Sacramento-San Joaquin Delta
Regional Ecosystem Restoration Implementation Plan

Ecosystem Conceptual Model

Sedimentation

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PREFACE

This Conceptual Model is part of a suite of conceptual models which collectively articulate the current scientific understanding of important aspects of the Sacramento-San Joaquin River Delta ecosystem. The conceptual models are designed to aid in the identification and evaluation of ecosystem restoration actions in the Delta. These models are designed to structure scientific information such that it can be used to inform sound public policy.

The Delta Conceptual Models include both ecosystem element models (including process, habitat, and stressor models); and species life history models. The models were prepared by teams of experts using common guidance documents developed to promote consistency in the format and terminology of the models http://www.delta.dfg.ca.gov/erpdeltaplan/science_process.asp .

The Delta Conceptual Models are qualitative models which describe current understanding of how the system works. They are designed and intended to be used by experts to identify and evaluate potential restoration actions. They are not quantitative, numeric computer models that can be "run" to determine the effects of actions. Rather they are designed to facilitate informed discussions regarding expected outcomes resulting from restoration actions and the scientific basis for those expectations. The structure of many of the Delta Conceptual Models can serve as the basis for future development of quantitative models.

Each of the Delta Conceptual Models has been, or is currently being subject to a rigorous scientific peer review process. The peer review status of each model is indicated on the title page of the model.

The Delta Conceptual models will be updated and refined over time as new information is developed, and/or as the models are used and the need for further refinements or clarifications are identified.

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INTRODUCTION

Key Findings

1) Sediment supply: The supply of sediment from the watershed to the Delta is limited. Sediment supply is decreasing due to trapping behind dams and diminishment of the hydraulic mining sediment pulse.

2) Sustainability: The Delta is depositional and adequate sediment deposition is required for wetlands to keep up with sea level rise.

3) Restoration: Typical suspended-sediment concentrations in the Delta range from 10-50 mg/L except during river floods when it can exceed 200 mg/L. Natural wetland sedimentation when concentration is 100 mg/L is about 0.025 m/yr, so deposition rates in the Delta are smaller.

4) Light and biota: Suspended sediment is the primary attenuator of sunlight in the water column of the Delta. Photosynthesis, primary production, and fish behavior depend on light.

5) Model uncertainty: Physical processes are qualitatively understood but difficult to quantify. Erosion is more difficult to quantify than deposition. Biological processes that affect sedimentation are not as well understood qualitatively and are very difficult to predict quantitatively.

Outcomes

The four primary outcomes of this conceptual model are:

1) Bed sediment character (size, organic content)
2) Geomorphic change
3) Suspended sediment character (concentration, organic content, settling velocity)
4) Water column light

These outcomes are used by habitat, stressor, and species models. The first three outcomes are also drivers in this model because of feedback loops. This conceptual model also has many intermediate outcomes that are used as drivers in the model and are available to other models.

Time scale

The time scale of this conceptual model is tidally-averaged. This scale is primarily for simplicity and compatibility with the hydrodynamic/transport model that is a driver of this sediment model. We are not attempting to resolve the tidal time scale, although the model should be applicable to tidal time scales. Sediment deposits and resuspends at the tidal time scale. For example, suspended sediment deposits at slack tide when water velocity and turbulence are small and bottom sediment is resuspended when tidal currents are maximum because the shear stress is greatest. The integration of deposition and erosion over a tidal cycle provides a tidally-averaged rate of deposition or erosion. The drivers are tidal time scale processes but the outcome is tidally averaged. Geomorphic change takes place over years and decades and is estimated by summing deposition and erosion of the tidally-averaged model over time.

Although the model is tidally-averaged, nontidal sedimentation processes are largely episodic. For example, most sediment is supplied by rivers to the Delta over only a few days per year during large floods. This episodic nature is driven largely by sediment pulses from the Sacramento River that deposit in the Delta and move into San Francisco Bay (Fig. 1, Wright and Schoellhamer 2005). During water years 1999-2002, 82% of the sediment was delivered during the wet period (31% of the time) (Wright and Schoellhamer 2005).
McKee et al. (2006) found that for sediment supplied to San Francisco Bay from the Delta 1) a large flood in January 1997 transported 11% of the sediment supplied from 1995-2003, 2) 88% of the annual sediment supply occurred during the wet season, and 3) 43% of the annual sediment supply occurred during the wettest 30-day period. Another episodic forcing is wind waves and associated sediment resuspension in shallow water generated by storms (Ruhl and Schoellhamer 2004).

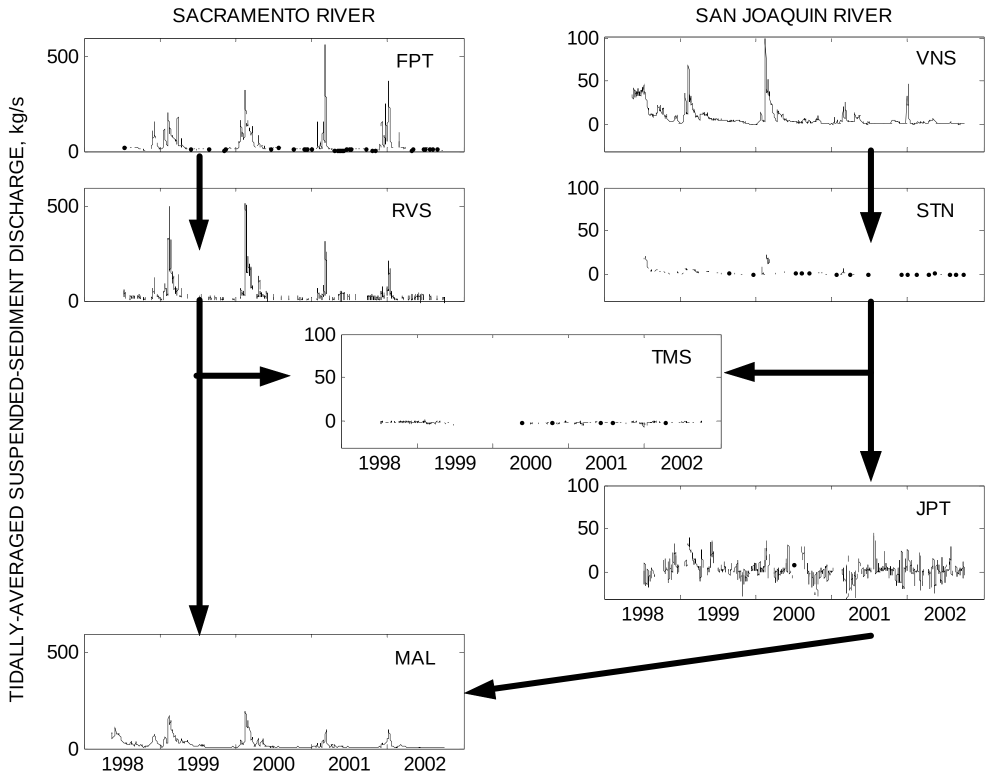

Figure 1. Tidally-averaged suspended sediment flux in the Delta, 1998-2002 (Wright and Schoellhamer 2005). Arrows indicate downstream/down estuary flow paths for the Sacramento (left) and San Joaquin (right) Rivers. The vertical scale for the Sacramento River flow path is larger than that for the San Joaquin River flow path and Three Mile Slough (TMS). Sacramento River at Freeport (FPT) and Rio Vista (RVS), San Joaquin River at Vernalis (VNS), Stockton (STN), and Jersey Point (JPT), and Mallard Island (MAL) are also shown.

Regional transport and local deposition and erosion

Changes in suspended and bed sediment character at a point are determined by transport of sediment from elsewhere to the point, local deposition of that sediment, and local erosion of sediment from the bed. Transport is how sediment moves from the rivers and Suisun Bay at the boundaries of the Delta to a point in the Delta. Deposition and erosion occur along the transport pathway. The hydrodynamic model moves sediment or any constituent suspended in the water column and the processes of erosion and deposition must be added to get sediment transport.

Our conceptual model includes a regional model that transports sediment from rivers to a point and from (or to) the point to (or from) Suisun Bay. At the point, local erosion and deposition occurs.

Suspended and bed load

Sand and coarser sediment (diameter larger than 63 μm) not only move in suspension but also can move along the bed by rolling, sliding, and saltating, called bed load. Based on measurements in the late 1950s, Porterfield (1980) estimated that the bed load was 109 metric tons per day in the Sacramento River at Sacramento. This bed load was only 1.4% of the total sediment load. From 1998-2000, Dinehart (2002) collected several pairs of bedform measurements about one week apart to estimate bedload transport rates of 15-73 metric tons per day at Garcia Bend downstream from Sacramento. Wright and Schoellhamer (2005) report that the daily suspended sediment load at Freeport, about 6 kilometers downstream from Garcia Bend, averaged about 3,000 metric tons per day during water years 1999-2002. Although not temporally aligned, comparison of these more recent measurements appear to confirm Porterfield's finding that suspended load is about 2 orders of magnitude greater than bed load is still valid. Because bedload is a small fraction of suspended load, this conceptual model neglects the mass of sediment transported as bed load. Particle motion, erosion, and deposition due to bed load will be considered.

RIVER SUPPLY

Sediment supply from rivers, primarily the Sacramento River, greatly influences sedimentation in the Delta. This conceptual model of riverine sediment supply provides the linkage between sedimentation in the Delta and the watershed (Fig. 2). This river supply submodel is not intended to be a complete watershed submodel.

