Suisun Marsh Conceptual Model/ Impairment Assessment Report for Organic Enrichment, Dissolved Oxygen, Mercury, Salinity, and Nutrients

November 26, 2013

Prepared by:

Tetra Tech, Inc. Lafayette, CA and Wetlands and Water Resources, San Rafael CA

Table of Contents

List of Figures

List of Tables

Acronyms

BDAT:	Bay Delta and Tributaries
BOD:	Biological Oxygen Demand
BY:	Boynton Slough
CASTNET:	Clean Air Status and Trends Network
CDFG:	California Department of Fish and Game
CMS:	Cubic Meter per Second
CTR:	California Toxics Rules
CWA:	Clean Water Act
DO:	Dissolved Oxygen
DOC:	Dissolved Organic Carbon
DWR:	Department of Water Resources
EC:	Electric Conductivity
EST:	Estuarine habitat
FI:	Fluorescence Index
FSSD:	Fairfield- Suisun Sewer District
GY:	Goodyear Slough
MDN:	Mercury Deposition Network
MeHg:	Methylmercury
MIGR:	Fish migration
MZ:	Montezuma Slough
NADP:	National Atmospheric Deposition Program
OC:	Organic Carbon
OM:	Organic Matter

POC:	Particulate Organic Carbon
PT:	Peytonia Slough
RARE:	Preservation of rare and endangered species
REC-1:	Water contact recreation
REC-2:	Noncontact water recreation
RMP:	Regional Monitoring Program
Regional Water Board:	San Francisco Bay Regional Water Quality Control Board
SC:	Specific Conductivity
SEW:	Suisun Ecological Workgroup
SMSCG:	Suisun Marsh Salinity Control Gates
SPWN:	Fish Spawning
SU:	Suisun Slough
SUVA:	Specific Ultraviolet Absorbance
SWRCB:	State Water Resources Control Board
TCMS:	Thousand Cubic Meters per Second
TDS:	Total Dissolved Solids
THg:	Total Mercury
TKN:	Total Kjeldahl Nitrogen
TSS:	Total Suspended Solids
WARM:	Warm freshwater habitat
WILD:	Wildlife habitat

EXECUTIVE SUMMARY

Suisun Marsh is listed on the Clean Water Act (CWA) 303 (d) list for impairment by metals, nutrients, organic enrichment/low dissolved oxygen and salinity/TDS/chlorides (Regional Water Board, 2007). In this report, conceptual models are developed and impairment assessments performed for Suisun Marsh for the following parameters: dissolved organic carbon, dissolved oxygen, mercury, salinity, and nutrients.

Suisun Marsh is one of the largest brackish wetlands in western North America. The marsh is primarily comprised of diked managed wetlands, tidal marshes, and connected to Suisun Bay by sloughs and channels. These wetlands are managed to provide habitat for wildlife. The wetlands were flooded and drained during fall and experienced several flood and drain cycles in spring, and remain dry during the summer season. The managed wetlands have significant impacts on water quality in the sloughs in terms of dissolved organic carbon, dissolved oxygen, mercury, salinity, and nutrients.

In developing the conceptual models, sources of each constituent class to Suisun Marsh were evaluated. Sources were quantified where adequate data were available. Processes within the marsh that affect the distribution of these constituents, particularly the roles of managed wetlands on dynamics of these constituents, were emphasized. Spatial and temporal variations in constituent concentrations across the marsh were also evaluated. The observed constituent concentrations were compared to the Basin Plan water quality objectives to determine the impairment due to each constituent. For mercury, sampled fish tissue mercury concentrations were compared to the EPA guidelines for fish tissue concentrations for protection of human health or wildlife to determine the impairment.

The conceptual model/impairment assessment of organic carbon in Suisun Marsh is summarized below.

- Sources of organic carbon to Suisun Marsh include:
    - Internal production: macrophytes in shallow water, attached algae in shallow calm areas, phytoplankton in deep open water, and wetland soils (Enright et al. 2009);
    - Other sources: organic materials tidally transported from Grizzly Bay, surrounding watersheds, treated wastewater from the Fairfield Suisun Sewer District (FSSD) plant, and release from managed wetlands.
- The managed wetlands are characterized by higher organic carbon concentrations than the adjacent sloughs (2.5–7 times). Sources of organic carbon in managed wetlands include releases from wetland soils, in situ primary production and organic carbon inputs from sloughs.

- Organic carbon concentrations in managed wetlands increased after fall flood-up and then decreased. Upon release, the managed wetlands discharge sent pulses of high organic carbon water to the adjacent sloughs.
- Although data across wetlands is limited, the nature of vegetation management may affect organic carbon export to sloughs.
- Given the extent of quantification that could be performed with available data, the discharge from managed wetlands appears to be a dominant pathway of organic carbon loads to the sloughs.
- Specific ultraviolet absorbance (SUVA) measurements suggested lower aromatic content from fresh plant and algae and higher aromatic content from degraded organic matter (OM) from plants and soils. There was an increase in SUVA after a few weeks of fall flooding, indicating consumption of labile OM and release of OM from soils.
- Currently there are no documented water quality objectives for DOC for comparison, although there is a link between high DOC and low DO, for which there are water quality objectives as discussed is subsequent sections.

The conceptual model/impairment assessment of dissolved oxygen is summarized below.

- Causes of low DO in Suisun Marsh sloughs include:
  - Various sources of biochemical oxygen demand (BOD) in the water column:
    - Tides (and delta outflow) that bring BOD from the Delta and Suisun Bay
    - Surrounding watersheds that drain agricultural and urban areas
    - Wastewater treatment plant effluent
    - Managed wetlands discharges that are low in DO and high in BOD
    - Tidal marshes
  - Slough size: narrow slough width limits mixing, resulting in low DO. Low DO is often found in smaller sloughs.
- The preliminary load estimates presented here, given available data, suggest that the most significant drivers of low DO are vegetation and water management activities in the managed wetlands that result in releases of low DO water, as well as water containing high concentrations of organic carbon. These can be directly linked to low DO in adjacent small sloughs. Inputs of BOD from tributaries and the wastewater treatment are also contributors, although to a lesser degree than the managed wetlands. Limited mixing in small sloughs further exacerbates the low DO problem.
- DO monitoring conducted at two managed wetlands suggested that during fall drain events, DO concentrations at perimeter monitoring stations decreased to

near 0 mg/l and remained at 0 mg/l for several days. DO at interior stations showed prolonged periods of low DO concentrations near 0 mg/l throughout the fall period. Spring drain events lowered DO concentrations to near 0 mg/l but were able to recover quickly.

- DO monitoring at Peytonia, Boynton, Goodyear and Denverton Sloughs suggested low concentrations below water quality standards during fall and spring drain periods.
- For all tidal waters above the Carquinez Bridge, the applicable water quality objective for DO is 7 mg/l. DO concentrations at several sloughs monitored are below 7 mg/l for over 50% of the time (Peytonia, Boynton, Goodyear and Denverton Sloughs) and are considered as impaired by low DO. DO concentrations measured at Montezuma and Suisun sloughs showed occasional low concentrations below 7 mg/l and are also considered as impaired by low DO although to a much lesser degree.
- DO concentration at reference sites: the First and Second Mallard Slough data suggested occasional low DO concentrations during fall months of below 5 mg/l, suggesting a DO target of 7 mg/l may not be met at all times even at reference sites.

The conceptual model and impairment assessment of mercury (Hg) may be summarized as follows:

- Sources of mercury to Suisun Marsh include: inflow from the Sacramento-San Joaquin Delta, tributary inputs, atmospheric deposition, coastal embayment and internal sources of Hg. High Hg concentrations have been found in sediments of Suisun Marsh wetlands. The Delta and tributaries are the primary mercury inputs.
- Higher methylmercury (MeHg) concentrations were found in managed wetlands than other habitats. The managed wetlands are characterized by the highest level of reactive inorganic Hg (Hg(II)) and methylation potential. The drying and wetting regime, high organic carbon and low DO concentrations in managed wetlands promote formation of reactive Hg(II) and methylmercury production.
- MeHg concentrations in managed wetlands increased after fall flood-up and then decreased. Higher MeHg concentrations were found in the interior than the edge of managed wetlands. MeHg concentrations were correlated to DOC.
- Higher total mercury concentrations were found in sediments of sloughs than wetlands, while higher MeHg concentrations were found in managed wetlands, suggesting higher methylation potential in managed wetlands.
- Elevated Hg concentrations in silversides above EPA criteria of fish tissue Hg to protect human health were found in Suisun Slough and Cutoff Slough, suggesting impairment of Suisun Marsh by mercury.

The conceptual model/impairment assessment of salinity in Suisun Marsh is summarized below:

- Salinity in Suisun Marsh is strongly affected by Delta outflow, Suisun Marsh Salinity Control Gates, tidal exchange with Suisun Bay, local creek inflows and the managed wetlands.
- Temporal variations in Suisun Marsh salinity are regulated by Delta outflow. Increases in Delta outflow resulted in lower salinity in Suisun Marsh. Suisun Marsh salinity showed a spatial gradient of increasing salinity from the east to west, due to proximity to the Delta outflow in the eastern marsh.
- The operation of Suisun Marsh Salinity Control Gates is effective in regulating salinity in Suisun Marsh (Enright and Culberson, 2009; Siegel et al. 2011).
- The tributary inflows have impacts on salinity most significantly during winter storm events and in the northwest corner of Suisun Marsh.
- The management of wetlands alters salinity by flushing saline water from wetland soils to sloughs.
- Overall, salinity appears to be within range in the larger sloughs, with occasional exceedances limited to smaller sloughs. The frequency of exceedances where they occur are relatively small. For the purpose of the current TMDL, given the larger-scale efforts at managing salinity in Suisun Bay by the State Water Resources Control Board, the salinity appears to not be a significant impairment under current targets.

The conceptual model/impairment assessment of nutrients in Suisun Marsh is summarized below.

- Secondary impacts associated with nutrients, such as chlorophyll a, are somewhat elevated in some locations, but are not higher than in designated reference stations. Using current data, impairment by nutrients is not clearly established and needs to be assessed through further data collection and evaluation.
- The review of data for the nutrient conceptual model highlights the need for a systematic sampling at key locations in the marsh (major tributaries, sloughs, and selected managed wetlands). Such sampling will provide the basis for a quantitative assessment of nitrogen and phosphorus loads to the marsh.
- The only nutrient constituent with a presently established numeric water quality objective in the San Francisco Bay region is ammonia, where the median concentrations are to be below 0.025 mg/l as nitrogen, with maximum values in Central Bay receiving waters not to exceed 0.16 mg/l as nitrogen. The ammonia concentrations observed in the tributary sloughs are compared to the calculated criterion, and no exceedance of either the acute or chronic toxicity criteria was found.

- Evidence of elevated organic carbon and impacts on DO and mercury methylation suggest that excess algal growth in managed wetlands, fueled by nutrients, may constitute an impairment of narrative criteria for nutrients in Suisun Marsh.

1. INTRODUCTION

1.1. GENERAL SETTING

Suisun Marsh, located 35 miles northeast of San Francisco in southern Solano County, is the largest set of brackish water marshes in the western coast of North America (DWR, 2003; Figure 1-1). The marsh provides habitat for many species of plants, fish and wildlife, including rearing and spawning grounds for migratory fish and waterfowl. The species found at Suisun Marsh include more than 221 avian species, 45 mammalian species, 16 reptilian and amphibian species and over 40 fish species. The predominant habitat types in Suisun Marsh are tidal perennial aquatic habitat, tidal wetland, seasonal nontidal (managed) wetlands, seasonal brackish managed marsh, and grassland. Currently the marsh contains 52,000 acres of seasonal non-tidal (managed) wetlands, 6,300 acres of tidal wetlands, 27,700 acres of upland grassland and 30,000 acres of bays and sloughs (CDFG, 2008).

