Suisun Marsh Tidal Marsh and Aquatic Habitats Conceptual Model

Chapter 1: Physical Processes

FINAL REVIEW DRAFT
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Suisun Marsh Habitat Management, Restoration and Preservation Plan

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1 Physical Processes

Chapter 1 of the Suisun Marsh Tidal Marsh and Aquatic Habitats Conceptual Model presents the physical processes that fundamentally control the ecosystem services provided by Suisun's tidal marshes and aquatic open water environments and the outcomes of tidal marsh restoration. These processes are identified in Figure 1-1, which clusters the primary physical drivers such as water flows and sediment supply, the intermediate physical processes influenced by those primary drivers such as inundation regime and water quality, and the ecological functions that are the ultimate outcomes that this Conceptual Model seeks to explain. Chapters 2 through 4 then draw upon this information when considering aquatic functions (Chapter 2), tidal marsh functions and restoration outcomes (Chapter 3), and target species (Chapter 4).

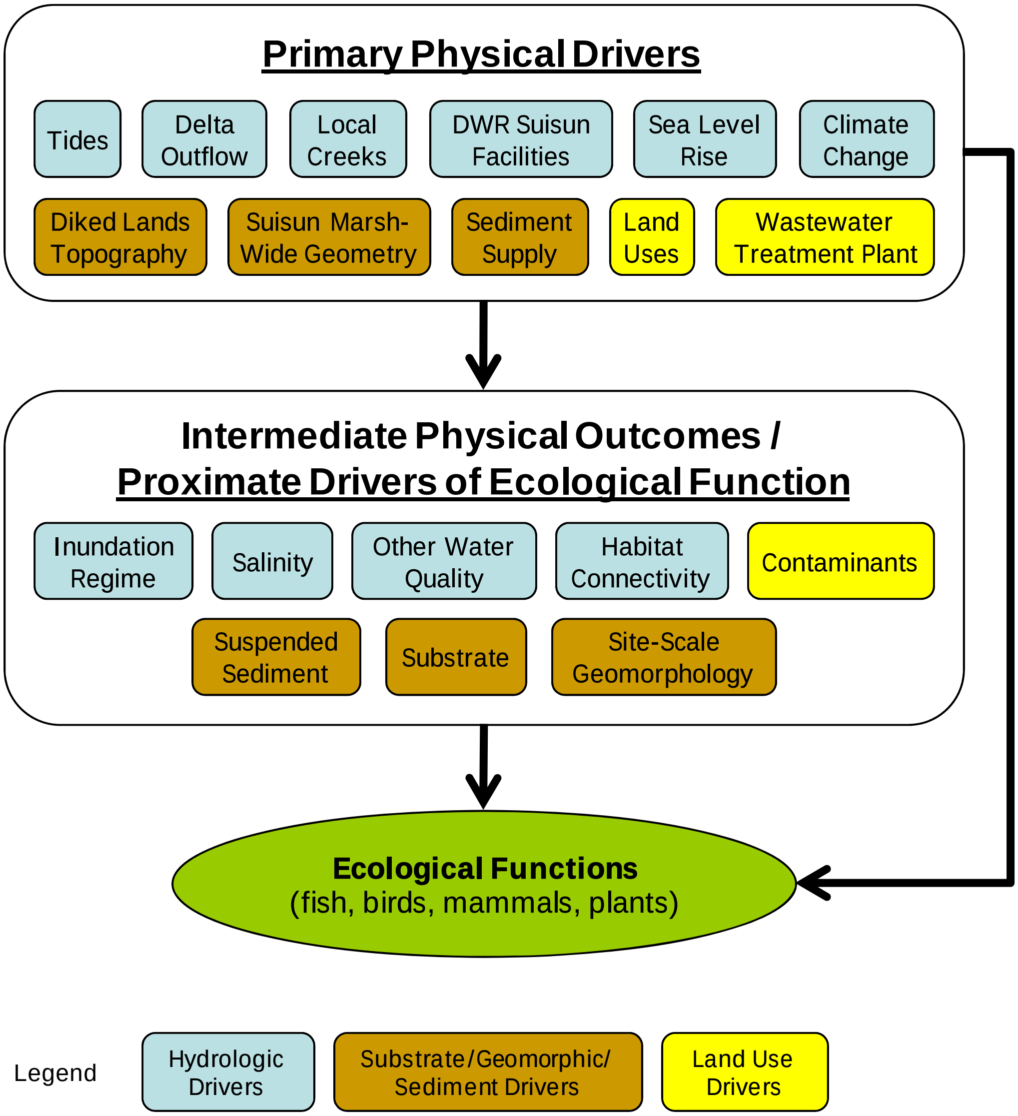

Figure 1-1. Overview of Physical Processes Roles in Suisun Marsh and Bay Ecology

This chapter covers each of these primary and secondary drivers, describing their existing conditions, what influences them, and what they influence:

- 1.1: General Description of Suisun Marsh and Bay
- 1.2: Hydrologic Drivers
- 1.3: Meteorological Drivers
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1.1 General Description of Suisun Marsh and Bay

1.1.1 Setting within the San Francisco Bay-Delta Estuary

Suisun Marsh sits in the center of the San Francisco Bay-Delta Estuary, upstream of San Pablo Bay and Central Bay and downstream of the Sacramento-San-Joaquin River Delta (Figure 1-2). Tides reach Suisun Marsh through Carquinez Straits, an incised river channel drowned during Holocene sea level rise of the past 10,000 years. The southeast border of Suisun Marsh is the confluence of the Sacramento and San Joaquin rivers which drain California's Central Valley, about 40% of the State's land mass. Upstream of this confluence is the Delta, roughly 750,000 acres of diked, subsided lands supporting a broad array of agriculture. In Suisun Marsh and Bay is where the freshwater outflows of the Central Valley meet the tides, resulting in brackish salinity with strong salinity gradients, complex patterns of flow interactions, and generally the highest biomass productivity within the entire estuary.

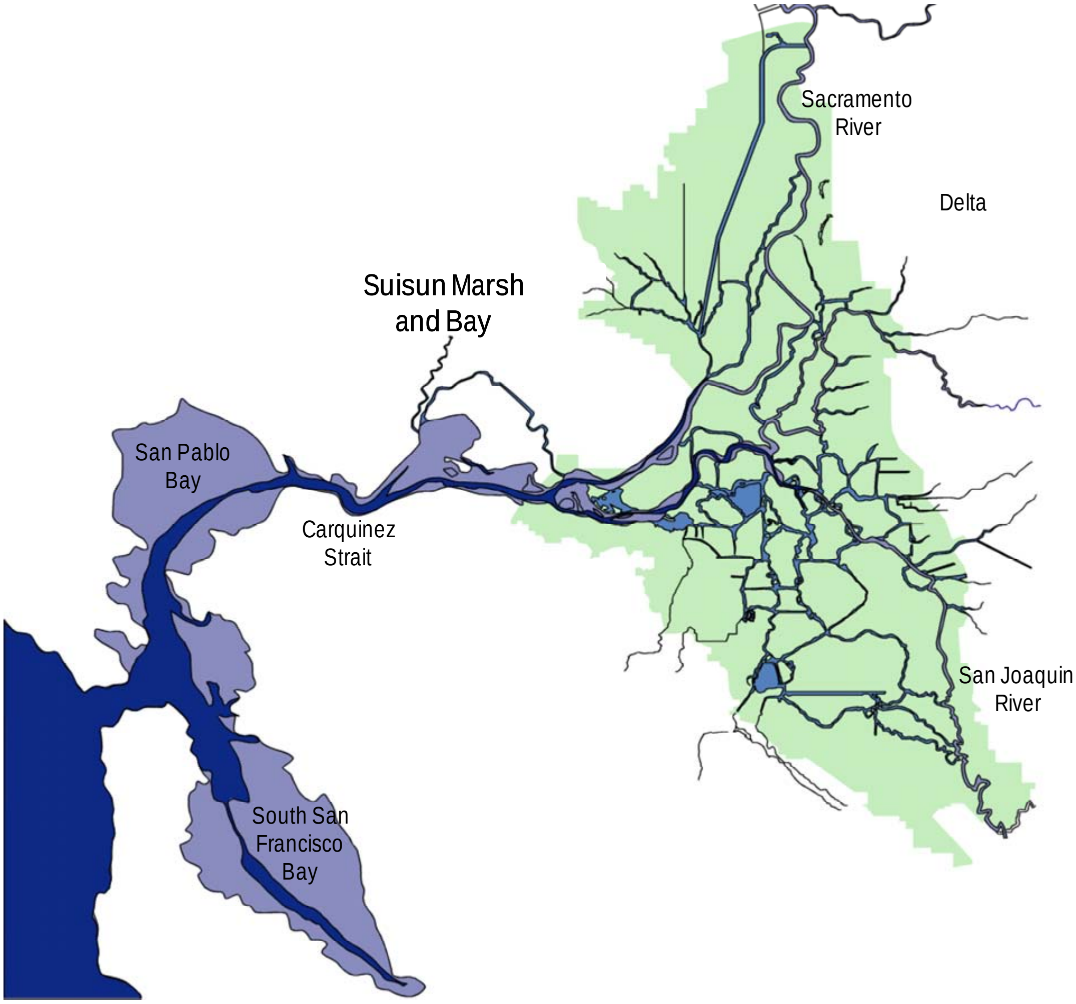


Figure 1-2. Suisun Marsh Setting within the San Francisco Estuary and Sacramento-San Joaquin River Delta

1.1.2 Land Uses Within and Around Suisun Marsh and Bay

The Suisun Marsh Plan area consists of several distinct land uses (Figure 1-4), summarized by acreage in Table 1-1. Land uses within Suisun Marsh itself consist predominantly of private and public managed wetland hunting areas. Also within the Marsh are some areas of cattle grazing (northwest, on Grizzly Island, and northeast), sheep grazing (southeast) and row crops (northwest). A few tidal marsh restoration projects have been constructed, are under construction, or are planned for Suisun Marsh (Figure 1-3).

Table 1-1. Suisun Marsh Acreage by Habitat Type

Habitat	Total [1]
Tidal	7,672
Diked managed wetlands and associated uplands [2]	52,112
Minor sloughs [3]	1,108
Developed [4]	312
Riparian	26
Upland [5]	16,354
Suisun Slough	913
Montezuma Slough	1,299
Bays (including Little Honker) [6]	22,346
TOTAL acres	102,142

Source: California Department of Fish and Game January 16, 2008.

[1] Acreages based on the map of regions provided by SRCD and with data layers primarily from San Francisco Estuary Institute (SFEI). 1998. EcoAtlas: Spatial analysis of the baylands ecosystem. Version 1.50b4, as well as the following sources:

- 1999 and 2003 DFG vegetation maps and associated files
- Interpretation of the 2003 aerial photos of Suisun Marsh
- 2003 property line map

[2] "Uplands" component of diked baylands represents levees and other "non-wetland" landscape features associated with the diked managed wetlands.

[3] Includes all ungated sloughs except Montezuma and Suisun Sloughs.

[4] Parking lots, major structures (excludes most homes and clubhouses), railroads, etc.

[5] Above tidal inundation. Includes Potrero Hills, Kirby Hill, and acreage on the east and northwest edges of Suisun Marsh.

[6] Includes Suisun and Honker Bays to the county line and Little Honker Bay.

Wetlands and Waterways

Suisun Marsh contains a complex network of channels, sloughs and water control structures (Figure 1-3). Montezuma Slough spans the Marsh, connecting to Grizzly Bay (a shallow embayment within Suisun Bay) on the west and the lower Sacramento River on the east. The longest slough in the Marsh is Suisun Slough, which meanders from Suisun City in the north towards the south where it connects to western Grizzly Bay. Several smaller slough systems radiate from Montezuma and Suisun sloughs, including the Nurse Slough complex in the northeast Marsh, the Hill Slough complex in the north-central marsh, Peytonia and Boynton Sloughs in the northwest marsh, and the Cutoff/Mallard Slough complex in Rush Ranch in central Suisun Marsh. Most Marsh channels and sloughs are bordered by levees protecting managed seasonal wetlands, with fringing tidal marsh often located between the open water of these sloughs and the managed wetland levees. These fringing marshes constitute about 3,754 acres (1,519 hectares) of the

7,782 acres (3,149 hectares) of tidal marshes in Suisun; the remaining tidal marshes include remnant pre-European marshes (e.g., Rush Ranch) (see Table 1-1) and marsh that has formed since diking began (e.g., lower tip of Joice Island) that provide variable amounts of interior slough networks bordered by tidal marsh plains. Aside from the remnant tidal marshes, the connectivity between channels and sloughs and the managed lands is limited through water control structures such as culverts or weirs. The shallowness of Grizzly Bay leaves a large portion of exposed mud flats at low tides. Little Honker Bay in the northeastern marsh is relatively shallow and isolated from the other two bays.

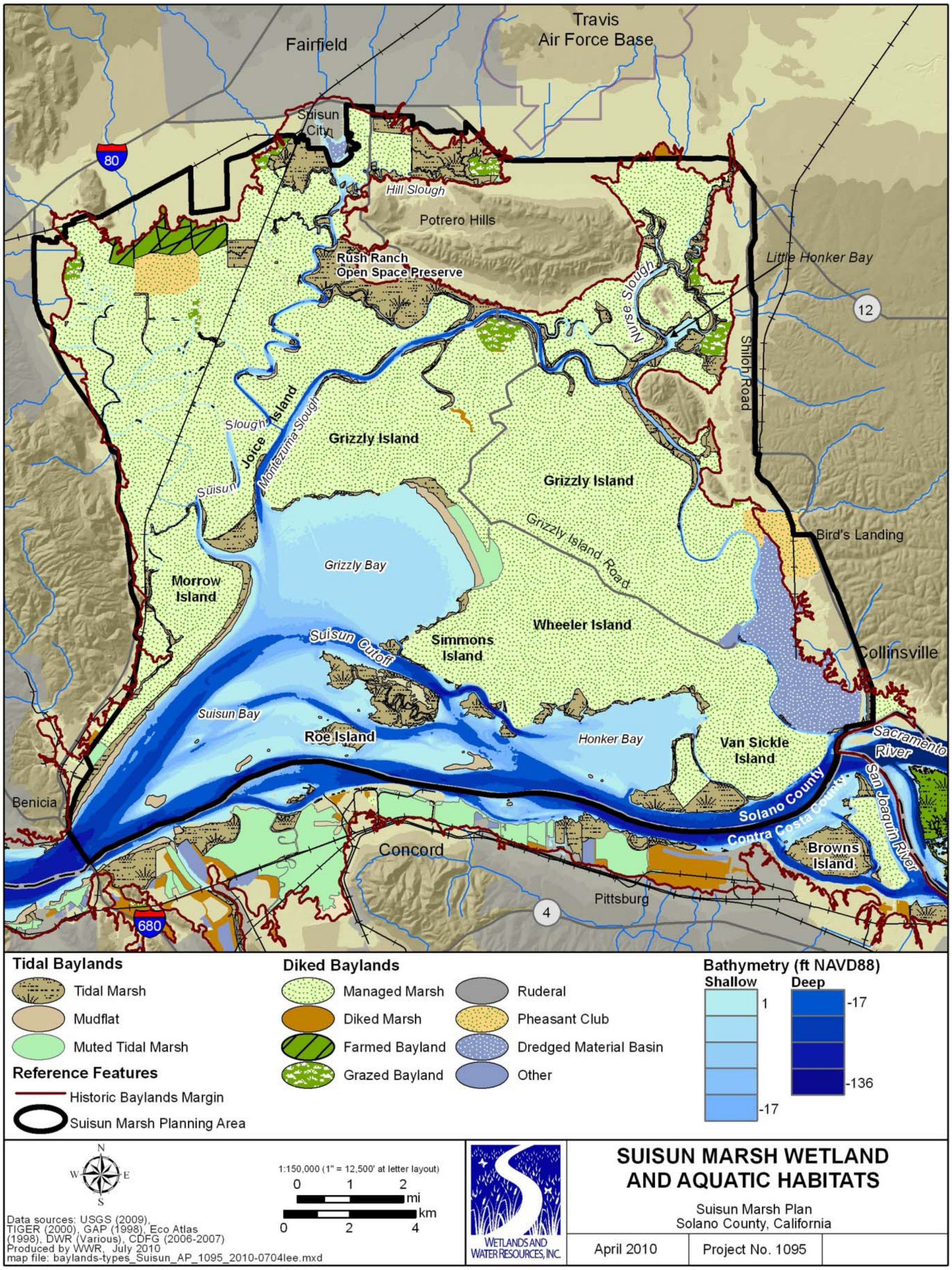


Figure 1-3. Suisun Marsh and Bay Habitats

Infrastructure within the Suisun Marsh Plan Area

Grizzly Island Road is the primary paved road within Suisun Marsh, extending from Fairfield to the DFG and SRCD headquarters on Grizzly Island, crossing Montezuma Slough at Beldon's Landing. Grizzly Island Road continues as a maintained gravel road from the headquarters area southeast to the Roaring River distribution facility. Numerous smaller gravel and dirt roads are located throughout Suisun Marsh, providing access to the many ducks clubs.

Infrastructure within Suisun Marsh includes roads natural gas wells at various locations, pipelines that carry natural gas from the wells and also refined petroleum products traversing the marsh in the west, north, and east. Presence of any such facilities must be investigated on a site-by-site basis when considering restoration or other work.

Infrastructure Surrounding the Suisun Marsh Plan Area

Freeways and highways bound the west and north sides of Suisun Marsh, I-680 on the west, I-80 on the northwest, and 12 on the north. A small county road, Shiloh Road, bounds the east side of the Marsh. The railroad crosses through, not around, Suisun Marsh on its western side from Benicia to Suisun City.

Cities and Towns

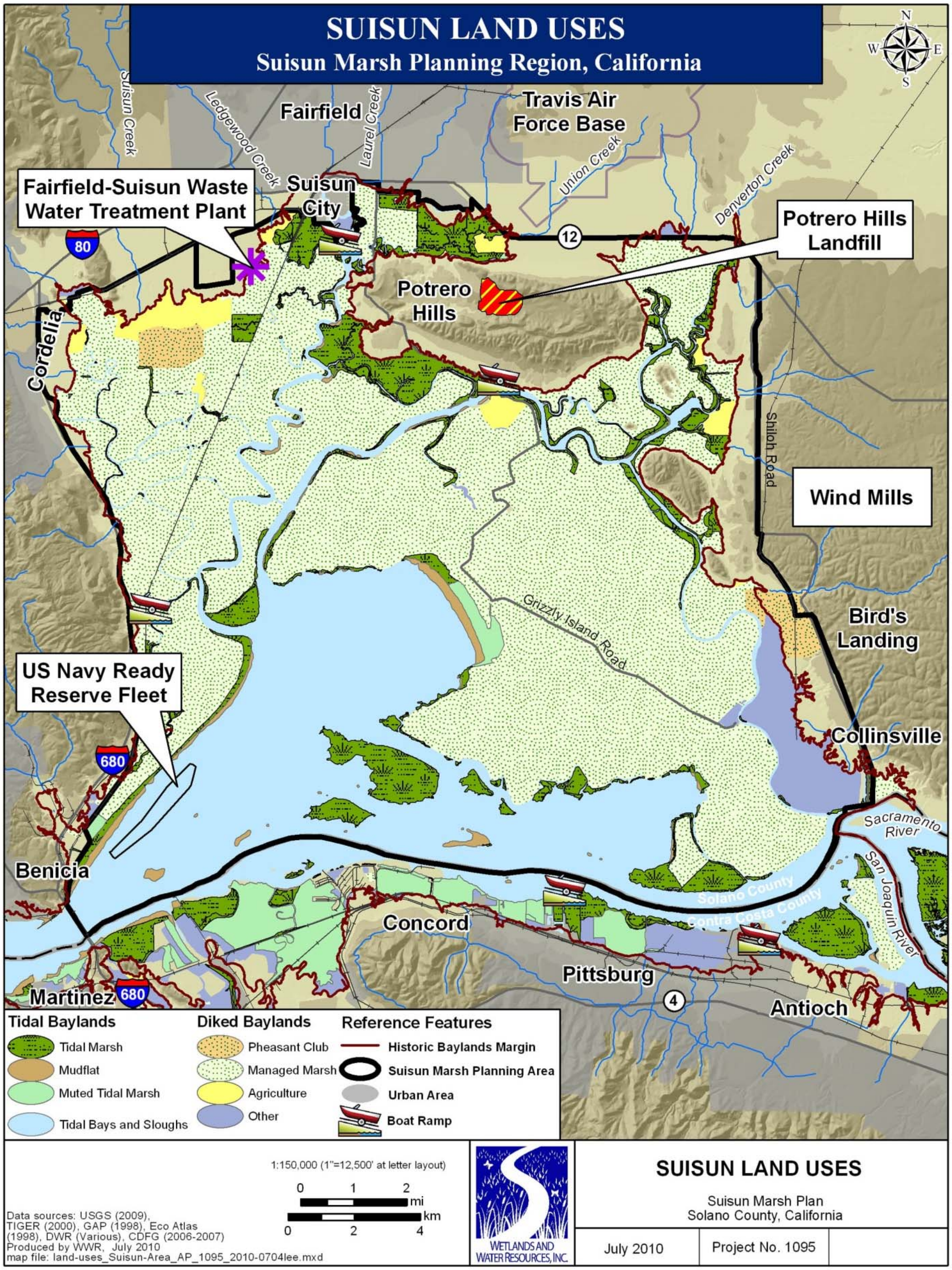
Several cities, small communities, and military facilities are spread around Suisun Marsh and Bay. Fairfield and Suisun City border to the north-central, Cordelia at the northwest corner, and Benicia at the southwest corner. South across Suisun Bay on the Contra Costa County shoreline are Martinez, Concord, Pittsburg, and Antioch. Two very small communities are in the southeast corner: Birds Landing and Collinsville.

Military Facilities

Travis Air Force Base borders to the northeast and Concord Naval Weapons Station to the south. Roe and Ryer Islands in Suisun Marsh are U.S. Navy property. The "Mothball" or Ready Reserve Fleet is a group of World War II navy vessels anchored for decades in the southwest portion of Suisun Bay. These ships are the source of contaminants into sediments of Suisun Bay and the subject of remediation planning by the U.S. Navy.

Wastewater Treatment Plant

The Fairfield/Suisun City Wastewater Treatment Plant is located in the northwest corner of Suisun Marsh. The treatment plant handles the sanitary waste flows only; storm flows do not pass through the plant but drain directly into Suisun Marsh. Details of plant discharges and water quality are discussed under the sections on Freshwater Inflow (Section **Error! Reference source not found.**) and Other Water Quality (Section 1).