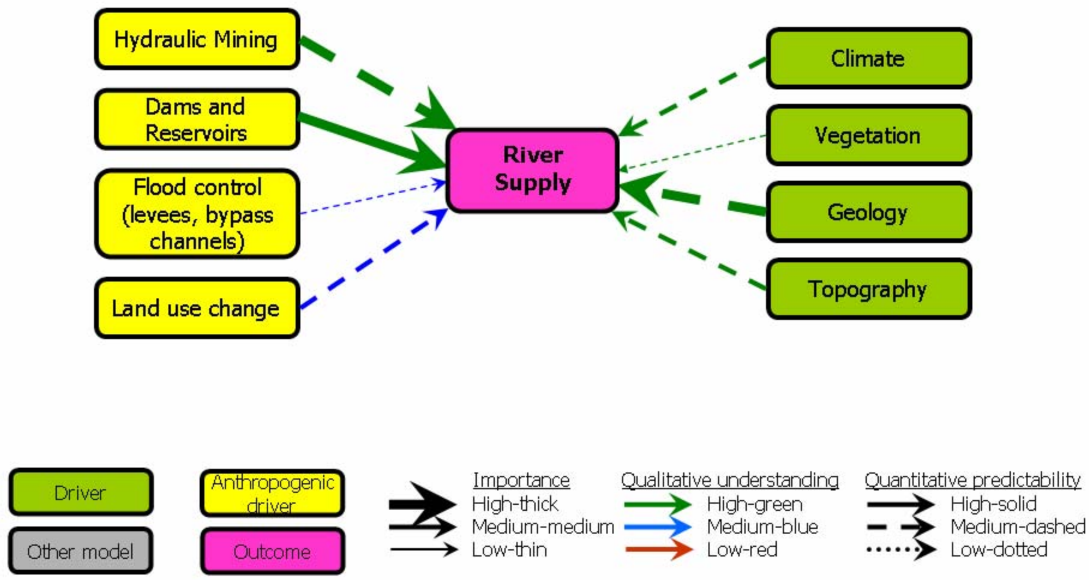

Figure 2. River Supply Submodel. Each box is a driver and each arrow is a linkage. River Supply is a driver of the regional and local sedimentation submodels.

Outcomes

The primary outcome of the river supply submodel is the amount of suspended sediment entering the Delta from the river sources. Several studies (e.g. Porterfield 1980, Wright and Schoellhamer 2005) have documented the dominance of the Sacramento River with respect to sediment supply to the Delta. The structure of this conceptual submodel, however, is such that it could be used to describe the sediment supply from any of the Central Valley watersheds.

The watersheds that drain to the Sacramento-San Joaquin Delta have been heavily impacted by human activities since the discovery of gold along the American River in 1848. In general, human activities tend to increase the amount of sediment transported in rivers through soil erosion, but this increase can be offset by sediment retention in reservoirs, leading Syvitski et al. (2005) to conclude that the worldwide flux of terrestrial sediment to the oceans has decreased from prehuman conditions. A detailed accounting of the changes to the landscape that have occurred in the Central Valley of California is far beyond the scope this conceptual model. Rather, we focus on the more significant changes, with respect to sediment supply to the Delta, and describe conceptually how each of these changes can affect sediment transport. Many of the anthropogenic drivers are interrelated. For example, as climate change alters the volume and timing of water runoff from the Sierra Nevada, this may in turn affect how reservoirs are operated. To keep it simple and make the conceptual model user-friendly, we describe the effects of each anthropogenic driver separately.

Drivers and associated linkages

Climate, geology, topography, and vegetation

The amount of water and sediment delivered to a watershed outlet, under natural conditions, is a complex function of the climate, geology, topography, and vegetation of the watershed. For the watersheds that drain to the Sacramento-San Joaquin Delta, precipitation comes primarily during winter months as rain and snow. The amount and timing of water (i.e., flow regime) reaching the watershed outlet is then determined by hydrologic processes acting throughout the watershed (e.g., snowmelt, evapotranspiration, infiltration, etc.). The amount of sediment reaching the watershed outlet is determined by the flow regime of the river (which sets the transport capacity, i.e., the amount of sediment that could be transported if the supply were unlimited) and the supply of sediment available from the landscape. For the size of sediment that dominates the yield to the Delta (finer that 63 um, or silt and clay), it is likely that the available supply limits sediment transport volumes. Observations of seasonal variability in the relationship between sediment concentration and flow, where sediment concentrations are higher for the same flow during "first flush" events and lower during spring snowmelt events (Schemel et al. 1996, Goodwin and Denton 1991, Curtis et al. 2006) support the conclusion that fine sediment is supply limited. Thus, human activities that alter watershed sediment supply are likely to have a greater effect on river supply to the Delta than those that modify the flow regime (most activities influence both). In accord with this philosophy, we have not included two anthropogenic drivers that affect hydrology but not sediment supply directly, climate change and consumptive water use.

Hydraulic Mining

Probably the most significant anthropogenic driver, with respect to river sediment supply, is hydraulic mining. During the late 1800s and early 1900s, large deposits were washed into flumes using high-powered water jets in order to separate out gold. The mine tailings were routed into the rivers which dramatically increased the sediment supply. Gilbert (1917) estimated a 9-fold increase in sediment supply to San Francisco Bay during the mining period. Though the primary pulse of mining sediment has moved through the system, remnant terrace deposits remain in many of the watersheds (Meade 1982, James 1991). Also, recent estimates of river sediment supply to the Delta are substantially higher than Gilbert's pre-mining estimate, but have continued to decrease since the mid-1950s potentially indicating continued exhaustion of remnant miningderived deposits (Wright and Schoellhamer 2004). Thus, although hydraulic mining has stopped and does not seem likely to occur in the future, its legacy may still be affecting river sediment supply and thus should be included in the conceptual model for assessing future scenarios.

Dams and Reservoirs

Two major water supply projects have been constructed in the watersheds draining to the Delta, the Central Valley Project and the State Water Project, with each project containing multiple large dams are reservoirs. Dams have also been constructed for other purposes, such as trapping hydraulic mining sediments. The U.S. Army Corps of Engineers National Inventory of Dams (http://crunch.tec.army.mil/nid/webpages/nid.cfm) contains 1,483 dams in California (see webpage for inclusion criteria) and Nilsson et al. (2005) classified the Sacramento-San Joaquin basin as "strongly affected" by dams in their recent study of flow regulation of the world's large river systems. The Operations model conceptually describes how these dams are operated and how they affect Delta inflow. The primary effect of dams on sediment supply is retention of sediment in the reservoir; the channel immediately downstream from the dam will erode to a new equilibrium (Porterfield et al. 1978) providing a short-term sediment source, but the long-term effect is decreased sediment supply (Williams and Wolman 1984). Dams also affect the flow regime, typically reducing high flows and increasing low flows (Singer 2006), which also has the effect of reducing downstream sediment supply. It follows that dam removal would increase downstream sediment supply (compared to with the dam in place) by making reservoir sediment deposits available (short-term) and by no longer retaining incoming sediment (long-term).

Flood Control

A major system of levees and bypass channels has been constructed in the basin to reduce flood hazards, particularly in the lower reaches of the Sacramento River watershed (Kelley 1998). Prior to this flood control system, the Sacramento River would overflow its banks and fill vast flood basins for significant periods of time during wet years. The Operations model conceptually describes how the bypass channels affect Delta inflow. The channelized system of today would tend to transport more sediment to the Delta because 1) the flood basins were a sink for fine sediments, and 2) the leveed channels will experience greater bed shear stress because more flow is kept in the channel; however, to counteract this increased shear stress the channels are often lined with bank protection materials such that this effect is probably small. It follows that levee setbacks and floodplain restoration would tend to decrease sediment supply to the Delta by promoting floodplain deposition along upstream reaches.

Land-use Changes

Much of the Central Valley has transformed to agricultural and urban land-uses. Logging has also taken place in many of the watersheds. As stated above, transformation of the landscape by humans typically results in increased soil erosion (Syvitski et al. 2005), thus increasing river sediment supply. Though this effect may be counteracted by dams and reservoirs, much of the land-use changes, particularly agriculture and urbanization, have taken place downstream from the major dams on the system. Thus, these changes are likely to have increased sediment supply to the Delta; even in the early 1900s Gilbert (1917) estimated substantial increases in sediment supply from human activities other than mining. Today, erosion control practices are often used to minimize these impacts.

Relative importance of river supply drivers

The anthropogenic drivers that are well known to have had significant impacts on river sediment supply are hydraulic mining and dams; thus, these are probably the most important drivers. Gilbert (1917) estimated a 9-fold increase in sediment supply during the period of hydraulic mining (attributed primarily, but not exclusively, to hydraulic mining). Wright and Schoellhamer (2004) showed that the amount of sediment trapped annually in just a few dams in the Sacramento River watershed is of the same order of magnitude as the annual watershed sediment supply, indicating that dams are significantly affecting the supply. It is more difficult to similarly quantify the effects of the other anthropogenic effects (land-use changes, flood control system), and the studies required to do this have not been conducted to date. However, given the extensive land-use changes that have occurred in the Central Valley, and the understanding that these changes generally result in accelerated erosion (Syvitski et al. 2005, American Society of Civil Engineers 1975), it seems likely that land-use changes have also been an important driver of river sediment supply.

REGIONAL TRANSPORT

The Delta is where the rivers that drain the Central Valley merge and become an estuary. The regional model transports sediment from the rivers into the Delta. The regional model also transports sediment from the Delta to Suisun Bay. It is also possible to transport sediment from Suisun Bay landward into the Delta due to complex hydrodynamics in Suisun Bay and the western Delta.

For the regional transport submodel, the Delta is represented as a triangle (fig. 3). The northeast (upper right) apex is where the Sacramento River enters the Delta and the southeast (lower right) apex is where the San Joaquin River enters. For convenience, these apexes are considered at the USGS sediment gages at Freeport on the Sacramento River and Vernalis on the San Joaquin River. The Yolo Bypass diverts high Sacramento

River flows around the city of Sacramento to the Delta and is shown as an arrow entering the northwest side. The Mokulumne and Cosumnes Rivers enter on the east side. The western (left) apex is the boundary between Suisun Bay and the Delta located at the USGS continuous suspended sediment monitoring station at Mallard Island.

