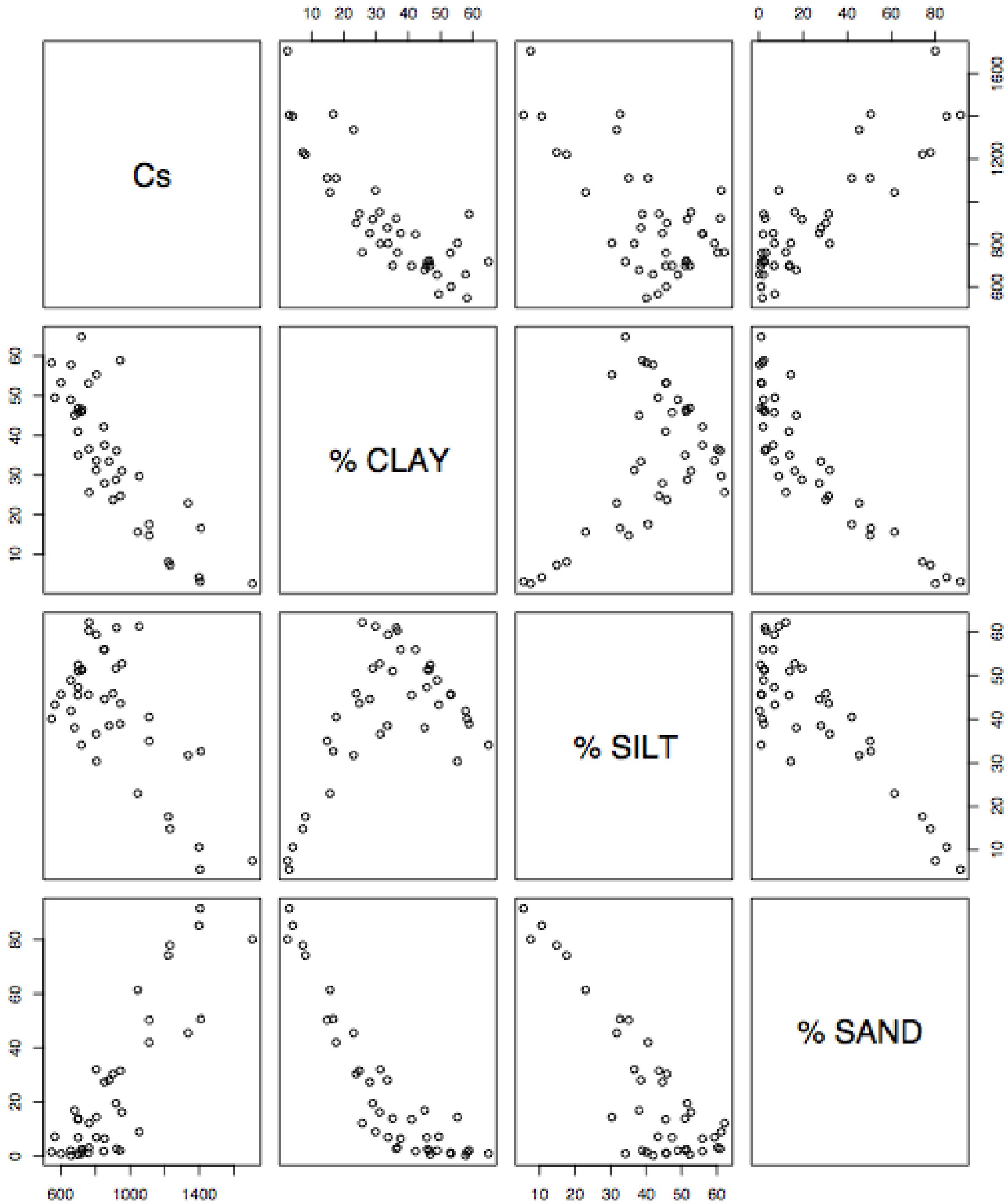
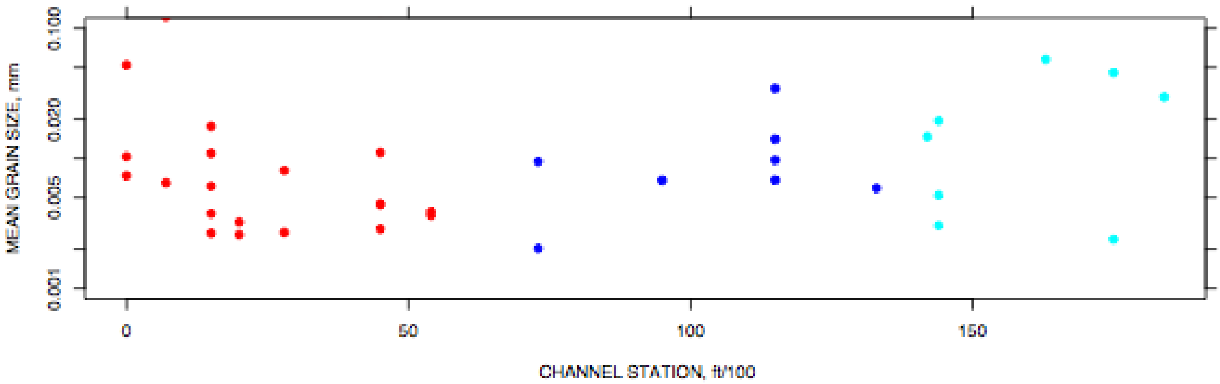
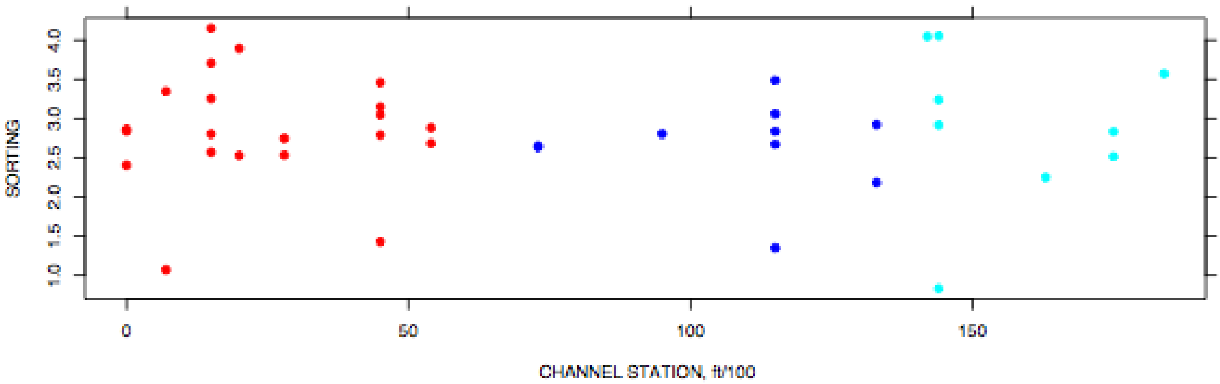


Figure B-10. Scatter plots of clay, silt, and sand percentages and unit dry weight (solids content, kg/cu m).





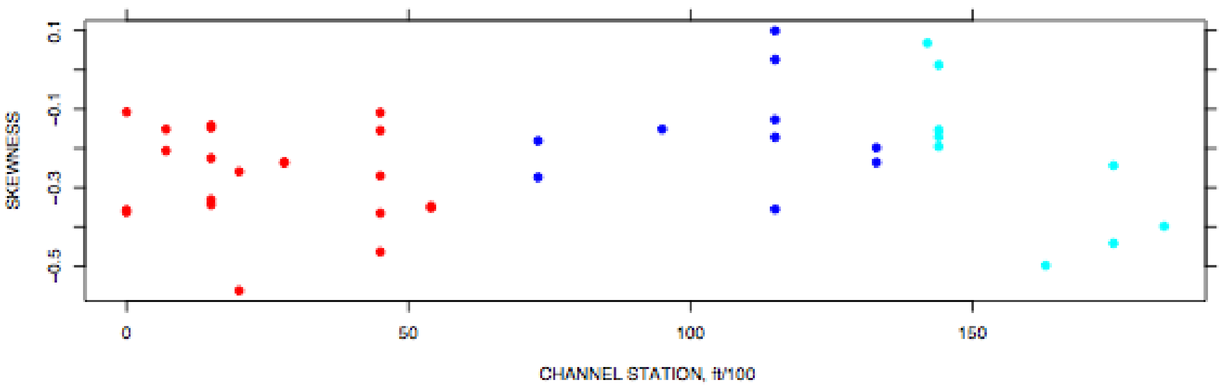


Figure B-11. Grain size distribution statistics plotted by channel station.

Note: Color coding is as described for Figure B-1.