Data sources: USGS (2009), TIGER (2000), GAP (1998), Eco Atlas (1998), DWR (Various), CDFG (2006-2007)
Produced by WWR, July 2010
map file: land-uses_Suisun-Area_AP_1095_2010-0704lee.mxd

Figure 1-4. Land Uses in Suisun Marsh Planning Region

1.1.3 Bathymetry of Aquatic Environment

Figure 1-4 shows the most recent bathymetry of Suisun Bay and the sloughs throughout Suisun Marsh. The most extensive current bathymetric data set for Suisun Marsh was compiled by the United States Geological Survey (USGS) (Foxgrover *et al*. 2003). USGS created a 10-m grid of depth based on data collected from several agencies, including NOAA, DWR, USGS, USBR, and USACE. Approximately 350,000 soundings were used for the Suisun Bay portion of the grid. The grid does not cover sloughs within Suisun narrower than 10 m wide; data from the SFEI EcoAtlas (SFEI 1998) fills that gap here.

Subtidal water depths in Suisun range from 1 foot (0.3 m) to nearly 90 feet (27 m) (Figure 1-3). The deepest areas are in the Suisun Bay deepwater ship channel traversing the southern boundary of Suisun Marsh. Depths through the Carquinez Straits to the west extend to well over 100 ft. Depths in larger sloughs, such as Montezuma and Suisun, generally range from 10 to 30 feet (3 to 9.1 m) with maximum depths of about 60 feet (18 m), while depths in smaller sloughs, such as Cutoff Slough, are shallower, ranging from 1 to 18 feet (0.3 to 5.5 m).

A significant fraction of the aquatic environment in Suisun, about 43% (~11,000 ac), is very shallow subtidal, within 6 ft below MLLW. Another 29% (~7,500 ac) is the remaining depths that SFEI classifies as “shallow subtidal,” to -18ft MLLW. Deep subtidal accounts for 24% (~6,000 ac). Intertidal mudflats have limited extent within Suisun Marsh, covering only about 4% (<1,000 ac). Figure 1-5 shows the acreage distribution by depth within Suisun Bay.

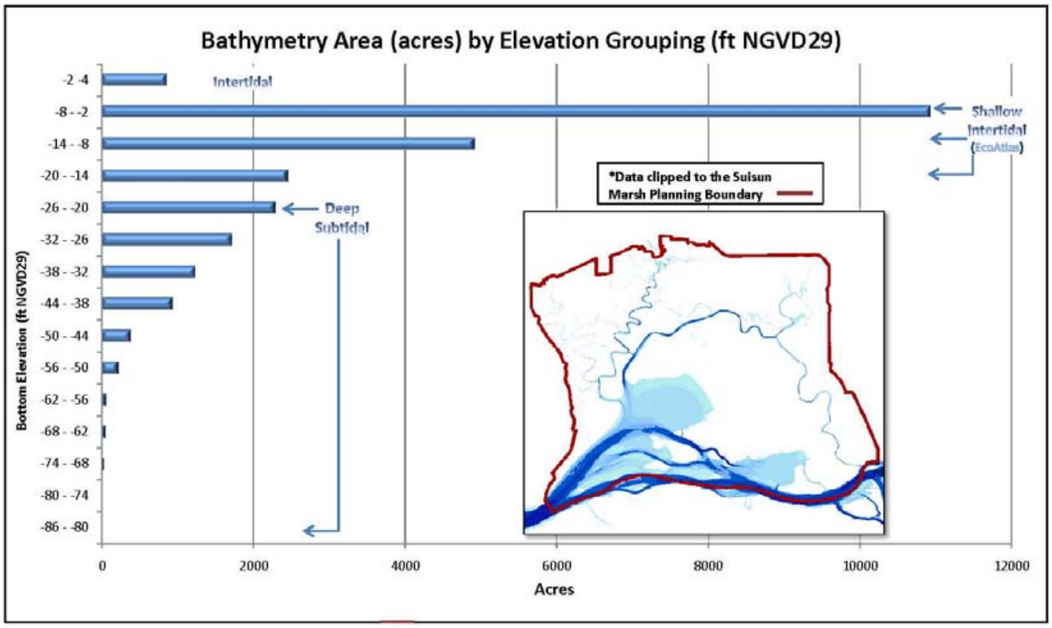


Figure 1-5. Histogram of Suisun Bay and Large Slough Bathymetry

Data derived from the USGS 2003 10-meter grid data set and SFEI 1998 EcoAtlas. Source: Wetlands and Water Resources.

Volume and area values for Suisun Bay were calculated based on bathymetry grid data (Foxgrover *et al*. 2003). Resource Management Associates recently calculated the volume of the larger sloughs in the interior marsh to be approximately 46,000 acre-feet (56.7 m^3) at Mean High Water (MHW) and 34,000 acre-feet (41.9 m^3) at Mean Low Water (MLW).

1.1.4 Topography of Tidal and Diked Managed Marsh

Suisun Marsh has undergone varying levels of subsidence on lands that have been diked from the tides. To restore diked lands to tidal marsh, the primary restoration opportunity in Suisun, this subsidence has to be reversed through mineral and/or biological accretion. The time scale over which restoration sites evolve is largely a function of starting elevation and suspended sediment concentrations. Higher starting elevations are inherently closer to the “mature” marsh such as Rush Ranch, yet their time scale for maturing is driven by sediment deposition and plant matter accumulation. Consequently, the geography and interactions of subsidence and sediment supply are key drivers in tidal restoration efforts.

LiDAR topographic data has inherent accuracy limitations in wetlands because of vegetation interference. Suisun Marsh vegetation varies from plants less than 1ft tall to 5-10ft tall bulrush and tules. DWR evaluated several methods to account for this variable interference and settled upon a uniform 1.5ft lowering within the wetlands. No simple method will be accurate and no complex approach has been tried. This adjustment likely works well in some areas yet is too large or too small elsewhere. Consequently, the data presented here must be considered approximate and are best used for more regional patterns than providing a definitive land surface elevation of any given parcel of land.

Figure 1-6 maps the geographic distribution of diked lands topography within Suisun Marsh and the immediately surrounding upland areas, and Figure 1-7 shows the histogram of acreage by depth intervals.

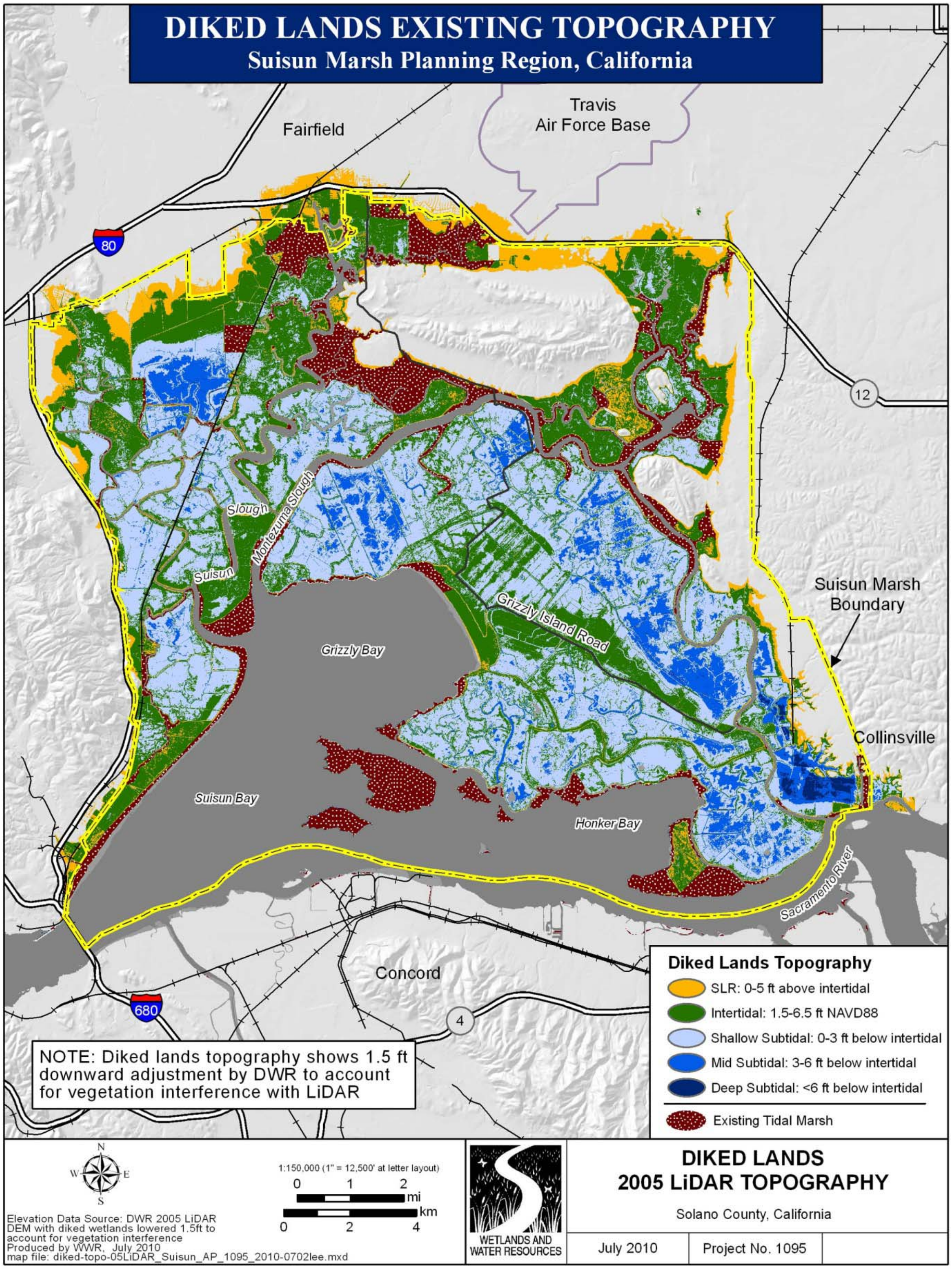


Figure 1-6. Topography of Suisun Marsh, DWR 2005 LiDAR with 1.5-foot vegetation modification

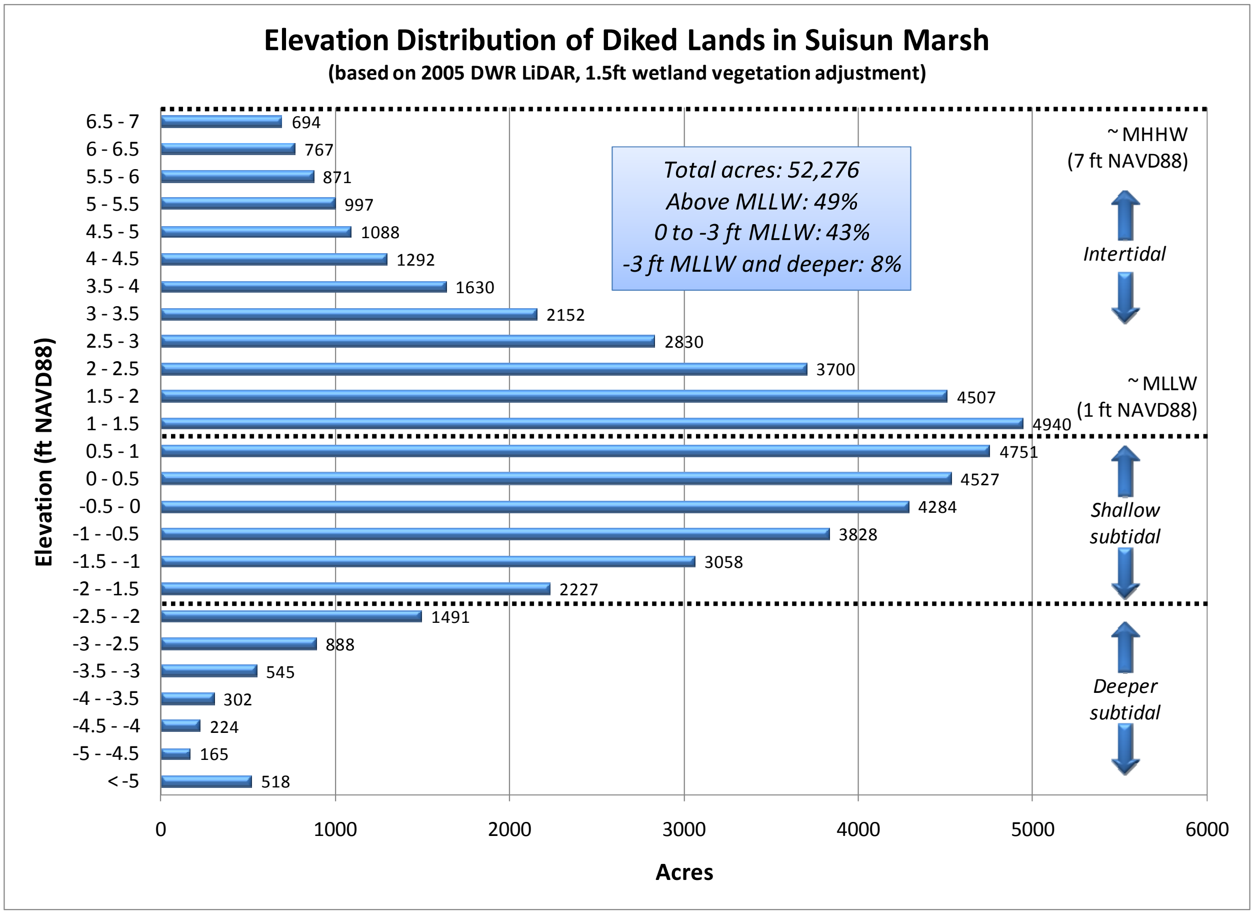


Figure 1-7. Histogram of Diked Lands Topography

Geographic Patterns of Subsidence in Suisun Marsh

Diked lands in the northern part of Suisun Marsh are mostly within intertidal elevations and exhibit the least amount of subsidence. These lands generally also have fairly broad, gently-sloping upland edges. This combination sets an important restoration stage – wetland-transition-upland ecosystem complexes and space to accommodate lateral migration of tidal marshes with sea level rise (see lands denoted as “SLR 0-5ft” in Figure 1-6). Other intertidal elevation diked lands are found in the southwest around Goodyear Slough, the southern portion of Joice Island, and a central ridge through southern Grizzly Island. All these areas have levees or rail lines as their upland edge, offering little if any opportunity for transitional habitats or sea level rise accommodation. Southern Grizzly Island may have some potential.

Subtidal elevation diked lands are distributed throughout much of Suisun. Considerable subtidal acreage is west of Suisun Slough with some lands being moderately subtidal (3 to 6 ft <MLLW). The northern portion of Joice Island is shallow subtidal (0 to 3 ft <MLLW). Much of Grizzly, Wheeler, and Van Sickle islands and Mein’s Landing are subtidal, with a reasonable portion being moderately subtidal. The southern portion of the Montezuma Wetlands Project is the most subsided portion of Suisun, being more than 6 ft <MLLW.

Degree of Subsidence in Suisun Marsh

A vast majority of the diked lands in Suisun have undergone subsidence (Figure 1-7). Today, half the 52,000 acres of diked baylands in Suisun are above MLLW (intertidal) and half are below MLLW (subtidal). Lands subsided to shallow subtidal depths (0 to 3 ft <MLLW) make up 43% of the total diked acreage and 85% of all lands subsided below MLLW. The most subsided lands, up to 9 ft < MLLW, make up 8% of the total diked lands area.

1.2 Hydrologic Drivers

This section describes the five hydrologic drivers on Suisun Marsh: tides (Section 1.2.1), Delta outflow (Section 1.2.2), local watershed (Section 1.2.3), Fairfield-Suisun Wastewater Treatment Plant (Section 1.2.4), and the managed wetlands (Section 1.2.5).

Suisun Marsh receives freshwater inflows from three sources: Delta outflow, the dominant source (Section 1.2.2), local watershed runoff mainly from the north (Section 1.2.3), and wastewater treatment plant discharge into the northwest Marsh (Section 1.2.4).

1.2.1 Tides

Tide Characteristics

The San Francisco Estuary experiences a mixed, semi-diurnal tidal regime with a 24.8-hour cycle in which two daily tides of unequal height occur (Figure 1-8). During each tidal cycle there is a higher high, high, low, and lower low tide. Three main periodic variables control tide stage patterns: (1) spring-neap tide cycle (~ 2 weeks) tied to moon phase, (2) solstice-equinox cycle (3 months) tied to the seasons, and (3) complex astronomical controls that comprise the 18.6-year tidal epoch.

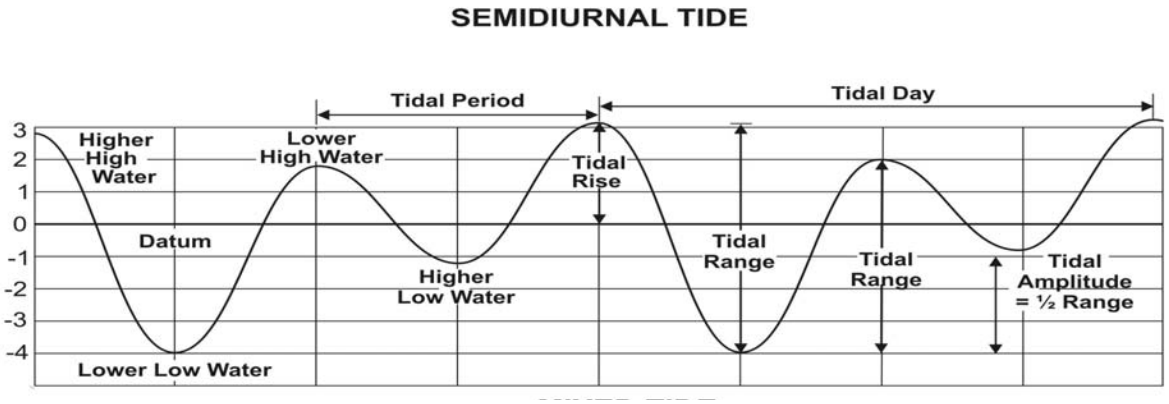


Figure 1-8. Diagram of Mixed, Semi-Diurnal Tides of the San Francisco Estuary

Source: National Ocean Service

The spring tide range (mean lower low water to mean higher high water) at the Golden Gate Bridge is 1.78 m (5.84 ft) (NOS 2003a). Tide range varies throughout the Estuary, with the South Bay experiencing a standing wave that amplifies tides (2.74 m or 8.99 ft at Coyote Creek [NOS 2003b]) and the North Bay, Suisun and the Delta experiencing a progressive wave combined with Delta outflow that dampens tides (1.50 m or 4.92 ft at Port Chicago [NOS 2003c]; 1.24 m or 4.07 ft at Rio Vista [NOS 2003d]). This tidal exchange is a fundamental determinant of water surface levels, direction, and volume of flow and salinity and thereby exerts a fundamental influence on the biological, chemical, and physical conditions of the Estuary.

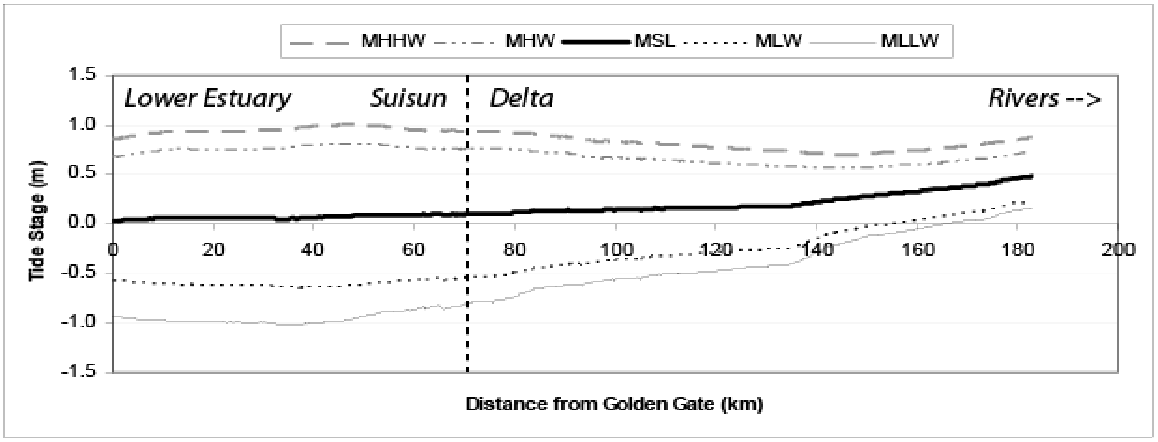


Figure 1-9. San Francisco Estuary-Delta Tidal Datum Profile (modeled)

Source: DWR, 2004

Tidal exchange volumes at Carquinez Strait on the west side of Suisun Bay (i.e., tidal linkage to the lower estuary) are ±600,000 cfs and at Collinsville on the east side of Suisun Bay (i.e., tidal linkage to the Delta) are ±300,000 cfs (Figure 1-10). For perspective, the flood of record on the Sacramento River (1986) at Freeport is approximately 600,000 cfs (J. Burau, pers. comm.) and its average summer/fall flow ranges between roughly 10,000 to 20,000 cfs (DWR 2008).