The managed wetlands in the marsh contain levees to control water levels and seasonal flooding with freshwater is employed to balance soil salinities (CDFG, 2008;). A network of channels, sloughs and tidal creeks are located within Suisun Marsh. The extensive network of sloughs conveys tidal flows and freshwater into the marsh. Montezuma Slough is the largest slough that connects Suisun Marsh from the east to the west (Figure 1-2). The slough is an important nursery area for many species of fish, including Chinook salmon, striped bass, splittail, and Delta smelt. Suisun Marsh Salinity Control Gates (SMSCG), located near the eastern entrance of Montezuma Slough, are used to control the inflow of saltwater from the Bay into Suisun Marsh. Suisun Slough is another large slough located in the northwest of the marsh, connecting Suisun City and the Grizzly Bay. Several tributary sloughs which are smaller in size are 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 Cutoff/Mallard Slough complex in the central Suisun Marsh (Figure 1-2). Other sloughs in the northwest include Goodyear Slough and Cordelia Slough. The channels and sloughs are bordered by levees along managed seasonal wetlands, and fringing tidal marshes located near open water.

This chapter presents an overview of the principal driving forces behind the water quality processes in Suisun Marsh. In particular, impairment related to several of the constituents that are the focus of this work (organic carbon, dissolved oxygen, nutrients, and to a certain extent, mercury) are inter-related, as shown schematically in Figure 1-3. Thus, increased organic matter supply provides fuel for bacterial respiration that consumes dissolved oxygen and causes adverse impacts to biota. Similarly, increased nutrient supply increases algal biomass, and eventually the creation of detritus that consumes oxygen. Finally, anaerobic conditions may enhance the activity of bacteria that methylate mercury and increase mercury bioaccumulation, although this relationship is more complex than for organic matter and nutrients. Individual constituents and their inter-relationships explored in greater detail in Chapter 2 (organic carbon), Chapter 3 (dissolved oxygen), Chapter 4 (mercury), Chapter 5 (salinity), and Chapter 6 (nutrients).

Water quality in Suisun Marsh is influenced by several key factors:

- Hydrology (e.g., flooding and drying of the managed wetlands, delta outflow, local creek inflows)
- Hydrodynamics (e.g., tidal exchange)
- Land use (e.g., urban development, agricultural lands)
- Point sources (e.g., sewage discharge)

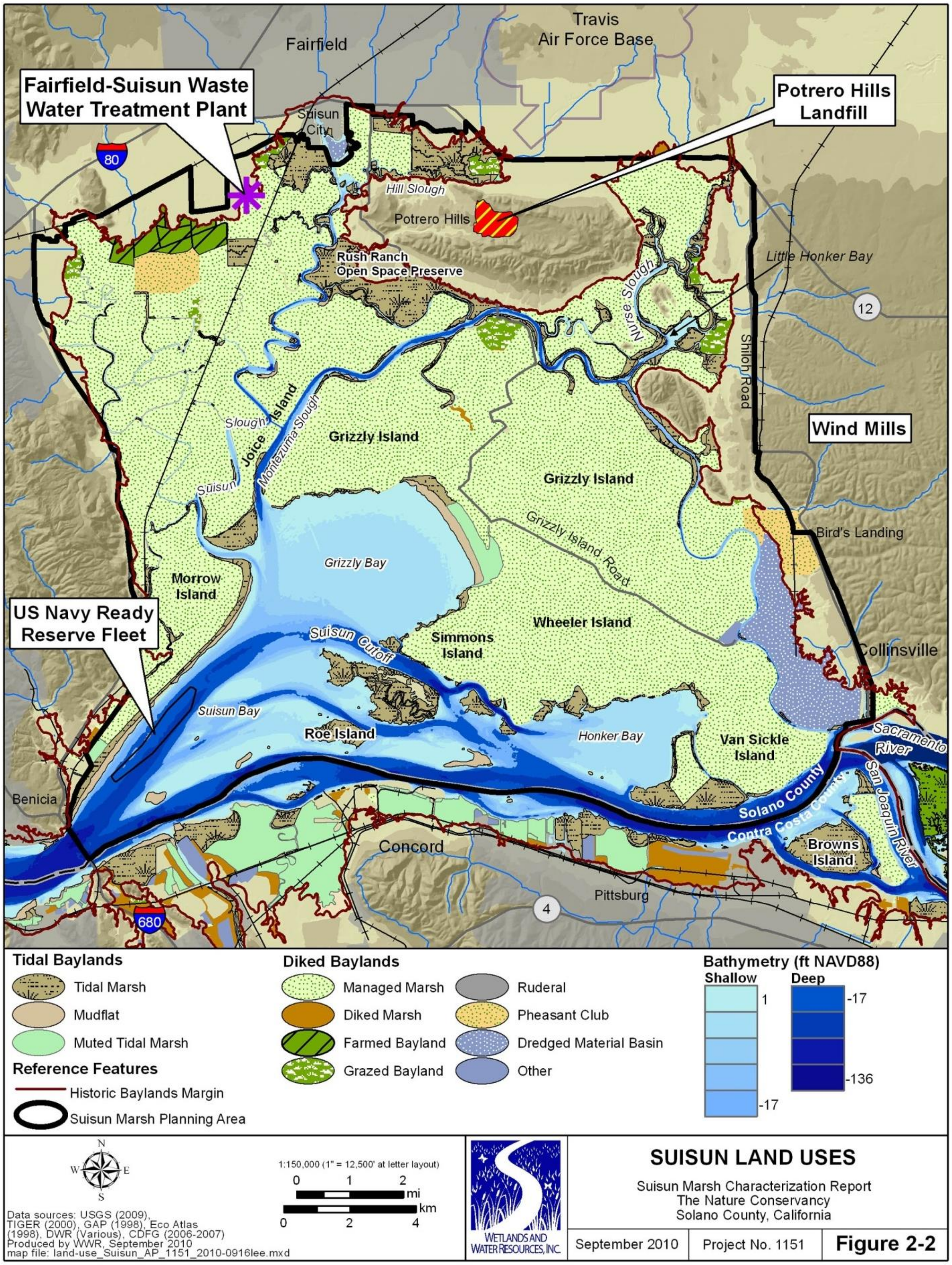


Figure 1-1 Land uses of watershed surrounding Suisun Marsh (From: Siegel et al. 2011).

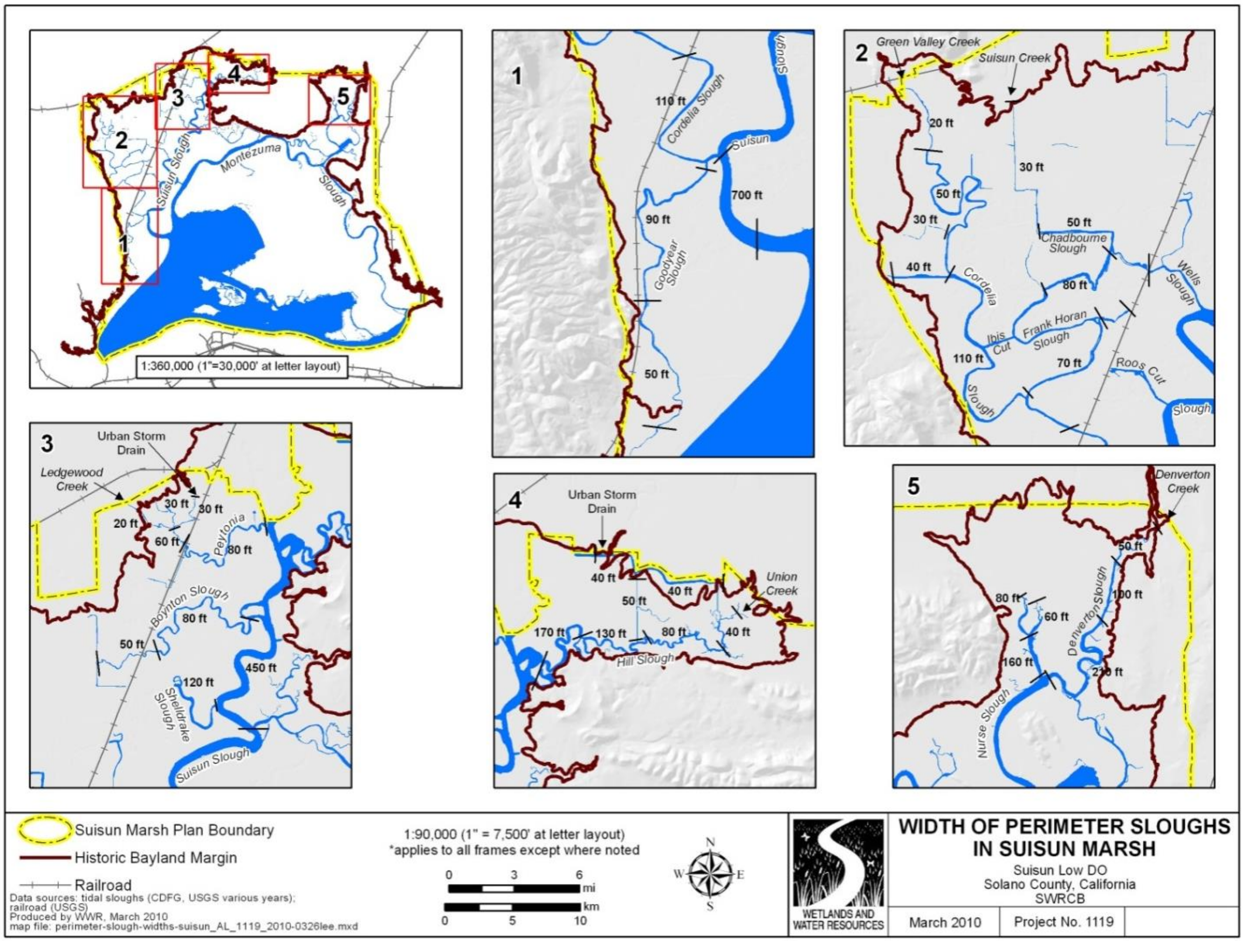


Figure 1-2 Slough networks within Suisun Marsh (from: Siegel et al. 2011).

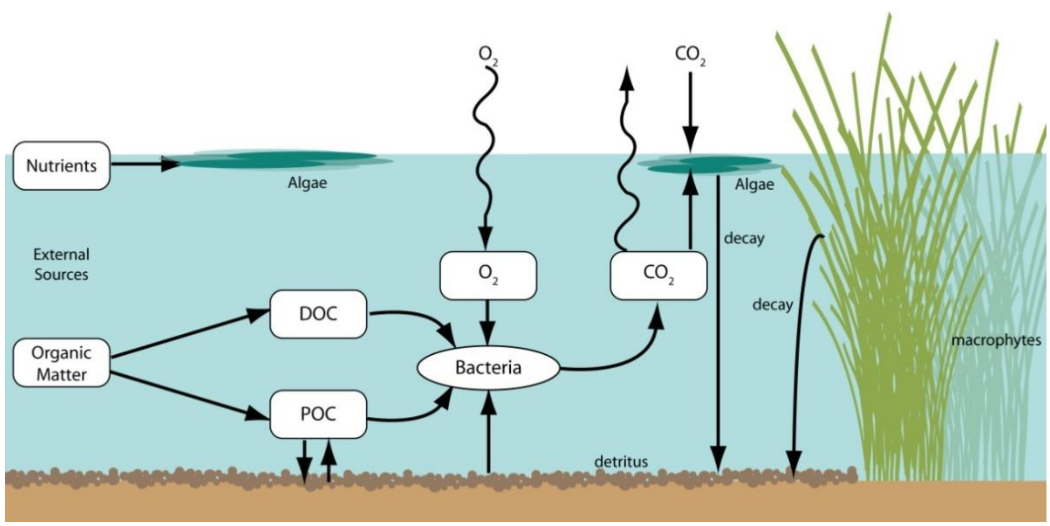


Figure 1-3 Inter-relationships between organic carbon, nutrients, and dissolved oxygen in waters of Suisun Marsh.