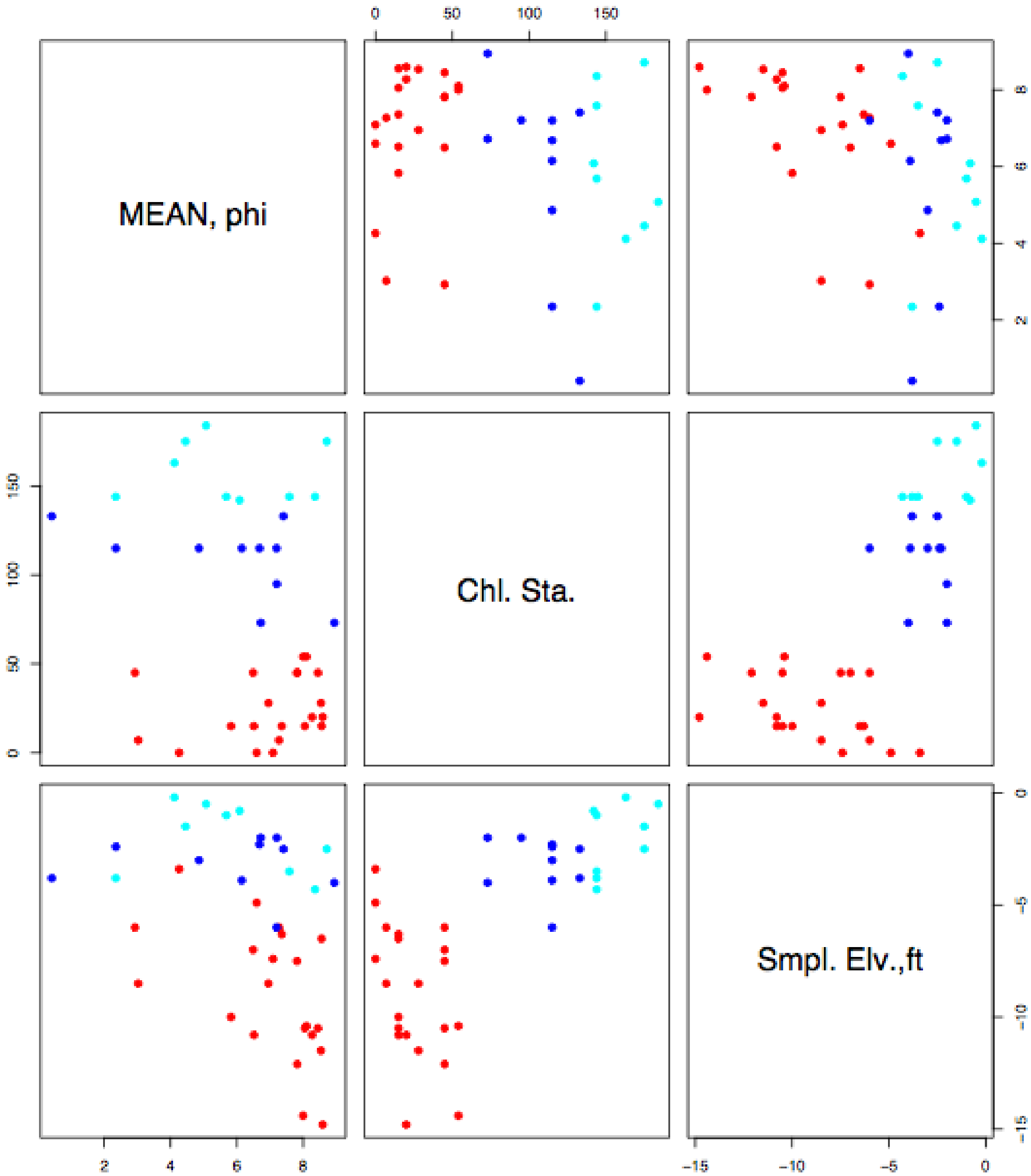


Figure B-12. Scatter plots of mean grain size in phi-units (small values are larger sized), channel station (ft/100), and sample elevation (ft, mtl).

Note: Color coding is as for Figure B-1 and B-11.

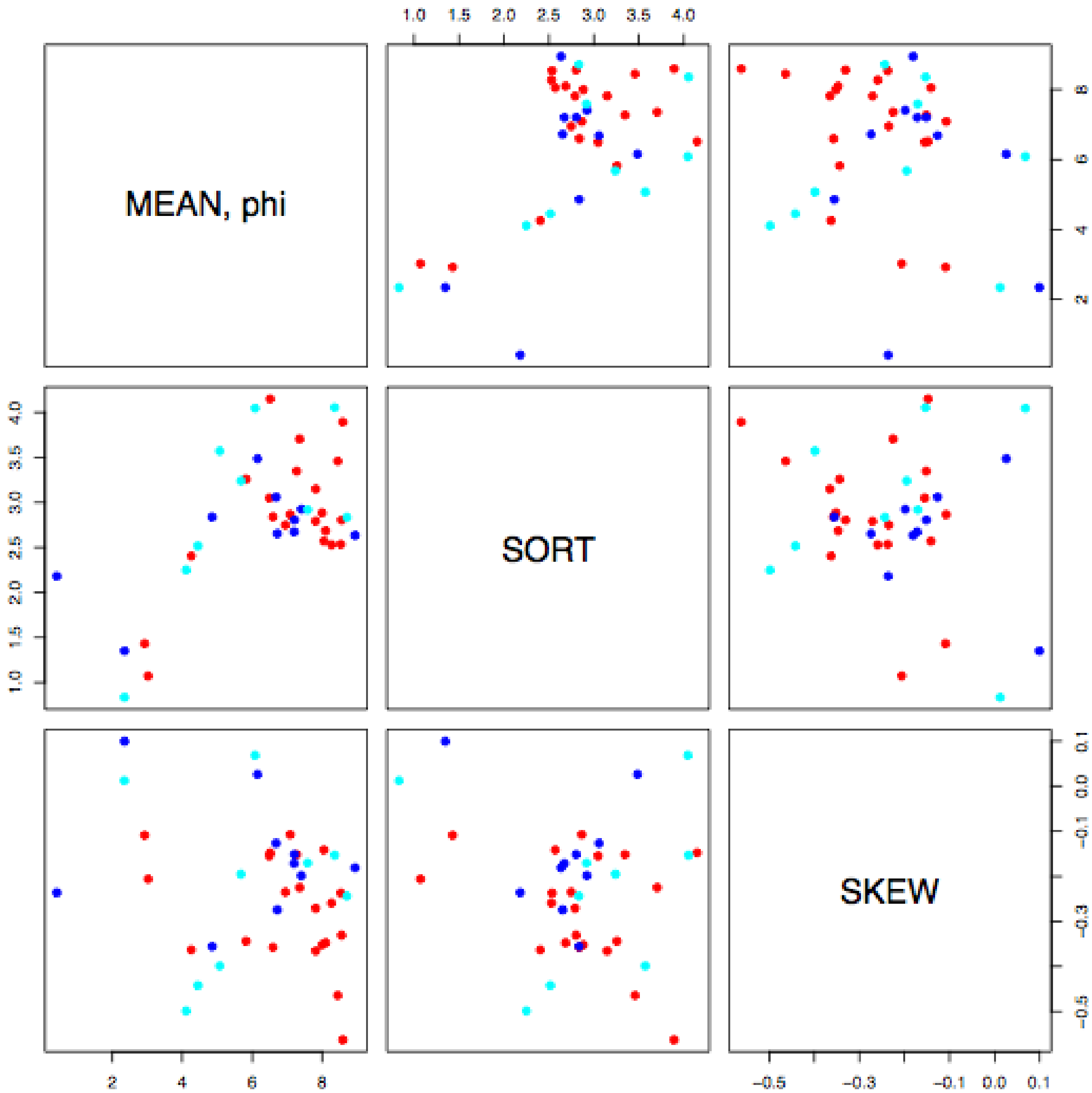


Figure B-13. Scatter plots of mean grain size in phi-units (small values are larger sized), sorting, and skewness.

Note: color coded by channel reach as described in Figure B-1.

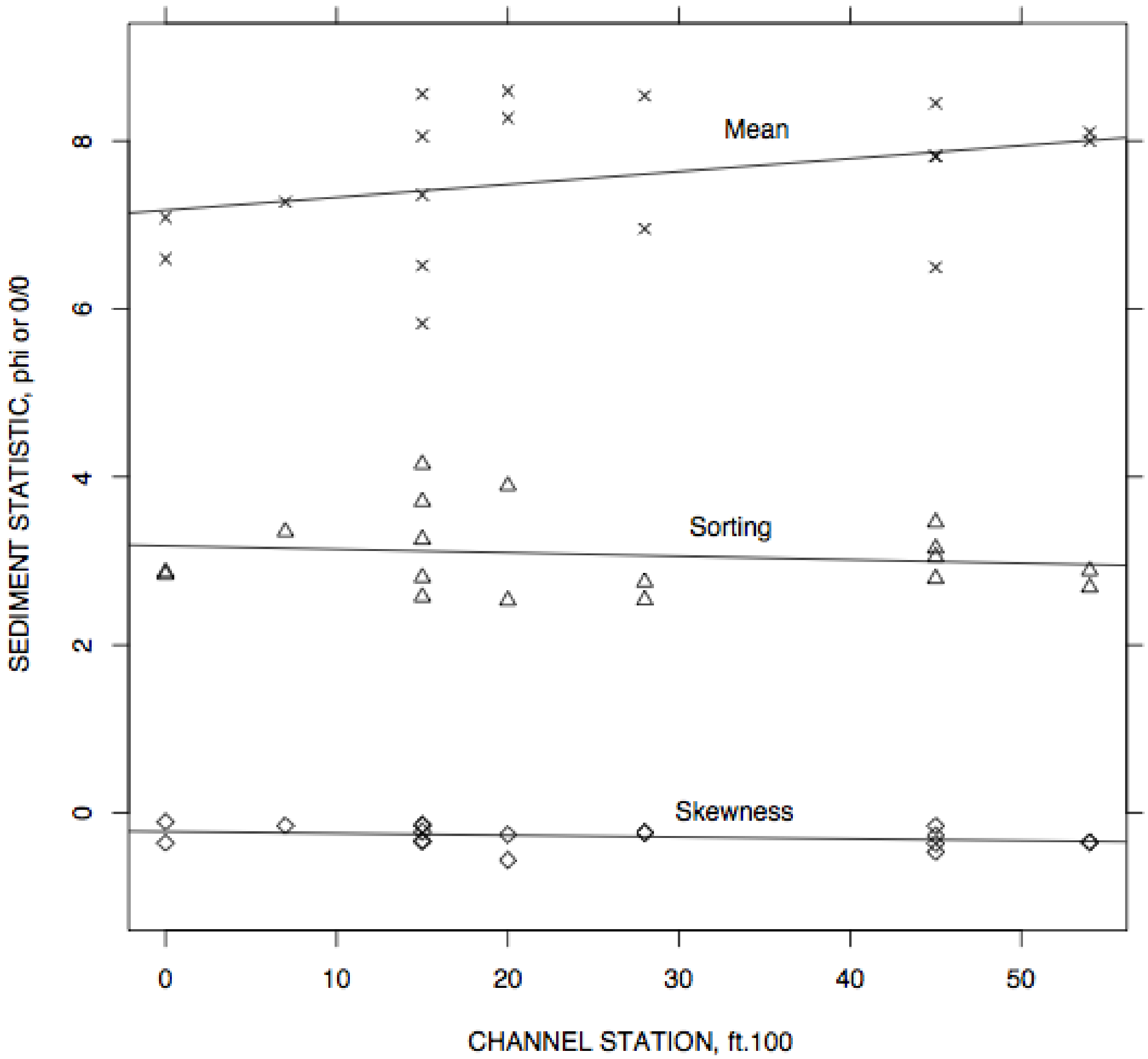


Figure B-14. Lower project reach below Waterfront Road mean sediment phi size (x's where smaller numbers are larger sized), sorting (triangles), and skewness (diamonds) with least-squares trend lines.