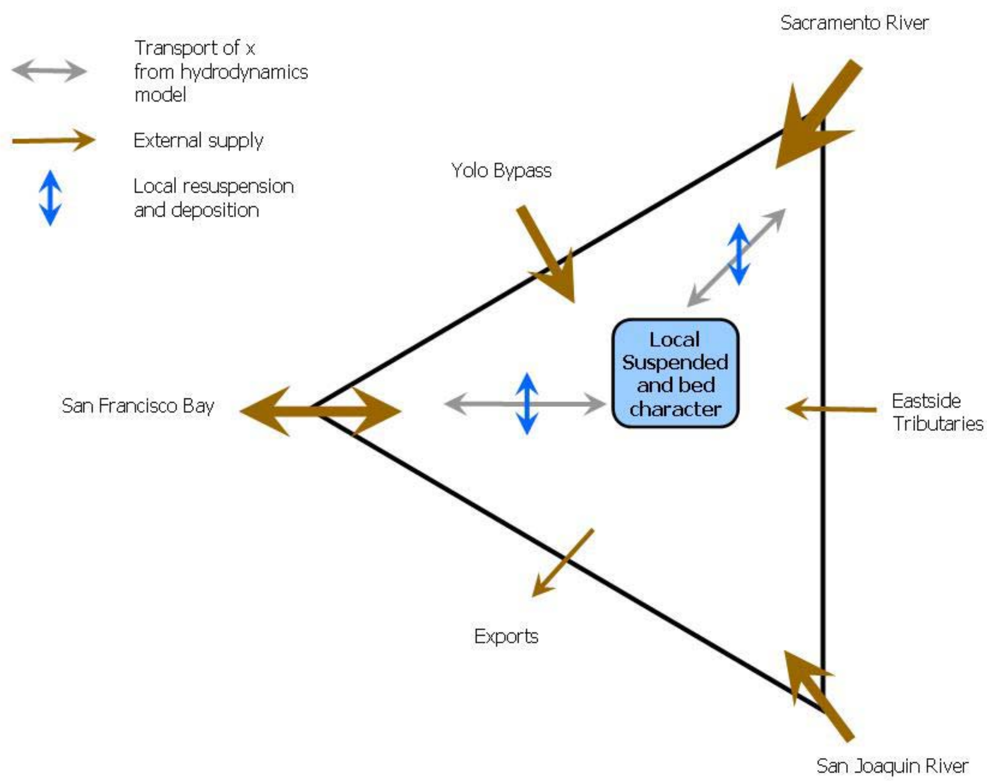

Figure 3. Regional submodel of sediment transport in the Delta. Line thickness indicates approximate importance of external sediment supplies (Fig. 4). The Delta exchanges sediment with San Francisco Bay.

Several rivers supply sediment to the Delta. A large arrow is shown for the Sacramento River. During water years 1999-2002 the sediment discharge at Freeport (FPT) on the Sacramento River was 5 times greater than the San Joaquin River at Vernalis (VNS, fig. 4, Wright and Schoellhamer 2005). Sediment discharge at Freeport decreased by about one-half from 1957 to 2001 due to the diminishment of the hydraulic mining pulse of sediment and sediment trapping behind dams (Wright and Schoellhamer 2004). The second largest source of sediment was the Yolo Bypass (YOL, 28% of the sediment discharge at Freeport). Note that a rating curve based on data from the 1957-1961 and 1980 were used to determine Yolo Bypass sediment flux and a large uncertainty (42%) is associated with that value. In addition, the effect of decreased sediment yield from the Sacramento Valley is unknown due to lack of data. Uncertainty in sediment supply leads to uncertainty answering basic questions about the Delta such as what the deposition rate is, the quantity of sediment available for restoration, and whether the Delta will be sustainable given sea level rise. The east side tributaries (EAST) supplied only 3.3% of the sediment discharge at Freeport. As previously stated, most sediment is supplied during high flows (McKee et al. 2006, Schemel et al. 1996, Wright and Schoellhamer 2005).

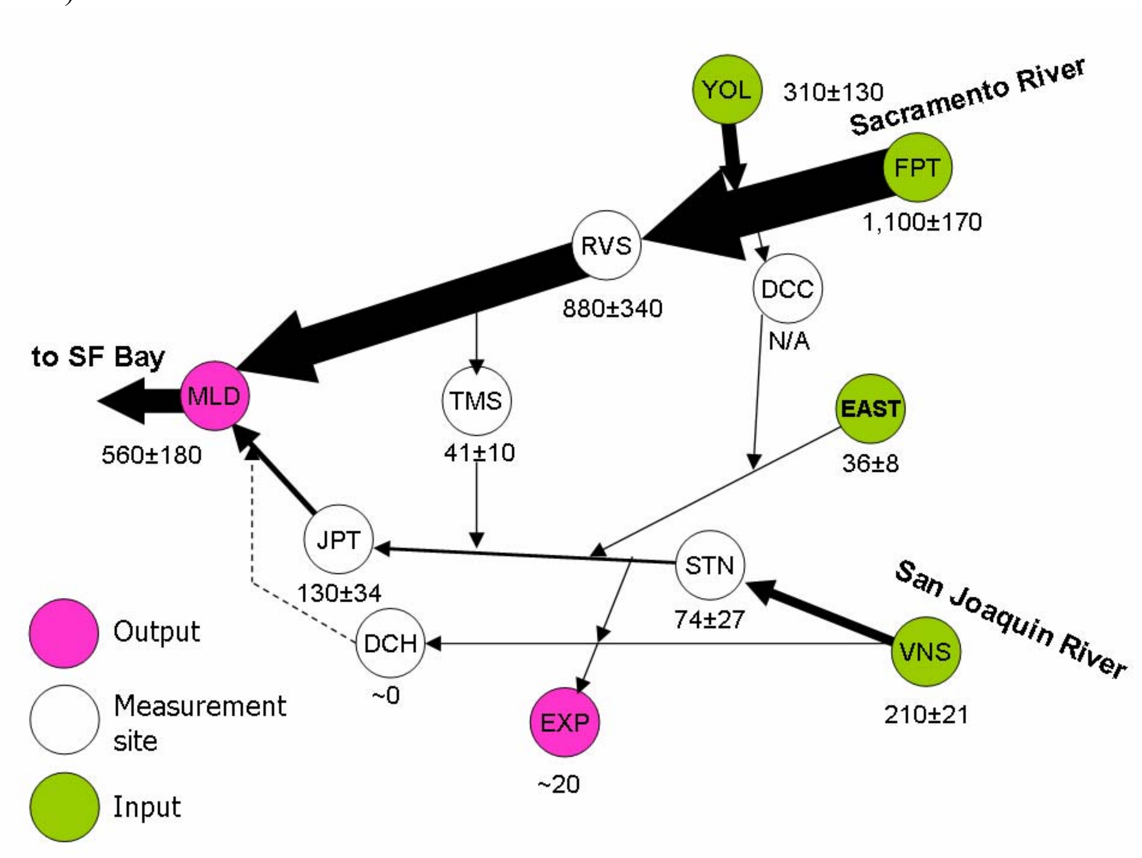

Figure 4. Average annual Delta sediment budget based on water years 1999 – 2002, except for Three Mile Slough (TMS) which is based on water years 2001 and 2002 only (Wright and Schoellhamer 2005). Numbers are the annual suspended-sediment flux and the estimated error in thousand metric tons. Arrow thickness indicates relative magnitude of the suspended-sediment flux. Sediment deposition accounts for the decreased sediment fluxes from east to west. Additional sites are Sacramento River at Freeport (FPT), Yolo Bypass (YOL), Delta Cross Channel (DCC), Sacramento River at Rio Vista (RVS), Mallard Island (MAL), Eastside tributaries (EAST), San Joaquin River at Vernalis (VNS), San Joaquin River at Stockton (STN), exports from the State and Federal water projects (EXP), Dutch Slough (DCH), and San Joaquin River at Jersey Point (JPT).

The State and Federal water projects export water from the southern Delta (EXP). Wright and Schoellhamer (2005) used sediment deposition volumes in Clifton Court Forebay to estimate that exported sediment was about 2% of the sediment discharge at Freeport.

Tidally-averaged sediment transport is usually from the Delta into Suisun Bay. For water years 1999-2002, Mallard Island suspended sediment flux was seaward and 51% of the

Freeport sediment discharge (Wright and Schoellhamer 2005). On a daily time scale, which is roughly tidally-averaged, McKee et al. (2006) found that sediment transport was landward 9 of 198 days for which data were available. Small river flows, gravitational circulation (see hydrodynamic model), and tidal asymmetries such as higher concentrations in Suisun Bay due to wind wave resuspension (Ruhl and Schoellhamer 2004) or a turbidity maximum (Schoellhamer 2001) and greater bottom shear stress during flood tide (Brennan et al. 2002), account for occasional net sediment transport from Suisun Bay into the Delta (Tobin et al. 1995). Landward sediment transport is approximately 11% of the seaward sediment transport during high flows and 52% during low flows (McKee et al. 2006). On a tidal time scale, flood tides transport sediment from Suisun Bay into the Delta and ebb tides reverse sediment transport. Tides thus exchange and mix suspended sediment between Suisun Bay and the Delta.

Water movement within the Delta transports suspended sediment. The hydrodynamic model describes the transport of a constituent in the water column, in this case suspended sediment which is represented with gray arrows in figure 3.

Suspended sediment has an additional complication because the bed acts as a source due to erosion or sink due to deposition, represented by blue arrows in figure 3. For example, in order to determine the quantity of sediment from the Sacramento River delivered to a point in the Delta, transport from the hydrodynamic model and deposition and erosion along the transport pathway must be considered. On the tidal time scale, deposition is more likely to occur near slack tides when water velocity and turbulence are small and erosion is more likely to occur during strong tides when water velocity and turbulence are greatest. On a time scale of years, Wright and Schoellhamer (2005) found that two-thirds of the sediment that entered the Delta deposited in the Delta during water years 1999-2002.