1.1.1 Hydrology

Delta Outflow

Delta outflow is considered to be the most significant driving force in Suisun Bay and Suisun Marsh (Siegel et al. 2011). Delta outflow represents total inflow from the Sacramento River, the San Joaquin River, east side tributaries, northwest tributaries, southwest tributaries, minus in-Delta diversions and exports to the State Water Project, the Central Valley Project, the North Bay Aqueduct and Contra Costa Water District. The inter-annual variability of Delta outflow is due primarily to variability in precipitation in the watershed, followed by Delta exports. Delta outflow can have significant effects on tidal stage in Suisun Marsh.

Delta outflow provides the primary source of fresh water for Suisun Bay and Suisun Marsh (DWR, 2001). Water quality in Suisun Marsh, particularly in terms of salinity, is influenced by Delta outflow. During high Delta outflow periods, the eastern Suisun Marsh has lower channel salinity than the western marsh, due to proximity to the Delta. The correlation between long-term trends in precipitation, Delta outflow and salinity in Suisun Marsh were recently explored by Enright and Culberson (2009). For the four-decade period of 1967–2006, the Delta outflow has shown a small decrease of approximately 5 cubic meters per second per year, driven by climate. In contrast, a monitoring station (Belden’s Landing) in Suisun Marsh shows a small, albeit significant, salinity decrease over the same period.

Local Creek Inflows

Several creeks enter Suisun Marsh (Figure 1-4), including Green Valley Creek, Suisun Creek, Ledgewood Creek, Laurel Creek, Union Creek and Denverton Creek. These creeks drain some large and urbanized watersheds in the north of Suisun Marsh. Ledgewood Creek flows along the west edge of the City of Fairfield and the east side of the cultivated agricultural lands. These creeks convey seasonal freshwater to Suisun Marsh as well as urban pollutants such as total suspended solids (TSS), metals, biological oxygen demand (BOD) and nutrients (Siegel et al. 2011). Peak flow of storm runoff from the watershed approaches 6,400 cfs. The base flow of the watershed is 4 cfs (Siegel et al. 2011).

Managed Wetlands

The primary goal of seasonal wetland management in Suisun Marsh is to provide wintering habitat for waterfowl, with a secondary goal of salinity control. This requires the water level in the wetlands to be within a certain range (8–12 inches). Wetland management usually begins in early October by flooding managed wetlands (or ponds) with water from the adjacent sloughs and channels (DWR, 2001). The water management contains several flood and drain cycles, including one major cycle in the fall and several during late winter/spring. Complete and half drainage of the ponds begins after the waterfowl season ends in January. The management of wetlands also includes management of vegetation through mowing, disking or using pesticides to remove standing vegetation, which can contribute to organic carbon buildup. After the end of the waterfowl season, the ponds are usually left dry through the summer. Problems are associated with dry conditions due to the loss of soil water through evaporation and increases in soil salinity.

Other problems associated with the flooding and drying management practice are the releases of high organic carbon (OC) and low dissolved oxygen (DO) water during the wetland drainage events. Wetlands are productive areas for macrophytes, phytoplankton and other vegetation that contribute to high organic carbon, which can consume oxygen upon decomposition and result in low DO in the water. Organic carbon in the adjacent sloughs and channels is also brought into wetlands during the fall flood-up. The low DO and high dissolved organic carbon (DOC) levels also provide conditions that favor production of methyl mercury (MeHg). Releases of low DO water into receiving waters (tidal sloughs) impact aquatic organisms, resulting in occasional fish kills, and impair fish nursery habitat by sending water with high OC to the receiving sloughs.

Meteorological Drivers

Suisun Marsh contains a mosaic of emergent aquatic vegetation that is highly efficient in transpiring water including tule, bulrush, cattail, and rush species, which can transpire 2 to 9 feet of water per year depending on temperature, wind and humidity (Siegel et al, 2010a). During late spring and summer, net flows in terminal sloughs can be negative due to vegetation evapotranspiration losses along the slough.

1.1.2 Hydrodynamics

Tides

Tides are the dominant force in the tidal sloughs of Suisun Marsh. The marsh experiences mixed semi-diurnal tides, with two daily tides of unequal height (Siegel et al. 2011). It was documented that in Boynton Slough tidal flows ranged between -800 and +1200 cfs and in Peytonia Slough tidal flows ranged between about -700 and + 800 cfs. The variations of tidal stage depend upon three time scales of tidal processes: the daily unequal high and low tides, the biweekly spring-neap tides, and the quarterly seasonal tides (Schureman, 1971; cited in Siegel et al. 2011).

Salinity monitoring throughout Suisun Marsh indicates that in certain regions, tides have significant impacts on channel water salinity, while in other regions this impact is less significant (DWR, 2001). Typically, higher salinity is found at high tide.

The effects of tides on the hydrology of managed wetlands were quantified in detail in a recent study of two managed wetlands in Suisun Marsh (Bachand et al. 2010a). The study found that the effects of tides on managed wetlands can overwhelm precipitation and evaporation effects. Evapotranspiration in early fall through late spring typically ranged from 0.5 to 0.8 inches/week. During the same period, precipitation ranged from about 0.5 to 2.0 inches/week. In contrast, at the two locations studied, tidal exchange ranged from 4–11 inches/week at Wetland 123 and 3–8 inches/week at Wetland 112.

1.1.3 Land Use

Land use for watersheds draining Suisun Marsh includes a mixture of urban, agricultural and open space lands (Figure 1-4;Table 1-1). Almost all the sloughs with low dissolved oxygen receive some degree of hydrologic inputs from urban areas in the surrounding watersheds. The City of Fairfield and Suisun are located in the watersheds surrounding the marsh. These urban areas can contribute to pollutant loads to Suisun Marsh during the wet season.

The Fairfield-Suisun Sewer District (FSSD) conducted monitoring for a few creeks for its urban runoff management program. Dry season monitoring of total and dissolved metals, total suspended solids, coliform bacteria, and two pesticides (diazinon and chlorpyrifos) was conducted during the summer of 1999 and 2000. The monitoring indicated that water quality was good in these creeks considering the urban environment (STA, 2002).

Land uses within Suisun Marsh itself consist predominantly of private and public managed wetland hunting areas. Within the marsh there are some areas of cattle grazing, sheep grazing and row crops (Siegel et al. 2011).

Table 1-1
Land use distribution within the Suisun Marsh Watershed (Siegel et al. 2011)

Land use type	Acres
Irrigated perennials	5519
Irrigated annuals	3,410
Dairy and pasture	283
Mixture of agriculture, urban, native vegetation	837
Non-irrigated crops	8,685
Farmstead, fallow and idle	2,938
Mixture of urban and native classes	4,706
Native vegetation	243,927
Urban	109,618
Water	37,110
Total acres	417,033

1.1.4 Point Source

The Fairfield-Suisun Wastewater Treatment Plant is located in the northwest Suisun Marsh and serves more than 130,000 residential, commercial, and industrial customers. The plant discharges 90% of its effluent into Boynton Slough. A smaller discharge point exists on Ledgewood Creek in the case of high effluent flows or failure of the primary discharge point to Boynton Slough. A portion of the discharge enters directly into three managed wetlands: identified as wetlands 112, 122 and 123. The treatment plant operates to tertiary treatment standards. The average discharge rate of the FSSD treatment plant is at 16 mgd. 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 discharge elevated levels of nutrients (Siegel et al. 2011).

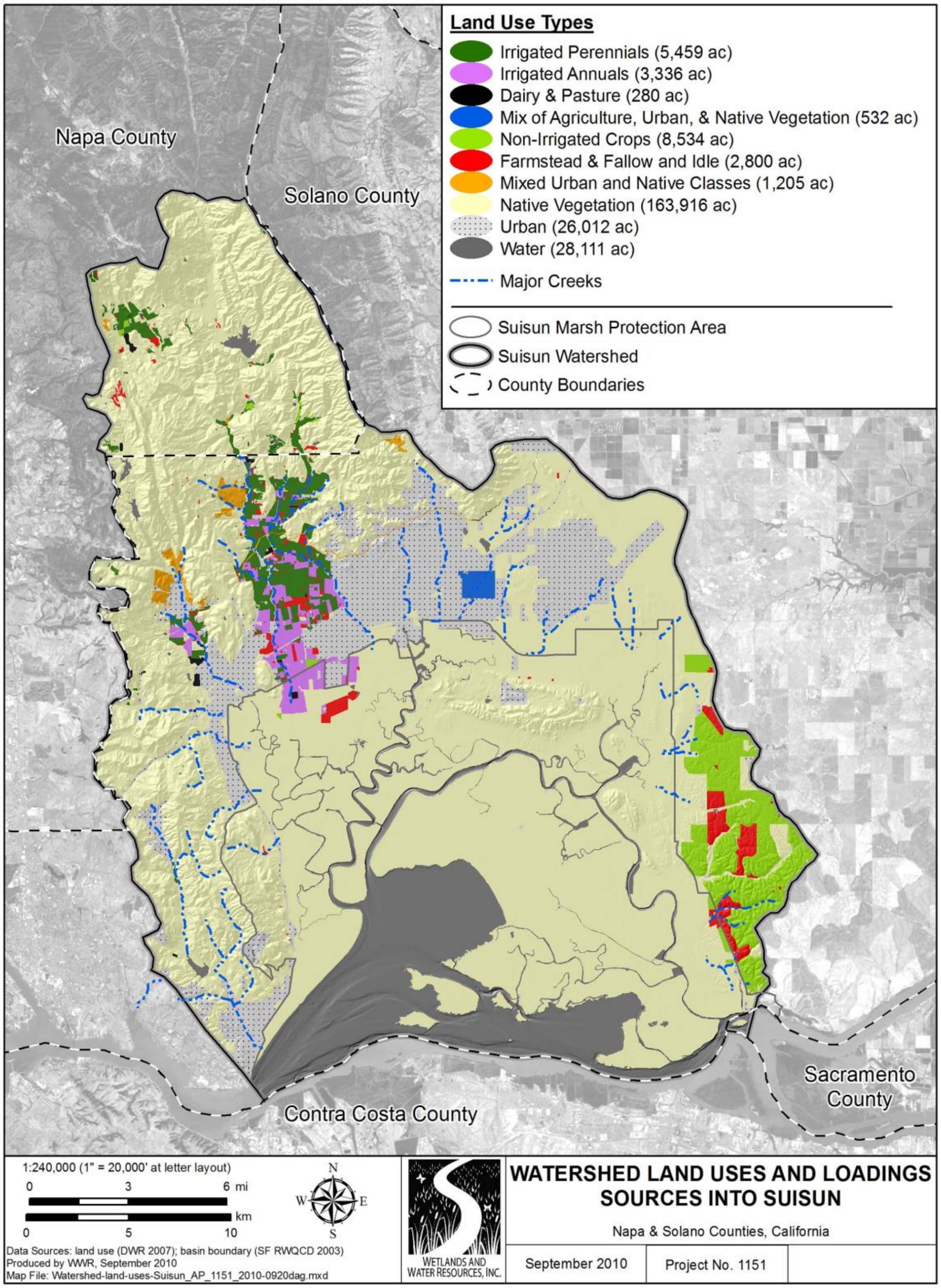


Figure 1-4 Land uses of watershed surrounding Suisun Marsh (From: Siegel et al. 2011).

1.2. KEY WATER QUALITY ISSUES

The water quality in Suisun Marsh is influenced by temperature, turbidity, contaminants and salinity (STA, 2002). When data across the 20th century are compared, it is found that salinity in Suisun Marsh has increased due to the initiation of the State Water Project withdrawals in 1967, although over shorter time frames salinity may exhibit patterns driven by climate. Freshwater input from local creeks, precipitation, and wastewater discharge are also important contributors to water quality. Finally, control structures (Suisun Marsh Salinity Control Gates) were constructed in Montezuma Slough in 1988 to control salinity in Suisun Marsh, and have had an impact on water quality in the marsh. Infrastructure elements in western Suisun Marsh that potentially influence water quality concerns in the marsh are shown in Figure 1-5.