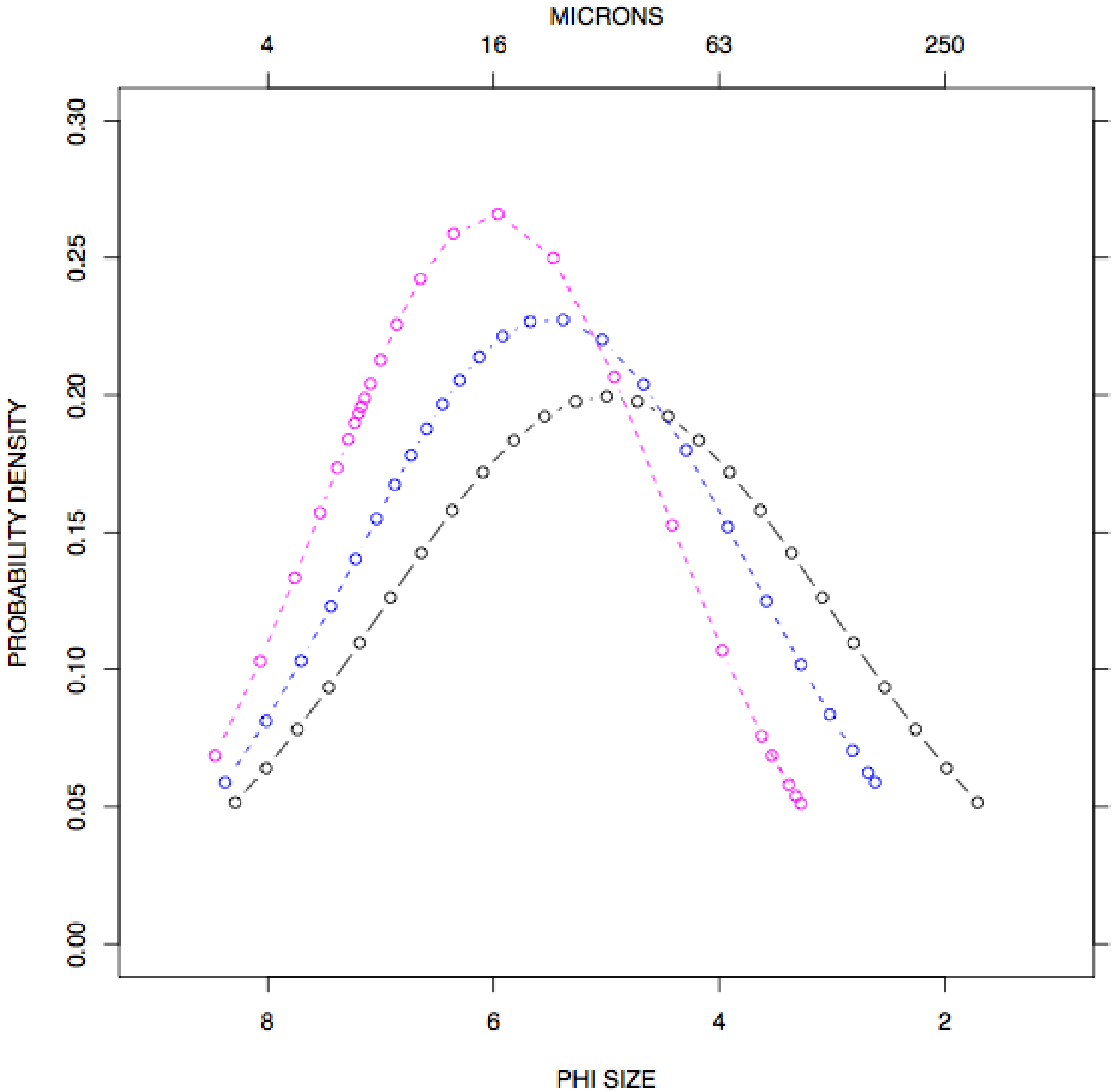


Figure B-15. An example series of hypothetical differential grain-size distributions which become finer, more well sorted, and more skewed in the larger direction along a depositional path from black to blue to pink.

Sediment Transport Parameters

Sediment parameters were estimated based on previous laboratory studies of dredged material from the San Francisco Bay area[7]. Composites of maintenance dredged material from the bay area were tested by the WES Hydraulics Laboratory (POC Teeter) and by the University of Florida (POC Mehta). Those tests, taken together, indicated a two-phase particle erosion where erosion is first initiated at a low level of shear stress (Type I/II) and then increases more sharply at higher shear stress (Type II). These threshold stresses and erosion rate estimates were used to set active and inactive layers. Mass erosion occurs when the sediment matrix yields (the yield point) and increases sharply with clay solids content. A value was selected here (10 Pa) that is probably on the low side for this sediment column type and density. However, the mass erosion threshold for freshly deposited clay material would be expected to be about 6 Pa. Threshold shear stresses for deposition are from Krone's tests on bay sediments.

HEC-6 card fields are presented in the two tables that follow first in SI and metric units and then in HEC-6 units. The special I2 cards will have to be repeated after the I3 card. Thus, silt and clay will be transported together.

TABLE B-3. HEC-6 Card Fields in SI Units				
Field	Card I2	Card I2 Spec. Active layer	Card I2 Spec. Inactive layer	CARD I3 Silt
2	MTCL =2	1	2	MTCL=2
3	ICS=1	DTCL=0.06 Pa	DTCL=0.06 Pa	IASL=1
4	LCS=1	STCD=1.0 Pa	STCD=1.0 Pa	LASL=4
5	SPGC=2.53	STME=10 Pa	STME=10 Pa	SPGC=2.53
6	DTCL=0.06 Pa	ERME=0.144 $g/cm^2/min$	ERME=0.144 $g/cm^2/min$	DTSL=0.08 Pa
7	-	ER2=60	ER2=60	-
8	PUCD=484 kg/m^3			PUSD=1314 kg/m^3
9	UWCL=484 kg/m^3			UWSL=1314 kg/m^3
10	CCCD=0			CCSD=0

[7] Teeter, A.M. (1987.) "Alcatraz disposal site investigation; Report 3; San Francisco Bat-Alcatraz disposal site erodibility," Misc. Paper HL-86-1, USACE, Waterways Exp. Station, Vicksburg, MS.

Conversions: 1 kg/m^3 = 0.06243 lbs/ft^3
1 Pa = 1 N/m^2 = 0.02089 lbs/ft^2
1 g/cm^2/min = 122.918 lbs/ft^2/hr

TABLE B-4. HEC-6 Card Fields in Required English Units

Field	Card I2	Card I2 Spec. Active layer	Card I2 Spec. Inactive layer	CARD I3 Silt
2	MTCL =2	1	2	MTCL=2
3	ICS=1	DTCL=0.00125 lbs/ft^2	DTCL=0.00125 lbs/ft^2	IASL=1
4	LCS=1	STCD=0.0209 lbs/ft^2	STCD=0.0209 lbs/ft^2	LASL=4
5	SPGC=2.53	STME=0.2089 lbs/ft^2	STME=0.2089 lbs/ft^2	SPGC=2.53
6	DTCL=0.00125 lbs/ft^2	ERME=17.70 lbs/ft^2/hr	ERME=17.70 lbs/ft^2/hr	DTSL=0.00167 lbs/ft^2
7	-	ER2=60	ER2=60	-
8	PUCD=30.2 lbs/ft^3			PUSD=82.0 lbs/ft^3
9	UWCL =30.2 lbs/ft^3			UWSL=82.0 lbs/ft^3
10	CCCD=0			CCSD=0

The HEC-6 standard particle fall velocity for a clay particle 2 to 4 µm (geometric mean = 2.8 µm) is estimated to be 0.00762 mm/sec (2.5e-5 fps) using the FISC method (report 12, 1957). The grain size determinations and solids content included material as small as 0.5 µm or less. The geometric mean of the clay material determinations is therefore about 1.6 µm since the upper cutoff for clay was 5 µm.

Specifying a fall velocity for clay particles is made difficult by the fact that even in fresh water they exist in floccules of many particles[8] - though not as large and dense as in seawater. The clay minerals in the Sacramento - San Joaquin river system and Suisun Bay are a mix of illite and montmorillonite[9] which have a very high surface-area to volume ratio due to their platy-, sheet-like

[8] Chase, R.R.P. (1979,) "Settling behavior of natural aquatic particles," *Limnol. Oceanogr*., 24:3, pp. 417-426.
[9] Knebel, H.J., Conomos, T.J., and Commeau, J.A. (1977.) "Clay-mineral variability in the suspended sediments of the San Francisco Bay system, California," *J. Sedim. Petrology*, 47:1, pp. 229-236.

particle configuration. Such flocs are fragile and difficult to study because their size and density depend on concentration, fluid shear rate in the water column, the presence of organic material, salinity, etc.

Previous laboratory tests on Detroit River sediment material 90 percent less than 10 μm in freshwater (with varied concentration and fluid shear rate) indicated an overall median floc fall speed of about 0.07 mm/sec at 20^{o} C[10]. Laboratory tests of resuspended Atchafalaya Bay channel deposits with a median diameter of about 2 μm indicated a median fall speed of 0.020 to 0.016 mm/sec in river water.[11] The same study performed 30 field settling tests on bay water suspensions at low-current sites and found that sediment settling speed deceased away from the river mouth. The median setting speed was 0.04 mm/sec (25 and 75 percentile values were 0.009 and 0.07 mm/sec, respectively).

Based on representative observed clay fall speeds, a flocculation factor of 3-6 is recommended to be applied to the HEC-6 clay fraction fall speed. Some model sensitivity tests with factors in this range might be appropriate.

[10] Burban, P.-Y., Xu, Y.-O., McNeil, J., and Lick, W. (1990.) "Settling speed of flocs in freshwater and seawater," J. of Geophys. Res., 95:C10, pp. 18,213-18,220.