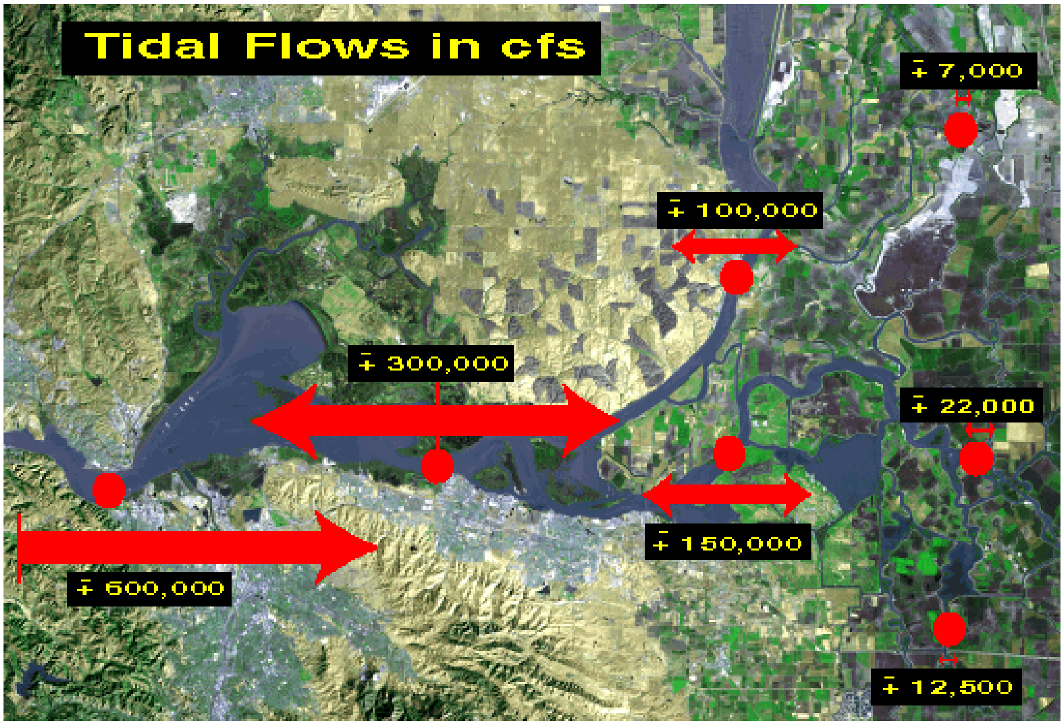


Figure 1-10. Tidal Flows Between Carquinez, Suisun, and the Delta

Source: USGS

Tides and Inundation Regime

The inundation regime is defined as the frequency, duration, and depth of flooding by surface waters. Inundation regime is one of the most significant drivers of marsh ecology (Mitsch and Gosselink 2000) as it influences substrate character, vegetation composition, and hydrologic connectivity. Tidal marshes are distinguished from many other wetland systems in that their inundation regimes are driven by tidal cycles as well as seasonal precipitation cycles. Tides bring water into a wetland once or twice daily depending on whether tides are diurnal or semi diurnal. River flows, both local tributaries (e.g., local Suisun streams) and main-stem rivers (e.g., Delta outflow) can add additional depth and duration to the tidal inundation regime, though the frequency of such contributions is much lower, less predictable, and occurs during the winter and spring months.

The depth, duration, and frequency of inundation at a specific location are primarily determined by (1) the height of the tides, along with any watershed inputs, relative to the ground surface elevation and (2) the nature of the hydraulic connection to tidal source waters. In general, higher elevation tidal marshes will experience more shallow inundation depths for shorter duration and less frequently than low elevation tidal marshes. In tidal aquatic environments below the lowest tide elevation, the substrate is always submerged and it is the depth of inundation that the tides control.

1.2.2 Delta Outflow

According to Kimmerer (2004), the biota of the San Francisco Estuary may have one of the strongest and most consistent responses to flow among large estuaries. Delta outflow is considered to be one of the most significant driving forces on Suisun Bay and its environs. Delta outflow represents total inflow from the Sacramento River (the primary source), San Joaquin River, east side tributaries, northwest tributaries (primarily via Yolo Bypass), and southwest tributaries less in-Delta diversions and less exports from the Delta by the State Water Project, Central Valley Project, and Contra Costa Water District. The Export-Inflow Ratio (E-I Ratio) is a commonly used metric to describe how much water is being used within and exported from the Delta. This ratio often ranges from above 50% in summer to an average of 1% in the spring (Kimmerer 2004). Figure 1-11 shows Delta outflow conditions across seasons and the interannual variability reflecting a range of wet to dry water year types.

Summer and fall Delta outflow is maintained by releases from CVP and SWP dams on the tributaries to the Delta as well as by hydroelectric facilities operated by other entities. The State and federal water projects are required through their water rights permits to maintain Delta outflow and salinity standards for the Delta and Suisun Marsh at varying levels according to season and water year type. Winter and spring Delta outflows are controlled by a combination of storm patterns, snow melt, and ability of reservoirs to store water to balance flood protection, water supply, power production, and recreation.

Interannual variability of delta outflow is due primarily to variability in precipitation followed by exports, with year-to-year carry-over effects during successive dry years (Harrell 2008). Cloern *et al.* (1983) notes that outflow can vary from a low of about 4,700 cfs (130 cms) at the end of the drought to more than 320,000 cfs (9,000 cms) during the El Niño outflow event in January and February of 1998 (Figure 1-11). This variation typifies the overriding influence of Delta outflow in Suisun. These events, though extreme, exemplify the seasonal and interannual changes the Bay and Marsh experience. In addition, winter storm Delta outflows can bring sediment into Suisun Bay (though amount and interannual variability are not well understood; see Section 1.6). Each season’s first storms carry a bulk of that sediment load, known as the “first flush” (Schoellhamer and Wright 2008).

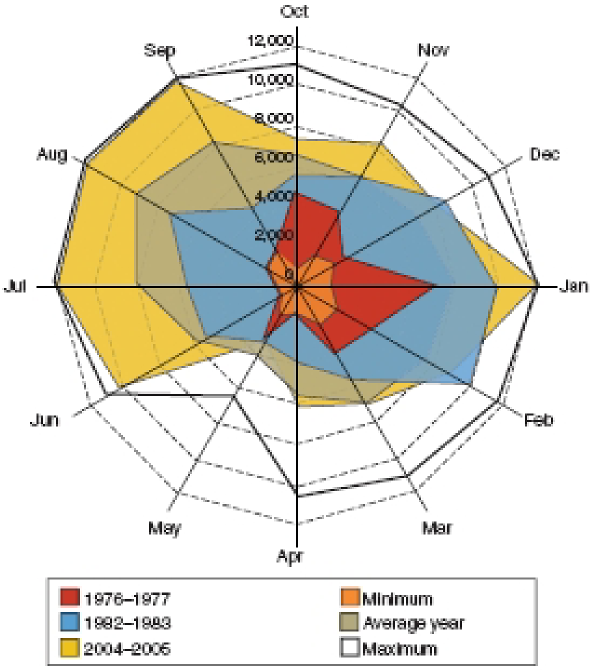


Figure 1-11. Delta Outflow Seasonal and Interannual Variability

Source: PPIC 2007

Delta outflow can have significant effects on tide stage in Suisun Marsh. Figure 1-12 illustrates the roughly 2 feet of stage increase associated with the major El Niño outflow events of early February 1998.

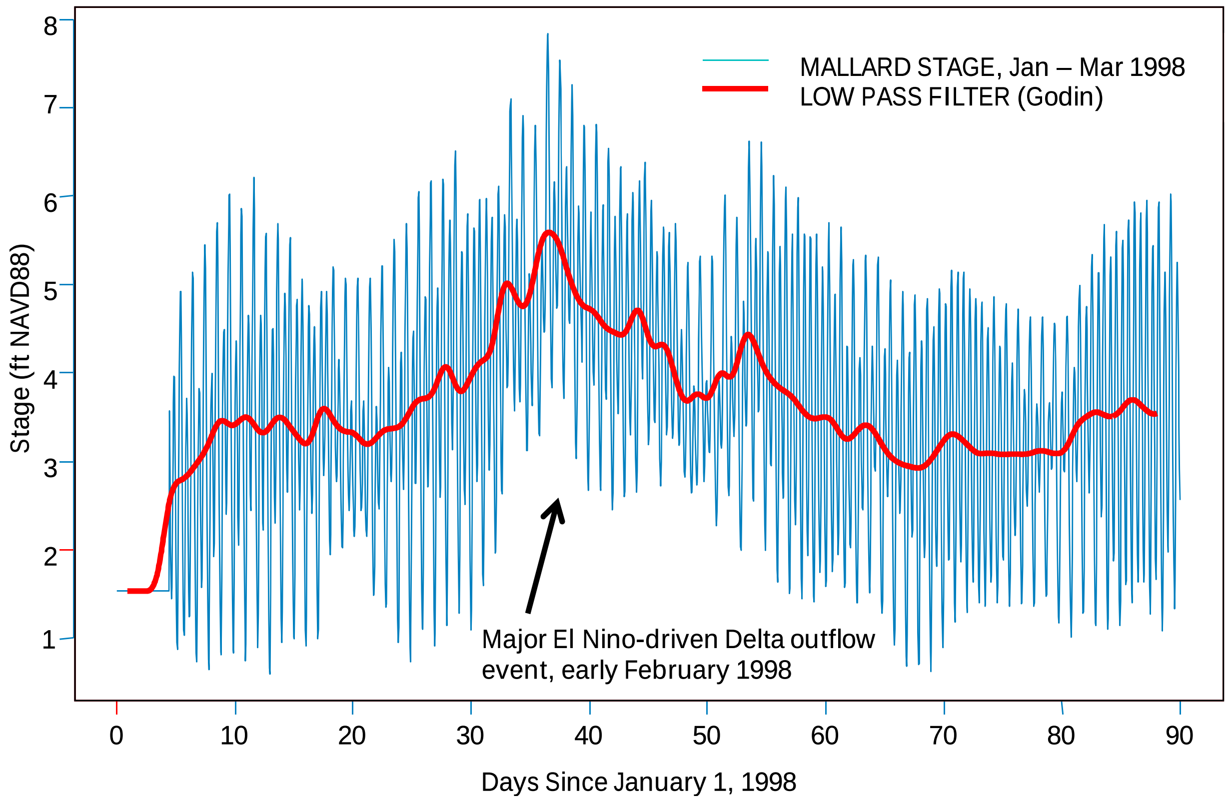


Figure 1-12. Effects of Delta Outflow on Suisun Tide Stage: the 1998 El Niño.

Source: DWR

1.2.3 Local Watershed

Several creeks enter Suisun Marsh from the west, north and east (Figure 1-4). The small drainages on the east and west are generally ephemeral. The larger northern watersheds are generally perennial; for much of the dry season, base flow in these creeks is derived from urban runoff. These larger creeks are Suisun, Green Valley, Ledgewood, Laurel, McCoy, and Union. The largest and only gauged creek inflows enter from Suisun and Green Valley creeks in the northwest Marsh. Storm runoff from ~30-50 square mile watersheds are usually short duration (1-5 days) with peak flows near 6,400 cfs (180 cms). Base flow is year round on the order of 4 cfs (0.1 cms). Suisun Creek flow is maintained year round by a water supply reservoir close to its terminus point in the Vaca Mountains above Suisun Marsh. However, this reservoir is not designed or used for flood control purposes.

Local creeks provide valuable riparian corridors and steelhead spawning habitat, but also deliver contaminants from land runoff to subtidal areas. Section 1.8 explores these contaminant concerns. In addition, residential and commercial developments immediately adjacent to the Suisun Marsh area continue to expand causing upland habitat loss and increased runoff and water quality impacts.

Although these creeks still yield sediment from the local watershed, the sediments are difficult to capture beneficially for tidal marsh restoration because they no longer enter the marsh system in a manner that the marsh can distribute and handle. Farming and urban development have encroached on the riparian zones of these creeks, leaving them open to scour and high sediment loads. Creeks have been channelized, causing bank erosion and flooding since the natural ecosystem no longer functions to slow and control discharge of water from the watershed into the marsh. Impaired creeks are characterized by virtually bare, undercut, and eroding banks, and movement of the creek out of its natural channel. Sediments are deposited high in the marsh, near the northern border. These areas have low energy flows from tides, wind, and currents. Consequently, sediments are left in place with suspension and minor positive movement into the central marsh.

1.2.4 Wastewater Treatment Plant

The Fairfield-Suisun Wastewater Treatment Plant is located in northwest Suisun Marsh and serves more than 130,000 residential, commercial, and industrial customers in central Solano County. The District treats an average of 16 million gallons (60.5 million L) per day, with about 90% of its waste stream being discharged into Boynton Slough (Figure 1-4). This effluent introduces a freshwater source, nutrients, biological oxygen demand (BOD) that influences water column oxygen levels for aquatic organisms, trace metals, and other pollutants to Suisun Marsh. The organic contaminant load contribution of the wastewater treatment plant to Suisun Marsh is at or below ambient levels (Yee *et al.* 2001). The treatment plant does, however, discharges elevated nutrient levels (Richard Looker, pers. comm.). The San Francisco Bay Regional Water Quality Control Board regulates discharge water quality via its National Pollutant Discharge Elimination System (NPDES) permit for the treatment plant. Storm water does not enter the wastewater treatment plant; it is discharged untreated into Suisun Marsh via the area’s creeks (Fairfield-Suisun Sewer District 2006).

1.2.5 Managed Wetlands

The diked managed wetlands of Suisun flood and drain from the tidal sloughs and bays of Suisun and they receive direct rainfall. Three wetlands also receive inputs from the Fairfield-Suisun City Treatment Plant. The general wetland management cycle includes fall flood up after summer periods when wetlands are relatively dry for annual maintenance activities. Fall flood up can result in net upstream flows in the smaller sloughs around the margins of Suisun Marsh, due to the large volume of water diverted from the sloughs to flood these lands. This phenomenon, observed as part of the Suisun Low Dissolved Oxygen/Methyl Mercury Study (Figure 1-13), reduces tidal exchange which can lead to reduced DO levels and increased concentrations of constituents such as methyl mercury entering these waters. These events occurred during the Suisun Low DO study for periods of roughly one month in early fall.

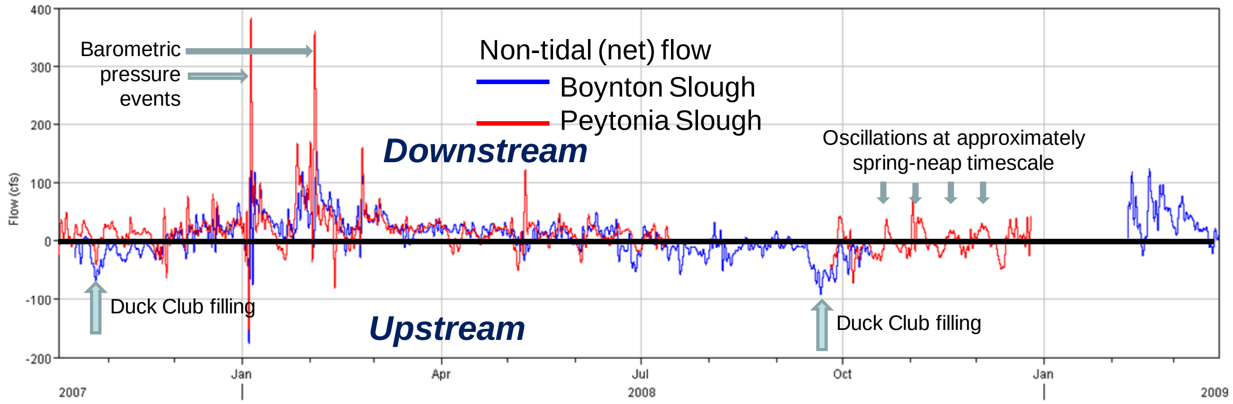


Figure 1-13. Net Upstream Flows in Peytonia and Boynton Sloughs During Fall Flood Up

Source: DWR

1.3 Meteorological Drivers

Along with river inputs and tides, flows are also driven by meteorological forcings including wind, evaporation, and barometric pressure change. These forcings are generally co-varying, but we present them one at a time and discuss interactions.

1.3.1 Wind forcing

The prevailing wind in Suisun Marsh is from the west and southwest direction. During low barometric pressure conditions, wind is generally southerly. Approximately 10% of the time, more often in winter during fair weather, the wind is out of the north. Since most Marsh channels meander, reaches that are oriented along the wind direction can experience high surface water shear that generates wind waves and high turbidity during wind events. Around the bend where the channel orientation approaches orthogonality with the wind, turbidity is lower and the water surface far more quiescent. If wind direction, magnitude, and duration are long enough, the water surface shear can “set-up” the water surface and affect water levels.

1.3.2 Evaporation

Suisun Marsh contains a mosaic of emergent aquatic vegetation that is highly efficient at evapotranspiring water. Tule, bulrush, cattail, and rush species (including *Schoenoplectus, Bolboschoenus, Typha*, and *Juncus* species) can evaporate 2 to 9 feet of water per year depending on temperature, wind, and humidity. During late spring and summer, net flows in terminal sloughs are slightly negative owing to vegetation evaporation losses along the slough or in adjacent marsh plains. Figure 1-18 shows tidal and net flows, and cumulative volume in First Mallard Branch and Sheldrake Slough. During the warm months, both sloughs begin to accumulate water volume. In particular First Mallard Branch accumulates water rapidly during spring tides when channel water overflows the bank and occupies the marsh plane where it is easily evaporated. This mechanism is an important advective transport process within small sloughs during the warm months.

1.3.3 Barometric pressure

Barometric pressure co-varies strongly with wind direction and evaporation. When it changes rapidly, it can generate barotropic flows and change tidal heights. Over 95% of the variance in peak northern reach sea level is controlled by storm induced coastal sea level variations and wind set-up (Walters 1985). Delta outflow generates a second, lower, peak in Suisun Bay non-tidal sea level that lags a few days.

1.4 Conceptual Model of Transport Processes as Controls on Ecosystem Functions of Suisun Marsh

Like all tidal marshes, Suisun Marsh produces a variety of ecosystem services for consumer organisms both in Suisun Marsh, and the wider estuary. Physical habitat attributes like marsh plains, tidal creeks, and tidal channels provide structural refuge and rearing habitat for organisms. In turn, exchanges of tidal flows between marsh attributes generate constituent gradients of scalars like temperature, nutrients, and salinity, as well as passive biota including phytoplankton, and zooplankton. Transport processes can generate sharp scalar gradients at intersections of physical habitat attributes that can be considered “ecotones” where physical, chemical, biological, and structural habitat characteristics change rapidly in space (Simenstad 2008). Native organisms are known to key into these structures and processes for growth, reproduction, and survival strategies. Tidal energy is the primary driving “engine” for all these processes with influence from river flows and meteorology. The geomorphology of the marsh landscape acts like a filter that modifies tidal energy by influencing wave propagation, tidal range, and hydroperiod (Malamud-Roam 2000). Thus, the tidal current regime we observe in Suisun Marsh is an emergent property of astronomical tides, river flows, sun, and weather, that is modified or filtered on geomorphic attributes of the Marsh. In turn, hydrodynamics and transport processes move and mix water column constituents according to the current regime. The outcome is a characteristic set of physical/chemical/biological habitat gradients that estuarine organisms respond to. Figure 1-14 illustrates how geomorphology mediates the estuarine forcing mechanisms (drivers) and link to ecosystem service outcomes through hydrodynamics and transport processes.

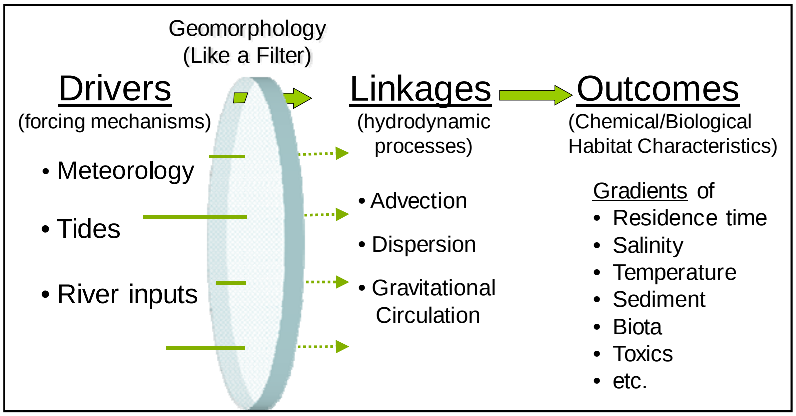


Figure 1-14. Geomorphology as Filter of Estuarine Drivers: Structure Determines Function

Figure 1-15 shows a conceptual model of several geomorphic habitat attributes within Suisun Marsh to illustrate how different physical attribute types (marsh plain, tidal creek, slough, channel, bay) interact at different time and space scales. Historical marsh plains (still observable in a few places like Rush Ranch) are the linkage to terrestrial upland environments. They are subject to radically shifting hydroperiods as they can be watered only by the highest tides. These exchanges recharge the marsh plain with surface and soil pore water, as well as channel borne sediments and nutrients. Subsequent ebb tides can export dissolved organic matter and detritus that fuels the microbial food web that, in turn, generates nutrients. The junctions between low order creeks can be strong ecotones of temperature and food availability (Knieb 1999). These systems also rapidly dissipate tidal energy by friction on shallow plains and creeks.

1. Marsh plain and tidal creeks

- Marsh plain and tidal creeks are directly connected to the terrestrial environment. In a natural marsh, tidal creek and marsh plain exchange processes are dominated by short-lived pulses (hours) of water from the creeks. These exchanges recharge the marsh plain with surface water, pond storage and pore water. Return to the channels from these marsh-plain overtopping events varies depending on the fine-scale geomorphology. These exchanges are strongly mediated by fortnightly variations in tides (e.g. spring/neap cycle) and seasonal changes in atmospheric pressure and hydrology (high water due to inland flooding).

2. Sloughs

- Sloughs provide conveyance of water and constituents between the tidal creek/marsh plain environments and the channels. Residence time in the sloughs varies from the tidal time scale near the slough mouths to fortnightly and longer timescales near the inflowing creeks. Lower sloughs mix efficiently with distributary channels through tidal trapping. Material fluxes through slough mouths integrate creek runoff, land use, and slough connectivity.

3. Channels

- Channels are characterized by larger cross sections, greater mass fluxes and aren't typically connected to the terrestrial environment. Channel/slough exchange depends upon channel connectivity. Closed channel loops (e.g., Montezuma, Suisun, Cutoff Sloughs) exhibit convergence zones where tidal waves merge from two directions. These zones can accumulate sediment, biota, and contaminants.

4. Bay

- The bay is characterized by open shallow water with partially standing wave hydrodynamics, and tidal trapping gyres. The water column is fully mixed by boundary layer shear flow and wind stress. Ebb-flood tidal flow asymmetry controls exchange with Suisun sloughs.