In addition, Suisun Marsh was identified as water quality limited by the Clean Water Act (CWA) Section 303(d) for impairments of trace metals, nutrients (e.g. nitrogen and phosphorus), organic enrichment and dissolved oxygen, and salinity/total dissolved solids (TDS)/chlorides (Table 1-2).

Table 1-2
2010 CWA Section 303(d) List of Water Quality Limited Segments (Regional Water Board, 2010)

Type	Name	Pollutant/ Stressor	Potential Sources	TMDL Requirement*	Estimated Size Affected (acres)
Wetland, Tidal	Suisun Marsh Wetlands	Mercury	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Nutrients	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Organic enrichment/ Low DO	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Salinity/TDS/ chloride	Flow regulation/modification Urban runoff/storm sewers	A	66339
River and Stream	Suisun Creek	Low Dissolved Oxygen	Habitat modification Removal of riparian vegetation Stream bank modification/destabilization	A	19 miles
		Temperature, water	Habitat modification Removal of riparian vegetation	A	19 miles

* A – TMDL is required

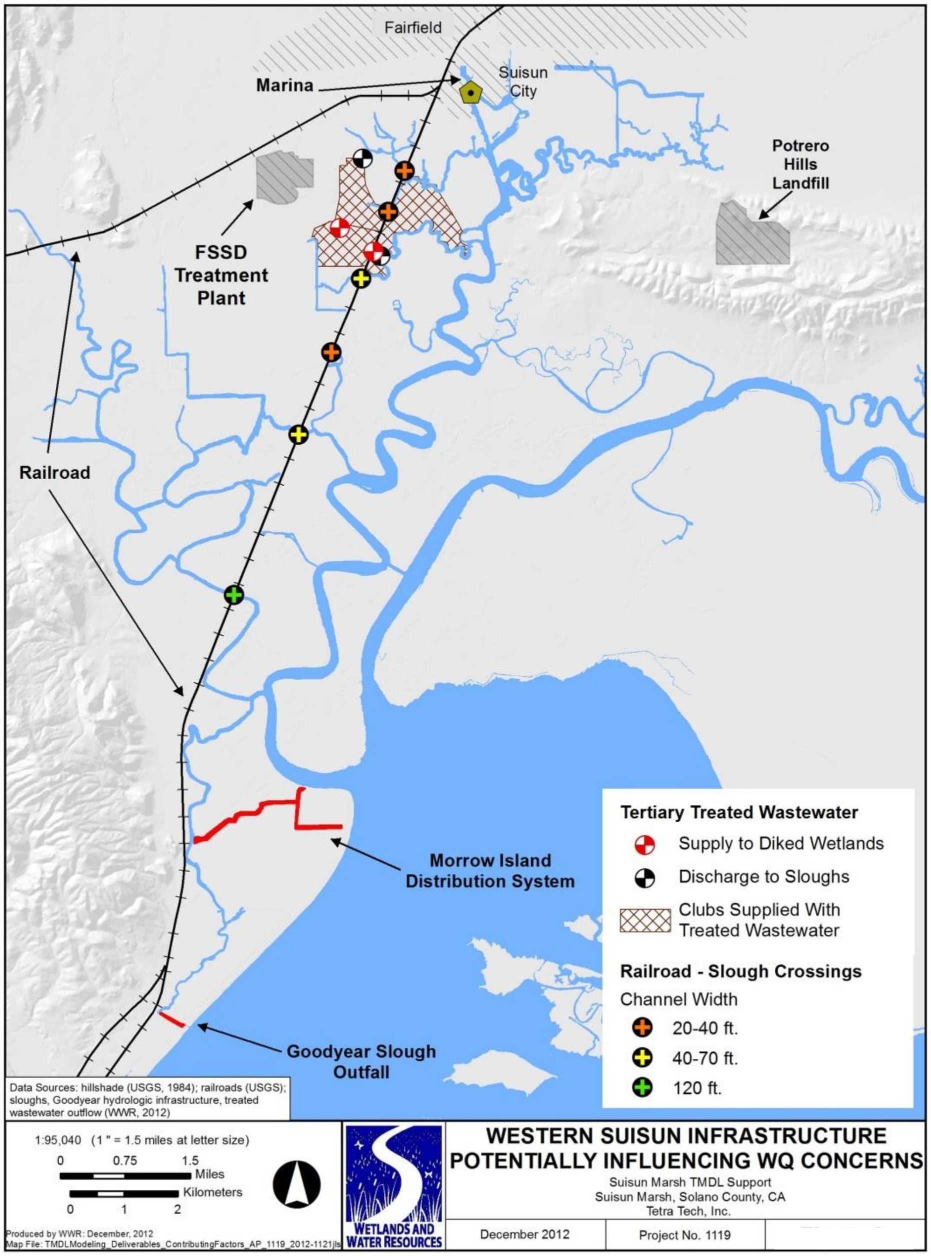


Figure 1-5 Infrastructure elements in western Suisun Marsh potentially affecting water quality.

The impairment of organic enrichment is partly due to the growth of macrophytes, phytoplankton and vegetation in marshes/wetlands and tidal sloughs. High organic carbon concentrations contribute to low dissolved oxygen concentrations due to the consumption of oxygen by organic carbon decay. In a study of carbon types and bioavailability in the Delta and Suisun, tidal marsh sloughs in Suisun were found to have the highest levels of dissolved organic carbon, particulate organic carbon (POC), and phytoplankton-derived carbon (Sobczak et al. 2002). High chlorophyll a concentrations in tidal sloughs were found and supported the growth of zooplankton. High levels of primary production in the interior of

Suisun Marsh were attributed to long residence time of water, nutrient availability, and absence of alien clams (CDFG, 2008).

In Suisun Marsh, low dissolved oxygen has been measured at a few tidal sloughs including Peytonia and Boynton Sloughs and the northwest areas of Suisun Marsh (Heim et al. 2010). It was found that flooding and draining of managed wetlands resulted in releases of high organic carbon and low DO water from managed wetlands to tidal sloughs during drain events. Low DO in water and drainage from managed wetlands was found to be a significant threat to aquatic species. In areas with low DO, fish kills have been observed (Schroeter et al. 2006).

During winter, water quality in Suisun Marsh can be influenced by rainfall and stormwater runoff from the surrounding streams and the associated pollutants such as eroded soil, nutrients from concentrated livestock grazing areas, and oil and grease from paved roadways. High nutrient levels in streams draining Suisun Marsh have also been attributed to agricultural runoff (STA, 2002). Inputs from Delta outflow, exchange with Suisun Bay and discharge from wastewater treatment plant are other potential sources of nutrients to Suisun Marsh.

A large input of ammonia (as NH_4) enters the Delta from agricultural fertilizer runoff, livestock operations and municipal sewage treatment plant outflows (CDFG, 2008). It has been suggested that tidal marsh is able to retain up to 40% of the NH_4 entering the marsh through a single tide, and transform 30% of the NH_4 through nitrification. The nitrification rate in the marsh system was 4–9 times that of the adjacent water column (Gribsholt et al. 2005).

The water quality problems associated with trace metals are mostly related to mercury and copper. Mercury inputs enter Suisun Marsh from Delta outflow, tidal exchange with Suisun Bay, atmospheric deposition and tributaries. A large portion of the mercury is also present in the system due to deposition of sediments from Suisun Bay or San Pablo Bay. The elevated organic carbon and low DO conditions in Suisun Marsh favor methylmercury production. Copper is a stormwater-associated pollutant. Potential sources of copper to Suisun Marsh include stormwater runoff, exchange with Suisun Bay sediments, and Delta outflow. Copper has been attributed to uses as anti-algal agent in pools and drinking water reservoirs, as anti-fungal for horse and cattle in agriculture, wastewater treatment plants, and uses in brake pads in urban areas (Siegel et al. 2011).

Currently water quality objectives for dissolved copper have been established for San Francisco Bay by segments (lower San Francisco Bay south of Hayward Shoals, and portions of the Delta located in the San Francisco Bay Region, Suisun Bay, Carquinez Strait, San Pablo Bay, Central San Francisco Bay, and portions of lower San Francisco Bay north of the Hayward Shoals (Regional Water Board, 2010).

1.3. Beneficial Uses of Suisun Marsh

Beneficial uses of water bodies help establish water quality objectives. The beneficial uses of the water bodies fall into two main categories: 1) those for human consumptive uses; and 2) those for aquatic life and wildlife uses. Existing human consumptive uses for Suisun

Marsh include freshwater replenishment (FRSH) in the tributaries (Suisun Creek and Ledgewood Creek) (Table 1-3). Existing aquatic life uses for Suisun Marsh include fish spawning (SPWN) and warm freshwater habitat (WARM) in the Suisun Slough and Montezuma Slough, and cold freshwater habitat (COLD), warm freshwater habitat (WARM), fish migration (MIGR), and fish spawning (SPWN) in the creeks. All the tributaries and sloughs are required to support wildlife habitat (WILD) and water contact recreation (REC-1) and noncontact water recreation (REC -2) uses.

Beneficial uses for the wetland areas include estuarine habitat (EST), fish migration (MIGR), preservation of rare and endangered species (RARE), water contact recreation (REC1), non-contact water recreation (REC2), fish spawning (SPWN) and wildlife habitat (WILD; Table 1-4).

1.4. Applicable Water Quality Objectives

There are two types of water quality objectives that can be applicable: narrative and numerical. Water quality objectives for surface waters documented in the Basin Plan (Regional Water Board, 2010) include numerical objectives for dissolved oxygen. For all tidal waters, the applicable objectives are: 5.0 mg/l minimum downstream of Carquinez Bridge and 7.0 mg/l minimum upstream of Carquinez Bridge in the Bay. For all nontidal waters, the following objectives apply: 7.0 mg/l minimum for cold water habitat, and 5.0 mg/l minimum for warm water habitat. A few of the sloughs (Suisun Slough and Montezuma Slough) support the WARM water use, therefore the applicable DO criteria in these two sloughs are 5.0 mg/l. Several creeks (Denverton Creek and Suisun Creek) support COLD water use, and the applicable DO objective in these creeks are 7 mg/l. The basin plan also states that median dissolved oxygen concentration for any three consecutive months shall not be less than 80% of the dissolved oxygen content at saturation.

Regarding salinity, the narrative water quality objective is: controllable water quality factors shall not increase the total dissolved solids or salinity of waters of the state so as to adversely affect beneficial uses, particularly fish migration (MIGR) and estuarine habitat (EST).