Regional spatial variability of suspended sediment within the Delta is dominated by supply from the Sacramento River. The Sacramento River is the primary pathway for sediment transport (fig.4, Wright and Schoellhamer 2005). At least 82% of the sediment entering the Delta from the Sacramento River watershed either deposits along the Sacramento River or moves past Mallard Island into Suisun Bay. No more than 18% moves into the San Joaquin River portion of the Delta. The suspended sediment signal of the San Joaquin River attenuates more rapidly than that of the Sacramento River (fig. 1, Wright and Schoellhamer 2005).

LOCAL SEDIMENTATION

Processes at a horizontal point in space determine the rate of sediment erosion from the bed and the rate of deposition from suspension onto the bed. As a parcel of water moves from the river into the Delta, it tidally oscillates within the Delta, and ultimately exits the Delta, the integration in time of erosion and deposition in addition to dispersion from the hydrodynamic model determine the suspended-sediment concentration (SSC) of the parcel and the character of the suspended sediment. At a fixed point in the Delta, the time history of erosion and deposition determine the character of the bed material. Tidally-averaged rates of deposition and erosion are integrated over decades to determine the geomorphic evolution of a fixed point in the Delta.

We will present local submodels of sedimentation for different Delta habitats. These submodels contain the same outcomes, drivers, and linkages but the importance, qualitative understanding, and quantitative predictability assigned to the linkages varies between habitat submodels. Then, the outcomes and drivers and associated linkages presented in all the submodels will be discussed.

Habitats

Local sedimentation processes will differ in different habitats. We present four variations of a local sedimentation submodel for open water, marsh, floodplain, and riparian habitats. The area that each habitat covers in the Delta is given in table 1. Each submodel contains the same drivers and outcomes; only the importance, qualitative understanding, and quantitative predictability of the linkages differ.

Delta habitat		Sedimentation habitat submodels	
Type	Area (acres)	Type	Area (acres)
Open water	55,168	Open water	55,168
Permanently flooded estuarine emergents	20	Marsh	12,464
Tidal estuarine emergents	1,121		
Permanently flooded palustrine emergents	11,323		
Seasonally flooded palustrine emergents	6,130	Floodplain	45,362
Seasonally flooded agriculture	39,232		
Riparian woody	3,754	Riparian	3,754

Table 1. Delta habitats (California Department of Water Resources 1995).

Open Water

Open water is the largest habitat type (table 1) and includes channels and flooded islands. Delta channels provide the pathways for sediment from the watershed to move through the Delta and enter San Francisco Bay (Wright and Schoellhamer 2005). The hydrodynamics model describes motion of open waters. Most linkages are qualitatively understood but difficult to quantify (fig. 5). Erosion is more difficult to quantify than deposition so erosive linkages have less predictability than depositional linkages. Biological processes are not as well understood qualitatively and are very difficult to predict quantitatively. *Egeria densa* is a submerged invasive plant that occupies over

12,000 acres of open water in the Delta (22%, Dr. Susan Ustin, UC Davis, personal communication), so vegetation is considered to be of medium importance in open water. Dredging occurs in open water and many Delta channels are armored. Suspended sediment is the primary limitation on light in the water column (Cloern 1987, Jassby et al. 2002).

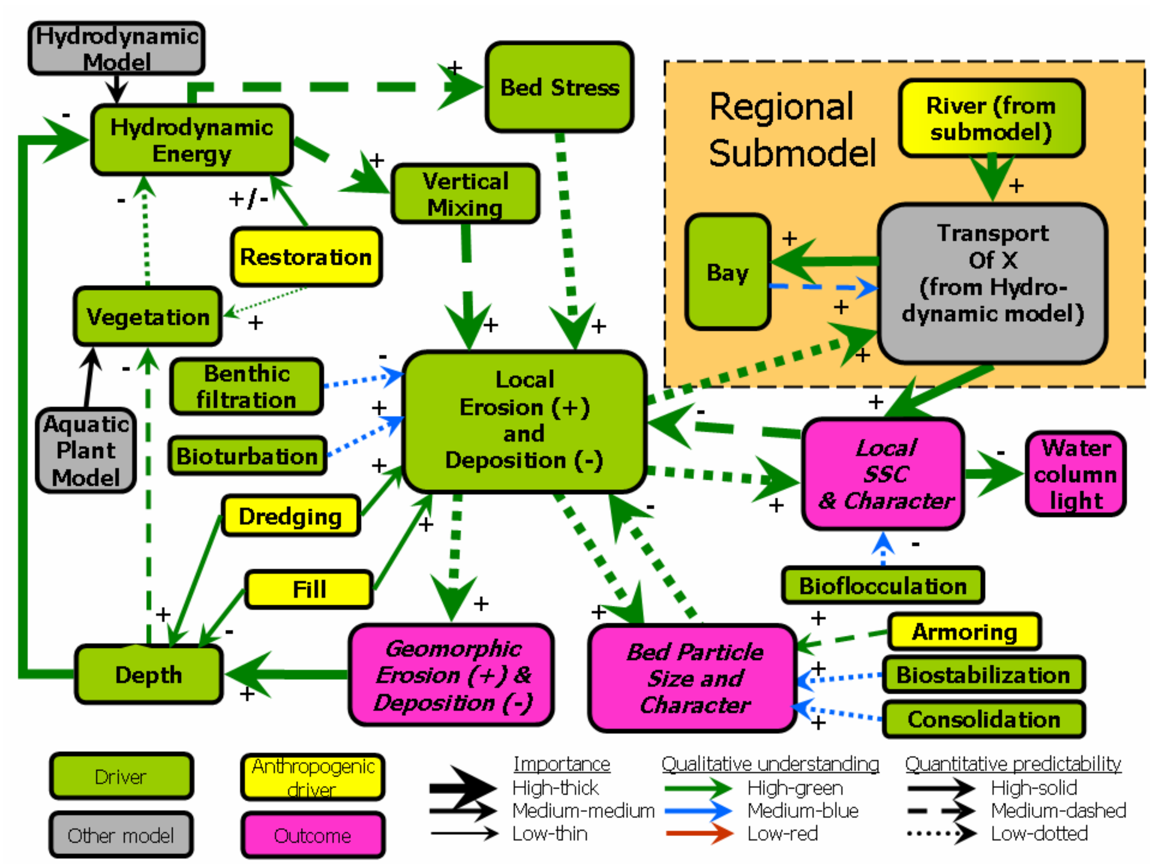

Figure 5. Local sedimentation submodel for open water. Each box is a driver and each arrow is a linkage. An increase in a driver either increases (+) or decreases (-) the intermediate outcomes it affects. In addition to being outcomes, purple boxes are also drivers. In addition to being drivers, several green boxes are also intermediate outcomes.

Wetland restoration sites usually are initially open water immediately after the surrounding levee is breached. Depositing sediment increases the elevation of the site until vegetation colonizes the site and creates a marsh. Deposition rate at a restoration site increases as SSC of the water inundating the site increases. Williams and Orr (2002) used a numerical model to show the effect of SSC on vertical accretion assuming no erosion of bottom sediment (fig. 6). SSC in the Delta is usually less than 100 mg/L, the smallest SSC considered in their study, so it would take at least several decades for one meter of sediment to deposit at a Delta restoration site. Vertical accretion when SSC is 100 mg/L is about 0.025 m/yr, so deposition rates in the Delta are smaller.

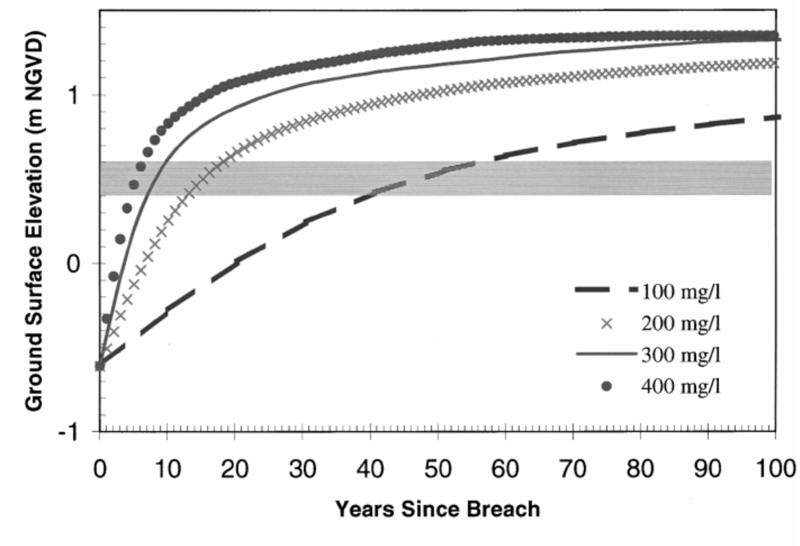

Figure 6. Effect of suspended sediment concentration on marshplain evolution over time for a site sheltered from wind wave action. Shaded bar identifies the approximate *Spartina* colonization elevation. Prediction is based on tides at the San Francisco Presidio, no sea level rise, and 550 kg/m^3 dry density of inorganics typical for San Francisco Bay. NGVD, National Geodetic Vertical Datum, a vertical datum fixed at the mean sea level of 1929. From Williams and Orr (2002).