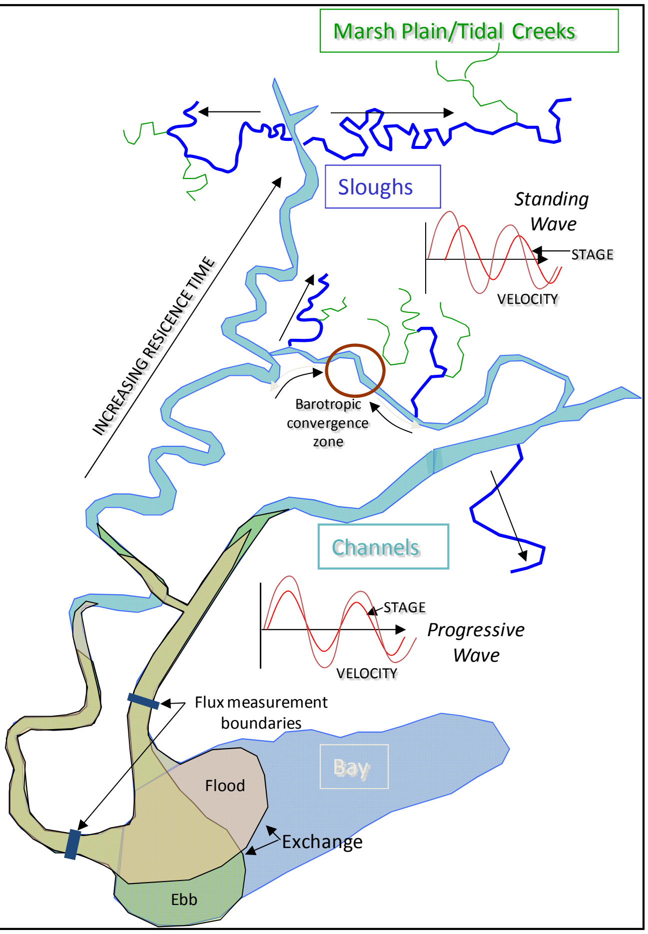


Figure 1-15. Conceptual model of hydrodynamics and mixing across spatial scale connectivity

The figure shows how tide stage and velocity are differentially related depending on location and topography, and how water and constituents may be exchanged with Grizzly Bay. Source: Chris Enright, DWR

Tidal sloughs are the primary conveyors of water and constituents to and from marsh plains. Most of the water entering a tidal slough is exchanged each tidal cycle allowing rapid near region (within a tidal excursion) transport of water borne constituents. Tidal dispersion of constituents is efficiently carried out by a mechanism known as "tidal trapping" as water masses are mixed at channel junctions by spatial differences in the phasing between tidal currents and tidal stage. Tidal currents and stage tend to be more in phase in larger channels while dead-end sloughs tend to exhibit "standing waves" where tidal currents and tidal stage are almost perfectly out of phase. Examples of relatively highly functioning tidal sloughs in Suisun Marsh include First and Second Mallard Branch within Rush Ranch as well as portions of the Hill Slough and Peytonia Slough.

The larger channels crossing Suisun Marsh are unique attributes both because of their size and because their lengths are longer than the excursion of the tide. Therefore, while channels are tidally energetic, they significantly contain the full tidal excursion or tidal "slosh" within their length. Another feature of the large tidal channels in Suisun Marsh is that several of them form "loops" either naturally or because of historical channel cutting. Propagating tidal waves enter each of these loops from both ends with variable timing and come together in "convergence zones." Figure 1-16 shows the general location of convergence zones in Cutoff Slough, the Nurse Slough complex, and eastern Montezuma Slough. The speed of tide propagation depends on water depth; therefore convergence zone locations are variable. However, in the region where convergences occur, we generally observe lower overall current velocities and shallow depths because sediment is more likely to be deposited in these areas.

Suisun marsh is connected at three primary locations to Suisun Bay. Therefore, to the extent that Suisun Marsh is a net producer of energy to the Suisun Bay food web, the key water mass exchanges are made here. The details of these exchanges are not well known at this time. Figure 1-16 shows how a volume of water that is exported from Suisun Marsh through the mouth of Suisun Slough and Western Montezuma Slough can be replaced on the following flood tide partly by that same water, and partly by other water that had been resident in Grizzly Bay. This partial "exchange" is also affected by the strong wind shear in Grizzly Bay as well as by the dynamics of variable ebb and flood tide strength.

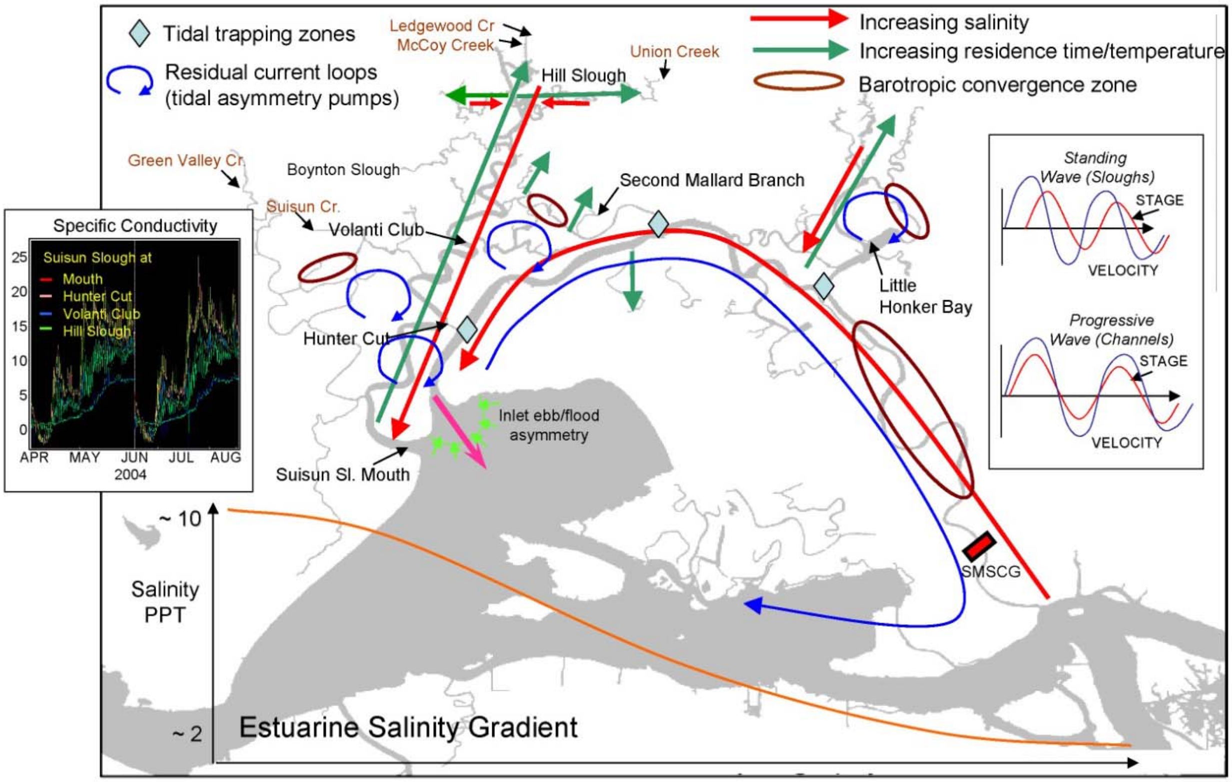


Figure 1-16. Conceptual model of hydrodynamic complexity due to plan form connectivity among various parts of Suisun Marsh

This model highlights the spatial variability in salinity, residence time, and the locations of barotropic convergence zones, residual current loops, and tidal trapping zones. Also shown are the locations of inflowing creeks and the ebb/flood asymmetry of flow at the western end of Montezuma Slough. SMSCG is the Suisun Marsh Salinity Control Gate. Source: Chris Enright, DWR

Other aspects of hydrodynamic and transport complexity in Suisun marsh are illustrated in Figure 1-16. Suisun Marsh exhibits strong salinity gradients in both the east-to-west and north-to-south directions by different mechanisms. The estuarine salinity gradient is a balance between freshwater river flow (advection) and mixing of ocean salinity by tidal currents (dispersion). Located in the geographic center of the northern reach of the San Francisco estuary, Suisun Bay generally experiences the strongest east-to-west salinity gradient. This gradient is partially responsible for net currents driven by the east-to-west density difference, especially during slack tides. These density currents, called “gravitational circulation,” are thought to be important for upstream transport of salinity and sediment, as well as being used by some organisms to move and maintain position in the estuary. Inputs of freshwater from northern Suisun Marsh creeks generate a persistent salinity gradient from north-to-south. The inset chart on Figure 1-16 shows a salinity timeseries between April and August 2004 showing progressively increasing salinity along Suisun Slough toward the south.

Returning to the marsh plain/tidal creek/tidal slough scale, a specific example of how geomorphic landscape patterns affect hydroperiod and ultimately ecosystem outcomes can be seen by comparing proximate sloughs with different adjacent land use patterns. Sheldrake Slough and First Mallard Branch essentially share the same source water from Suisun Slough (Figure 1-17). Sheldrake Slough is typical of most Suisun Marsh sloughs that are severed from their former marsh plain by levees and are now connected only through water control culverts. Surrounding land elevation is low because it has subsided 1-2 m from its former elevation near mean-higher-high-water. In contrast, First Mallard Branch retains much of its historic geomorphology. It includes several orders of tidal channels surrounded by a marsh plain that maintains a natural elevation at about mean-higher-high-water.

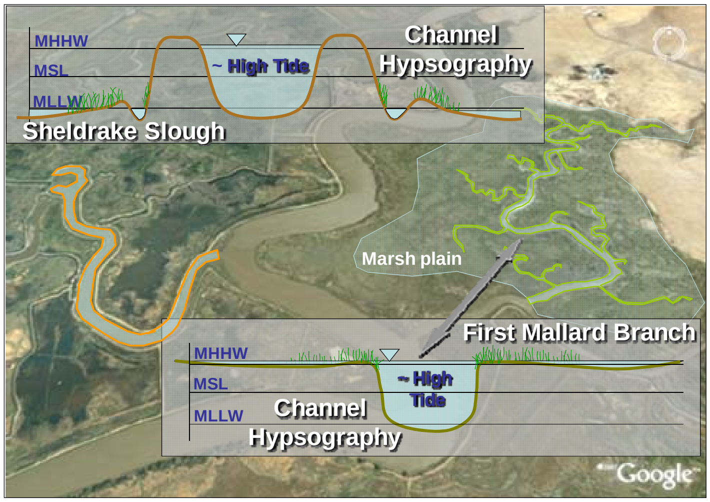


Figure 1-17. Structural Comparison of Slough Bordered by Diked vs. Tidal Marsh

Compare Sheldrake Slough disconnected from the adjacent marsh plains vs. First Mallard Slough connected to the adjacent tidal marsh and thus its vast tidal prism at overbank tides. Source: Chris Enright, DWR

Oceanographic instruments deployed near the mouth of both sloughs recorded tidal currents and constituent concentrations including salinity, temperature, chlorophyll a, pH, and turbidity (Enright in prep). Analysis of temperature data showed a striking example of an emergent property of hydroperiod. Figure 1-18 shows the water temperature tidal time series between April and August 2004. The top panel shows the high frequency flow time series for both sloughs. Flow magnitudes are quite similar during neap tides while spring tides bring a marked departure between sloughs. The flow signal at First Mallard Branch increases rapidly near the full and new moon. This indicates that strong high tides have overtopped the marsh plain. Since Sheldrake Slough is completely diked, only the astronomical tide signal is recorded. Therefore, the morphology of the remnant natural marsh creates an elevation threshold beyond which abiotic conditions change rapidly. In other words, the geomorphic "filter" that mediates tidal energy in each slough generates a very different channel current signal and wetting regime in the surrounding landscape. Hydrodynamics and transport processes link the common tide signal to very different ecosystem service outcomes. The lower panel in Figure 1-18 exhibits the corresponding high frequency water temperature signal. Vertical red lines indicate times of the first large ebb tide subsequent to the first marsh plain overtopping tide. The temperature signal exhibits a very large drop, more than 5°C within two tidal cycles. Further inspection of the event sequence shows that the initial marsh plain overtopping occurs near midnight. This allows shallow water on the marsh plain to cool by latent heat exchange with the atmosphere. The subsequent ebb tide returns significantly cooler water that is sensed by the instruments as the ebb tide proceeds. This is an example of estuarine water temperature as an emergent property of the interaction between tides and landscape morphology.

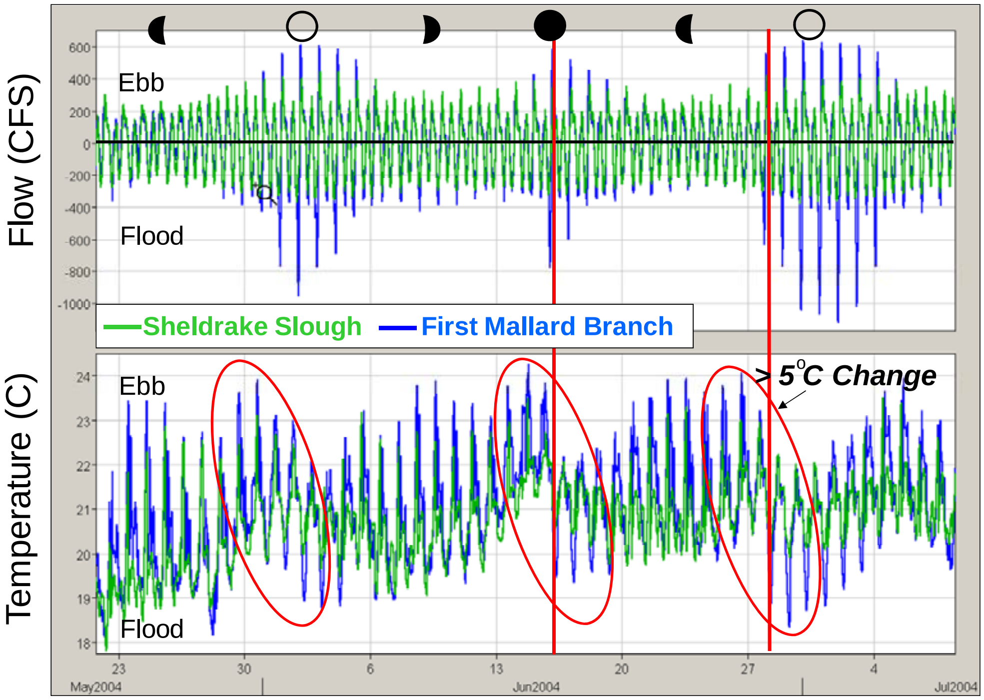


Figure 1-18. Flow and Temperature Differences Between Sloughs with Diked vs. Tidal Marsh

Upper plot shows tide stage in Sheldrake Slough (dikes on both sides of tidal slough) and First Mallard Branch (tidal marsh [Rush Ranch] on both sides of tidal slough). Lower plot shows surface water temperatures in each slough. Plot shows diel variation in water temperatures in both sloughs for all tides. Spring tides of June and July 2004 reach heights that cause overbank flooding onto the tidal marsh during the night; evaporative cooling lowers that water by approximately 5ºC and that water drains back off the marsh plain on ebb tide and into the tidal sloughs. This cooling effect is not observed in Sheldrake. Source: Chris Enright, DWR.

Considering Suisun Marsh as a whole, small time and space scale attributes and processes integrate together to produce the overall abiotic and biotic conditions that interacts with Suisun Bay and the larger San Francisco Estuary. As a result of the landscape configuration, Suisun Marsh contains complex hydrodynamic and bathymetric environments and experiences a diversity of transport mechanisms across temporal and spatial scales unsurpassed elsewhere in the San Francisco Estuary (Figure 1-16). Suisun Marsh is adjacent to the maximum estuarine salinity gradient within the estuary and exhibits diverse topography, providing a broad range of aquatic and terrestrial environments. Hydrodynamic interactions between major habitat types (marsh plain, tidal creeks, sloughs, channels, cuts, mudflats, bays) control sediment erosion, transport, and deposition and influence salinity gradients, chemical transformations, and biological production (Friedrichs et al. 2001). Native plants and animals often depend on this habitat diversity, hydrodynamic complexity, and variable salinity for their persistence (Mount 1995, Bay Institute 1998, Matern et al. 2002). The dispersion and exchange of chemical and biological constituents at a variety of temporal and spatial scales ultimately determines the contribution of Suisun Marsh to the greater estuary.

The geometry of the marsh influences water movement into, through, and out of the marsh and its adjacent bays, and subjects the region to almost instantaneous changes in chemical and sediment load from large interannual or episodic changes in flow (e.g. wet years following the drought of the late 1980's and early 1990's) (Cloern et al. 1983). Mixing of the water column in the bays and sloughs is driven by tides, river and stream flows, and wind action. These drivers are not always active (e.g., windless days, neap tides, low Delta outflow). The relative degrees of water circulation and stratification within different areas of the Suisun Marsh/Bay system affect the distribution of sediments, salt, primary productivity, and oxygen saturation throughout the system. Temperature and salinity stratification in particular are density-driven processes in opposition to mixing forces. Stratification strength scales with the square of water depth. Consequently, shallow areas tend to be mixed more often than deep areas, and the extent of mixing varies seasonally and with the spring-neap tidal cycle (Chris Enright, pers. comm.). In many small, shallow sloughs, if temperature and dissolved oxygen levels remain within levels capable of supporting aquatic organisms, they yield higher populations of zooplankton and other animals than deeper areas (Mueller-Solger, 2000).

Suisun Marsh is geomorphically and hydrodynamically complex. This complexity evolves directly from a significant gradient in tidal forcing across the Marsh and the propagation and dissipation of the tides within Suisun Marsh's network of channels and basins. Even though the wavelength of the principal partial tide (~450 km) is significantly longer than the Marsh itself (~18 km), differential tide wave propagation/ dissipation creates a variety of aquatic habitat and transport characteristics within the Marsh. Because most of Suisun Marsh consists of diked wetlands, tidal energy enters Suisun Marsh through the mouth of Suisun Slough and through the east and west ends of Montezuma Slough. The western Marsh is strongly influenced by tides (± 2 m) that propagate into the Marsh through Grizzly Bay and create large tidal exchanges between Montezuma (±1,800 cms) and Suisun Sloughs (±300 cms) and the Bay. The tides in the eastern Marsh are significantly less energetic (a tidal range of ±1.7 m and tidal discharges on the order of ± 200 cms), primarily due to strong dissipation of the tide wave (and tidal current) as it propagates through Suisun Bay (Walters 1995).

The tides dissipate as they propagate through the narrow and often sinuous network of channels in the Marsh, which leads to a general reduction in tidal forcing from south to north (±1,800 cms in Montezuma Slough west compared to ±50 cms in Hill Slough) and from west to east (±1,800 cms in west Montezuma Slough compared to ± 200 cms in the east) in the Marsh. Exceptions to this general rule occur at Hunter Cut and Nurse Slough (Figure 1-16). Hunter Cut is a narrow, constructed channel that conveys approximately ±350 cms between Suisun and Montezuma Sloughs due to tide wave propagation asymmetries across its ends. Nurse Slough, on the other hand, maintains by far the largest tidal discharge within the Marsh (±350 cms), because of its connection to the tidal prism associated with Little Honker Bay, the only embayment interior to the marsh. The tides not only create large exchanges of water within the Marsh system; they also create fast currents. Hunter Cut is an extreme case, where tidal currents peak at ~120 cm/s (4 ft/s). Most importantly, these tidal currents can move individual water masses significant distances over a single half tide cycle, or ~6 hour period. For example, simultaneous drifter releases at the ends of Cutoff Slough (February 2004) resulted in tidal excursions on the order of 8 km. These tidal excursions encompass a significant fraction of Suisun Slough's overall length (approximately 18 km) and thus provide the possibility of exchange/mixing of water of different origins and of significant dispersion of organisms and material within the marsh.

Diked versus tidal marsh adjacent to the sloughs affects the exchange of water and its constituents between the marsh and the sloughs and these sloughs into nearby larger sloughs. For example, as discussed above, Sheldrake and First Mallard sloughs offer an instructive comparison between sloughs of similar size that have different land use and consequently different tidal exchange characteristics. Sheldrake Slough is diked along its entire length and receives highly managed drain water from adjacent managed wetlands (waterfowl clubs). The tidal exchange in Sheldrake Slough is similar to most of the rest of Suisun Marsh. By contrast, First Mallard Slough is adjacent to remnant tidal marsh at Rush Ranch and is regularly connected to the surrounding marsh through flooding at high spring tides. This distinction establishes fundamental differences in important terrestrial-aquatic exchanges of carbon, nutrients, biota, and possibly contaminants.

1.5 Salinity

Salinity within the Suisun Marsh-Bay system is an important habitat characteristic that exerts a major control on both physical and ecological processes. As a result, salinity control has been the focus of water management activities in the Marsh since the 1970s. Salinity influences chemical processes such as sorption-desorption and flocculation, physical processes such as density stratification and vertical mixing, directly influencing the distribution and form of many trace substances (Cloern 1983), and the ecological suitability for organisms as a function of physiological tolerances. For example, the Suisun Ecological Workgroup concluded that fish species native to Suisun Marsh require low salinities during the spawning and rearing periods, stating that salinities exceeding 8 parts per thousand (ppt) could be limiting to spawning and rearing of native fish (SEW 2001). Meng *et al.* (1994) found that overall fish abundance and species diversity declined in Suisun Marsh over a 14-year period due to decreases in freshwater outflow and increases in salinity.

1.5.1 Salinity regime

The Suisun Bay-Marsh system contains both the maximum estuarine salinity gradient and low salinity zone within the San Francisco Bay Estuary. The position of the low-salinity zone, called X2, is measured as the distance from the Golden Gate to the 2 ppt bottom isohaline. X2 has been used as an index of estuarine productivity within the Bay/Delta system that integrates several physical, chemical, and biological parameters (Kimmerer 2004). High productivity in upper trophic levels often occurs within X2 (Kimmerer 2004) and along the maximum estuarine salinity gradient (Jassby *et al*. 1995,). The system's overall estuarine salinity gradient trends from west to east, with higher salinities in the west and lower salinities in the east. The west-east salinity gradient across Suisun Marsh (via Montezuma Slough) generally is consistent with the Suisun Bay salinity gradient. Exceptions to this dominant regime are encountered when the Suisun Marsh Salinity Control Gate (SMSCG; discussed below) operates in the fall and winter. The salinity gate tends to compress the Montezuma Slough salinity gradient. Despite salinity gradient compression, tidal salinity variability is reduced because the flood tide is arrested by the closure of the gate (Enright, 2004). Suisun Marsh also exhibits a persistent north-south salinity gradient (Figure 1-16). Despite low and seasonal flows, the surrounding creeks have a significant water freshening effect due to long residence times in upper sloughs. Wastewater discharges into Boynton Slough from the Fairfield-Suisun Treatment Plant also contribute to locally reduced salinity.

1.5.2 Long-Term Salinity and Control Structures

Water management in Suisun Marsh has focused on salinity control since the 1970's. The State and federal water projects built several salinity control structures in the Marsh between 1970 and 1990, including the Roaring River Distribution System, Morrow Island Distribution System, Goodyear Slough Outfall, Lower Joice Island Unit, Cygnus Unit, and the Suisun Marsh Salinity Control Gate (SMSCG). The SMSCG is the largest and most effective salinity control structure within Suisun. Located at the east end of Montezuma Slough (Figure 1-19), when operational the salinity gate is opened on ebb tide to allow low salinity Sacramento River water into the Marsh during the fall and early winter period (October-January). The gate closes on flood tide to prevent ocean water incursion into the western end of Montezuma Slough. When the gate is operating, net flow in Montezuma Slough is more than 70 cms (2,500 cfs) (east to west) compared to nearly zero when not operating. By comparison, the discharge in the Sacramento River measured at Freeport (near Sacramento) during the typical period of gate operation is on the order of 200-500 cms (7,000-18,000 cfs). When not operational, the gate is left in the fully open position, allowing full tidal exchange between Montezuma Slough and the lower Sacramento River.