[11] Teeter, A.M., and Pankow, W. (1989.) "The Atchafalaya River Delta; Report 2 Field data; Section 2: Settling characteristics of bay sediments," Techn. Rpt. HL-82-15, USACE, WES, Vicksburg, MS.

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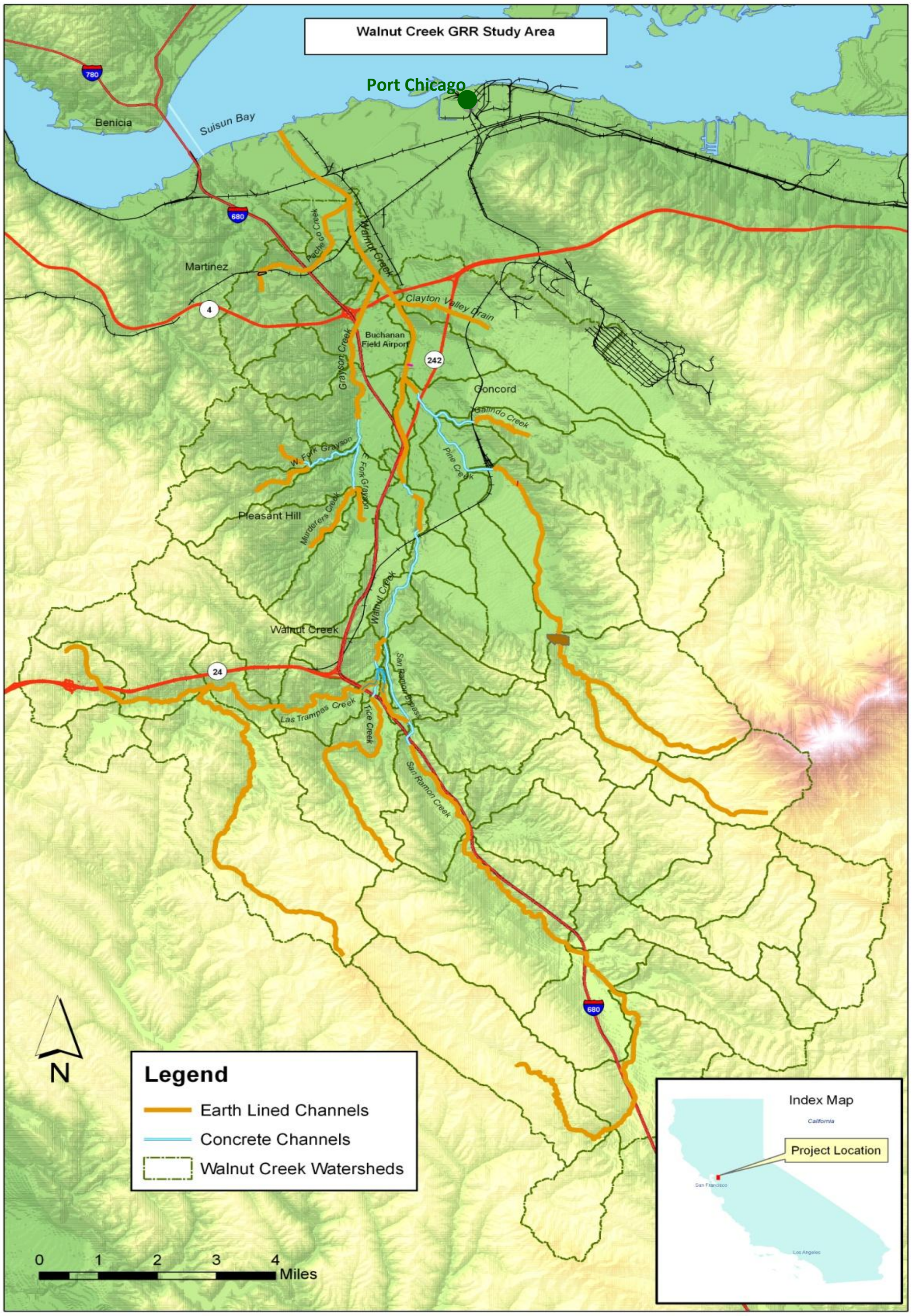