Table 1-3
Existing and Potential Beneficial Uses of Water Bodies in Suisun Marsh Region (Regional Water Board, 2010)

Water Body	FRESH	COMM	COLD	EST	MIGR	RARE	SPWN	WARM	WILD	REC-1	REC-2	NAV
Goodyear Slough		E		E	E	E			E	E	E	
Cordelia Slough		E		E	E	E			E	E	E	
Suisun Slough		E		E	E	E	E	E	E	E	E	E
Boynton Slough		E		E		E			E	E	E	
Peytonia Slough		E		E	E	E			E	E	E	
Hill Slough		E		E		E			E	E	E	
Cutoff Slough		E		E	E	E			E	E	E	
Montezuma Slough		E		E		E	E	E	E	E	E	E
Denverton Slough		E		E	E	E			E	E	E	
Nurse Slough		E		E	E	E			E	E	E	
Suisun Creek	E		E		E	E	E	E	E	E	E	
Green Valley Creek	E		E		E	E	E	E	E	E	E	
Denverton Creek						E	E	E	E	E	E	
Suisun Marsh				E	E	E	E		E	E	E	

E – existing; P – potential

COLD – cold freshwater habitat

COMM – ocean, commercial, and sport fishing

EST – estuarine habitat

FRESH – freshwater replenishment

MAR – marine habitat

MIGR – fish migration

NAV – navigation

RARE – preservation of rare and endangered species

REC1 – water contact recreation

REC2 – noncontact water recreation

SPWN – fish spawning

WARM – warm freshwater habitat

WILD – wildlife habitat

Table 1-4
Beneficial uses of wetland areas (Regional Water Board, 2010)

	Wetland Types		Beneficial Uses						
Basin /Marsh Area	**Fresh**	**Brackish**	**EST**	**MIGR**	**RARE**	**REC1**	**REC2**	**SPWN**	**WILD**
Suisun Marsh Area	X	x	x	x	x	x	x	x	x

For metals, the water quality objectives listed in the Basin Plan are mostly from the California Toxics Rules (CTR; Table 1-5). For mercury, the San Francisco Bay Mercury TMDL criteria, which cover Suisun Marsh area, are applicable (Figure 1-6). For copper, the site-specific dissolved copper water quality objectives have been implemented for the North Bay. The established copper water quality criteria at 6.0 and 9.4 µg/l for the 4-day average and 1-hr average concentrations, respectively. Observed dissolved copper concentrations by Regional Monitoring Program (RMP) in Suisun Bay have not exceeded these criteria (mean: 1.89 ± 0.44 µg/l; range: 1.13–3.0 µg/l).

The Basin Plan water quality objectives are also used in the 303(d) list data screening (Regional Water Board, 2009). In the 303(d) listing, some sediment water quality thresholds were applicable (Table 1-6).

Table 1-5
Freshwater and Marine Water Quality Objectives for Toxic Pollutants for Surface Waters (all values in µg/l; Regional Water Board, 2007)

Compound	Freshwater		Marine Water	
	4-day Average	1-hr Average	4-day Average	1-hr Average
Arsenic [b,c,d]	150	340	36	69
Cadmium [b,c,d]	e	E	9.3	42
Chromium VI [b,c,d]	11[e]	16[e]	50	1100
Copper [c,d,f]	9.0[e]	13[e]		
Lead [b,c,d]	2.5[e]	65[e]	8.1	210
Mercury[h,k]	0.025	2.4	0.025	2.1
Nickel [b,c,d]	52[e]	470[e]	8.2	74
Silver [b,c,d]		3.4[n]		1.9
Zinc [b,c,d]	120[e]	120[e]	81	90

a. Freshwaters are those in which the salinity is equal to or less than 1ppt for 95% of the time. Marine waters are those in which the salinity is equal to or greater than 10 ppt 95% of the time.

b. Source: California Toxics Rule or CTR, May 18, 2000

c. These objectives for metals are expressed in terms of the dissolved fraction of the metal in the water column

d. These objectives are expressed as a function of the water-effect ratio (WER), which is a measure of the toxicity of a pollutant in site water divided by the same measure of the toxicity of the same pollutant in laboratory dilution water

e. The objectives for cadmium and other noted metals are expressed by formulas where H = ln(hardness) as $CaCO_3$ in mg/l.

f. Water quality objectives for copper were promulgated by the CTR and may be updated by U.S. EPA.

h. Source: U.S. EPA ambient water quality criteria for mercury (1984). .

k. Source: U.S. EPA quality criteria for Water 1986 (EPA 440/5-86-001), which established a mercury criterion of 0.012 µg/l. The Basin Plan set the objective at 0.025 based on considerations of the level of detection attainable at that time.

n. The objective for silver is based on hardness. The table value assumes a hardness of 100 mg/l $CaCO_3$.

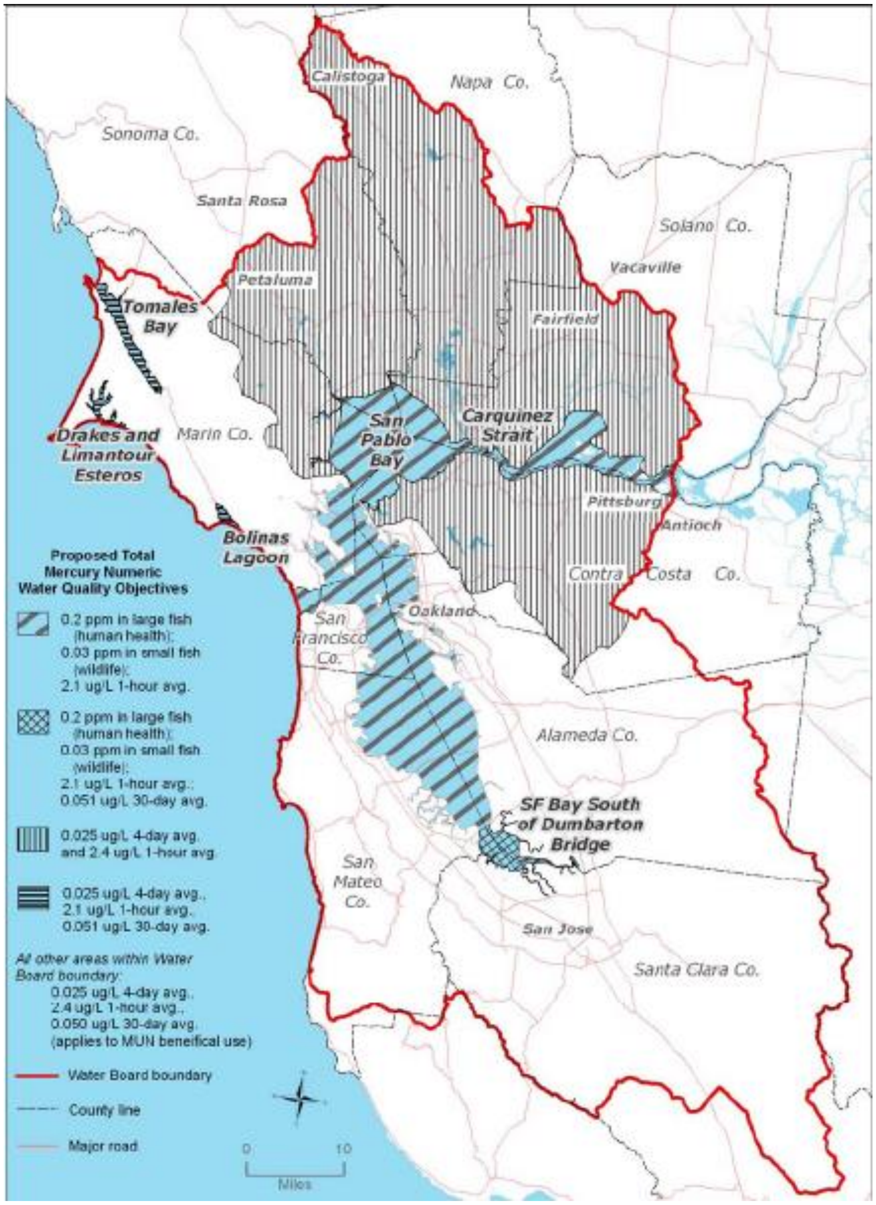


Figure 1-6 Existing mercury numeric water quality objectives (Regional Water Board, 2006).

Table 1-6
Freshwater Sediment Quality Pollutant Threshold for 303(d) Data Screening (Regional Water Board, 2009)

Metals	Probable Effect Concentrations (mg/kg)
Arsenic	33
Cadmium	4.98
Chromium	111
Copper	149
Lead	128
Mercury	1.06
Nickel	48.6
Zinc	459

For copper, the sediment threshold criteria are applicable. Recent core sampling from wetlands in Suisun Marsh (Point Edith) by the San Francisco Estuary Institute (SFEI) (Yee, 2010, personal communication) however suggested maximum concentrations of 107 mg/kg along the depth profile (mean: 56.6 ± 30.4 mg/kg), which has not exceeded the criterion of 149 mg/kg.

2. Organic Carbon

Tidal marshes and managed wetlands are naturally rich in organic carbon and low in dissolved oxygen, due to the growth of submerged aquatic plants and macrophytes in these environments, and their subsequent decay. Allochthonous loads of organic carbon from tributaries, Delta outflow, and wastewater treatment plant and exchange with Suisun Bay constitute additional sources of organic carbon to Suisun Marsh. Anthropogenic inputs of nutrients to Suisun Marsh from various sources can fuel primary production in habitats in Suisun Marsh, therefore increasing internal production of organic carbon. Additionally, wetland management activities including flooding and draining, and mowing/disking of vegetation in managed wetlands can potentially increase the release of organic carbon from wetland soils and vegetation, beyond what would naturally occur. Upon decomposition, these natural and anthropogenically enhanced organic carbon loads consume oxygen and cause low dissolved oxygen concentrations. Organic carbon also fuels microbial activity which results in methylation of mercury into the more toxic form of methylmercury. Currently Suisun Marsh wetlands are listed for impairment due to organic carbon enrichment and low DO (Regional Water Board, 2007).

The potential sources of organic carbon can be evaluated by characterizing the quality of the organic carbon. Specific ultraviolet absorbance (SUVA) that measures aromatic content of organic carbon suggests relatively low SUVA concentrations (fresh plant and algae) in the incoming water to the managed wetlands, a spike in SUVA during the first few weeks of the flooding events, and decrease after several weeks of the flooding. This indicates that the main source of organic carbon in slough waters include fresh plant material and algae, although the release from managed wetlands may send some naturally occurring plant residues to the sloughs.

2.1. Sources of Organic Carbon in Suisun Marsh

The high organic carbon concentrations in Suisun Marsh have been attributed to high levels of primary production in the interior of Suisun Marsh and tidal sloughs (Enright et al. 2009). These include primary production of macrophytes in shallow water areas, attached algae in shallow calm areas (e.g., tidal creeks), and phytoplankton production in deeper, clearer areas with intermediate residence times (e.g., small sloughs). High levels of primary production in the interior of Suisun Marsh have been attributed to high residence time of water, nutrient availability, and absence of alien clams (CDFG, 2008).

In addition to the internal production of organic carbon, several other sources of organic carbon can reach Suisun Marsh. These include: 1) tidal exchange with San Francisco Bay; 2) creeks from the surrounding watersheds; 3) wastewater treatment plant discharge; 4) managed wetland discharge; and 5) tidal marshes. It has been documented that tidal emergent vegetation detritus can be sources of substantial amounts of organic matter (OM) in estuaries and coastal oceans (Raymond and Bauer, 2001). Adjacent uplands that remain hydrologically connected also contribute vegetation detritus. The managed wetlands in

Suisun Marsh can discharge significant amounts of organic matter. Finally, suspended sedimentary material can be tidally transported from the adjacent Grizzly Bay.

The sources of organic carbon distributed across Suisun Marsh landscape are affected by geographic locations (Mueller-Solger and Bergamaschi, 2005). Tidal and managed wetlands areas support vascular plant production. Phytoplankton production occurs in open water areas. Shallow areas support benthic and epibenthic algal and submerged aquatic vegetation. The distribution of organic matter is affected by hydrologic and meteorological forces. The hydrologic connectivity of these habitats affects the dominant OC sources. A conceptual model of sources and distribution of organic carbon is shown in Figure 2-1.