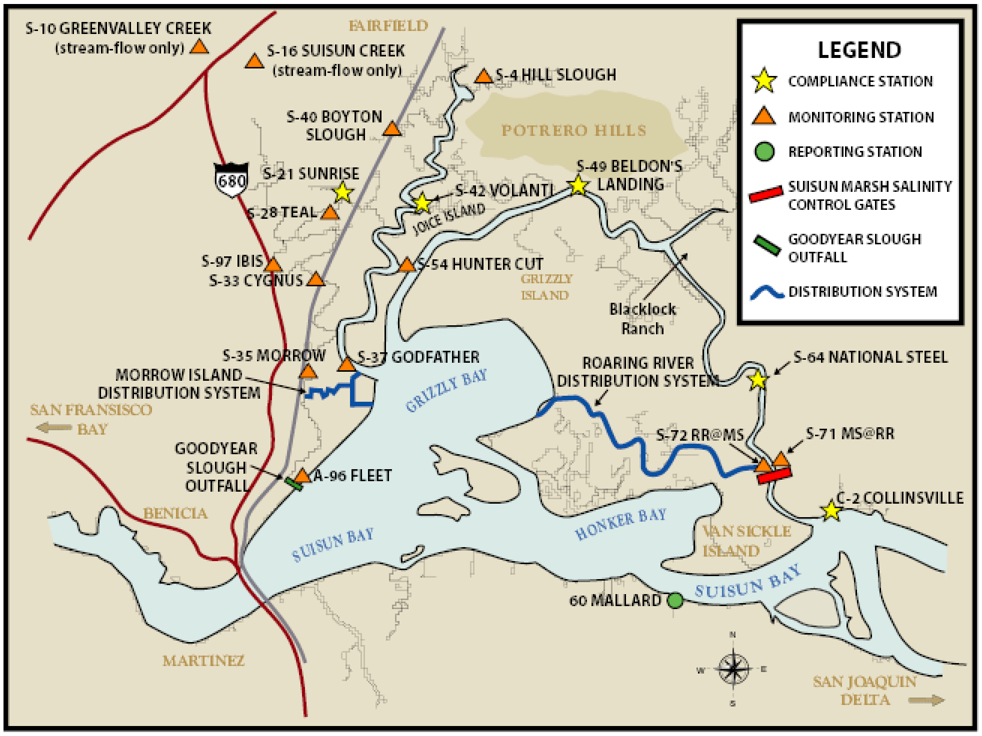


Figure 1-19. Suisun Marsh Salinity Control Features and Monitoring and Compliance Stations

Source: DWR

Gate operations are effective at controlling salinity levels at most locations in the Marsh. The magnitude, timing, and duration of salinity reduction in response to the SMSCG operation vary with proximity. Water quality stations are located throughout Suisun Marsh (Figure 1-19). A drop in salinity due to gate operations is seen immediately at monitoring station S-64 (National Steel) and about one day or so later at S-49 (Montezuma Slough at Beldon's Landing) because both are located close to the gates (Figure 1-19). However, it takes about two to three days before a salinity drop can be observed at S-42 (Suisun Slough and Volanti) and S-21 (Chadbourne Slough at Sunrise Club), because both are located in the north-central part of the marsh. Salinity levels at C-2 (Sacramento River at Collinsville) tend to increase slightly from gate operations because of interactions between tidal exchange, outflow, and gate operations. At S-35 (Goodyear Slough), gate operations are effective in controlling salinity, but to a lesser magnitude and with a longer time lag due to the distance of the station from the gates. At S-97 (Ibis), gate operations are not effective in controlling salinity because of its location in the far western portion of the marsh.

The effectiveness of gate operations on salinity control at three stations is illustrated in Figure 1-20. This figure shows the results of model runs of salinity with and without gate operations at three stations across the marsh from 1920 to 2006. The analysis was done using the DWR Delta Simulation Model. The boundary condition for the model is the 19-year mean tide at the Golden Gate where constant ocean salinity is maintained. The model has been calibrated against historical flow, water level and salinity. The model was run with gate operation under the State Water Resources Control Board Decision 1485 standard and hydrology[1]. Salinity in the Marsh without SMSCG operations generally ranges from 1 ppt to 25 ppt depending on the season and location. Modeled salinity variability in the eastern marsh is significantly dampened by operation of the SMSCG (Figure 1-20), benefiting organisms that gain from reduced salinities and potentially adversely affecting organisms that depend on the variability. This modeled dampening effect is less pronounced in the western portion of the marsh (Figure 1-20).

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[1] DWR currently operates the SMSCG to meet the State Water Resources Control Board Decision 1641 standards and the standards in the Revised Suisun Marsh Preservation Agreement.

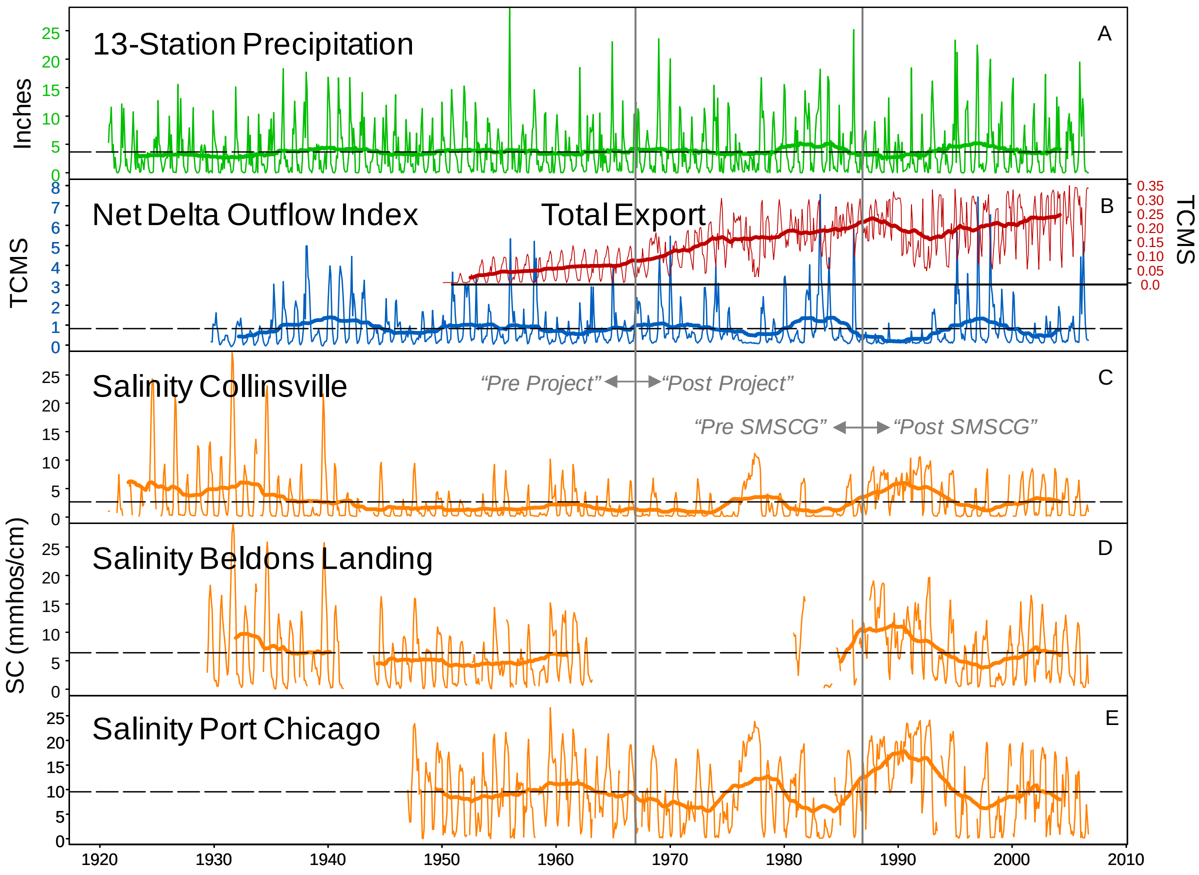


Figure 1-20. Suisun Bay Salinity 1920-2006

(A) Monthly average of 13 Sierra Nevada foothill precipitation stations on tributaries of the San Francisco Estuary watershed (1920-2006). (B) Monthly Delta outflow index; right axis is monthly average total water project export. (C, D, and E) Monthly average specific conductivity for Collinsville, Beldon's Landing, and Port Chicago, respectively. Prior to 1966, SC is estimated from approximately four high tide TDS grab samples per week. Heavy solid line is 5-year running average. Dotted line is period of record mean. Source: DWR

1.6 Sediment

Sediment nourishes the tidal marshes, comprises the aquatic substrate, provides turbidity beneficial to some species, and influences the chemistry, transport, and consumption of metals and organic contaminants. Suisun Marsh sits at a very key position with the San Francisco Estuary-Delta: where the freshwater outflows of the Central Valley meet the saline waters of the tides. These "mixing zones" within estuaries are well known to have turbidity maxima due to the mixing processes of these two water bodies, and with them very high productivity levels. In this section we will first examine briefly the input of sediment from the Delta, the major external sediment source to Suisun (Section 1.6). Next, we will examine the Suisun Estuarine Turbidity Maxima and the unique conditions that make Suisun unlike typical estuaries around the world (Section 1.6.2). We then examine the role of suspended sediment concentration on marsh accretion, a necessary process for tidal marsh restoration on the subsided lands of Suisun Marsh (Section 1.6.4). Lastly, we look at the limited available data on suspended sediment concentrations in Suisun to relate marsh accretion potential with available sediment supply (Section 1.6.5). Section 1.8 examines the contaminant aspects.

1.6.1 Delta Sediment Supply to Suisun

Sediment discharge from the Delta into Suisun is the primary source of external sediment inputs into Suisun Marsh and Bay (Schoellhamer 2001). Schoellhamer et al. (2008) developed a conceptual model of sediment supply for the Delta that described supply discharged into the lower estuary (Figure 1-21). That work found that Delta sediment supply is limited and decreasing due to trapping behind dams and diminishment of the hydraulic mining sediment supply. It also found SSC to be in the range of 10-50 mg/L except during river floods when SSC can exceed 200 mg/L.

Roughly 40% of the sediment that enters the Delta is transported into Suisun Bay, representing an average annual sediment flux of 0.56±0.18 million metric tons (Mt) during water years 1999-2002 (Figure 1-21). That sediment comes mainly from the Sacramento River (66% of total Delta sediment influx) with the Yolo Bypass, San Joaquin River, and east side tributary rivers contributing 19%, 13%, and 2%, respectively. Mallard Island in eastern Suisun Bay is a primary reporting station for Suisun water quality. Annual suspended-sediment loads from 1995-2003 at Mallard Island (see Figure 1-19) averaged 1.2 ±0.4 Mt, varying from 0.26 ±0.08 Mt in WY 2001 to 2.6 ±0.8 Mt in WY 1995. Given that the average water discharge for 1995-2003 was greater than the average discharge for the previous decade, it seems likely that the average suspended-sediment load at Mallard Island may be less than 1.2 ±0.4 Mt. Annual sediment loads at Mallard Island for WY 2002 and WY 2003 were 0.31±0.09 and 0.55±0.18 Mt, respectively, which were less than half the long-term annual average load (Leatherbarrow *et al.* 2005). The largest controls on interannual variability and long-term trends of sediment discharge from the Delta are amount of runoff (climate and reservoir management), whether or not Yolo Bypass is inundated which occurs in wetter years only, and sediment capture behind dams (Schoellhamer *et al.* 2008).

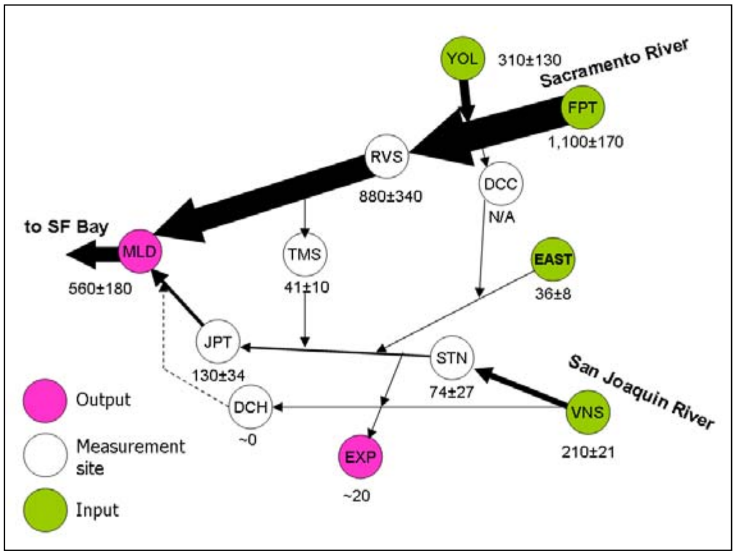


Figure 1-21. Average Annual Delta Sediment Budget

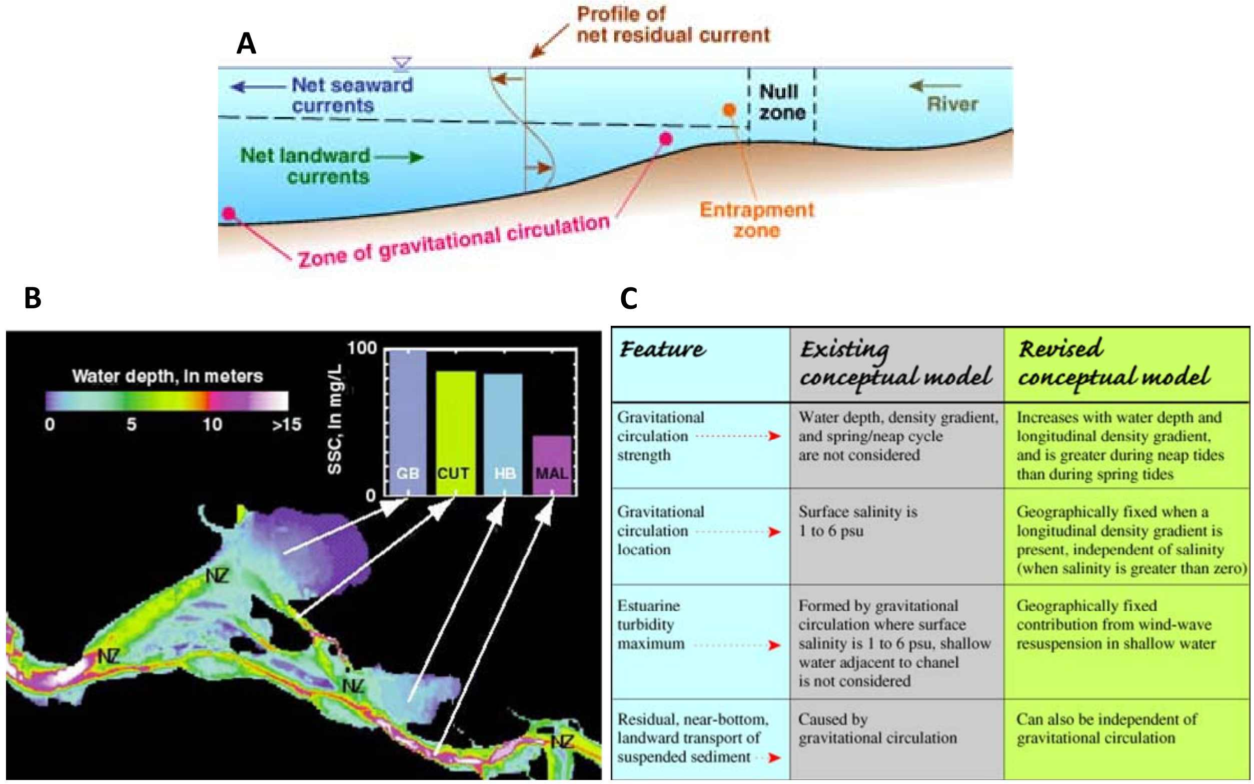
Data based on water years 1999 – 2002, except for Three Mile Slough (TMS) which is based on water years 2001 and 2002 only (Wright and Schoellhamer 2005). Numbers are the annual suspended-sediment flux and the estimated error in **thousand metric tons**. *Arrow thickness indicates relative magnitude 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). Source: Schoellhamer et al (2008)*

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, 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.

Taking a longer historical perspective on the role of Delta sediment exports, long-term patterns of sedimentation in Suisun were altered by the input of hydraulic mining debris from the Sierra Nevada from 1850 to the late 1800s. Capiella *et al.* (2001) used historical bathymetric data to determine sediment and bathymetry changes in Suisun Bay (including Grizzly and Honker bays) from 1867-1990. From 1867 to 1887 approximately 115 million m^3 of sediment, much of it hydraulic mining debris, was deposited in Suisun Bay. From 1887 to 1990, Suisun Bay eroded due to a decrease in sediment supply, a result of the ban on hydraulic mining and an increase in water diversions and flood control projects upstream of the Bay. As a result of this erosion, Suisun Bay has lost over 100 million m^3 of sediment and 40 km^2 of tidal flat area since 1887 (Capiella *et al.* 2001).

1.6.2 The Suisun Estuarine Turbidity Maximum

One of two significant physical processes that generates water column turbidity and thus suspended sediment that can be tidally transported throughout Suisun Bay and Marsh is the Estuarine Turbidity Maximum. The San Francisco Estuary is somewhat unique in how its ETM functions. In many estuaries around the world, the mixing of riverine freshwater and ocean salt water is driven largely by the density differences of the fresher (lighter) and saltier (heavier) waters and the rising and falling of the tides (Figure 1-22). Those processes do operate in this estuary.



Feature	Existing conceptual model	Revised conceptual model
Gravitational circulation strength ➤	Water depth, density gradient, and spring/neap cycle are not considered	Increases with water depth and longitudinal density gradient, and is greater during neap tides than during spring tides
Gravitational circulation location ➤	Surface salinity is 1 to 6 psu	Geographically fixed when a longitudinal density gradient is present, independent of salinity (when salinity is greater than zero)
Estuarine turbidity maximum ➤	Formed by gravitational circulation where surface salinity is 1 to 6 psu, shallow water adjacent to chanel is not considered	Geographically fixed contribution from wind-wave resuspension in shallow water
Residual, near-bottom, landward transport of suspended sediment ➤	Caused by gravitational circulation	Can also be independent of gravitational circulation

Figure 1-22. Existing (Classic) Model of Estuarine Mixing and New Model for Suisun Bay

(A) Existing (classic) modeling of estuarine mixing and estuarine turbidity maximum; (B) Location of three bathymetric sills in Suisun Bay that generate added gravitational circulation component; (C) Comparison of key features of existing and revised model for Suisun Bay. Source: USGS (http://sfbay.wr.usgs.gov/sediment/circulation/index.html)

The very important additional process at play in Suisun Bay are three large bathymetric sills, one a short distance east of the Benicia Bridge and two more associated with Suisun Cutoff (Figure 1-23). These abrupt bathymetric sills cause strong vertical mixing in the water column the action of which resuspends mobile sediments. These processes operate more strongly on spring tides.

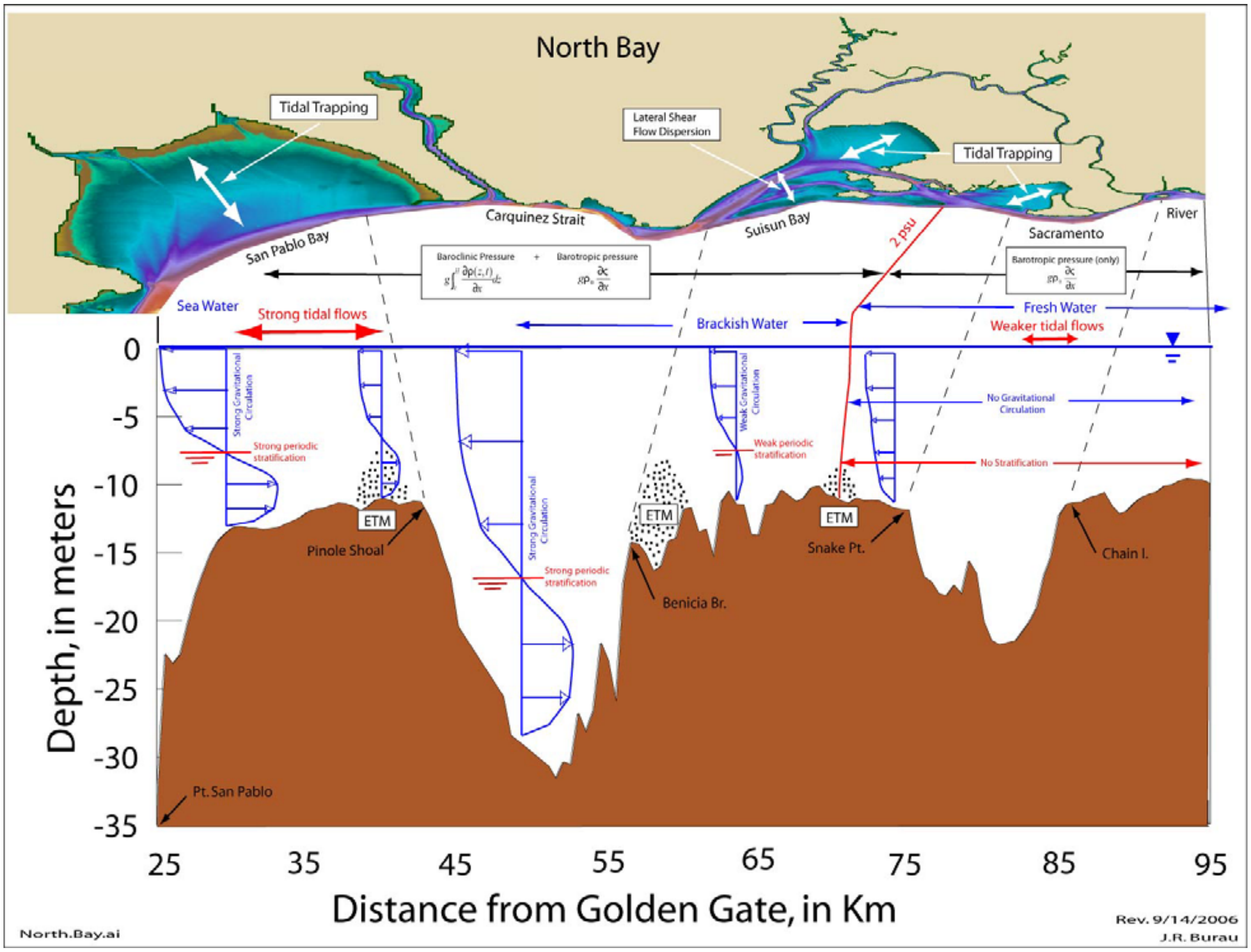


Figure 1-23. Current Model of Suisun Bay Mixing

Source: Jon Burau, USGS

During the summer months when wind-wave action resuspends sediments in San Pablo Bay to the west, this mechanism can transport those sediments into Suisun Bay where they can become actively mixed in the water column.