Plate 1. Study Area

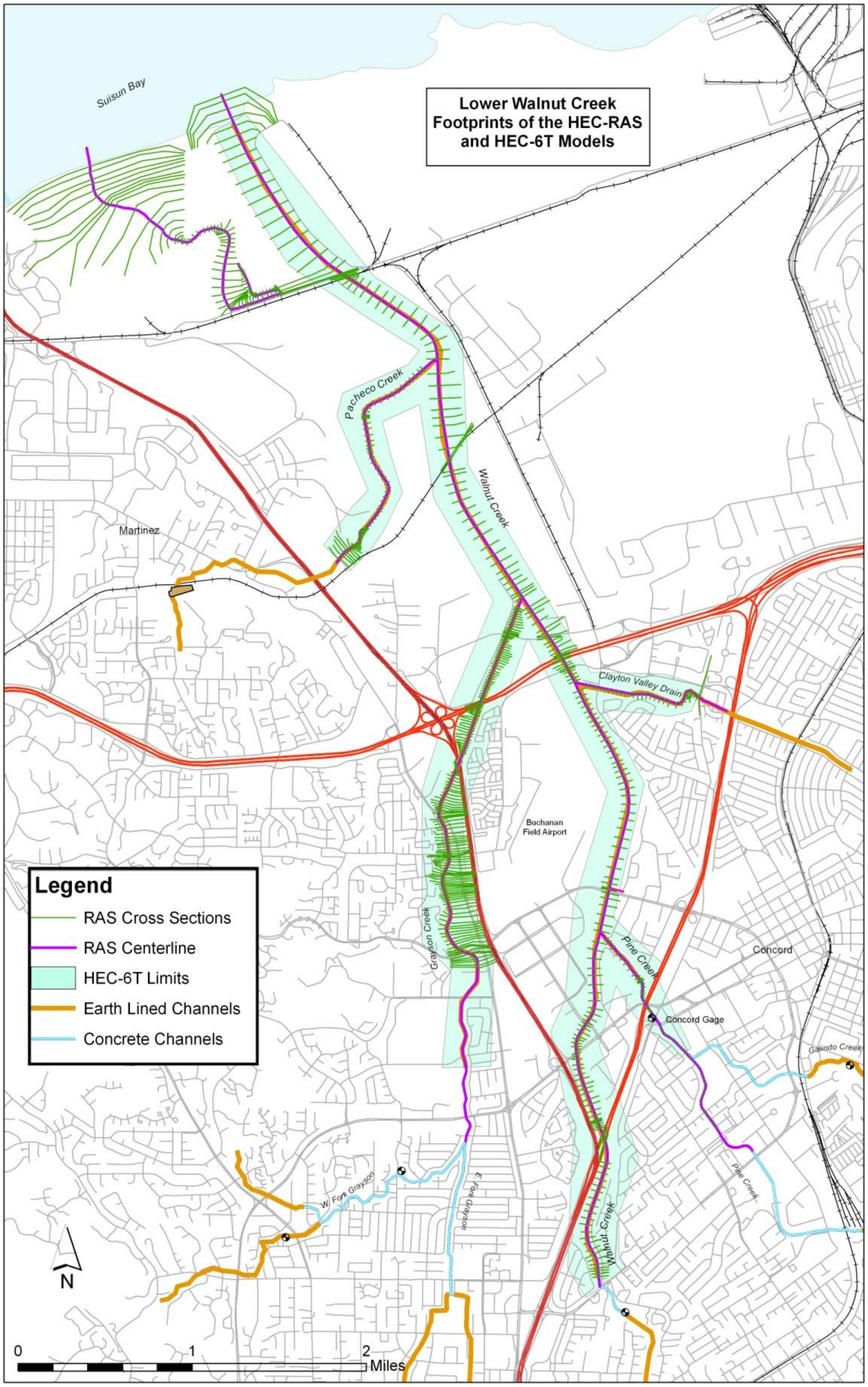


Plate 2. HEC-RAS and HEC-6T Model Limits

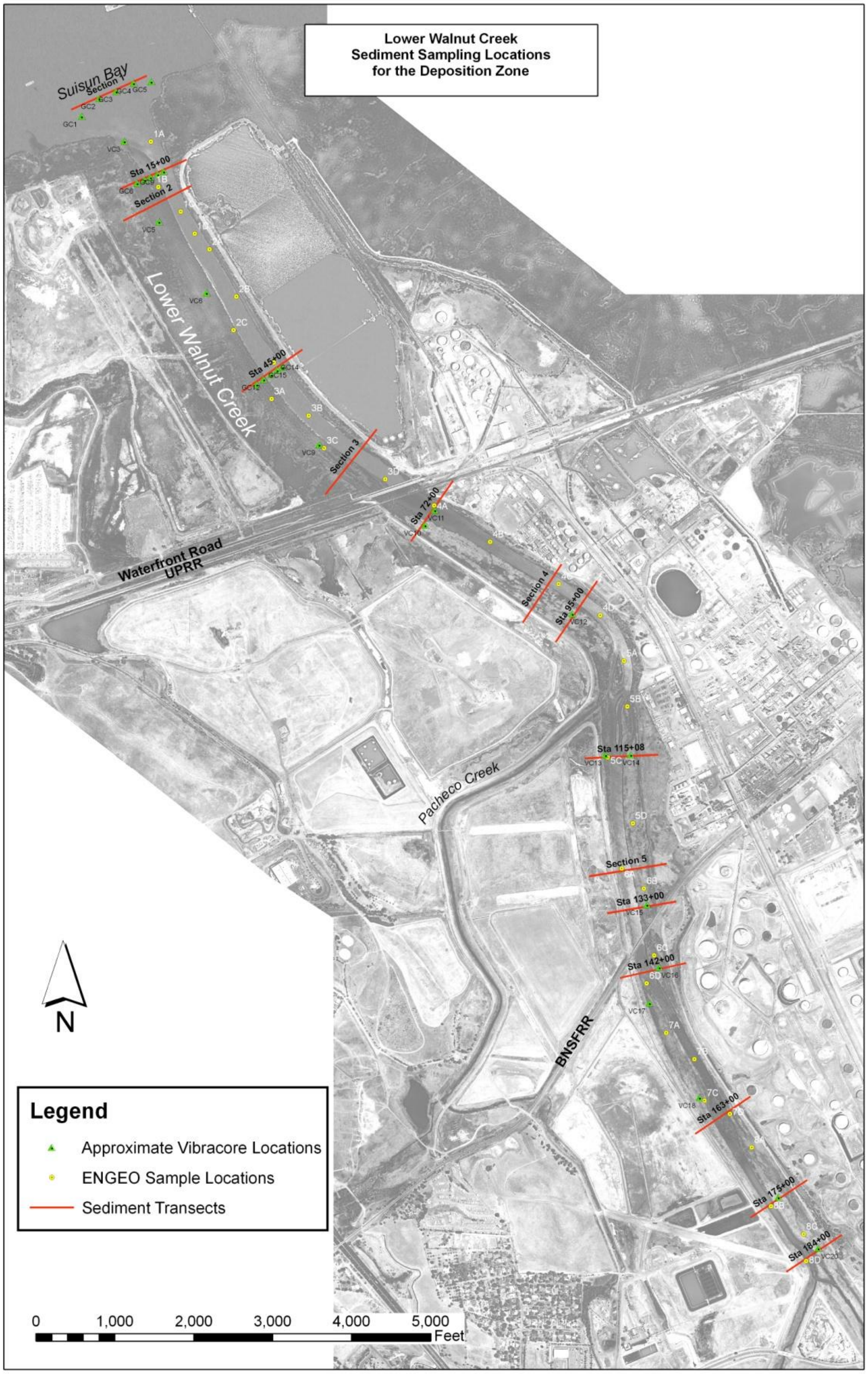


Plate 3. Sediment Transects and Vibracore Sampling Locations

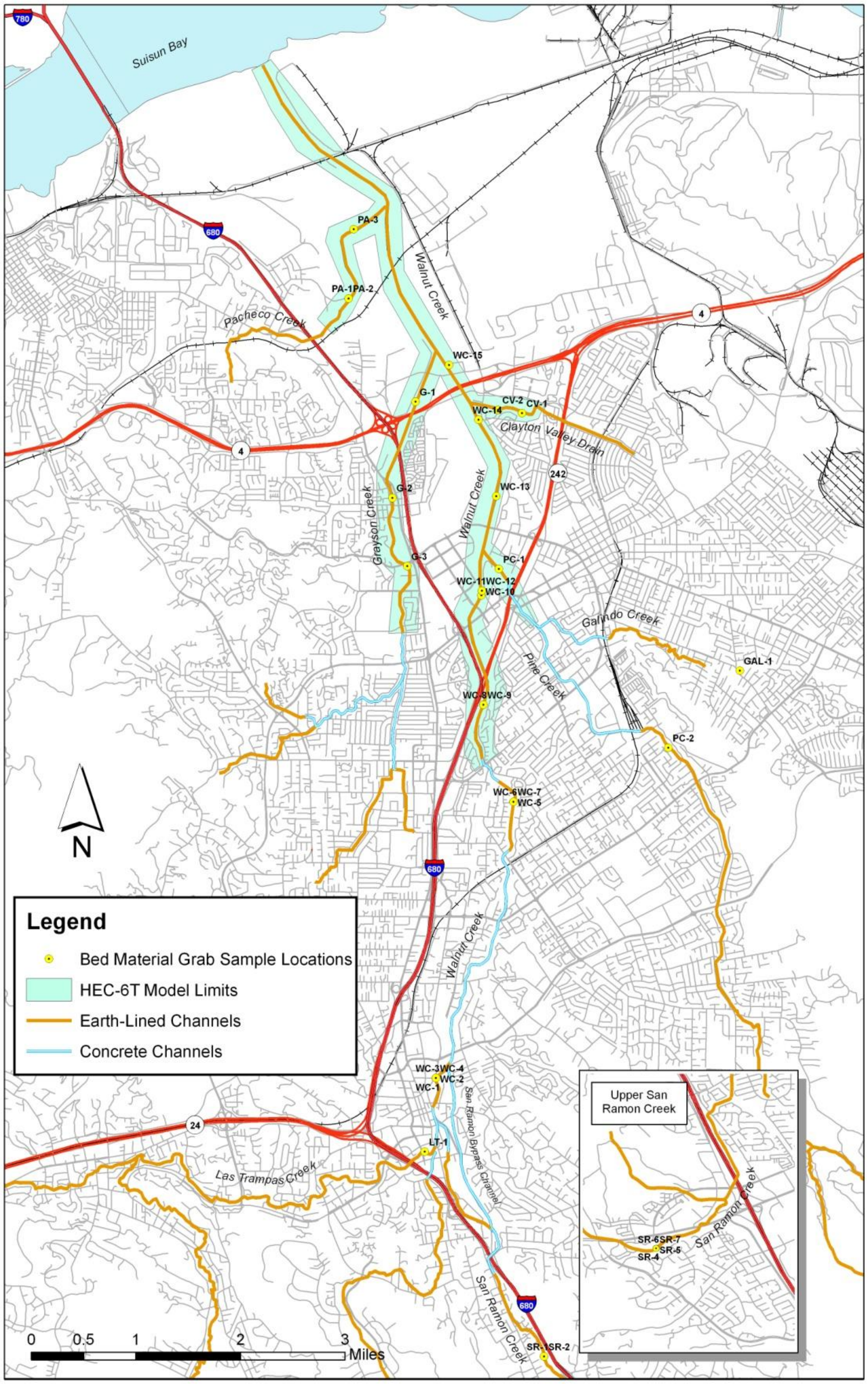


Plate 4. Sediment Sampling Locations

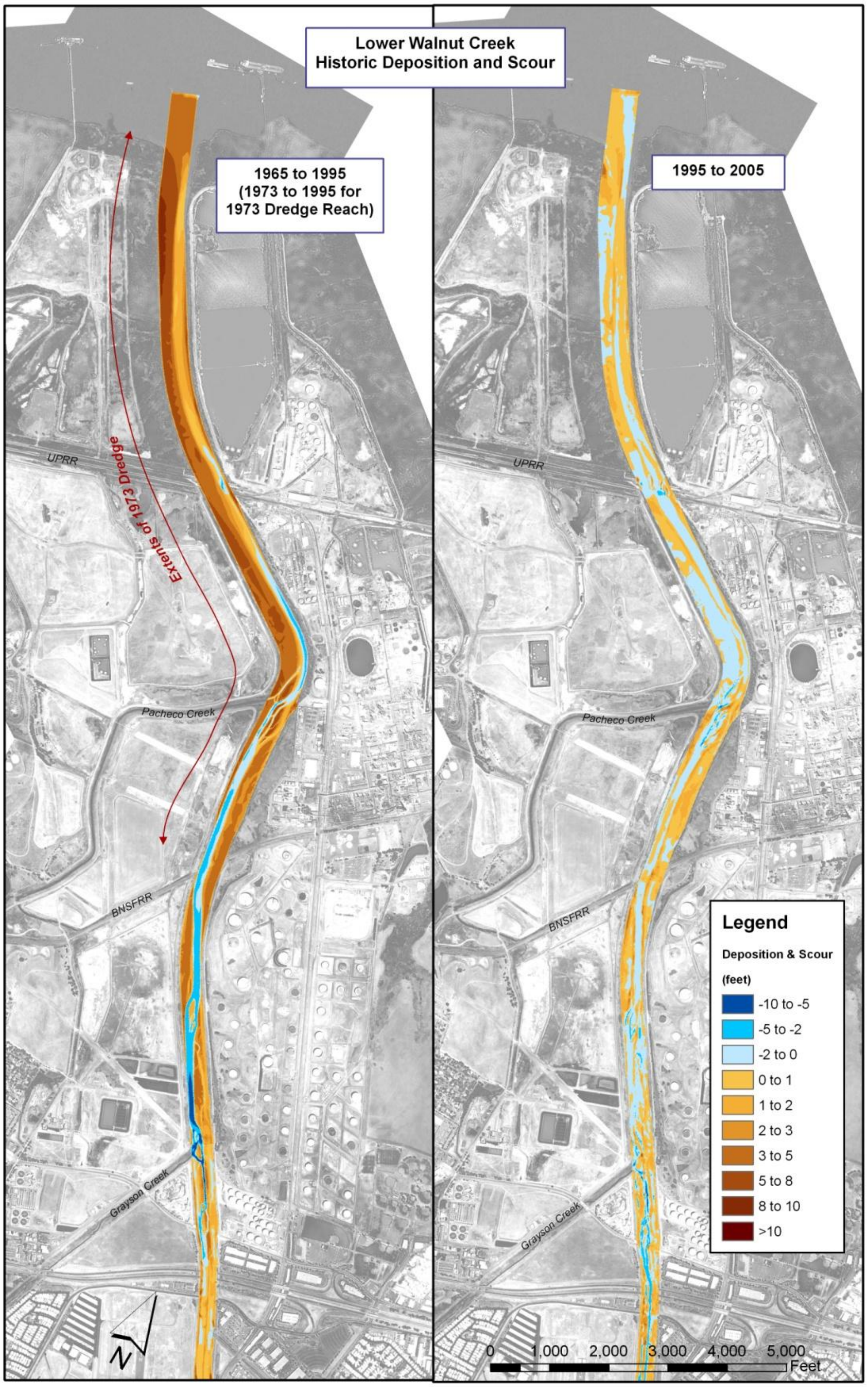
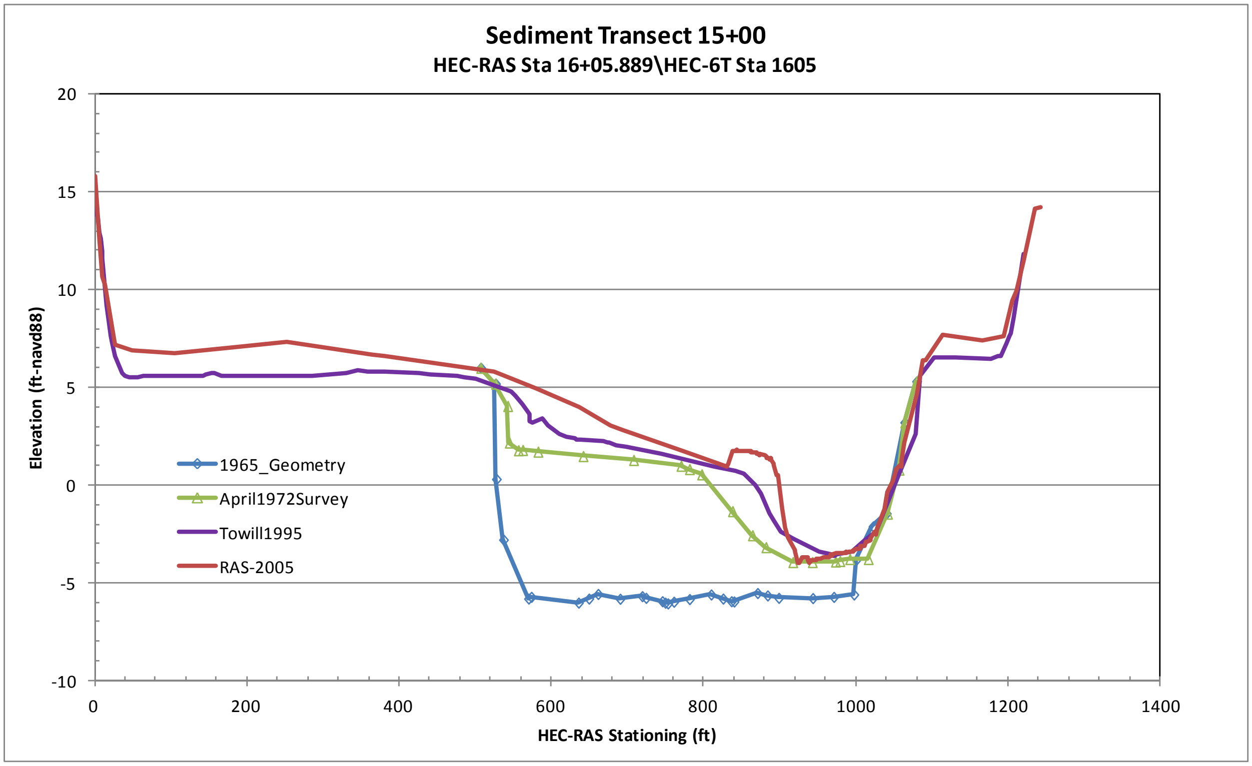