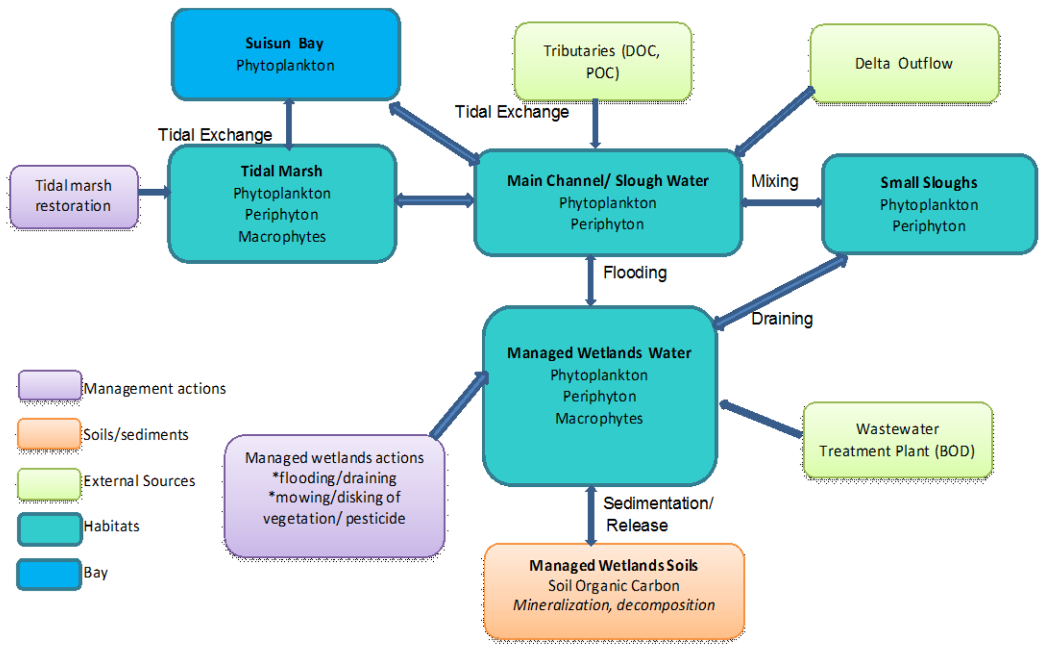


Figure 2-1 Conceptual model of sources and distribution of organic carbon in Suisun Marsh.

2.1.1 Tides

Tides are the dominant hydrological forces in the tidal sloughs in Suisun Marsh. Suisun and Montezuma sloughs are two largest sloughs conducting tides throughout Suisun Marsh. Organic carbon from delta outflow and in-bay production can be transported to Suisun Marsh through tidal exchange.

2.1.2 Surrounding Watersheds

Several creeks enter Suisun Marsh. These creeks include Green Valley Creek, Suisun Creek, Ledgewood Creek, Laurel Creek, Union Creek, and Denverton Creek. The creeks receive runoff from watersheds that drain agricultural, urban and open land use areas. Runoff from these creeks can be sources of organic carbon (e.g. vegetation debris, in-situ phytoplankton production) to the marsh. The tributary inputs of organic carbon or BOD were estimated based in a previous modeling study by Davis et al. (2000). Davis et al. (2000) estimated BOD loads and runoff for watersheds surrounding SF Bay. The loads for the sub-watersheds can be estimated as proportional to the runoff volume of each watershed. The Fairfield sub-watersheds were estimated to export a total of 3,776.5 kg/day of BOD or 1,416.2 kg/day of organic carbon at a rate of 15.7 kg/ha/yr BOD or 5.9 kg/ha/yr organic carbon.

Export rates of organic carbon estimated for the forest/rangeland areas of the Sacramento River are 4.1 kg/ha/yr and 17 kg/ha/yr for dry and wet years, and 5.6 and 16 kg/ha/yr for the agricultural areas (Roy et al. 2006; Table 2-1). In the same study, Yuba River watershed which has the least percentage of agricultural and urban land uses was used to estimate background organic carbon export. The Yuba River basin dry and wet year export of 4.1 and 17 kg/ha/yr are compared with the estimate of 9.6 kg/ha/yr for an relatively undeveloped watershed in the Rocky Mountains (Boyer et al., 2000). The estimated export rates by Davis et al. (2000) ranged from 6–19 kg/ha/yr of BOD or 2.3–7.1 kg/ha/yr of organic carbon for the sub-watersheds. Therefore the estimated rates of organic carbon exports from Suisun Marsh tributaries are generally at the lower end of the undeveloped areas.

Table 2-1
Export Rates of Organic Carbon from Major Land Uses in the Central Valley (Roy et al. 2006)

Land Use	Dry Year Loads (tons/km^2/yr)		Wet Year Loads (tons/km^2/yr)		Source	
	Sac	SJR	Sac	SJR	Sacramento	San Joaquin
Agriculture	0.56	1.9	1.6	2.6	Colusa basin drain	Harding dam
Urban Runoff	1.3	0.67	2.4	1.2	Arcade creek	Calculated from Sacramento value
Forest / Rangeland	0.41	0.21	1.7	0.85	Yuba river	Calculated from Sacramento
Wetland-Dominated	1.4	0.69	2.0	1.0	Calculated from San Joaquin Value	Average of salt and mud slough

2.1.3 Sewage Treatment Effluent

The FSSD Wastewater Treatment Plant discharges a majority of its effluent to Boynton Slough. The plant is a tertiary treatment plant. Currently, the effluent limitation for FSSD (NPDES No. CA0038024) is an average monthly concentration of 10 mg/l for BOD. The Plant presently treats an annual average flow of 16.1 mgd (2000–2002), with an average dry weather flow of 14.1 mgd. Of the flow treated, an annual average of 14.4 mgd was discharged, with 1.7 mgd reclaimed for agricultural irrigation. Therefore, the allowable discharge of BOD load to Suisun Marsh is estimated to be 545 kg/day or 204 kg/day as OC.

2.1.4 Managed Wetland Discharges

Managed wetlands provide conditions for macrophytes and phytoplankton growth. The managed wetlands can impact the organic carbon levels in sloughs through flooding and draining events. When flooding occurs, water is brought into wetlands from the channels. The draining events of managed wetlands send pulses of high organic carbon water into the receiving sloughs (Siegel et al, 2010b). High organic carbon concentrations in managed wetlands are attributed to several factors: 1) release of soil organic carbon; 2) growth of macrophytes; 3) growth of phytoplankton; and 4) inflow from channels.

Most managed wetlands are dry during summer and early fall. A series of flood-drain-flood cycles occur during the fall season. After that the wetlands circulate water through the winter and drain at variable times in the spring. These management activities result in the production of organic matter in the form of wetland and aquatic vegetation. During the fall flood-up event the decomposition of this organic material results in low DO in water. During fall and winter drain events, the low DO water can enter the receiving sloughs. The pond release is also rich in nutrients and organic matter, which can further stimulate microbial activity in the receiving waters, and increase BOD and lower DO in the receiving waters (Siegel et al. 2011). The management of vegetation through mowing or disking also increases release of organic carbon from soils.

The roles of managed wetlands on DOC in tidal sloughs were emphasized in the study of Bachand et al. (2010b) at two locations. Higher DOC concentrations were measured within managed wetlands than the adjacent sloughs. DOC concentrations increased within the first few weeks during fall flood-up events and then stabilized. Upon release, managed wetlands sent pulses of high DOC concentrations to the adjacent sloughs, resulting in increased DOC concentrations in tidal sloughs. Based on this analysis, the wetlands received 468 mg/m^2 (wetland area)/tide/inches during the flood event, and discharged 306 and 826 mg/m^2/in/tide at Wetland 112 and 123 during drainage events. Typically up to 2 inches of water is imported per flood event and 4 inches/tide event of water is discharged during drainage events. This suggested a load of DOC of 1,515 kg/day and 2,538 kg/day *from* the sloughs during flood events and 1,981 and 8,958 kg/day *to* the sloughs during drainage events at Wetland 112 and Wetland 123 respectively. The loads are large, although the two study areas differ substantially in their net exports.

Because the two study locations represent a small area of the total managed wetland area in Suisun Marsh (see Figure 2-2) but nonetheless constitute a potential load of several thousand kg/day, the total load from managed wetlands to the sloughs in Suisun Marsh is expected to be several times greater. It is clear that this source category is dominant in Suisun Marsh and exceeds the contributions of the watershed and the point source calculated in the previous section.

2.1.5 Tidal Marshes

Although fully surrounded tidal marshes are not very common in Suisun Marsh, Peytonia and Boynton Sloughs both have tidal marshes connected to them. Tidal marshes are productive systems that contribute organic matter to the receiving water body. In a study of carbon types and bioavailability in the Delta and Suisun, tidal marsh sloughs in Suisun were found to have the highest levels of dissolved organic carbon, particulate organic carbon, and phytoplankton-derived carbon (Sobczak et al. 2002).

2.2. Concentrations of Organic Carbon Observed in Suisun Marsh (Spatial Pattern and Seasonal Variations)

DOC concentrations in several managed wetlands (Wetland 112 and 123, Wetland 525, 529, and 530) were measured by Siegel et al. (2010a) during the period of October 2007–January 2008 when managed wetlands were flooded and drained. Locations of managed wetlands in Suisun Marsh and the wetlands selected for the study by Siegel et al. (2010a) are shown in Figure 2-2 and Figure 2-3. For the period during which data were collected, DOC concentrations were similar between Wetland 112 and 123 and among Wetlands 525, 529 and 530. DOC concentrations within these wetlands were higher than in the Montezuma Slough based on the limited data available in Montezuma Slough. From October through December, DOC concentrations in the wetlands were typically 2.5–7 times higher than found in the slough. Montezuma Slough water generally has DOC ranging from 3–5 mg/l

(Bachand et al. 2010b). Observed DOC concentrations in wetlands varied widely from 3 to 100 mg/l, with the highest DOC concentrations measured during drawdown in Wetland 123 in September 2008. DOC concentrations in wetlands were higher during the earlier weeks after flooding, dropped over time and stabilized after approximately 5 weeks of flooding (Figure 2-4).

Wetland 123 had higher levels of DOC following fall flood up than Wetland 112 (Figure 2-4). This is due to higher organic content in soils of Wetland 123 than those in Wetland 112. Wetland 123 uses disking for vegetation management compared to the mowing and use of herbicides at Wetland 112. Disking accelerates DOC movement through soil and this method is expected to increase DOC leaching from soils.

Organic carbon was not directly measured at FSSD discharge flows. Concentrations were measured at the outfall locations. Water sampled from these locations has low median DOC values (7 mg/l; Bachand et al. 2010b). Specific ultraviolet absorbance (SUVA) has been used to measure the aromatic content of organic carbon (Siegel et al. 2011). Bulk dissolved organic matter (DOM) from fresh plant and algae, has lower aromatic content compared to the more degraded DOM from plants and soils. In Wetland 123, there was a notable increase in SUVA values after the first few weeks of flooding. This suggested the consumption of more labile DOM and releases of DOM from soils and degraded plant materials (e.g. left over from spring growth and summer wetland management activities) which have higher aromatic content.

The fluorescence index (FI) has been used to indicate the relative contribution of algal versus terrestrial derived DOM (Downing et al. 2010). Algal derived materials have lower aromatic content, lower molecular weight and higher FI values. Terrestrial derived material has greater aromatic content, higher molecular weight and lower FI values (McKnight et al., 2001; Jaffe et al., 2008). FI values in Wetland 112 and 123 ranged between 1.2 and 2.0, suggesting a mixture of DOM from different sources and changes in DOM composition over time (Figure 2-5). Some increases in FI values in Wetland 123 were observed after 22 weeks of flooding (in March), suggesting DOM was generated from algal production and leaching from vegetation grown in the wetland. The change could be due to primary production within the wetland or inflow and exchange of water from the outside sloughs.