Movement of sediment is affected by sediment characteristics such as grain size and cohesiveness and flow characteristics such as turbulence and shear stress across submerged surfaces (Kimmerer 2004). Processes within the Bay strongly influence suspended sediment transport into and out of the marsh sloughs. Three factors have a potentially major influence on the distribution of suspended sediment within the Marsh: 1) barotropic convergence zones, 2) hydraulic controls, and 3) tidal channels that open to shallow water regions of the Bay (Figure 1-15). Barotropic convergence zones, where tidal flows are in opposition, can trap dissolved and suspended components on a tidal time scale (Swanson et al. 2003, Warner et al. 2003, Shellenbarger et al. submitted). Entrance controls, such as the salinity gates on Montezuma Slough (Figure 1-19), can affect the transport of materials by altering flow across the marsh

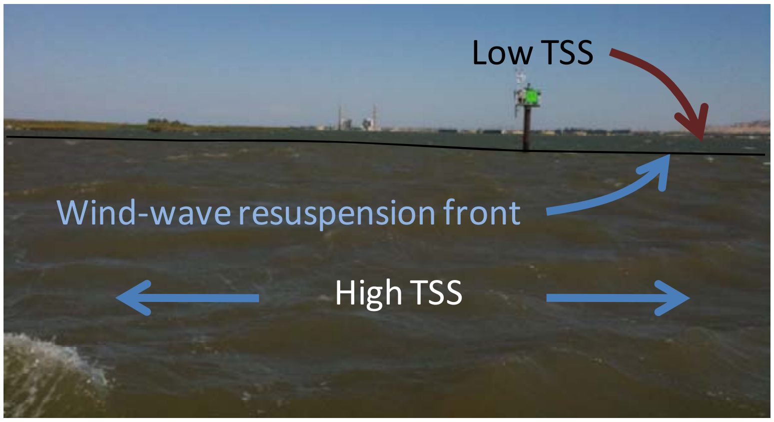
(Warner et al. 2003). In tidally influenced channels that open to the shallow Bay, physical processes operating on a tidal time scale can result in the oscillation of sediment between channels and the Bay. Flood tide currents can resuspend sediments outside the mouth of a channel and transport them up into the channel. As the tide goes slack, sediment becomes deposited in the channel. When the tide reverses, local currents increase and the sediment mass is resuspended. The mass is transported out of the channel and can be redeposited outside the channel mouth (Schoellhamer et al. submitted, Ganju et al. 2004). This phenomenon was observed by Brennan et al. (2000), who found that sediments in Cutoff Slough eroded more readily during the first two hours of a spring ebb tide and that strong stratification developed during neap ebb tide conditions. They calculated the average landward flux of sediment on an 8 day interval to be 14 $g/s/m^2$.

Total suspended solids concentrations affect the depth to which light can penetrate the water column. This penetration depth in turn affects primary productivity and the production of chlorophyll-a and dissolved oxygen (DO). If secondary consumption is greater than primary production, oxygen saturation decreases to less than 100%. If primary producers outproduce consumption rates, the water column can become supersaturated with regards to DO. DO is discussed more in-depth in Section 1.7.2 below.

1.6.3 Wind-Wave Resuspension and Tidal Transport

Wind-wave resuspension combined with tidal transport provides a suspended sediment source. The Suisun Marsh region is renowned for persistence, strong winds; so renowned in fact that much of the lands extending from the east side of the Marsh to Rio Vista now support extensive wind mills generating large quantities of electricity. These winds generally originate from the west. The large shallow embayments of Suisun Bay, Grizzly Bay, and Honker Bay in the south and the smaller Little Honker Bay in the northeast can produce high suspended sediment loads. Their physical orientation relative to prevailing winds (Figure 1-3) often optimizes wind-wave resuspension. These processes are readily visible in the water as shown in the photographs taken near Chipps Island (Figure 1-24). Figure 1-25 illustrates how these mechanisms tidally transport and deposit from the shallow bays into the large sloughs and thus become available for marsh accretion; the primary consideration is that TSS concentrations decrease with distance upstream of the shallow embayments, meaning that restoration sites near these bays have a comparatively high sediment load and sites far from these bays have a comparatively small sediment load.

A) Honker Bay wind-wave resuspension on flood tide; front of higher TSS waters tidally transporting east



B) Plume of Honker Bay wind-wave resuspended sediments transporting on flood tide through Spoonbill Slough (between Chipps and Van Sickle Island) into deepwater channel

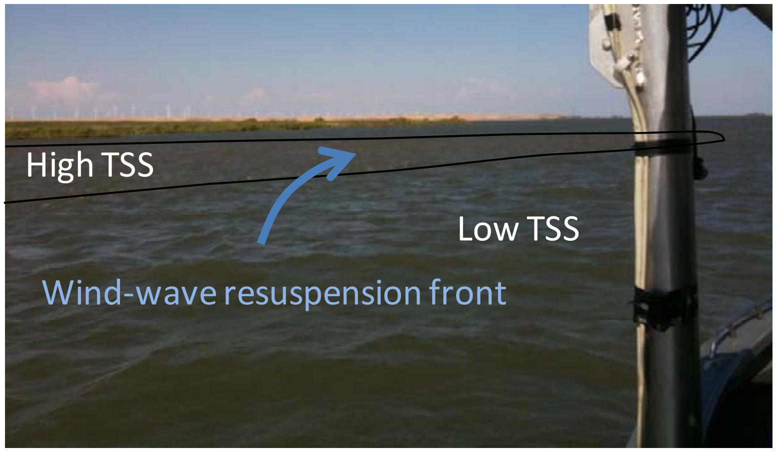
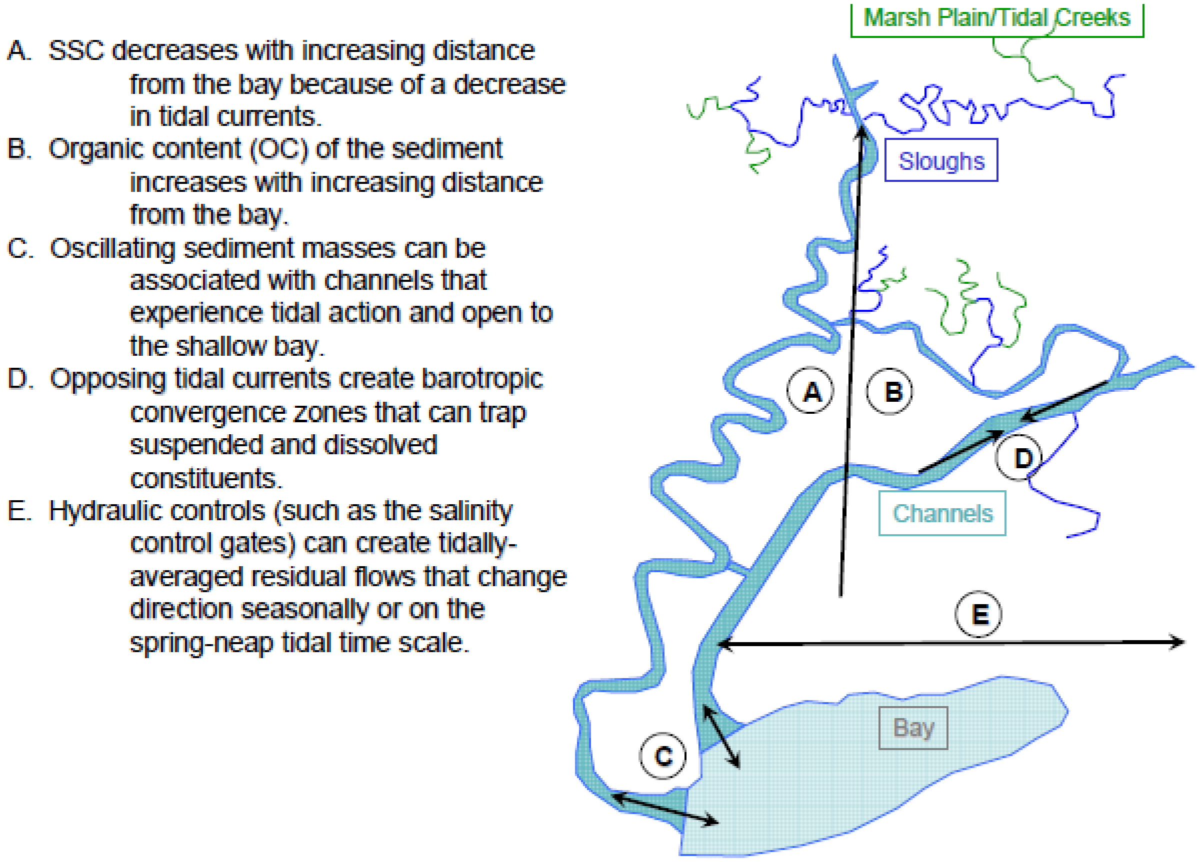


Figure 1-24. Wind-Wave Resuspension and Tidal Transport, Honker Bay and Deep Water Channel

Photos taken 7-29-2009 within first two hours of flood tide with moderately strong wind-wave energy resuspending sediment from Honker Bay. Photos by Stuart Siegel



A. SSC decreases with increasing distance from the bay because of a decrease in tidal currents.
B. Organic content (OC) of the sediment increases with increasing distance from the bay.
C. Oscillating sediment masses can be associated with channels that experience tidal action and open to the shallow bay.
D. Opposing tidal currents create barotropic convergence zones that can trap suspended and dissolved constituents.
E. Hydraulic controls (such as the salinity control gates) can create tidally-averaged residual flows that change direction seasonally or on the spring-neap tidal time scale.

Figure 1-25. Conceptual Model of Tidal Transport of Suspended Sediment

Source: Chris Enright, DWR

1.6.4 Suspended Sediment and Marsh Persistence

The long-term sustainability of a marsh at any given site depends on the relative rates of sea level rise, plant productivity, sediment accretion/erosion, compaction, and subsidence which interact to maintain marsh elevations in dynamic equilibrium with tide levels (Mitsch and Gosselink 1986, French 1993, Callaway *et al.* 1996, Allen 2000, Morris *et al.* 2002, Orr *et al.* 2003). The rate of accretion is vital to the ongoing sustainability of the marsh as restored marshes need sufficient accretion of sediment and biomass to persist in the long term. As shown in Figure 1-26, vertical accretion occurs at an exponential rate. Sedimentation rates decrease with increasing elevation due to shorter inundation duration. Once vegetation colonization begins, sedimentation rates increase due to sediment trapping by plants (Eisma and Dijkema 1997, Friedrichs and Perry 2001). The elevation at which plants colonize, a function of water salinity, thus plays an important role in influencing sedimentation patterns and processes. Vegetation colonizes the brackish tidal marshes of Suisun at lower elevations than in the saline lower estuary and at higher elevations than in the freshwater Delta.

Note the sediment concentrations described in Figure 1-26. At 100 mg/L, many decades are required for sedimentation to raise site elevations. At the 400 mg/L level, rapid sedimentation can occur. As will be described below in Section **Error! Reference source not found.**, sediment concentrations in Suisun Marsh and Bay are generally at or below the lower end of the values shown in Figure 1-26.

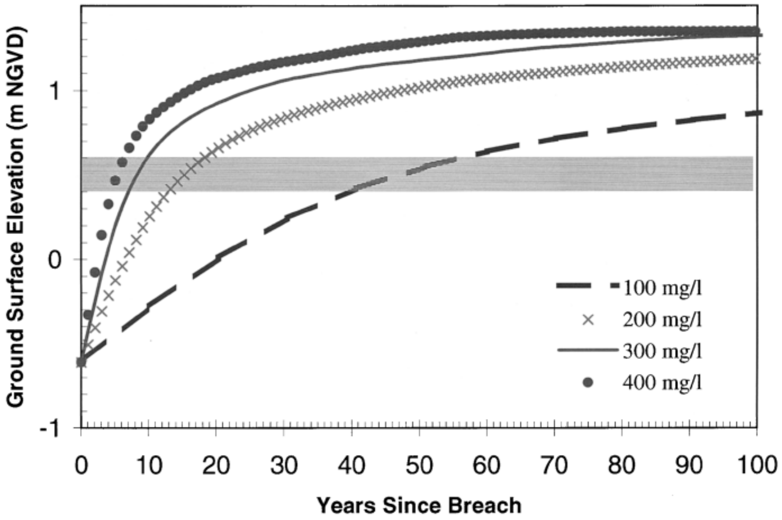


Figure 1-26. Approximate Timelines of Accretion as a Function of Sediment Supply

This plot is for the lower, saline region of the San Francisco Estuary. Applies to sites sheltered from wind-wave action. The 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. Source: Williams and Orr (2002).*

There are three physical processes that can slow or prevent the physical evolution of a subsided restored site to a vegetated marsh: 1) restricted tidal exchange due to narrow levee breaches or small inlet channels, which limit the amount of sediment entering the site, thus delaying vegetation establishment; 2) a limited sediment supply from the absence of a reliable source or small size of a reliable source; and 3) internally generated wind waves, which can potentially prevent deposition by creating turbulence and resuspending sediment which may then be exported on the ebb tide (Williams and Orr 2002).

1.6.5 Suspended Sediment Concentrations Overview

No systematic monitoring of suspended sediment concentrations spatially or temporally has occurred in Suisun Marsh. There are, however, a moderate number of discrete data sets available that provide some insight into sediment concentrations. These data sets were each collected for their own particular objectives and thus have highly varying spatial and temporal coverage. Table 1-2 provides a list of these data sets and each is discussed afterwards.

One important factor to consider is that SSC in Suisun is highly variable spatially, seasonally, and interannually. Wind-driven resuspension is a major contributor to SSC throughout much of the summer (westerlies) and during winter storms (southerlies) and is not as significant a contributor at other times of years. Delta sediment inputs occur largely with storm events, with the first major storm of the winter carrying much of the year's sediment supply. Local creek sediment input occurs only with storm events so again is limited in duration. Lower estuary inputs occur during neap tide series mainly in the summer when wind resuspension in San Pablo Bay provides a supply that can be transported upstream into Suisun Bay.

Table 1-2. Suspended Sediment Data Summary for Suisun Marsh

Location	Data Collection Period	Mean SSC (mg/L)	Source
Honker Bay	December 1996	32-44	Ruhl and Schoellhamer 2004
Mallard Island channel	December 1996	27	Ruhl and Schoellhamer 2004
Honker Bay	April-July 1997	102-151	Ruhl and Schoellhamer 2004
Mallard Island channel	April-July 1997	65	Ruhl and Schoellhamer 2004
Little Honker Bay	Dec 2004 – Jan 2006	97	WWR, unpublished data (Blacklock restoration planning for DWR)
Arnold Slough	Dec 2004 – Jan 2006	83	WWR, unpublished data (Blacklock restoration planning for DWR)
Brown's Island main channel	Oct 2003 to May 2005	12.5	IRWM, unpublished data
Montezuma and Nurse Slough	Single samples, summer 2005	104	Snow, unpublished data

*Poor resolution in low SSC range resulted in clipping below 10 mg/L.

Ruhl and Schoellhamer Data

Ruhl and Schoellhamer (2004) measured SSC at a shallow water site (Honker Bay) and adjacent deep-water channel (Mallard Island) from December 1996 through July 1997. Flow velocity, conductivity, temperature, depth, and SSC were continually measured at both sites. Generally, SSC were higher at the shallow water site than at the adjacent deep water channel. The study observed temporal trends in both the shallow-water and deep-channel sites. In December, SSC was low at both sites, but increased dramatically following the extreme first flush winter storm event. The mean SSC increased 3-5 times between December and the spring months in Honker Bay, while the mean SSC doubled over the same period at Mallard Island. Similar trends were observed by WWR at the Blacklock Restoration Site in northeast Suisun Marsh (see below).

WWR Blacklock Restoration Planning Data

WWR measured SSC at two shallow sites adjacent to the Blacklock Tidal Marsh Restoration Project (Figure 1-3), as part of project planning by DWR. The Little Honker Bay station was at the east or downwind side of the small embayment within the interior of Suisun Marsh. The Arnold Slough station was within a terminal tidal slough on the south side of the restoration site. These data indicate a number of patterns of SSC. First, the Little Honker Bay station had higher sediment concentrations than did the Arnold Slough station throughout most of the data period; this difference likely reflects its closer proximity to the Little Honker Bay sediment resuspension source. Second, both stations reveal distinct seasonal patterns with fall months having the lowest concentrations well below 100 mg/L. Third, both stations indicate a strong signal with the daily and spring-neap tidal cycles. Lastly, SSC ranges often within the 100-200 mg/L range, which is relatively low in the context of the sediment accretion timelines shown in Figure 1-27.

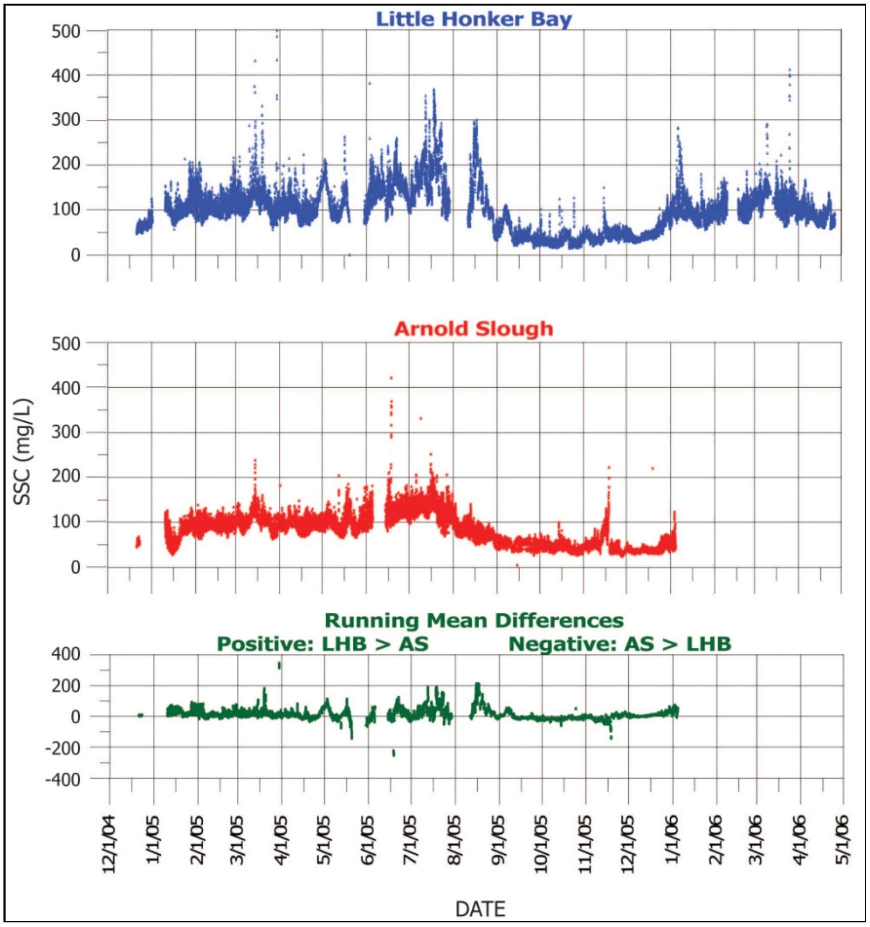


Figure 1-27. Suspended Sediment Concentration Data Outside Blacklock Restoration Site, Pre-Restoration, December 2004 to April 2006

Little Honker Bay (LHB) and Arnold Slough (AS) 12-minute data from optical backscatter sensor. Data are filtered, calibrated, and adjusted for sensor fouling. Difference plot is 2-hour running mean. Source: Wetlands and Water Resources

CALFED Integrated Regional Wetland Monitoring (IRWM) Data

The IRWM project studied six tidal marshes to examine how restoration affects ecosystem processes at multiple spatial and temporal scales. Study sites were Sherman Lake (restored) and Browns Island (natural) in the west Delta; Coon Island (natural), Bull Island (restored), and Pond 2A (restored) in the Napa-Sonoma Marsh complex; and Carl's Marsh (restored) at the mouth of the Petaluma River. Field work took place from fall 2003 to spring 2005. For Browns Island where the Delta meets the southeast corner of Suisun Marsh, SSC values averaged 12.5 mg/L, very low on average, with a maximum value of 850 mg/L (Figure 1-28).

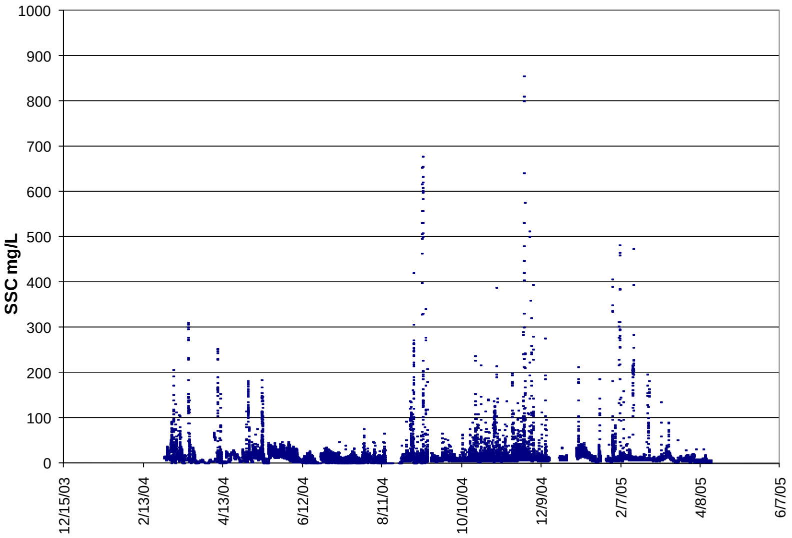


Figure 1-28. Browns Island SSC Data, Oct 2003 - May 2005

Data collected at 12-minute intervals with optical backscatter sensor from main channel approximately 1 foot above channel bed. Source: IRWM (2007).

Snow Data

Snow (2005) conducted a small study of SSC concentrations measured longitudinally along Montezuma Slough and up Nurse Slough toward the Blacklock restoration site. Twenty-three SSC depth profiles were collected along Montezuma Slough and Nurse Slough over three non-consecutive days and at different times throughout the tide cycle, which limits interpretation potential. Figure 1-29 displays the sample locations and their average SSC.