Plate 5. Historic Deposition in Lower Walnut Creek.



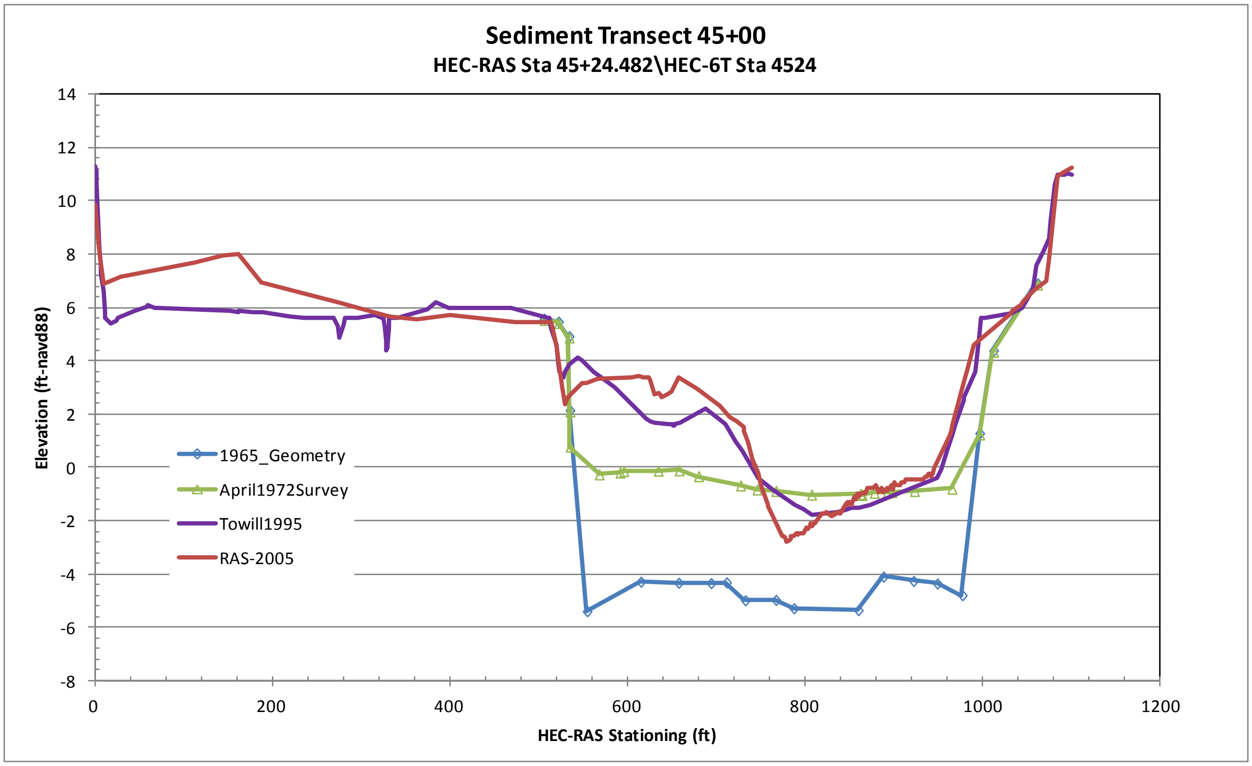
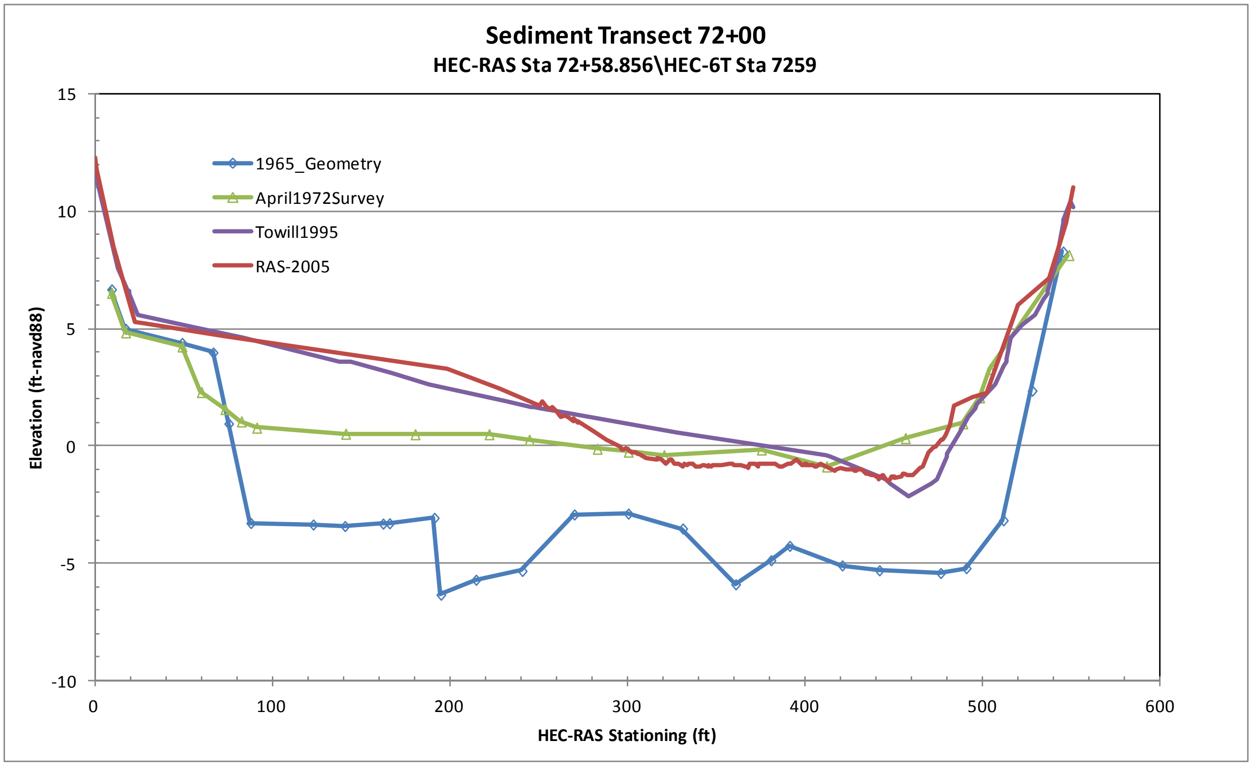