Marsh

Marsh area in the Delta is less than one quarter of the open water area (table 1). The permanently flooded palustrine emergents category in table 1 appears to include tidal and non tidal marsh. Tidal marshplain processes are described in the tidal marsh model. The marsh submodel for sedimentation (fig. 7) differs from the open water submodel in several ways. Vegetation has a stronger influence on sedimentation in a marsh compared to open water because it dampens hydrodynamic energy which favors deposition over erosion. Thus, the marsh submodel shows depositional linkages being more important than erosional linkages. Vegetation can also provide shading, so the effect of suspended sediment on light water column light is less important than open water. Dredging, filling, and armoring now rarely occur in marshes so we consider them unimportant. A common goal of restoration projects is to encourage marsh vegetation, so we consider the linkage between restoration and vegetation to be highly important. Deposition of leaf litter is not considered in this submodel.

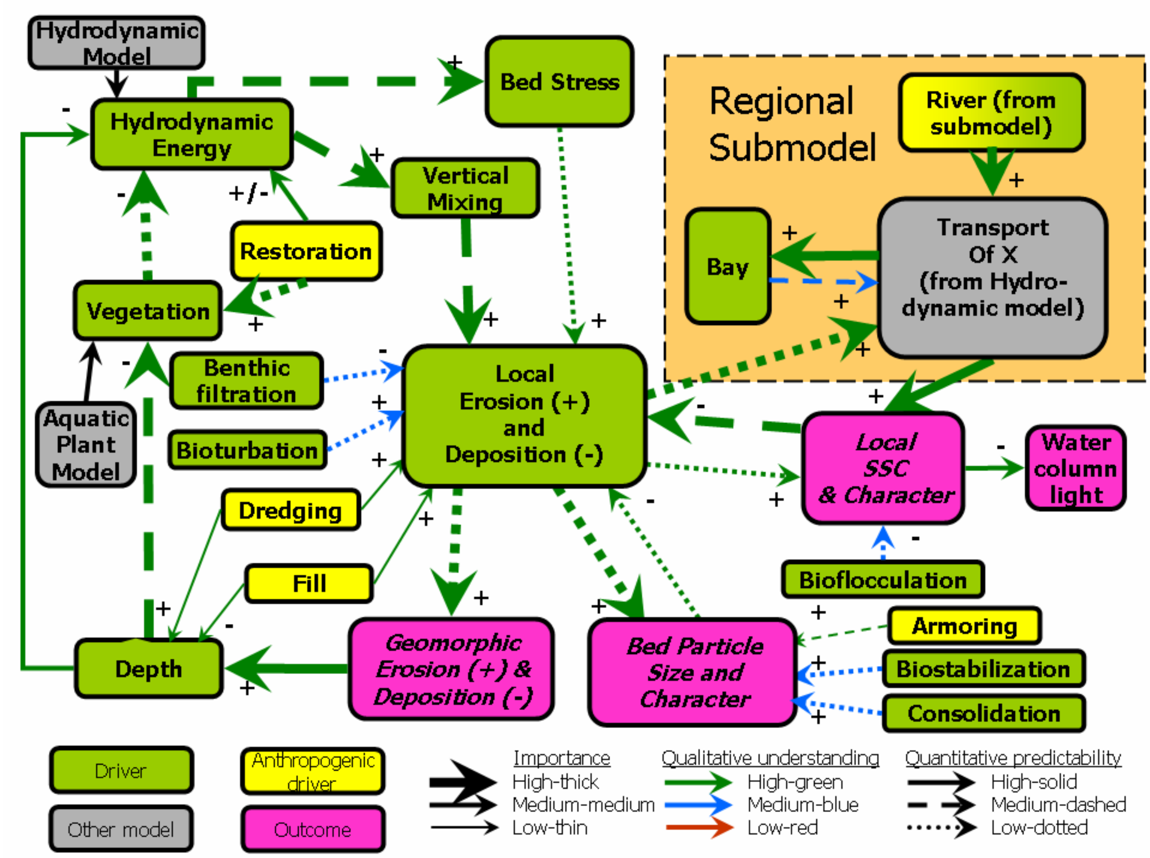

Figure 7. Local sedimentation submodel for marsh. Each box is a driver and each arrow is a linkage. An increase in a driver either increases (+) or decreases (-) the intermediate outcomes it affects. In addition to being outcomes, purple boxes are also drivers. In addition to being drivers, several green boxes are also intermediate outcomes.

Floodplain

Floodplain is the second largest habitat category covering 82% of the area covered by open water in the Delta (table 1). Floodplain processes are described in that model. The local sedimentation submodel for a floodplain (fig. 8) is similar to that for a marsh because vegetation can be a controlling factor. The goal of floodplain restoration is typically to reconnect a floodplain with a river, not to allow plant colonization as with a marsh restoration, so restoration is a less important driver on vegetation in floodplain than in marsh. Floodplain inundation is seasonal and episodic, so relatively slow processes like benthic filtering and bioturbation are not important.

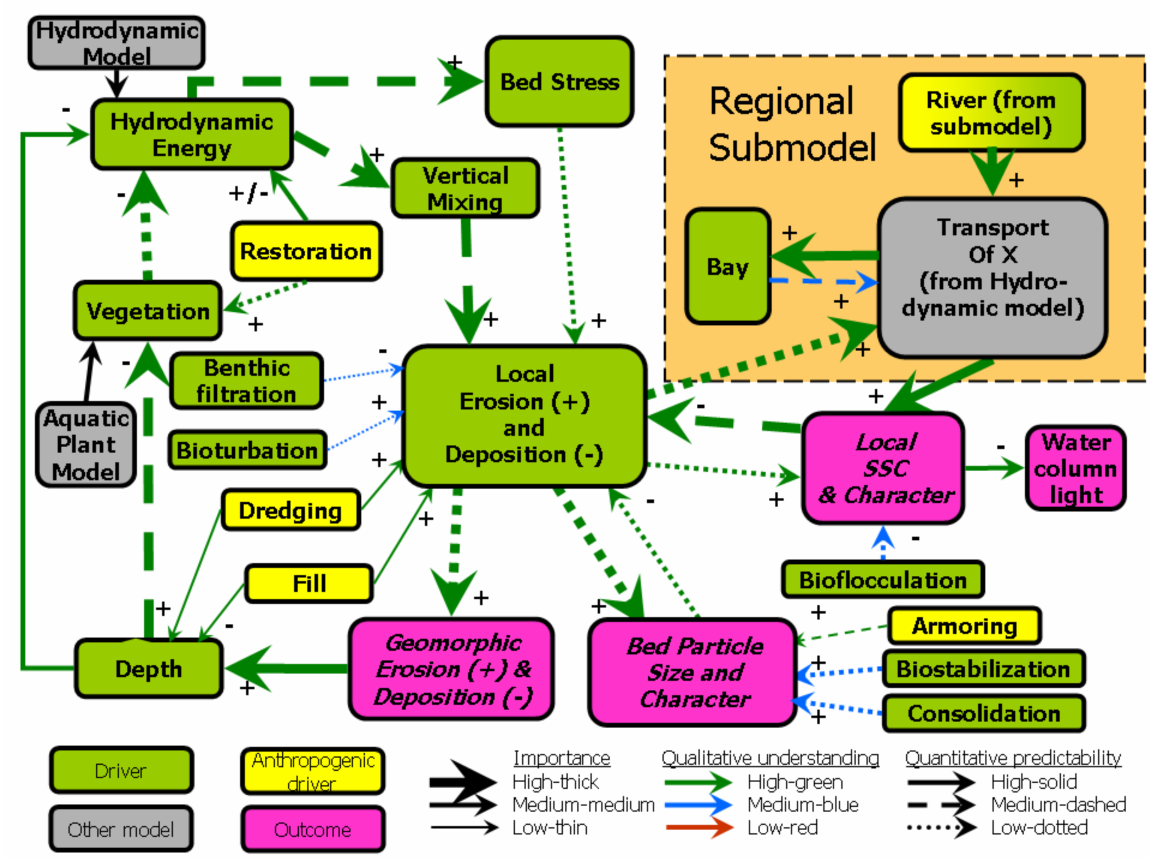

Figure 8. Local sedimentation submodel for a floodplain. Each box is a driver and each arrow is a linkage. An increase in a driver either increases (+) or decreases (-) the intermediate outcomes it affects. In addition to being outcomes, purple boxes are also drivers. In addition to being drivers, several green boxes are also intermediate outcomes.

Riparian

Riparian is the smallest habitat category covering 7% of the area covered by open water in the Delta (table 1). Riparian processes are described in that model. The local sedimentation submodel for riparian habitat (fig. 9) is similar to that for open water because neither are predominately depositional, unlike floodplain and marsh habitats. Bank erosion is of greater concern than bottom erosion. The effect of depth on hydrodynamic energy is more complicated in riparian habitat because deeper waters tend to be faster than shallower waters but wind waves and boat wakes provide more energy to shallower waters. Vegetation, including woody debris, can decrease hydrodynamic energy. Vegetation also can provide shading, so the effect of suspended sediment on light water column light is less important than open water