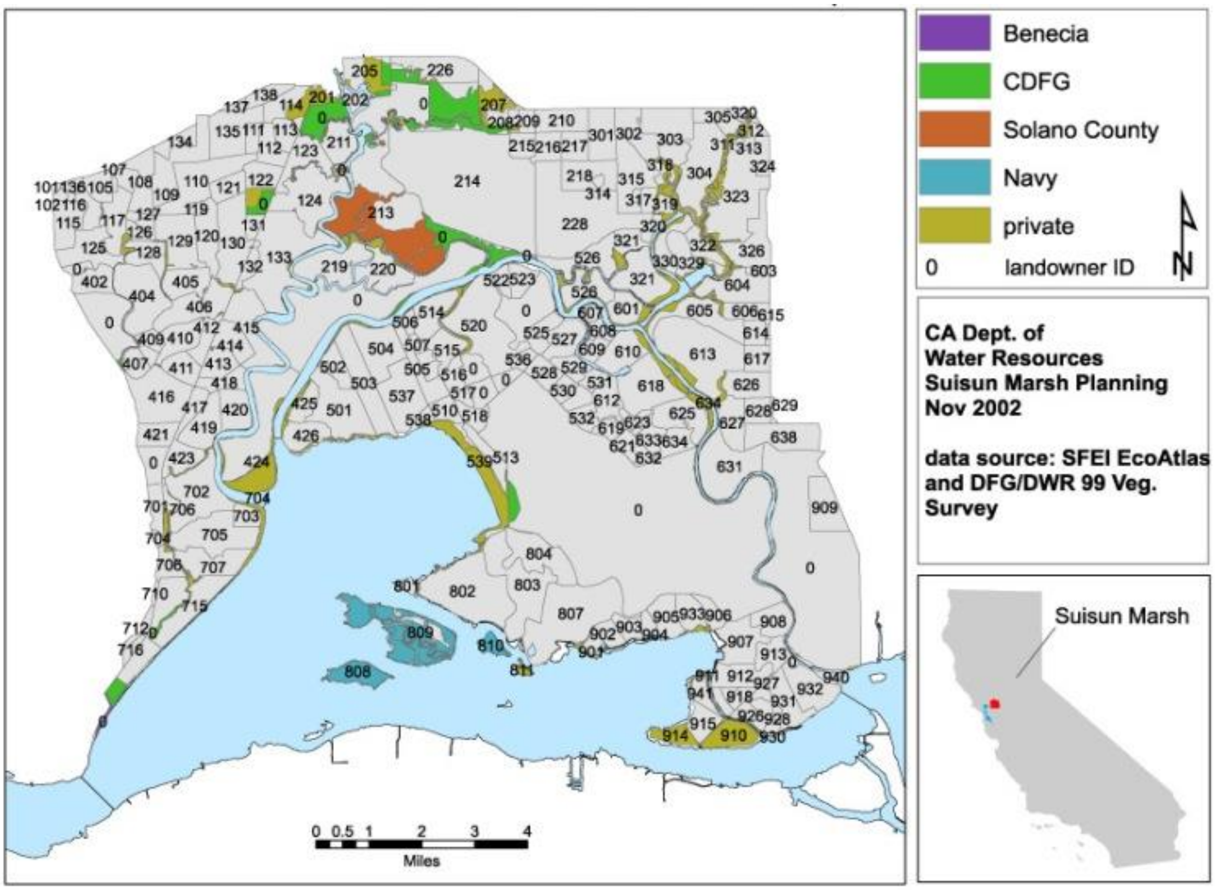


Figure 2-2 Managed wetlands in Suisun Marsh (Source: DWR).

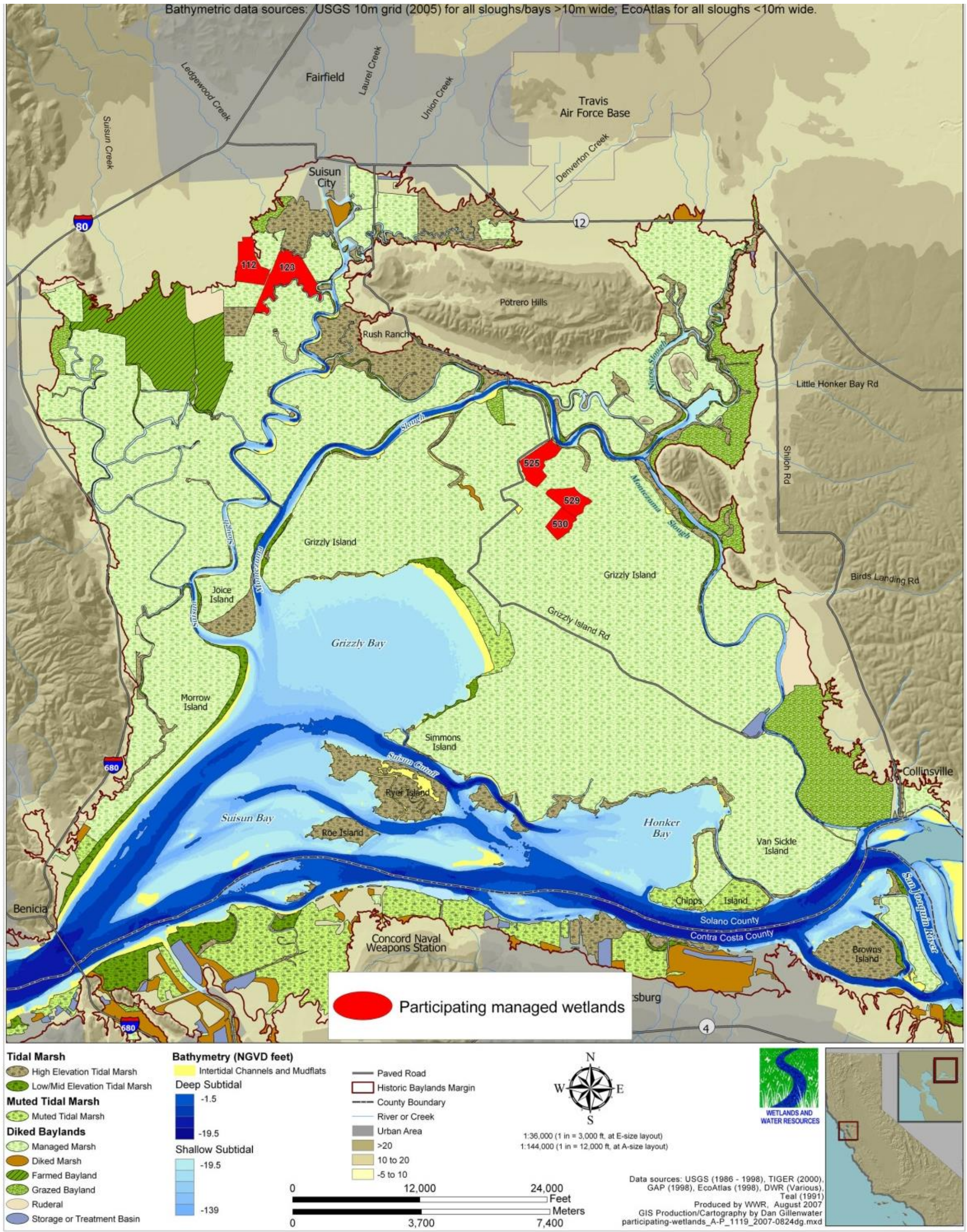


Figure 2-3 Locations of managed Wetlands 112, 123, 525, 529 and 530 selected for investigation by Siegel et al. 2011.

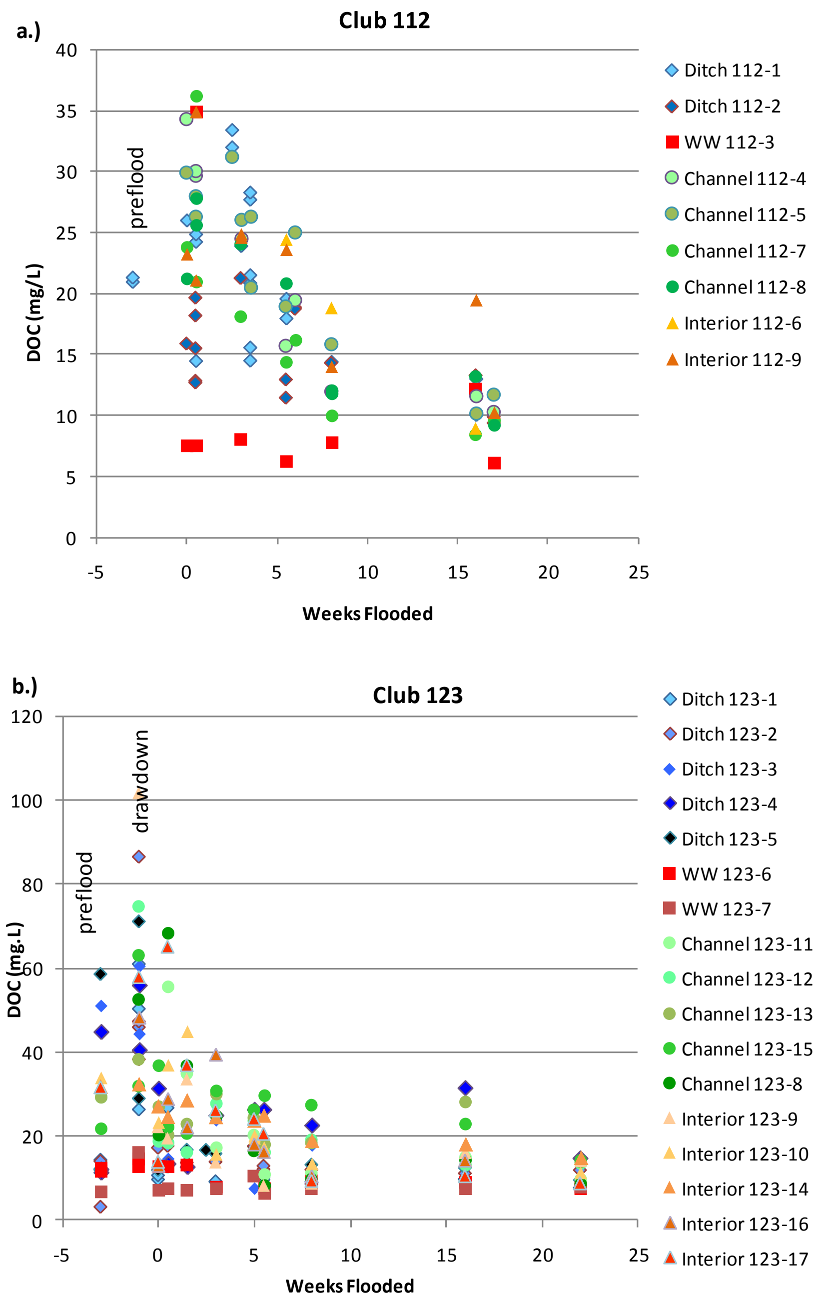


Figure 2-4 **DOC levels in samples from (a) wetland 112 and (b) wetland 123 (Siegel et al., 2010a).**

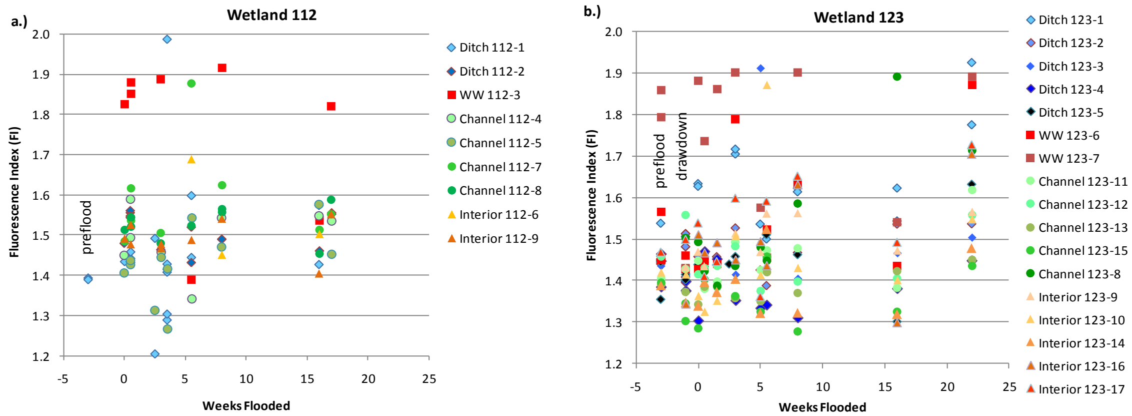


Figure 2-5 **Fluorescence Index (FI) by site for both years of sampling plotted against weeks since flooding for a) Club 112 and b) Club 123. Negative weeks represent pre-flood and drawdown, as indicated (Downing et al. 2010).**

2.3. Roles of Organic Carbon Enrichment on Other Water Quality Parameters

Organic carbon enrichment has impacts on marsh chemistry in several ways (Enright et al. 2009):

- Organic matter fuels microbial production
- Algal production fuels marsh food chain
- Decomposition of organic carbon consumes oxygen
- Organic matter fuels microbial activity including methylation of mercury by sulfate reducing bacteria.