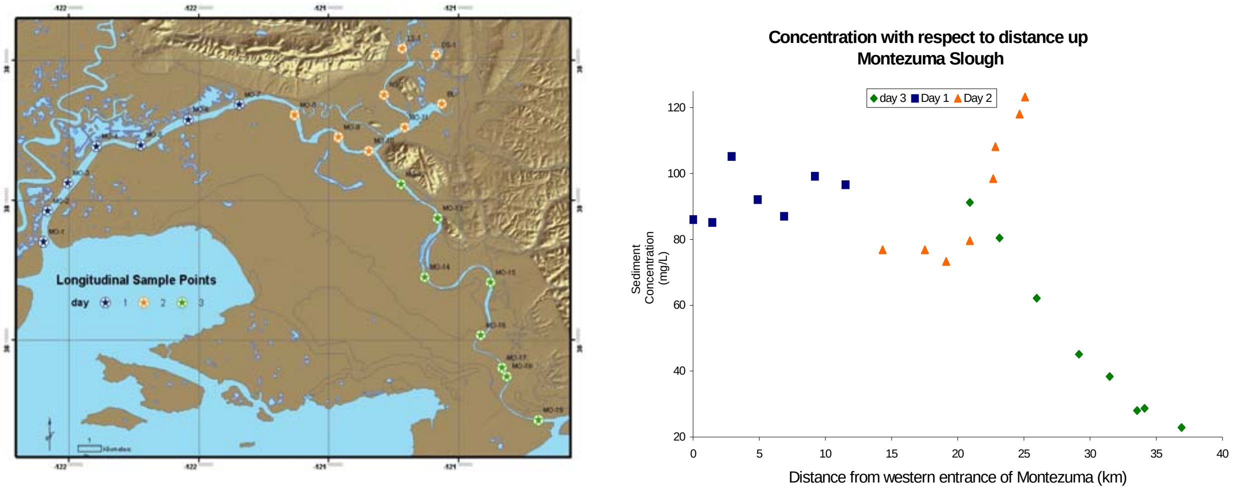


Figure 1-29. Montezuma and Nurse Slough Single-Sample Longitudinal SSC Profile, Summer 2005

Samples collected over course of three days (6/22/05, 6/28/05, and 7/11/05). Each data point represents a single data collection event consisting of one depth-integrated measurement per location. Source: Snow (2005).

The data indicated a slight SSC increase in the western mouth of Montezuma Slough, roughly similar SSC in the middle reach of Montezuma Slough, and strongly decreasing SSC between the Nurse Slough confluence southeast to the Sacramento River confluence. Nurse Slough SSC indicated an increasing concentration from Montezuma Slough north, with the highest SSC observed in the northernmost region of Nurse Slough around Little Honker Bay.

1.7 Other Water Quality Constituents

1.7.1 Temperature

Temperature is an important variable for biological processes. Changes in temperature can stimulate biological responses such as spawning and movement (Kimmerer 2004). Water temperature in Suisun is continuously measured at several monitoring stations throughout the marsh (Figure 1-19). Data from monitoring stations in Suisun Marsh demonstrate that on an annual basis, water temperature generally tracks ambient air temperatures, which generally vary between 8°C and 22°C east of the Coast Range, and annual water temperature values appear to be consistent throughout the marsh (Figure 1-30). Other influences on temperature include the temperature of tidal source waters and the temperature of river flows (the latter is especially important during higher flow periods) (Kimmerer 2004).

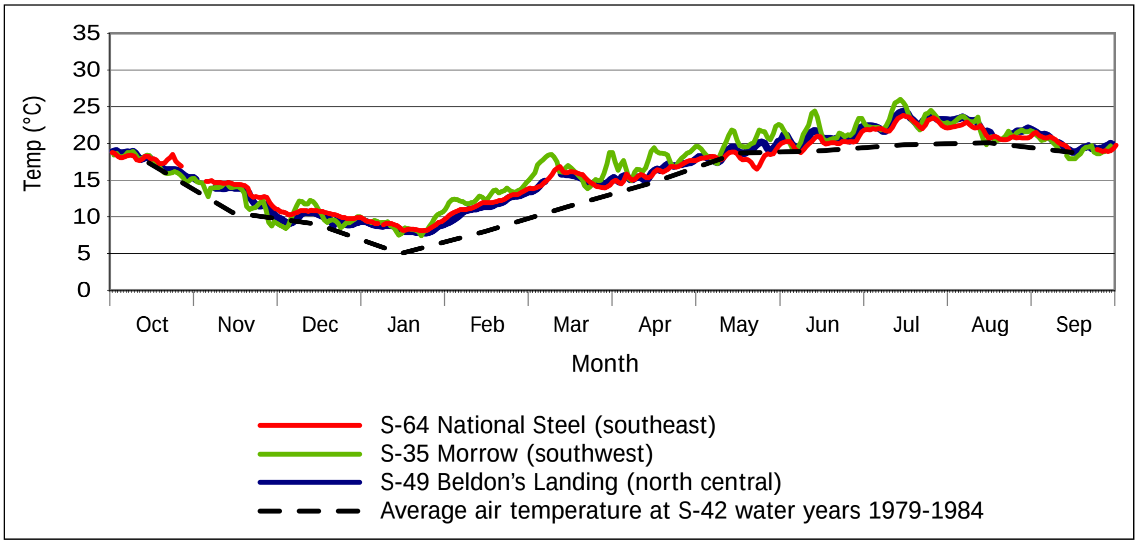


Figure 1-30. Seasonal Patterns in Air and Water Temperature

Source: DWR

The effects tides have on water temperature are more evident, with variability associated with the spring-neap tidal cycle. Water temperature appears to decrease during the spring tides (as the estuary fills) and increase during neap tides (as the estuary drains). Variability in daily temperature follows a similar pattern with an increase in daily variability during the neap tides and a decrease during the spring tides. Daily temperature variability also appears to be influenced by proximity to freshwater creeks. Stations S-64 and S-49, which are both located along Montezuma Slough, a relatively large slough, have less daily temperature variability than S-35, which is located in Goodyear Slough, a smaller slough that has a greater freshwater influence and less tidal exchange.

Summer spring-tide overbank flooding of tidal marshes at night-time exert a significant effect on lowering surface water temperatures. During the summer months, the higher-high tide of the spring tides occurs during night-time, the opposite being the case in winter (Malamud-Roam 199x). A DWR study in spring and summer 2004 in First Mallard Branch, one of the large sloughs within the large, natural tidal marsh at Rush Ranch, found that water temperatures dropped more each night (1-2 ºC) during large spring tides than that observed in a similar sized slough nearby (Sheldrake Slough) surrounded by dikes rather than tidal marsh (Figure 1-18 above) (Enright, 2004).

1.7.2 Dissolved Oxygen

Appropriate levels of dissolved oxygen (DO) are critical to organisms in aquatic environments. In general, organisms will become stressed when DO drops to 5 mg/L, the water quality standard set by the San Francisco Bay Regional Water Quality Control Board. Hypoxia occurs at DO values between 2 to 5 mg/L and anoxia occurs below 2 mg/L. A DO sag can act as a barrier to the movement of aquatic organisms, depending on the location of the sag and the organisms' ability to tolerate low DO. This sag limits fishes and other organisms access to areas of the marsh that might otherwise provide predator escapement or are rich in food resources, and they can result in mortality. In addition, other water quality problems for aquatic organisms such as increased methyl mercury concentrations and elevated ammonia and hydrogen sulfide levels are associated with low DO events (Mark Stephenson, pers. comm.). These concerns warrant further research (Schroeter and Moyle, 2004, 2005). According to Cloern et al*.* (1983), Suisun typically is below 100% oxygen saturation, but these conditions are not static and change interannually, seasonally, and episodically. For example, in the spring large freshwater flows are moving through the marsh; primary productivity during these times often exceeds consumption because the rivers provide an external source of primary production. As freshwater flows decrease and salt water starts to intrude into the Delta, primary production is overtaken by secondary consumption. This pattern has not always been the case. Prior to the introduction of *Corbula amurensis,* Suisun experienced a mild late spring phytoplankton bloom. There is evidence that water clarity in the Delta and Suisun is improving due to the efficiency of *C. amurensis* at filtering the water column (Kimmerer 2004).

Suisun Marsh waterfowl club landowners manage water for the benefit of waterfowl and other wetland species. Most managed wetlands are dry during the summer and early fall months when land managers carry out maintenance activities. Fall flood-up typically involves a series of one or more flood-drain-flood cycles after which the wetlands circulate water through the winter and drain at variable times in the spring depending on particular property management objectives. These managed wetlands activities result in the production of organic matter (OM) in the form of wetland and aquatic vegetation that peak in quantity in spring and summer months. When this OM decomposes, it creates high biological oxygen demand (BOD) from microbial respiration. With fall flood-up comes removal of DO from the pond water column by this BOD. The fall flood-up and drain cycle can thus create low DO waters that upon release send low DO plumes into receiving waters (tidal sloughs). These pond releases can also be rich in nutrients and organic matter that stimulates further microbial activity, thereby increasing biological oxygen demand (BOD) in the receiving waters, which can continue to reduce receiving water DO after pond drainage has ceased. Possible sources of excess nutrient loading into Suisun Marsh waterways include the Fairfield-Suisun wastewater treatment plant that discharges into Boynton Slough (see Figure 1), incidental discharges at the Suisun City marina, and fertilizer in runoff from agricultural and residential areas that enter Suisun Marsh via the creeks and storm drains.

The extent to which low DO and high BOD managed wetland discharges adversely affect receiving water quality depends on residence times in the receiving water. Large tidal sloughs exchange water rapidly and thus are not as subject to low DO problems. Small and especially dead-end sloughs exhibit less exchange and thus longer residence times and consequently are particularly susceptible to low DO problems. Recent data collected on the nature of the DO sags in the marsh (Schroeter and Moyle, 2004) have shown that many sags occur in small, dead-end sloughs. The most significant problem areas have been Boynton, Peytonia, and Suisun Sloughs in the northwest marsh.

The processes behind low DO events and their relationships to other water quality concerns are relatively poorly understood in Suisun Marsh. To fill this knowledge gap, the *Suisun Marsh Low Dissolved Oxygen and Methyl Mercury Best Management Practices for Diked Wetlands* is an applied research project funded by the State Water Resources Control Board. The project was a collaboration between SRCD, USGS, DFG-MLML, DWR, UC Davis, and Wetlands and Water Resources, Inc., and had the participation of five duck club ownerships and the Fairfield-Suisun Treatment Plant. Field work took place in 2007 and 2008 and the final report is anticipated for later in 2010. The study examined operational changes at two clubs in the northwest Suisun Marsh, along Peytonia and Boynton Slough, and collected baseline data at three clubs on Grizzly Island. At the two intensively studied clubs, data collection included continuous water stage and quality in the sloughs and club interiors (depth, temperature, conductivity, pH, DO, turbidity), grab samples at tide gates and within the clubs (organic carbon, methyl mercury, sediment), soil samples for organic carbon and methyl and total mercury, vegetation mapping, topography, flow at the mouths of Peytonia and Boynton sloughs with Suisun Slough, and water quality discharge data from the Treatment Plant.

1.7.3 Organic Matter

The information in this section is a summary of the Water Quality Organic Matter Conceptual Model developed for the Suisun Marsh Plan.

Organic matter (OM) plays an essential role in sustaining food webs, mediating contaminant dynamics, and determining drinking water quality. Several OM sources can reach Suisun Marsh though no studies have quantified their relative contributions. Tidal emergent vegetation detritus can be the source of substantial amounts of OM in estuaries and coastal oceans (Raymond and Bauer 2001). Adjacent uplands that remain hydrologically connected can also contribute vegetation detritus. Phytoplankton and attached algae may also contribute a significant amount of OM, and large algal blooms have been observed in Suisun Marsh (Schroeter *et al*. unpublished, Enright *et al.,* unpublished). The managed wetlands in Suisun often contain significant amounts of organic matter in their discharges. Finally, suspended sedimentary material tidally transported from adjacent Grizzly Bay transfers OM into Suisun Marsh.

1.1.1.1 Geographic framework

The five OM sources are distributed across the marsh landscape primarily according to bathymetric limitations on growth. Tidal and managed wetland areas will primarily support vascular plant production. Phytoplankton production will occur in open water areas where sufficient light penetration occurs. Shallow quiescent areas will support benthic and epibenthic algal and submerged aquatic vegetation production. Intertidal mudflat areas will support epibenthic algal production.

1.1.1.2 Hydrologic and meteorological constraints

Hydrodynamic and meteorological forces have varying effects on different OM sources, governed largely by the hydrologic connectivity of geographic sources to channel networks and the Bay. For example, areas with higher elevations, slough-marsh plain hydrological connectivity during spring tides, and managed wetlands are the primary sources of vascular plant-derived DOM and detrital material in Suisun Marsh. Return flows through organic rich surface soils may result in high exports of DOM from marsh plains. An example of a meteorological effect is the potential suppression of phytoplankton production by wind-wave resuspended sediments tidally advected into Suisun Marsh from Grizzly Bay (Schoellhamer *et al.* 2003).

1.1.1.3 Effects on biology and chemistry

Vascular plant exudates, soil leachates, and particulate and colloidal plant detritus may represent the most important carbon source for microbial production (Kirschner and Velimirov 1999) and fuel ecosystem metabolism in Suisun Marsh. However, organic matter originating from algae is thought to be of greater bioavailability than vascular plant derived organic matter (Sobczak *et al.* submitted) and may stimulate microbial activity (Preen and Kirchmann 2004). Thus, algal OM production fuels the marsh food chain and high rates of biological organic matter utilization and transformation.

Plant-derived OM may be relatively rich in hydrophobic humic substances, with high concentrations of phenolics and other aromatic constituents, while phytoplankton derived OM may contain less humic substances. Dissolved OM (DOM) exported from wetlands is also rich in colloids, or finely divided solids which may be grazed directly or aggregate into larger sinking particles. These chemical characteristics influence OM bioavailability and may also impact the production, transport and uptake of mercury (Hg) into the food web. Up to 50% of the methyl mercury in the San Francisco Estuary has been found associated with DOM, and half of that associated with colloids (Choe and Gill 2003).

1.1.1.4 OM Exports

The amount of OM exported from Suisun Marsh is unclear; however, substantial organic matter exports have been found for the San Francisco Estuary (Jassby *et al.* 1993, Stepanauskas *et al*. 2003) and elsewhere (e.g., Raymond and Bauer 2001). The Suisun Organic Carbon conceptual model speculated that substantial DOM exports are more likely than substantial particulate (POM) exports.

1.1.1.5 Effects of Anthropogenic Changes

Anthropogenic changes to marsh geomorphology and hydrology may substantially alter the patterns and processes described above and lead to changes in (1) the quantity and quality of OM within and exported from the Marsh and (2) related biogeochemical processes. For example, a decrease in channel network complexity may be associated with increased connectivity with the Bay, decreased marsh plain connectivity, and fewer high and medium residence time areas which may result in lower plant and algae production and lower water and sediment OM concentrations. Altered timing and frequency of hydrological connectivity between marsh plains and sloughs (e.g., as the result of wetland management) probably causes substantial changes in OM dynamics and associated biogeochemical processes in wetlands and adjacent sloughs.

A better understanding of OM sources and fluxes as well as processes affecting OM quality and interactions in Suisun Marsh is needed to guide management and restoration efforts aimed at maximizing trophic transfer efficiencies and minimizing subsidence and contaminant transport and effects. Such fundamental information will also be transferable to similar restorations elsewhere in the Bay-Delta system. A discussion of the current understanding of the interrelationships among physical, chemical, and biological variables related to OM production, utilization, and chemistry along a hydrological connectivity gradient from San Francisco Estuary to Suisun Marsh uplands can be found in the Suisun Marsh Water Quality Conceptual Model: Organic Matter.

1.8 Contaminants

Contaminants have many possible sources and pathways of exposure to fish and wildlife and to humans that may consume sportfish and waterfowl and come into direct contact with waters and sediments in Suisun. Suisun Marsh is surrounded by urban, agricultural, and industrial land uses in Solano and Contra Costa counties. Figure 1-4 shows land uses within and immediately surrounding Suisun Marsh and Figure 1-31 shows land uses within the entire Solano and Contra Costa watersheds that drain directly into Suisun Marsh. In addition to these local watersheds, the entire Central Valley of California drains into Suisun Bay.

This section first presents an overview of key contaminant sources (industrial and commercial activities, agriculture, the Mothball Fleet, and Suisun diked and tidal wetlands). It then discusses specific contaminants of concern: mercury, organic compounds, copper, and selenium.

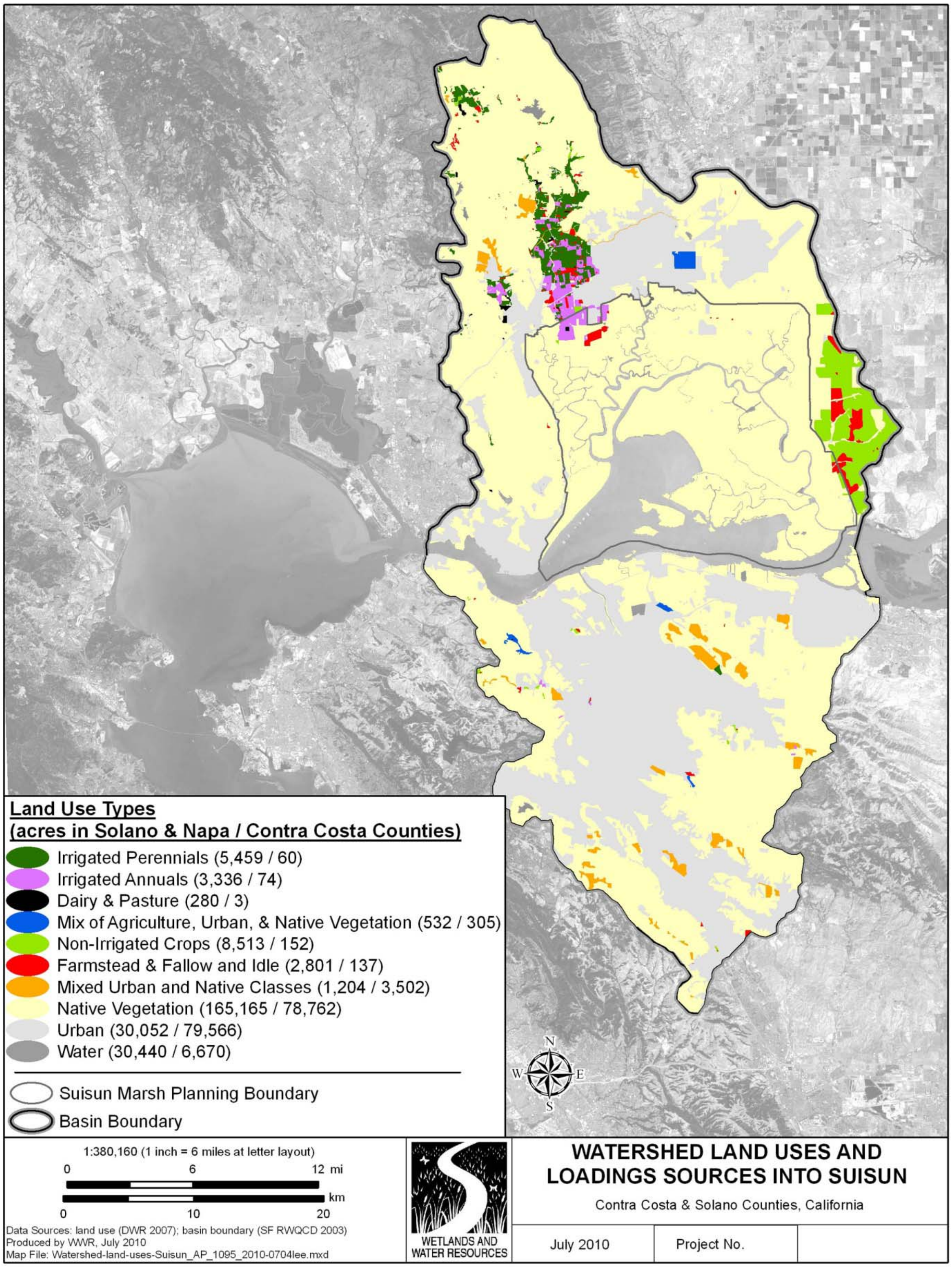


Figure 1-31. Watershed Land Uses

1.8.1 Contaminant Sources – Industrial and Commercial Activities

Suisun Marsh and Bay are susceptible to pollution from a suite of industrial and commercial activities that may degrade the quality and quantity of a broad range of habitats. Removal of substrate from the bay floor for dredging and mining purposes leads to a direct physical loss of subtidal habitat. Sand mining is currently allowed within 107 acres around Middle Ground shoal and adjacent shoals in Suisun Bay. The mined sand is used as aggregate in concrete for commercial construction within the greater San Francisco Bay area. Although mining operations can significantly impact benthic infauna and epifauna, it generally has a low likelihood of entraining macro-invertebrates and fish (MEC 1993). Dredging in order to maintain navigation channels also occurs in portions of Suisun Bay. The "Suisun Bay Channel" extends from the Carquinez Strait at Martinez to Pittsburg and is dredged annually to maintain its 300' wide and 35' deep profile. The "New York Slough" continues upstream from Pittsburg to Antioch and is dredged every four years to maintain its 250' wide and 20' deep channel (GS 2005).

Two power generating stations along the Contra Costa shoreline create a potential stressor on Suisun subtidal systems. These power plants draw as much as 3,240 cubic feet per second of water from Suisun Bay through unscreened pipes to cool their turbines. As a result, fish and invertebrate species are impinged and entrained by the plants' cooling system. Biological surveys in 1979 estimated as much as 86 million Delta smelt (*Hypomesus transpacificus*) and their larvae were being impinged or entrained annually; though it is likely that this number has decreased since then due to the fish's recent population crash (Taugher 2006). Moreover, thermal discharges from the plants into Suisun Bay can create lethal conditions for aquatic life, especially species' larval stages. Elevated temperatures can alter the biochemical processes of the environment and the behavior (e.g., migration) and physiology (e.g., metabolism) of marine organisms (Hanson et al. 2003).

The Suisun Bay shoreline along Benicia in Solano County and along much of Contra Costa County is home to numerous industrial enterprises including oil refineries, chemical plants, steel plants, boatyards, and the like. These industries as well as toxic hot spots contribute organic and inorganic pollutants into Suisun Bay waters which can have deleterious effects on aquatic organisms. Suisun Bay is also home to the U.S. Navy's Ready Reserve Fleet (the "mothball fleet"), a collection of retired naval ships anchored semi-permanently. This fleet may contribute small quantities of organic and inorganic pollutants into Suisun Bay via exterior paint deterioration and bilge pump discharge water.