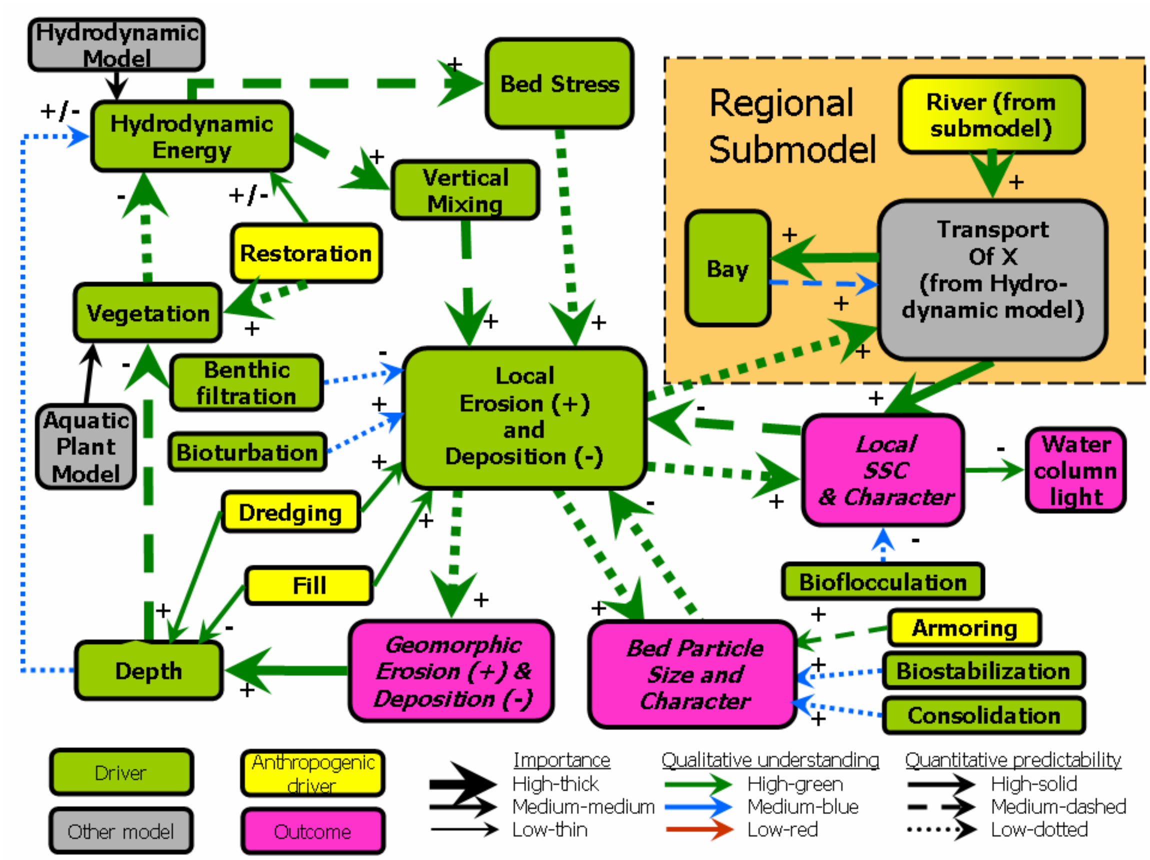

Figure 9. Local sedimentation submodel for riparian habitat. Each box is a driver and each arrow is a linkage. An increase in a driver either increases (+) or decreases (-) the intermediate outcomes it affects. In addition to being outcomes, purple boxes are also drivers. In addition to being drivers, several green boxes are also intermediate outcomes.

Outcomes

Local SSC and suspended sediment character

Suspended sediment concentration is expressed as mass of suspended sediment per unit volume. Typical SSC in the Delta ranges from 10-50 mg/L except during large river discharge when SSC can exceed 200 mg/L (Wright and Schoellhamer 2005, McKee et al. 2006).

Other characteristics of suspended sediment that are of interest include diameter, density, turbidity, and organic content. Suspended sediment is primarily fine sediment less than 63 µm in diameter. At Freeport on the Sacramento River the median percent of fine suspended sediment was 85% from July 1998 to September 2001 and the range was 46-98% (Schoellhamer and Wright 2003). Fine suspended sediment is cohesive and small primary particles combine to form larger flocs of suspended sediment. In other systems, fine sediment in rivers is flocculated (Droppo et al. 1997) and limited measurements from the Sacramento River at Freeport (Ganju, unpublished data) confirm this. Ganju et al. (2007) estimate that the primary particle diameter is 2.5 μm. During a slack after ebb tide at Rio Vista, the median volumetric floc diameter (D_{50}) increased from 20 μm near the water surface to 80 μm near the bed due to settling of larger flocs in the water column (Ganju et al. 2007). During maximum flood tide D_{50} was 45-65 μm and more uniform in the water column. At slack after flood tide D_{50} ranged from 40 – 110 μm increasing with depth. Salinity varied from 0 to 1.6 psu.

Schemel et al. (1996) found that the particulate organic carbon (POC) content of suspended sediment was inversely related to flow. During floods in 1983 and 1984, POC was 1-2% of the suspended sediment at Rio Vista. During periods of low flow, POC was higher (mostly 2-4%) of the suspended sediment at Rio Vista.

Water column light

Suspended sediment is the primary attenuator of sunlight in the water column of the Delta (Cloern 1987, Jassby et al. 2002). Light is included as an outcome of this sediment model because light is a driver for the floodplain, riparian, marsh, aquatic plant, fish, and dissolved oxygen models.

Turbidity and secchi depth are other measures of the light properties of Delta waters. Turbidity is an optical measure of light scattering in water with units of nephelometric turbidity units. As the number of fine particles in suspension increases, SSC and turbidity generally increase. Because a given mass of fine sediment is a more effective scatterer than the same mass of coarse sediment, turbidity and SSC are not necessarily correlated. In the San Francisco estuary, however, suspended sediment is predominantly fine sediment and floc sizes are spatially homogeneous, so turbidity and SSC are well correlated (fig. 10, Ganju et al. 2007). Another common measurement of light penetration in the water column is acquired with a secchi disk that is lowered into the water until it reaches a depth for which it is no longer visible.

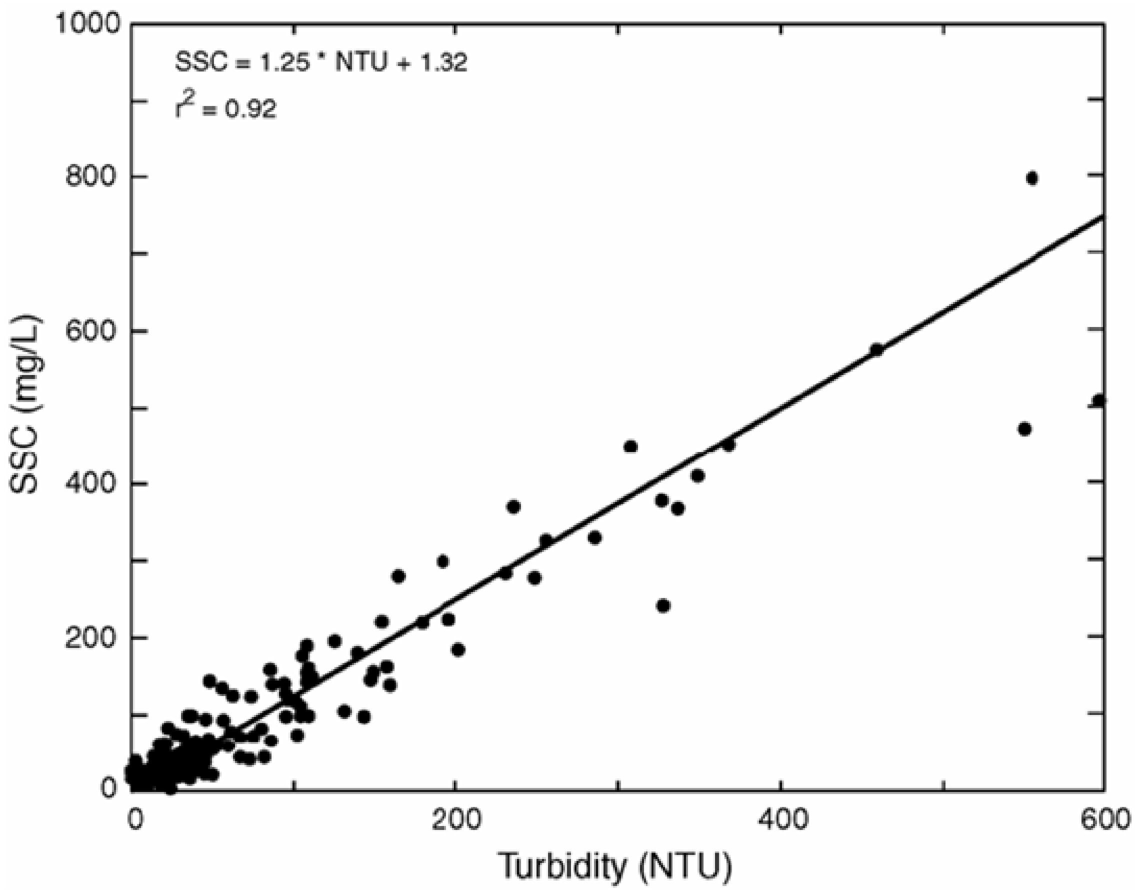

Figure 10. Comparison of turbidity and SSC measurements, from four locations in San Francisco Bay. From Ganju et al. (2007).

Bed particle size and character

The sediment on the bed is characterized by its size, density, and organic content. Sediment in channels that convey relatively large flows, such as the Sacramento River, San Joaquin River, and Threemile Slough, tend to be sandy and contain bed forms (Dinehart 2002). The relative quantity of fine sediment generally increases seaward. From 1993-2003, 18 bed samples collected by the Regional Monitoring Program (RMP) in the lower Sacramento River had a mean of 19% fines and a range of 8-50% (RMP 2007). 18 samples from the lower San Joaquin River had a mean of 48% fines and a range of 16-79%. Larger river floods that winnow fines from the bed and larger sand supply in the Sacramento River probably account for the difference between the two Rivers. At Rio Vista, Thompson et al. (2000) observed that large floods increased the percent of sand on the bed and benthic assemblages shifted from species that favor muddy sediment to sandy sediment. At Rio Vista the amount of sand varied from nearly

0% to nearly 100%. After floods, finer sediment deposited, the bed sediment became finer, and benthos that prefer muddy sediment returned. At two other sites in the Sacramento and San Joaquin Rivers, however, the fraction of sand varied over a similar range but appeared unrelated to flow, perhaps due to spatial heterogeneity. Fine sediments tend to deposit on vegetated wetlands (Bryne et al. 2001). Grain size affects substrate stability and establishment and growth of submerged aquatic vegetation (see vegetation model).