Plate 6. Sediment Transects – Stations 15+00 and 45+00



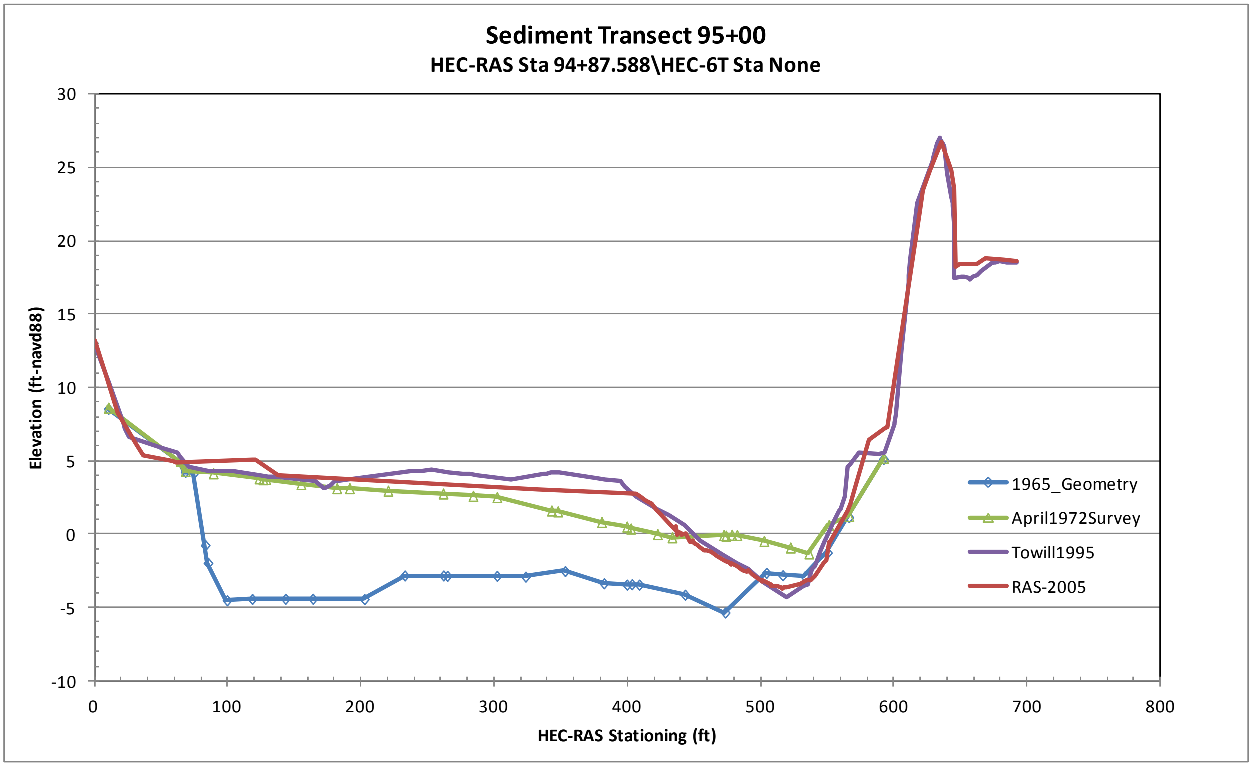
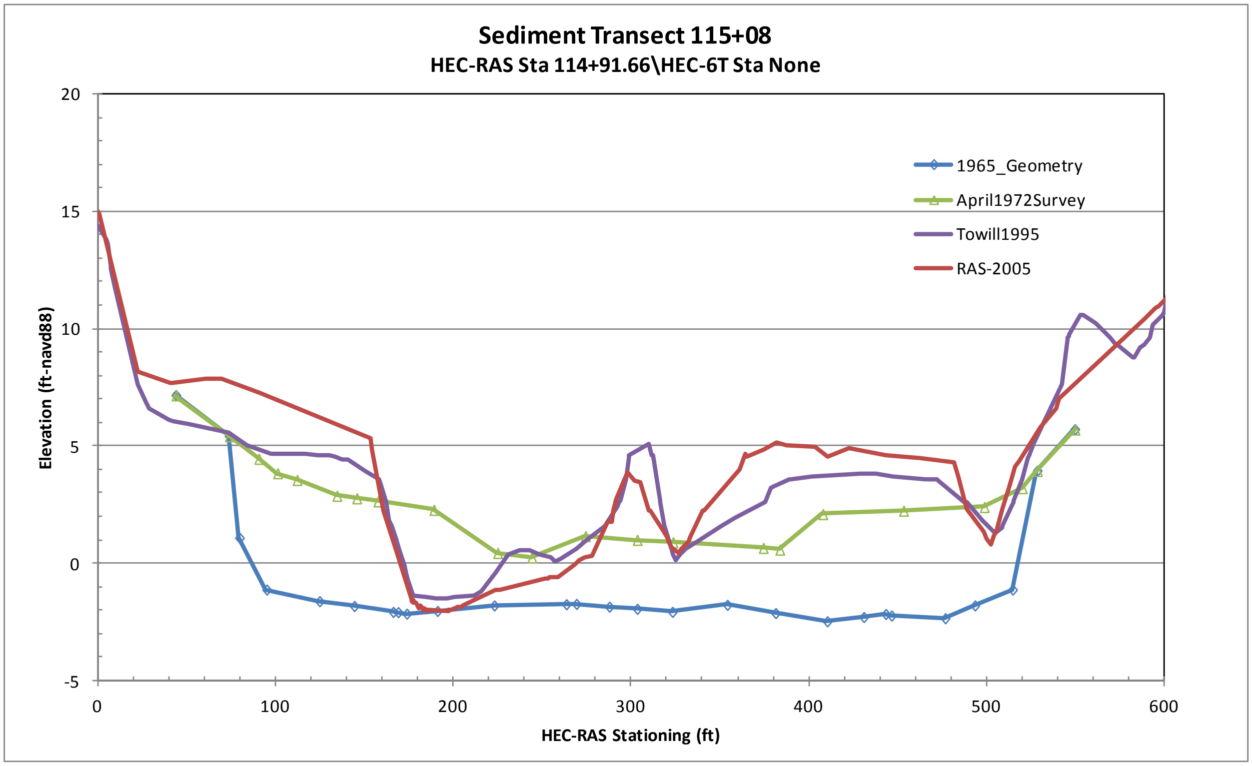


Plate 7. Sediment Transects – Stations 72+00 and 95+00



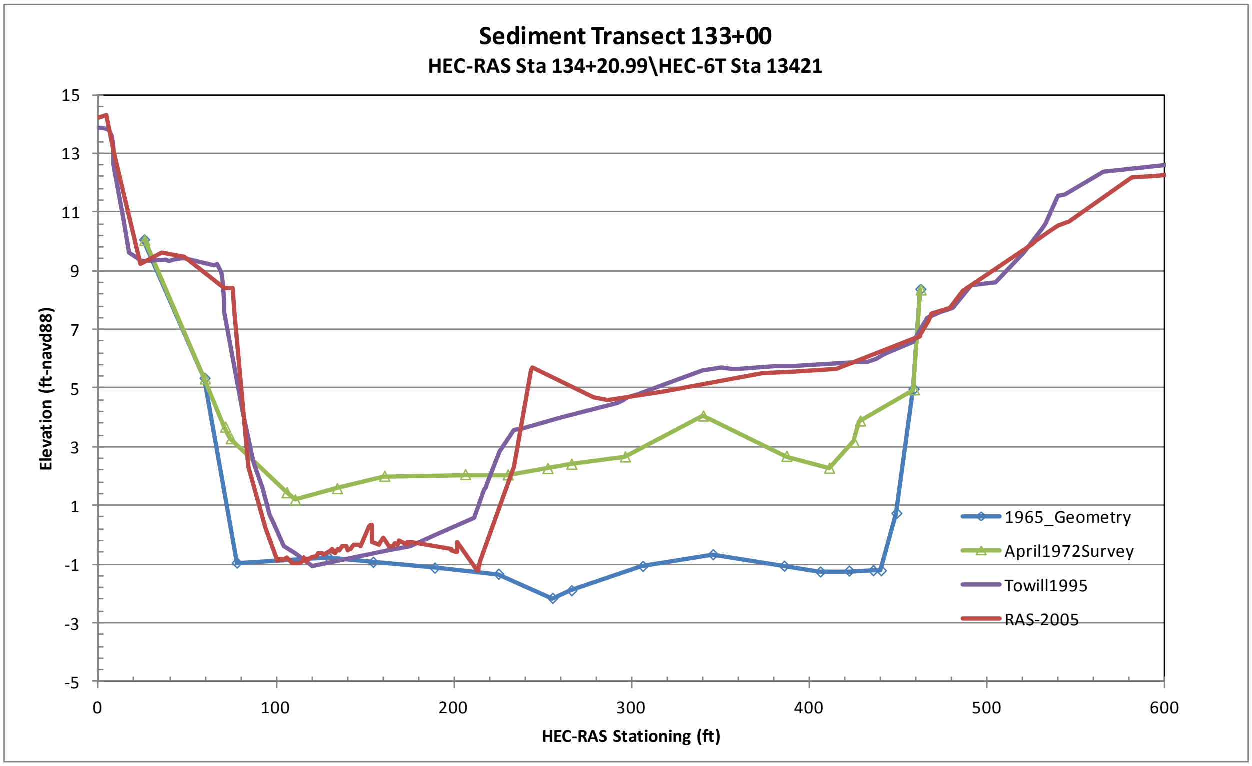
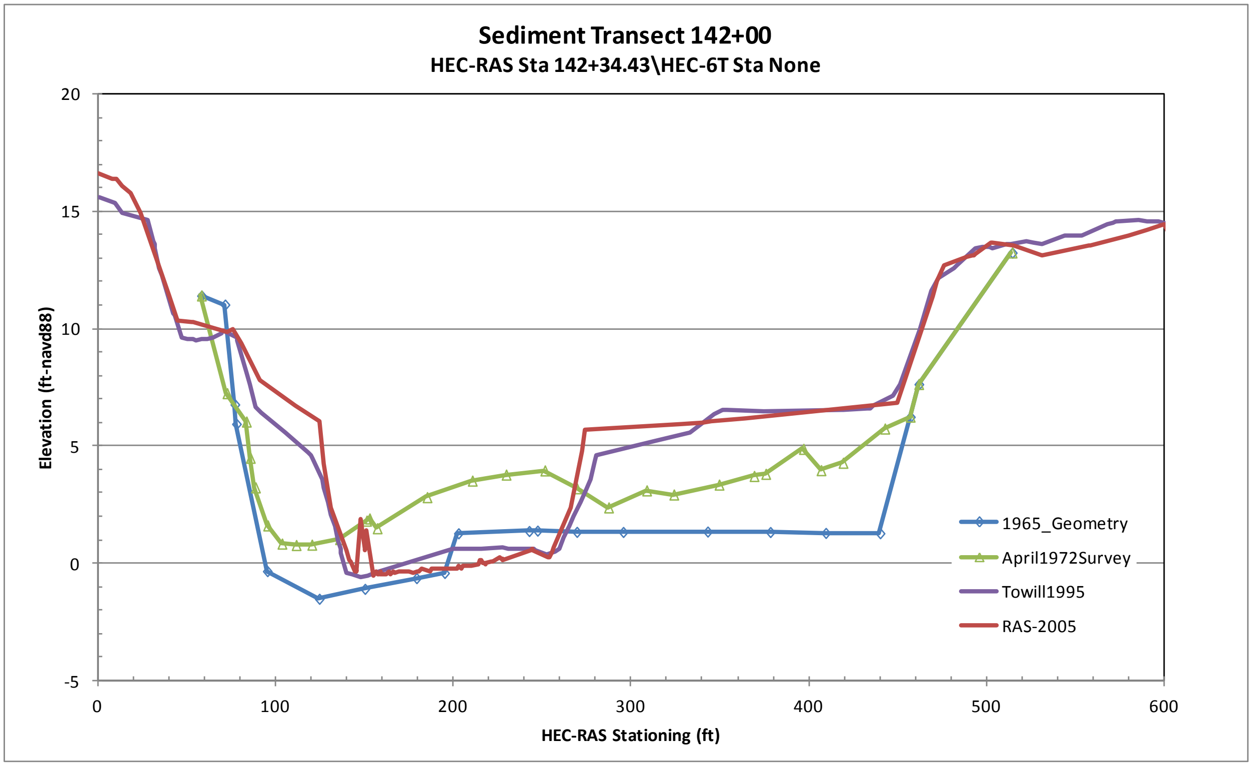