1.8.2 Contaminant Sources – Agriculture

Solano County supports a range of agricultural activities within the watershed draining into Suisun Marsh, and Contra Costa County has some operations within the watershed (Figure 1-31). Agricultural operations are generally in two areas relative to Suisun Marsh. Suisun Valley and Green Valley to the northwest support a variety of agricultural operations including irrigated perennial crops, irrigated annual crops, and dairy and pasture. The Montezuma Hills to the east support non-irrigated (dry land farmed) forage mainly supporting sheep pasture. Contaminant discharges from agricultural operations can vary widely based on the specific agricultural activity and how the operations are managed. Herbicides, pesticides, fungicides, fertilizers, and animal waste are the broad categories of discharges that could occur. This conceptual model has not undertaken any evaluation of the specific operations within the watershed.

1.8.3 Contaminant Sources – Mothball Fleet

The Suisun Bay Reserve Fleet Site (SBRF) or Mothball Fleet was established as part of the Merchant Ship Sales Act of 1946 to provide a reserve ship fleet for national defense and other emergencies. At one point, during the 1950's to early 1960's more than 500 ships were moored at the SBRF site, which is located 4½ nautical miles northeast from the Benicia-Martinez Bridge. Currently the SBRF is comprised of 72 vessels consisting of commercial and U.S. Naval auxiliary vessels and U.S. Coast Guard icebreakers and buoy tenders, ranging in size from 55-meters to 270-meters. The Fleet is maintained by the United States Maritime Administration.

In response to concerns raised by the State of California and multiple environmental groups regarding the probable release of heavy metals, anti-fowling agents, PCBs and other hazardous materials, in 2008 NOAA's Office of Response and Restoration received an appropriation from Congress to evaluate the potential impacts of the Mothball Fleet on the aquatic environment of Suisun Bay.

The results of this assessment were released in February 2009, which summarized the evaluation of contaminant loads in sediment, transplanted mussels, and resident clams at 72 sampling stations. Though metals were detected in over 99% of all individual analyses performed on sediment samples, the conclusions of this study indicate that levels of contaminants of ecological concern relative to the greater San Francisco Bay estuary, were not significantly elevated and thus sediments from the SBRF study area pose a low to moderately low potentially for toxicity to benthic invertebrates. Additionally, the incidence of PCB detection in surface sediments was low. Paint chips and metal debris were noted in 18% of surface sediment grab samples, which was consistent with observations that paint and materials continue to be released from the vessels and remains a matter of concern as an ongoing source of contamination in the bay. Manganese was the only contaminant that showed a statistically significant elevated mean concentration compared to other locations; however, this difference was not significant when compared to references areas in Suisun Bay.

An additional analysis of the potential impacts of the SBRF on sediment erosion and deposition indicated an overall trend of erosion for the SBRF area (an average change of -0.64 meters between 2002 and 2007), with sections of sediment shoaling between vessels and an apparent inshore longitudinal stretch of sediment accretion (ranging from 0.25 to 1.5 meters). Sampling methods for the sediment deposition study were derived from a conceptual model developed by NOAA, which initially assumed that Suisun Bay has been overall net erosional and thus contaminants released by the SBRF would likely be absorbed, transported, and deposited with suspended sediment and bed load. However, further review of hydrodynamic and sediment transport studies suggest that depositional features (specifically the inshore shoal) near the SBRF are most likely to contain contaminants or paint chips and would provide the best media for quantifying contaminants originating from SBRF over time.

The general lack of significantly elevated contaminant loads near SBRF was described by NOAA to potentially be due to the fact that contaminant releases from exfoliated paint would not be concentrated as seen in point source releases. It was additionally suggested that the dynamic hydrology of Suisun Bay both removes contaminants from the SBRF area shortly after release and contributes to mixing SBRF contaminants with contaminants from other sources. Following this analysis no sediment remedial actions are proposed for the SBRF region of Suisun Bay (NOAA 2009).

1.8.4 Contaminant Sources – Managed and Tidal Wetlands

Managed and tidal wetlands have the potential to contribute methyl mercury into waters of Suisun Marsh and thereby into fish and wildlife through food web bioaccumulation. Methylmercury can be produced where wetland marsh soils undergo oxic-anoxic shifts and where sufficient organic matter is available. The key process affecting methylmercury production in wetlands is the inundation regime; in general, long cycles of wetting and drying are necessary to support the shifts in soil anoxia that support the biogeochemical processes leading to mercury methylation. Tidal marsh that receive daily tidal exchange generally do not provide the necessary inundation regime. The upper reaches of tidal marshes where the infrequent highest spring tides flood the marsh do exhibit more suitable inundation regimes for mercury methylation. Managed wetlands are well suited to mercury methylation, with their long cycles of wetting and drying (Alpers et al. 2008). See further discussion about methylmercury below in Section 1.8.5.

1.8.5 Mercury

Methylmercury (CH_3Hg, commonly annotated MeHg) is a potent human and wildlife neurotoxin (U.S. EPA 2001). The primary route of exposure is from consumption of MeHg-contaminated fish. The San Francisco Estuary has been listed on the California 303(d) list as an impaired water body because of elevated methylmercury concentrations in fish. In addition, health advisories have been issued for the San Francisco Estuary and several of its tributaries cautioning people to limit their consumption of mercury-contaminated fish. The few studies that have been conducted in Suisun Bay and Marsh found some fish had high levels of methylmercury. Seven of eight striped bass from Suisun Bay were above the EPA screening level for protection of human health (Slotton *et al*. 2003). Two of five inland silversides (a small forage fish abundant in the Marsh) in Suisun Marsh were above the EPA screening level for protection of human health (Slotton *et al*. 2003). A discussion of the state of knowledge of mercury cycling processes in Suisun Marsh can be found in the Suisun Marsh Water Quality Conceptual Model: Mercury.

Mercury (Hg) originates in the San Francisco Estuary from a number of historic and current sources. Historically, the region supported several cinnabar mines, and some mines still cause legacy loading to the estuary. Beginning in the 19th century, gold mining in the Sierra Nevada used mercury to isolate gold from ore. The downstream transport of hydraulic mining debris from these activities eventually spread mercury throughout the estuary and into the Pacific Ocean. Tailings from hydraulic mining still contribute mercury to the estuary each year during spring flooding. Modern mercury sources include industrial and wastewater and atmospheric deposition (Davis *et al.* 2002).

Though Cinnabar mercury from the Coastal Range occurs in a stable mercury sulfide (HgS) form, mercury from hydraulic mining in the Sierra Nevada enters the estuary as elemental mercury. Conversion from elemental mercury requires reduction to Hg^{2+} before it can bond with other molecules such as sulfide or methane (CH_3). This process takes place within the aerobic/ anaerobic interface in wetlands and the substrates of bays and rivers. The anoxic conditions often found in tidal and managed wetlands can provide very suitable conditions for mercury methylation, with distinct periods of wetting and drying increasing methylation capacity. Data available for Suisun Marsh indicate that the managed wetlands can produce significantly higher methylmercury concentrations than those found in its tidal marshes (Mark Stephenson, in-progress research). Understanding the relative contributions from and controlling factors for methylmercury production in Suisun is essential to making informed decisions for management and restoration.

The scientific understanding of the processes that affect methylmercury production and cycling is relatively limited at this time. Several research efforts are underway throughout the region that examine factors influencing mercury methylation and demethylation, transport, organismal uptake, ecotoxicological effects, and ecosystem effects. These studies and efforts include, but are not limited to, the following projects:

- Transport, cycling and fate of mercury and monomethyl mercury in the San Francisco Delta and tributaries, an integrated mass balance assessment approach – San Jose State University Foundation: Moss Landing Marine Labs (CALFED)
- Mercury and methylmercury processes in North San Francisco Bay tidal wetland ecosystems – San Francisco Estuary Institute (CALFED)
- Measurement of mercury release from Delta wetlands: amounts, alterations, and implications – U.S. Geological Survey (CALFED)
- Methylmercury Conceptual Model for the Delta (CALFED DRERIP; Alpers et al. 2008)
- Regional Monitoring Program Methylmercury Annual Meetings (http://www.sfei.org/rmp)
- The Suisun Marsh Low Dissolved Oxygen and Methylmercury Study currently underway (SWRCB)

1.8.6 Organic Compounds

Marshes are often a sink for organic contaminants, especially hydrophobic compounds associated with sediments. Organic contaminants of greatest concern regionally can be generalized into three categories: polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organophosphate pesticides. Recent studies evaluating the relative contribution of different sources into Suisun Marsh (agricultural inputs from the Delta and upstream throughout the Central Valley, municipal wastewater, and industrial activities) indicate that the Delta is a major source for agricultural products and the Bay and the Delta may be major sources for PCBs and PAHs (Leatherbarrow *et al.* 2005). Within Suisun Marsh, organic contaminants can be bioavailable, move into the food web, and ultimately cause adverse ecological effects. The fate of organic contaminants depends on the individual physiochemical properties of each compound and the overall effect of ecosystem processes on transport, partitioning, and uptake by organisms. Knowledge about the occurrence of organic contaminants in the Marsh is critical for undertaking any restoration effort. This knowledge, coupled with an understanding of how the hydrologic, biochemical, geomorphic, and ecological processes influence the bioavailability of these contaminants, would provide information necessary for management and restoration decisions.

Contaminants from upland sources originate from a variety of anthropogenic activities. Residential, commercial, and industrial discharges are treated at the Fairfield-Suisun Treatment Plant (Fairfield-Suisun Sewer District 2006) and enter the Marsh via a pipeline to Boynton Slough on the northwestern edge of the Marsh (Figure 1-4). Stormwater discharges untreated to the Marsh and can include pesticides applied in urban and agricultural settings in Suisun Marsh uplands (Figure 1-31). The growing urban area around Fairfield is a source of pesticides used around homes and businesses that enters Suisun Marsh via untreated storm drains. Two creeks that drain into Suisun Marsh, Laurel and Ledgewood creeks, and Suisun Slough are on the US EPA 303(d) list for impairment by diazinon from urban runoff and storm sewers. Pyrethroid insecticides are replacing diazinon and chlorpyrifos and could become a problem in the future. In the adjacent agricultural areas, a variety of pesticides are applied to vineyards, orchards, and ornamental turf farms. Applications of pyrethroid and organophosphate insecticides for mosquito control are likely to increase as West Nile virus and Avian Flu become more of a concern in Northern California. Another upland source of contaminants is Travis Air Force Base. Hydrophobic organochlorine compounds, including legacy pesticides, from contaminated facilities at Travis Air Force Base (San Francisco Bay Regional Water Quality Control Board Adopted Order #99-072) are present in ground waters and surface waters adjacent to the marsh. Contaminants detected at the highest concentrations include alpha-chlordane, dieldrin, heptachlor epoxide, and PCBs. Herbicides and insecticides have been detected in water and sediments near the mouth of Montezuma Slough throughout much of the year (Domagalski and Kuivila 1993; Kuivila and Foe 1995; Kuivila and Moon 2004).

1.8.7 Copper

Copper is a toxin that can be lethal in aquatic environments to fish, invertebrates and amphibians, can reduce growth rates, and has been proven detrimental to embryonic development (USEPA 1993). Although bioaccumulation has not been demonstrated in fish, phytoplankton are highly sensitive to copper toxicity and therefore copper exposure could compromise the base of the food chain and higher trophic levels. Copper exposure could also reduce the efficiency of photosynthesis in phytoplankton and cyanobacteria (Brand et al. 1986). The toxicity of copper to aquatic autotrophs is demonstrated by its frequent use as an anti-fouling agent in marine coatings and as an anti-algal agent in pools, ornamental ponds, and drinking water reservoirs. Other copper sources include agricultural runoff (copper is used as a topical anti-fungal for horses and cattle), municipal wastewater plant discharges (from copper pipes used in many households), and runoff from road/paved areas (which contain particulate copper from brake pads).

The US EPA has placed elemental copper on the 303(d) Watch List for the San Francisco Estuary (SFEI 2005) and has published a draft document, 2003 Draft Update of Ambient Water Quality Criteria for Copper (EPA-822-R-03-026), which describes new criteria for aquatic life in both freshwater and saltwater (USEPA 2004). Currently, no regulatory standard for dissolved copper concentrations has been implemented for any region of the San Francisco Bay other than Lower South San Francisco Bay (SFRWQCB 2004). However, recent collaborations between the San Francisco Bay RWQCB and the Clean Estuary Project and others have made significant progress in addressing the State Implementation Policy. These efforts include the publication of a series of documents outlining recent results, applied methodologies, and conclusions relating specifically to water north of the Dumbarton Bridge (further separating the North Bay to include San Pablo Bay, Suisun Bay, and the Delta) and concluded impairment of beneficial uses in the Bay due to copper is unlikely (EOA 2005a-d).

1.8.8 Selenium

Selenium continues to be an element of concern in the San Francisco Bay Estuary and other waterways due to potential toxicity at higher levels and its implications in the aquatic food web. Toxicity of this element proves complicated because of its multiple oxidization forms (organic and inorganic), which effect bioavailability and toxicity. In its inorganic form, selenium has been shown to be at its most bioavailable form for phytoplankton uptake, thus integrating into the lower trophic levels and leading to further bioaccumulation in higher trophic levels (Purkerson et al. 2003). One of the major consumers of phytoplankton in the San Francisco Bay Estuary is the exotic Asian Clam (Corbula amurensis), which also accumulates much higher levels of some contaminants, including Se, than formally dominant bivalves. High concentrations of Se are particularly problematic to primary consumers of C. amerensis (diving ducks and sturgeon) because this element has a low margin between deficient and excess dietary levels leading to toxicity (Richman and Lovvorn 2004, Fox et al. 2005). Selenium toxicity in wild aquatic birds, especially diving ducks (scaups and scoter), has been associated with mortality, impaired reproduction, and teratogenesis (embryo defects) and has been found to cause reduced hatchability in eggs (Fox et al. 2005). Further study has also identified bioaccumulation of Se in lower level pelagic consumers, which provide an integral food source for many juvenile and adult fish; however, such levels in zooplankton communities were found to vary among species and may be influenced by seasonal influxes of Se from freshwater inputs (Purkerson et al. 2003).

Sources of Se in the San Francisco Bay estuary have been linked to freshwater inflows from the Sacramento and San Joaquin Rivers, with the Sacramento River contributing lower concentrations. High concentrations of Se are found in the San Joaquin River, which drains the naturally high seleniferious soils of the Southern Central Valley (Purkerson et al. 2003). Additionally sources are likely contributed from oil refineries and other agricultural run-off. Suisun Bay and the San Francisco Bay have been place on the USEPA 2006 303(d) list for impaired by elevated Selenium levels (USEPA 2007). Levels of Se are, as expected, higher in Suisun Bay and Carquinez Straight due to their proximity to oil refinery and riverine sources (Purkerson et al. 2003).

1.9 Future Drivers of Change

Suisun Marsh will experience several changes over the 30-year life of the Suisun Marsh Plan and beyond that have great potential to change conditions in the Marsh: climate change, large-scale restoration, and land use change within the watershed. Each of these topics is summarized here.

1.9.1 Climate Change: Sea Level Rise and Storm Frequency and Intensity

Climate change effects will affect California and the San Francisco Estuary in a number of ways. Climate change projections are sensitive to many future human actions and to highly complex atmospheric processes, making specific projections challenging at best. California is projected to retain its Mediterranean climate of cool and wet winters and warm and dry summers, including experiencing a high degree of variability in interannual precipitation amounts. Here we present two scenarios developed by a collective group of large studies funded by the California Energy Commission (CEC) under mandates of the Governor's Biennial Climate Change Report and utilized in early 2010 by the U.S. Environmental Protection Agency in its Climate Ready Estuaries pilot project for the San Francisco Estuary. A majority of the climate change projections presented here were developed by Cayan et al. (2009) based on projections from six leading climate models[2]. These models were selected based on their reasonable representation of historical simulation of seasonal precipitation, seasonal temperature, the variability of annual precipitation, and El Niño/Southern Oscillation (ENSO). All models were run with both a lower emission scenario (B1 SRES) and a mid-high emission scenario (A2 SRES) to capture a range of plausible future emission trajectories. Regional projections were developed by statistical downscaling.

For sea level rise projections in U.S. coastal locations, relative sea level rise may differ from global estimates due to a number of factors such as changes in local ocean circulation, ocean density, vertical land motion, erosion and sedimentation, gravitational effects, isostatic rebound, etc. Relative sea level rise in California has demonstrated similar rates of rise compared to global estimates (Cayan et al. 2008). Many California studies recommend using projections of global sea level rise estimates, which assumes California relative sea level rises continue at the same rate as global sea level rise. The "lower range" estimate is the mid-range of Rahmstorf (2007) and high-end of IPCC TAR. The "higher range" estimate is the high estimate of Rahmstorf (2007). Table 1-3 presents these projections.

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[2] (1) NOAA Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1; (2) the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); (3) NCAR Community Climate System Model (CCSM); (4) the Max Planck Institute ECHAM5/MPI-OM; (5) the Center for Climate System Research of the University of Tokyo MIROC 3.2 medium-resolution model; and (6) the French Centre National de Recherches Meteorologiques (CNRM) models.

Table 1-3. Summary of Climate Change Scenarios: Averages for Mid 21st Century

Source: U.S. EPA Climate Ready Estuaries Pilot Project for the San Francisco Estuary

Metric		"Lower Range" Scenario	"Higher Range" Scenario
Temperature [a]	Annual average [b]	+2.8ºF (1.6ºC)	+3.5ºF (1.9ºC)
	Average increase of winter temperature [c]	+2.5ºF (1.4ºC)	+2.7ºF (1.5ºC)
	Average increase of summer temperature [c]	+4.0ºF (2.2ºC)	+4.5ºF (2.5ºC)
	Extreme heat days [d]	+10 days/year	+16 days/year
Precipitation	Annual change [e]	-4.5%	-7%
	Winter change	Reduced winter precipitation [f]	
	Heavy events	Decline in frequency of precipitation events (exceeding 3mm/day) but not a clear signal in changes of precipitation intensity	
Sea Level	Total increase for 2050 [g]	+30 cm	+45 cm
	Hourly sea level rise exceedances [h]	1343	1438
Storms and wind [i]		Tendency toward a decline in storms [j]. Projections suggest an increased frequency for heightened sea level events to persist for more hours. ENSO is not projected to increase in frequency or intensity.	
Snow pack change		For the Central valley watershed, April watershed-total snow accumulation projected to drop 64% by 2060 [k]	
Spring runoff		Spring runoff occurring earlier and reduced overall	
Seasonal changes in the amount of freshwater inflow to the Bay from the Delta in 2060 [l]		October through February: inflow +20% March through September: inflow -20%	

Notes:

[a] *Averages are for 2035-2064 projections relative to 1961-1990 baseline for B1 and A2 emission scenarios*

[b] *Approximate results using B1 and A2 emission scenarios and three global climate models (PCM1, GFDL CM2.1, and HadCM3) (CEC 2006)*

[c] *Results for Sacramento, CA. Warming projected to be more moderate along coastline (50km from coast) and rising considerably inland (Cayan et al. 2009). Averages are for 2035-2064 projections relative to 1961-1990 baseline for B1 and A2 emission scenarios*

[d] *Extreme heat days defined as daily maximum temperature exceeding 95th percentile of temperature from 1961-1990 historical averages of May-September days. 1961-1990 baseline approximately 8 days/year based on model runs. Results from Cayan et al. 2009 using three global climate models (CNRM CM3, GFDL CM2.1, and MICRO 3.2 with bias-corrected downscaling) for B1 and A2 emission scenarios. Mid-century projections suggest hot daytime and nighttime temperate increase in frequency, magnitude, and duration (Cayan et al. 2009). Extreme warm temperatures in California, historically a July and August phenomenon, will increase in frequency and magnitude likely beginning in Jane and may continue into September (Hayhoe et al. 2004; Gershunov and Douville 2008, Miller et al. 2008).*

[e] *Results are averaged across six global climate models using the grid point nearest to Sacramento (Cayan et al. 2009) for B1 and A2 emission scenarios*

[f] *CEC (2008)*

[g] *Sea level rise relative to 2000. DRMS (2007) also provides recommended 2050 global sea level rise estimates relative to 1990 of 11 cm (direct extrapolation of observed 20th century data), 20 cm (low end of Rahmstorf (2007) and approximate mid-range of IPCC TAR), 30cm (approximate mid-range of Rahmstorf (2007) and approximate high end of IPCC TAR), 41cm (high end of Rahmstorf (2007)).*

[h] *Hourly sea level exceedance defined as maximum duration (hours) when San Francisco sea level exceeds the 99.99th percentile level (140cm above mean sea level) (Cayan et al. 2009)*

[i] *Cayan et al. 2008*

[j] *Storm defined as sea level barometric pressure falling below 1005 millibar*

[k] *Knowles and Cayan (2004) "business-as-usual" scenario relative to 1995-2005*

[l] *Knowles and Cayan (2004) accounts for reservoirs, in-stream valley diversions, and in-Delta withdrawals and assumes no future management adaptation or altered demand patterns*

1.9.2 Large-Scale Tidal Restoration in Suisun and the Delta

Restoration of up to 7,000 acres of tidal marsh is anticipated in the Suisun Marsh Plan, and other planning efforts have called for up to 25,000 acres of tidal restoration in Suisun. The primary effect of this restoration, beyond all of its target benefits to ecosystem functions for native and migratory species, is the potential to alter tidal hydrodynamics within Suisun Marsh. Hydrodynamic modeling conducted by RMA for the Suisun Marsh Plan has demonstrated that restoring tidal action to large areas of subsided lands absorbs significant tidal energy and reduces tidal range in the near region. Some of the modeled scenarios suggest that mean lower low water may be up to one-half meter higher than it is with the current channel configuration. This raising of the low water level effectively makes some of the remaining intertidal land area shown in Figure 1-6 lower than indicated, relative to the tides. The exact magnitude of this effect on tides depends on where tidal marsh restoration efforts are located. As restoration sites accrete through mineral sedimentation and plant matter accumulation, their tidal prisms will decrease and these tidal effects will reverse.

1.9.3 Land Use Change in the Watershed

The cities of Fairfield and Suisun City continue to grow, converting open space, abandoned industrial sites, and agricultural lands into urban land uses. The primary effects of these changes are increases in impervious surfaces leading to greater stormwater runoff that reaches Suisun Marsh and a change in nature of potential contaminant loadings associated with the land use changes. The other concern is that of mosquito control; more residences located near Suisun Marsh increases the demand for mosquito control in Suisun.