The dry bulk density of bed sediment is the mass of sediment per unit volume and it generally increases as grain size increases and organic content decreases. A survey of studies shows that bulk density can vary by a factor of two. Porterfield (1980) estimated that the dry bulk density of estuarine sediments was 851 kg/m^3. Ogden Beeman and Associates and Krone and Associates (1992) estimated a value of 529 kg/m^3. Caffrey (1995) measured a bulk density of 1,144 kg/m^3 for the top centimeter of bed sediment in the channel at Rio Vista.

Organic content of bed sediment is greatest in vegetated wetlands. Reed (2002) found organic contents of wetland soils ranged from 7.80 – 39.38%. From 1993-2003, 17 bed samples from the lower Sacramento River had a mean of 0.55% total organic carbon and a range of 0.14-2.10% (RMP 2007). 17 samples from the lower San Joaquin River had a mean of 0.68% total organic carbon and a range of 0.26-1.38%.

Geomorphic erosion and deposition

As erosion and deposition occur at a site, the bed elevation will change. When summed over many years, the result is a change in the land surface elevation. For example, large sediment supply during the period of hydraulic mining in the late 1800s caused deposition in Sacramento Valley rivers, the Delta, and San Francisco Bay (Gilbert 1917). In this conceptual model, local erosion and deposition are considered on a tidally-averaged time scale. Geomorphic change takes place on a decadal time scale and is the sum (or integration) of local erosion and deposition at a point. That integration includes any episodic riverine supply or erosion events.

Drivers and associated Linkages

Local erosion and deposition is a key driver affecting model outcomes. Model outcomes of suspended sediment concentration and character and bed particle size and character are also drivers of local erosion and deposition. Bed shear stress and vertical mixing are additional drivers that affect local erosion and deposition. These hydrodynamic drivers are intermediate outcomes from geographic, anthropogenic, and other hydrodynamic drivers and the geomorphic change outcome/driver.

Most of the drivers are fundamental physical processes that are always present in all habitats and the linkages between these drivers are generally important. Some drivers may or may not be present at a given location (restoration, dredging, fill, vegetation) and are irrelevant if absent. Because the drivers are linked by fundamental physical laws, the conceptual linkages between drivers are well understood. This includes the direction of change, i.e. increased bed stress will erode, not deposit, bottom sediment. Quantitative prediction of the linkages, however, is generally very difficult. This is especially true for the process of erosion. Floodplain and marsh habitats tend to be depositional, so our limitations on quantitative prediction of erosion are less daunting in these habitats.

Local erosion and deposition

Local erosion and deposition is a driver that affects all model outcomes (suspended sediment concentration and character, water column light, bed particle size and character, and geomorphic change). Suspended sediment concentration and character is altered by erosion and deposition. Net erosion increases SSC and net deposition decreases SSC. For noncohesive sediment, erosion of coarser material increases the average settling velocity of suspended sediment. Coarser material settles faster than finer material so settling velocity will decrease as deposition occurs.

Bed particle size and character are altered by erosion and deposition. If bed shear stress exceeds a critical value, particle motion will occur (American Society of Civil Engineers 1975) which decreases the stability of the bed and potential for establishment and growth of submerged aquatic vegetation (see vegetation model). Erosion tends to winnow finer sediment from the bed, making the bed coarser. Deposition supplies new sediment to the bed, changing organic content and usually decreasing bed particle size. For cohesive sediment, newly deposited material will have a low density and be relatively erodible (Brennan et al. 2002). Consolidation and biostabilization decrease the erodibility of cohesive bed sediment with time (Mehta 1989, Widdows et al. 2000).

Erosion and deposition over long time periods (decades) change the land surface elevation and geomorphology of the Delta. Channels may fill in or scour. Banks may erode, allowing rivers to meander and altering riparian and floodplain habitats (see riparian and floodplain models). When deposition on a tidal marsh equals or exceeds sea level rise, the marsh is sustainable. When deposition is less than sea level rise, the marsh will eventually become permanently flooded.

Benthic filtration

Benthic filter feeders feed by consuming water, filtering out the food, and discarding fecal pellets that primarily contain organically-bound inorganic sediment particles. Suspended sediment is thus removed from the water column and deposited on the bed.

Thompson (2005) found that shallow water *Corbula* in Northern San Francisco Bay filtered up to 3 m/d, more than the entire shallow water column.

Bioturbation

The benthic community can agitate bottom sediment and thus resuspend bottom sediment or make the bottom sediment more erodible (Brennan et al. 2002, Widdows et al. 2000).

Suspended sediment concentration and character

The model outcome of suspended sediment concentration and character is also a driver of local erosion and deposition. The depositional flux of suspended sediment (mass per unit bed area per unit time) is equal to the product of settling velocity and near-bed SSC. Net erosion increases SSC, which increases deposition. Net deposition decreases SSC which decreases deposition. Newly deposited sediment may be relatively erodible (Brennan et al. 2002).

Bioflocculation

Exopolymer secretions by bacteria and microalgae bind (or flocculate) suspended particles, especially where freshwater begins to mix with saltwater (Decho 1990, Eisma 1986, Wolanski et al. 2003) such as in the Delta. As the diameter of suspended flocs increases, the settling velocity of the flocs and deposition increases (Krone 1962). This occurs despite a decrease in floc density, which acts to decrease settling velocity but is less important than the increase in diameter. Settling velocity roughly varies linearly with submerged floc density and varies with the square of floc diameter. Salinity promotes flocculation in the lab (Krone 1962), but any possible effect of salinity on flocculation is difficult to infer from field data (Meade 1972, Ganju et al. 2007).

Bed particle size and character

The bed is a driver of erosion. As noncohesive sediment coarsens it is more difficult to erode and as it becomes finer it is easier to erode.

Biostabilization

The benthic community can bind or biostabilize the bottom sediment and thus decrease erodibility (Widdows et al. 2000). *Corbula* have been shown to stablize bed sediment with increasing density (Crimaldi et al 2002). Biostabilization can be thought of as increasing the effective particle size of the bed, and thus it is shown as increasing bed particle size in the local sedimentation submodels (figs. 5, 7-9).

Consolidation

As cohesive bed sediment consolidates it dewaters, becomes more dense, and is more difficult to erode (American Society of Civil Engineers 1975, Mehta 1989). Consolidation can be thought of as increasing the effective particle size of the bed, and thus it is shown as increasing bed particle size in the local sedimentation submodels (figs. 5, 7-9).

Bed stress

The occurrence and rate of erosion is a function of the bed particle size and character and of the shear stress exerted by flowing water. When the bed shear stress is below a critical value no erosion will occur. Erosion increases as bed shear stress increases above the critical value.

Vertical mixing

Suspended sediment is negatively buoyant and would all deposit on the bed in the absence of vertical mixing. Vertical mixing caused by turbulence partially counters settling and suspends sediment in the water column with SSC greatest at the bed and decreasing upward. Deposition decreases as vertical mixing increases.

Hydrodynamic energy

Water in the Delta moves primarily because of tides, waves, river flows, and pumping. Moving water exerts shear on sediment particles in the bed. Turbulence that causes vertical mixing is also generated. In general, faster water generates more shear stress and turbulence. Larger flows from rivers and stronger tides (i.e. spring tides) increase shear stress and turbulence (Brennan et al. 2002). Waves with relative large height and period will apply greater shear to the bed and increase erosion (Ruhl and Schoellhamer 2004). Winds are strongest and waves largest during spring and summer. Waves generated by boats can also induce erosion from the bed and bank. Bauer et al. (2002) found that levees in Georgiana Slough eroded 0.01-0.22 mm per boat passage.

Vertical gradients in salinity or temperature increase the density of near bottom water which can suppress turbulence and vertical mixing. During ebb tides, fresh river water tends to flow over saltier estuarine water, enhancing vertical stratification and decreasing vertical mixing and bottom shear stress (Brennan et al. 2002, Monismith et al. 1996). The result can be that flood (landward) sediment transport is greater than ebb (seaward) sediment transport when averaged over more than one tidal cycle (Tobin et al. 1995, Brennan et al. 2002). Additional details are provided by the hydrodynamic model.

Vegetation

The ability of macrophytes to slow water velocity is well established (Carpenter and Lodge 1986, Sand-Jensen and Mebus 1996). Macrophytes can choke streams and slow flow, sometimes forming dams that alter channel morphology and width (Wilcox et al. 1999). The impact of a particular macrophyte on flow is strongly related to its areal extent, density, canopy height, and phenology. There is a threshold velocity (i.e., extreme events) over which macrophytes can no longer reduce flow but simply bend out of the way (Wilcox et al. 1999).

By reducing velocity, macrophytes attenuate waves and reduce vertical mixing and bed shear stress, which in turn leads to deposition of sediment (Yang 1998, Braskerud 2001). Sedimentation in wetlands and near-shore environments is a function of sediment supply and retention. Whereas sediment supply depends on watershed processes (Wright and Schoellhamer 2004), sediment retention is greatly influenced by local-scale factors such as plant community composition and particular plant species characteristics (Alizai and McManus 1980, Eisma and Dijkema 1997, Pasternack and Brush 1998, 2001). Sedimentation rate is strongly related to plant architecture, canopy height, and plant density (Alizai and McManus 1980, Leonard et al. 2002, Yang 1998). The aquatic plant model provides details on the growth of vegetation.

Water depth

Water depth affects vegetation colonization. Where the land surface elevation is greater than mean tide level, brackish emergent vegetation can colonize the site (Orr et al. 2003). Freshwater emergent vegetation colonizes down to 0.2 m below mean lower low water (Simenstad et al. 2000). The aquatic vegetation model provides details on all the factors affecting vegetation.

Water depth affects hydrodynamics. As water depth decreases due to deposition or fill, water velocity will increase if the tidal prism and water flow passing through that point is unchanged. As water depth increases due to erosion, dredging, or sea level rise, water velocity will decrease if the tidal prism and water flow passing trough that point is unchanged. Wave bottom orbital velocity and resulting bottom shear stress increase as water depth decreases (Dean and Dalrymple 1984). Note that erosion and deposition associated with geomorphic change, an outcome and driver of this model alters water depth.