Plate 8. Sediment Transects – Stations 115+08 and 133+00



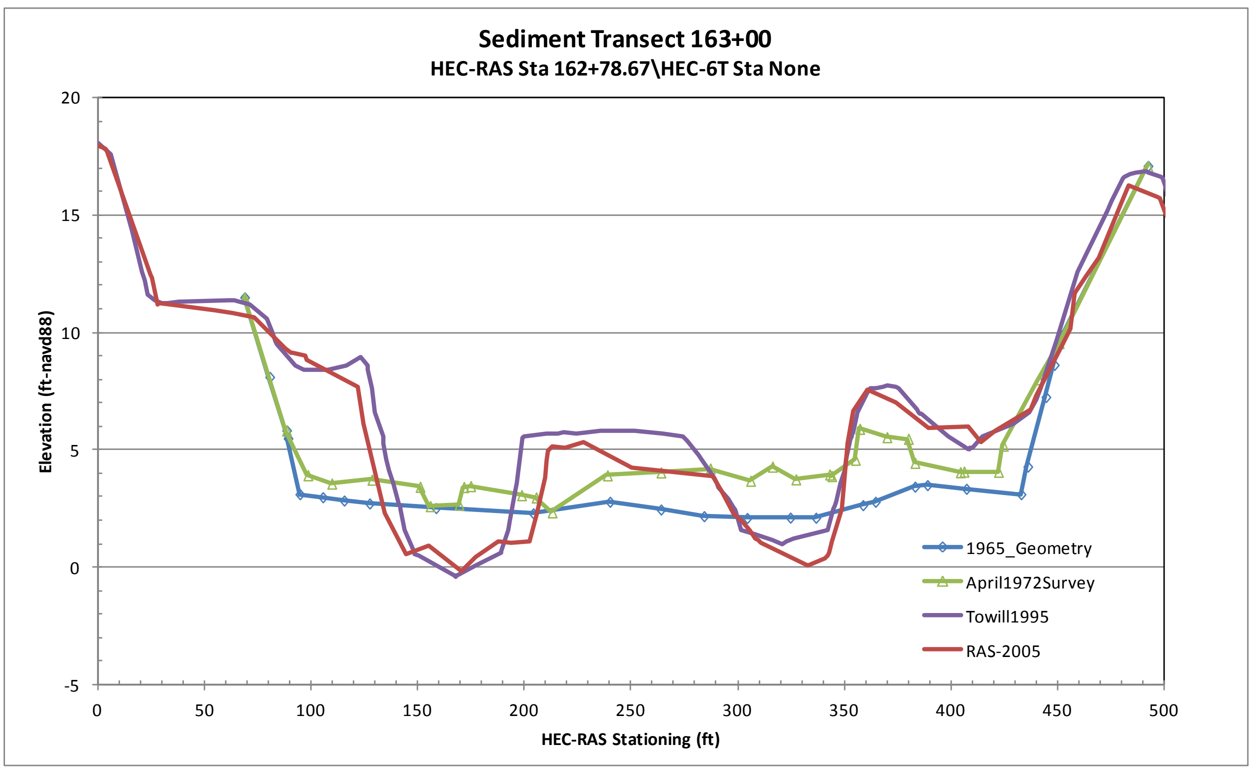
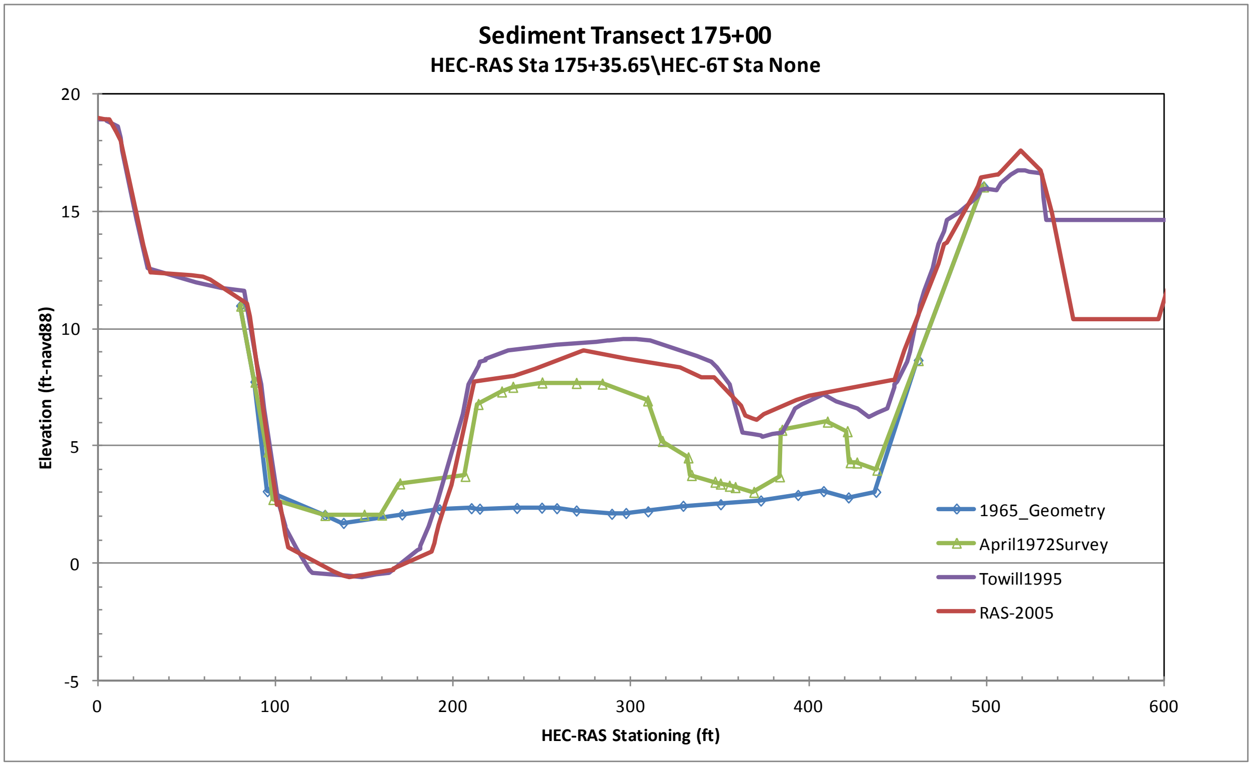


Plate 9. Sediment Transects – Stations 142+00 and 163+00



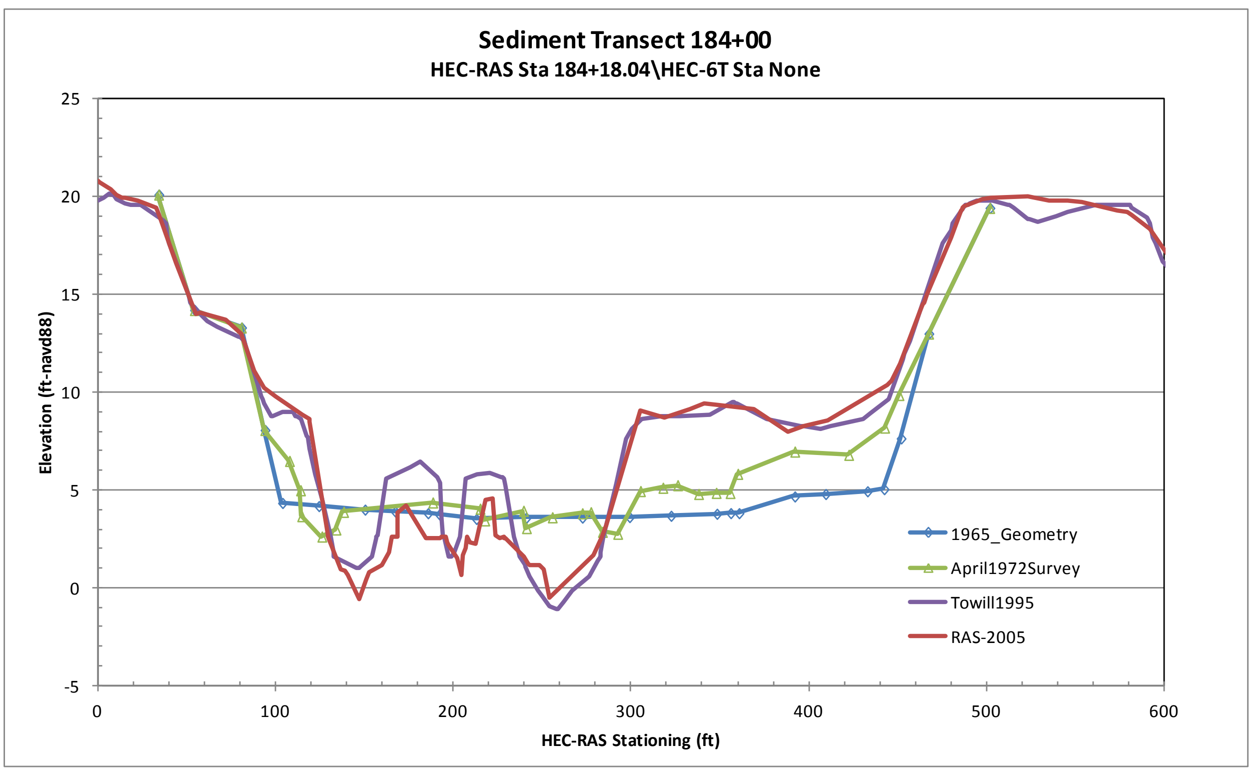


Plate 10. Sediment Transects – Stations 175+00 and 184+00