Armoring, dredging, fill, and restoration

If present, anthropogenic factors can greatly affect local suspended sediment. To prevent erosion, large boulders (rip-rap) are often placed on levees and the sides of channels. Armoring increases bed particle size and decreases erosion. Dredging deepens channels and can suspend bottom sediment. Fill or dredged material disposal decreases water depths and suspends sediment. Filling estuaries and diking tidal wetlands can reduce tidal prism in an estuary which decreases tidal velocities and increases deposition (Hood 2004). Wetland restoration projects are designed to increase vegetation and to provide low hydrodynamic energy at the restoration site to encourage deposition. Restoration of tidal flooding to diked lands can increase tidal prism and tidal velocities in channels adjacent to the restoration site, which in turn can erode the channels (Kirby 1990).

Regional influences

Regional transport is a driver of suspended sediment concentration and suspended sediment character at a specific site in the Delta. Regional drivers of local suspended sediment and character are shown in the dashed box in figures 5 and 7-9. River supply is probably the most important regional driver and it is discussed in the river supply submodel. Exchange with Suisun Bay was discussed in the regional submodel. Bay and river boundary conditions communicate with any point in the Delta via transport provided by the hydrodynamic model and local erosion and deposition along the transport pathway. An example of regional influence is that the dominant sediment transport pathway in the Delta is the Sacramento River (fig. 1, Wright and Schoellhamer 2005) and wetland deposition is greatest along the Sacramento River (Reed 2002).

EXAMPLE 1: A WETLAND RESTORATION PROJECT IN THE DELTA

To demonstrate application of this conceptual model, we will apply it to a hypothetical wetland restoration project in the Delta. We assume that the project breaches a levee to allow inundation of an area and tidal exchange with a Delta channel. Restoration increases the water depth of the restoration site from zero to subtidal positive value (fig. 3). We will apply the model to three locations: in the restoration site (initially open water that converts to tidal marsh), in the breach (open water), and in an existing tidal marsh near the restoration site.

Restoration site

Sediment is transported from river and perhaps Bay sources into the restoration site through the breach. This transport is governed by the regional submodel shown in figure 3. When the supply of river sediment increases during a flood, there is more suspended sediment available for transport to the restoration site, and SSC of waters entering the site will be relatively large.

Local sedimentation at the restoration site is described by the open water submodel in figure 5. Inside the restoration site, tidal water velocity will decrease with distance from the breach. Bottom shear stress and vertical mixing will also decrease, which increases deposition and decreases the likelihood of erosion. Suspended particles with the greatest settling velocity, most likely sand or large flocs, will settle closer to the breach than suspended particles with smaller settling velocity. This pattern of settling would be reflected in the character of the depositing bed.

Another hydrodynamic factor in the restoration site is wind waves (Williams 2001). Wind waves can increase bottom shear stress and vertical mixing, favoring erosion over deposition. The portions of the restoration site with a large fetch are expected to have the largest wind waves. Islands and peninsulas are often included in the design of a restoration site to decrease fetch and wind waves and encourage deposition. As water depth increases, the shear stress imparted by wind waves on the bottom decreases. As water depth decreases, wind waves may break and their energy reduced further downwind.

Vegetation is a biotic factor that affects sedimentation at the restoration site. Where the land surface elevation is greater than mean tide level, brackish emergent vegetation can colonize the site (Orr et al. 2003). Freshwater emergent vegetation colonizes down to 0.2 m below mean lower low water (Simenstad et al. 2000). When plants colonize the site, water velocity, wind waves, bottom shear stress, and vertical mixing are all reduced. This increases net deposition of sediment. In addition, the plants provide a new source of organic matter for the bed. As sediment laden water enters vegetation patch, suspended sediment deposits, reducing SSC and deposition further into the patch. Larger flocs and coarser sediment will deposit first, closer to open water.

Over a period of years, the geomorphology of the restoration site changes as net deposition increases the elevation of the restoration site and emergent vegetation colonizes the site. If the rate of deposition is greater than the rate of sea level rise, water depth will decrease and alter hydrodynamics and vegetation as described previously. The marsh model (fig. 7) will become more relevant than the open water model (fig. 5). As a marshplain develops, a system of tidal channels in the marsh will also form (Williams 2001).

Breach

A breach is open water so the open water local sedimentation submodel (fig. 5) is applicable. Initially after breaching, tidal water velocities will be relatively large because the tidal prism for some or all of the restoration site must pass through the breach every tidal cycle. The breach essentially acts as a choke point that restricts tidal exchange to the restoration site. Shear stresses will be large, bottom sediment will erode, and the sides of the breach will erode. Erosion will increase SSC and suspended particle size of water passing through the breach. Erosion will also selectively remove finer sediment from the bed, coarsening the bottom sediment in the breach.

As the breach and restoration site mature, the breach dimensions will come into equilibrium with the tidal prism passing through it and the breach will no longer grow. While the dimensions of the breach increase due to erosion, water velocity and shear stress decrease. As the bed coarsens, it becomes less erodible. Sometimes a breach is designed to be at its expected equilibrium dimensions in order to provide full tidal exchange to the restoration site immediately (Williams 2001).

Existing tidal marsh near the restoration site

A restoration site can reduce deposition on nearby tidal marsh (perhaps previously restored) by diverting available sediment supply. Deposition in the restoration site decreases the SSC of water leaving the site. In other words, the restoration site is a sink for sediment. If the system is otherwise unchanged (river and bay sources and regional transport), the tidally-averaged SSC of water inundating an existing tidal marsh will decrease. This in turn decreases the deposition rate on the existing marsh (fig. 7). The magnitude of the decrease will depend on the relative locations of the existing marsh, restoration site, and sediment supply. For example, SSC and deposition on the marsh will decrease more if the restoration site is between the sediment source and marsh rather than if the marsh is between the restoration site and the sediment source. Erosion may also be caused by alignment of the marsh, restoration site, and ocean. If the existing marsh is between the restoration site and ocean, increased tidal prism and tidal energy may erode the marsh, likely via bank erosion. If the deposition rate is still equal to or greater than sea level rise, the marsh will be sustained. If not, the marsh will subside relative to sea level, water depth will increase, vegetation may die, bottom shear stress increases, which further increases erosion. Deposition in the restored marsh is a driver that decreases SSC at the existing marsh due to transport of clearer water.

EXAMPLE 2: EVALUATING TURBIDITY EFFECTS OF SAN JOAQUIN REROUTING TO WEST DELTA

The Question

One of several water supply conveyance options for the Delta being considered involves rerouting the San Joaquin River into the west Delta via Old River requiring a series of barriers and siphons. The general intent of this option is to send San Joaquin flows past the south Delta intakes except presumably during high flow events and to direct the higher nutrient concentration waters of the San Joaquin to the west Delta where it would benefit primary production. One question surrounding this option is whether the higher turbidity levels of San Joaquin waters, in comparison to Sacramento waters, would increase turbidity in the west Delta thereby increasing light attenuation and thus reducing primary production.

Facts and Conclusions

This decade, average SSCs are 49 mg/L in the Sacramento at Freeport and 65 mg/L in the San Joaquin at Vernalis (USGS data reports). See table below.

Both sites have unidirectional flow but Freeport has tidal backwater and Vernalis does not. If all else were equal, this difference would tend to reduce Sacramento SSC, accounting for some of the difference.

Sacramento SSC has decreased about 50% since 1957 (or it used to be 100% more, Wright and Schoellhamer 2004).

Cyclic (local) erosion and deposition in the tidal western Delta would reduce this difference (local deposition and erosion reduces the effect of riverine sediment supply). For example, the SJR signal attenuates rapidly in the Delta (fig. 1).

Cyclic (local) erosion and deposition reduces SSC from east to west in the Delta. This decade average SSCs at Mallard Island were 35 and 43 mg/L surface and bottom.

The mean flow at Freeport is six times that in the San Joaquin, so simple mixing means that the Sacramento River will always determine western Delta SSC, unless all the Sacramento River water were to vanish into the proposed Isolated Facility. Including Yolo Bypass flow would increase this difference.

The increase in SSC in the Western Delta would be less, and probably much less, than the difference between Sacramento and San Joaquin River waters (33%). (Note the last key finding in the model: qualitative understanding is easy, quantitative prediction is hard.) If you now get 24,000 cfs at 49 mg/L and 0 cfs at 65 mg/L (see table), you get 49 mg/L when mixed.

If you change that to 20,000 cfs at 49 mg/l and 4000 cfs at 65 mg/l, you get 52 mg/l when mixed, a 5% increase. Delta hydrodynamics are more complicated than this, but the point is that the San Joaquin River can not have a significant effect on SSC in the western Delta.

Even assuming a 33% increase in SSC in the western Delta (the upper bound from diverting all the Sacramento River and replacing it with SJR and assuming the Delta ceases to be a sediment sink), this increase would be only 1/3 of the anthropogenic decrease caused by diminishment of the hydraulic mining pulse and dams since 1957.

Freeport

WY	cfs	mg/L
2000	25,290	41.2
2001	14,530	28.1
2002	18,100	41.9
2003	25,280	58.9
2004	23,590	54.6
2005		50.4
2006	38,110	66.4
Mean	24,150	49

SJR Vernalis

2000	3,920.00	64.7
2001	2,393	56.5
2002	1,928	56.1
2003	1,885	62
2004	1,891	65.2
2005	5,231	86
2006	10,150	62.9
Mean	3,914	65

Mallard Island

	2000	2001	2002	2003	2004	2005	2006	Mean
surface	37	41	39	38	34	27	27	34.71429
bottom	48	52	58	48	39	28	28	43

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