The wetland draining events resulted in decreases in DO concentrations to near 0 mg/l at perimeter stations around the wetlands. These events are caused by decomposing organic carbon loads drawing down DO levels in the managed wetlands. Decreases in DO concentrations have resulted in fish kills and fish leaving sloughs for higher DO water.

The discharge of high DOC water can also mediate Hg dynamics. Mercury methylation processes which require both available pools of mercury and organic carbon, are mediated by organic carbon inputs. High DOC concentrations and low DO provide conditions that can enhance methylmercury production.

2.3.1 DOC Concentrations vs. Dissolved Oxygen Concentrations

DO concentrations were measured at wetland 123 for a few sampling events (Downing et al. 2010). Observed DO concentrations showed a wide range of concentrations (0.1–12 mg/l). Although there was no significant correlation between DOC and DO, DO was consistently low in water with high DOC concentrations (Figure 2-6). DO concentrations were usually less than 1 mg/l at DOC concentrations exceeding 40 mg/l.

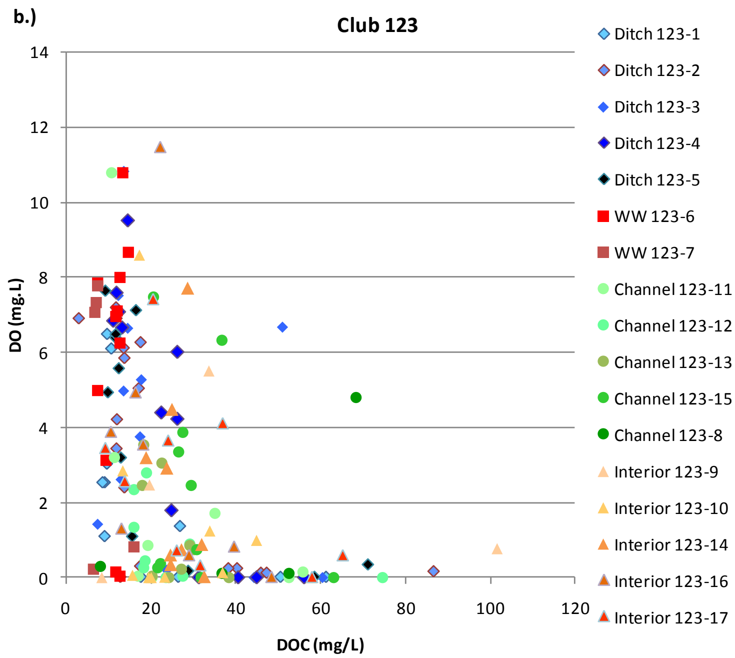


Figure 2-6 **Dissolved oxygen versus DOC concentrations at wetland 123 (from Downing et al. 2010).**

2.3.2 DOC Concentrations vs. Dissolved MeHg Concentrations

Dissolved MeHg concentrations measured at Wetland 112 and 123 for both sampling years were compared to DOC concentrations (Figure 2-7). For Year 1 sampling, a significant correlation between MeHg and DOC was found ($p<0.001$; Siegel et al. 2011) although not for the entire dataset. Samples with high concentrations of DOC (>20 mg/l) correspond with elevated concentrations of MeHg (> 1 ng/l; Downing et al. 2010), particularly for Wetland 123. The lack of a strong overall correlation could be due to (1) MeHg production occurring in sediments rather than in the water column and (2) the composition and reactivity of DOC varying across space and time with effects on the availability of reactive mercury for methylation.

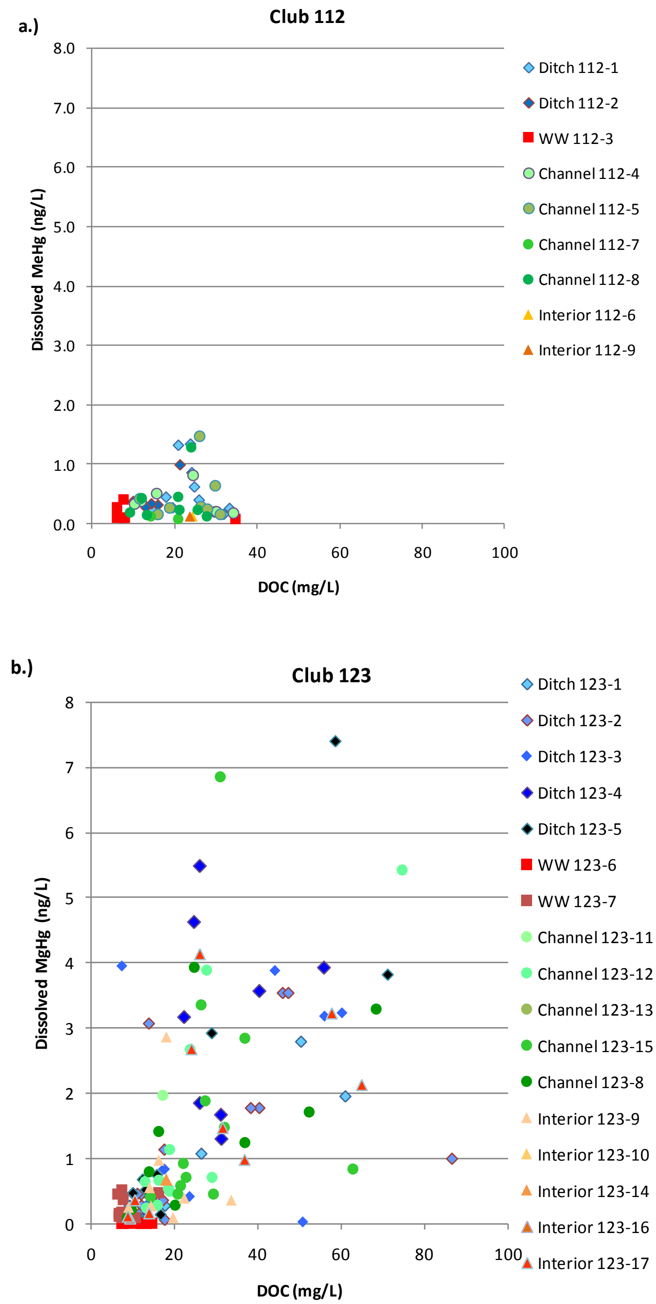


Figure 2-7 **Relationship between DOC concentration and dissolved MeHg concentrations for (A) Club 112 and (B) Club 123. Data shown includes both years of sampling (from Downing et al. 2010).**

2.4. IMPAIRMENT ASSESSMENT

Although organic carbon was listed as a pollutant of concern in the 303(d) list, there are no water quality objectives for organic carbon listed in the Basin Plan. Instead, the negative impacts due to high organic carbon were indirectly measured as resultant low DO concentrations, which could result in fish kills and adversely impact aquatic organisms. The applicable DO water quality objectives and comparison with observed concentrations are discussed further in the following section.

2.5. SUMMARY

The conceptual model/impairment assessment of organic carbon in Suisun Marsh can be summarized as follows.

- Sources of organic carbon to Suisun Marsh include:
  - Internal production: macrophytes in shallow water, attached algae in shallow calm areas, phytoplankton in deep open water, and wetland soils (Enright et al. 2009);
  - Other sources: organic materials tidally transported from Grizzly Bay, surrounding watersheds, sewage treatment effluents, and release from managed wetlands.
- The managed wetlands are characterized by higher organic carbon concentrations than the adjacent sloughs (2.5–7 times). Sources of organic carbon in managed wetlands include releases from wetland soils, in-situ primary production and organic carbon inputs from sloughs.
- Organic carbon concentrations in managed wetlands increased after fall flood-up and then decreased. Upon release, the managed wetlands discharge sent pulses of high organic carbon water to the adjacent sloughs.
- Although data across wetlands is limited, the nature of vegetation management may affect organic carbon export to sloughs.
- Given the extent of quantification that could be performed with available data, the release of managed wetlands appears to be a dominant pathway of organic carbon loads to the sloughs.
- Specific ultraviolet absorbance (SUVA) measurements suggested lower aromatic content from fresh plant and algae and higher aromatic content from degraded DOM from plants and soils. There was an increase in SUVA after a few weeks of fall flooding, suggesting consumption of labile DOM and release of DOM from soils.
- The fluorescence index (FI) measurements suggested DOM was generated from algal production and leaching from vegetation grown in wetland.
- Currently there are no documented water quality objectives for DOC for comparison, although there is a link between high DOC and low DO, for which there are water quality objectives as discussed is subsequent sections.

3. DISSOLVED OXYGEN

Appropriate levels of dissolved oxygen are critical to organisms in aquatic environments. In general, organisms will become stressed when DO levels are below 5 mg/l. Hypoxia may occur at DO values between 2 to 5 mg/l and anoxia occurs below 2 mg/l. Low dissolved oxygen concentrations (DO sags) have been observed in sloughs of Suisun Marsh, including Peytonia, Boynton, Goodyear and Suisun Sloughs. Low DO and fish kill events have been noted in sloughs of Suisun Marsh since 1999 and again in 2001, 2003 and 2004. In 2009, fish kills in Goodyear Slough have been observed due to the anoxic conditions (O'Rear and Moyle, 2010). Several species of fish including splittail, striped bass, and threespine stickleback have been killed. Currently, Suisun Marsh is listed for impairment due to dissolved organic carbon/low DO (Regional Water Board, 2007).

3.1. DO STANDARDS IN SUISUN MARSH

The Basin Plan for San Francisco Bay (which includes Suisun Marsh) states that the minimum DO concentration for all tidal waters upstream of the Carquinez Strait Bridge will be 7.0 mg/l (Regional Water Board, 2010). For non-tidal waters, the applicable water quality objectives are 5.0 mg/l for WARM water use and 7.0 mg/l for COLD water use. The sloughs are considered as tidal waters and therefore the applicable water quality standards in the sloughs are 7 mg/l. The Basin Plan also states that for any consecutive 3-months, the median DO concentrations will not be less than 80% of the DO concentration at saturation. The DO concentrations at saturation vary throughout the year as oxygen solubility is temperature dependent, with lower DO occurring when water becomes warmer.

Suisun Marsh wetlands include both fresh and brackish wetland types and support beneficial uses of estuarine habitat. The estuarine habitat provides habitat for anadromous fishes (salmon, striped bass) migrating into fresh or marine water conditions. The protection of estuarine habitat therefore is required for survival of fish species.

In the Bay:

Downstream of Carquinez Bridge	5.0 mg/l minimum
Upstream of Carquinez Bridge	7.0 mg/l minimum

For nontidal waters, the following objectives shall apply:

Waters designated as-

Cold water habitat	7.0 mg/l minimum
Warm water habitat	5.0 mg/l minimum

Given the recognition that some excursions of DO from these standards are inevitable in smaller, poorly mixed sloughs and in wetlands, the Regional Board is exploring the development of alternate DO targets that may be applicable to different types of waters within Suisun Marsh. These alternate targets may be based on observations in reference sloughs with minimal managed wetland discharges and on the physiological requirements of specific organisms inhabiting Suisun Marsh.

3.2. Causes of Low DO in Suisun Marsh

Significant depressions in dissolved oxygen concentrations (DO sags) have been observed in Peytonia, Boynton, Goodyear and Suisun Sloughs in Suisun Marsh (O'Rear and Moyle 2010, Schroeter et al. 2006). Peytonia, Boynton and Goodyear Sloughs are tributaries to Suisun Slough in western and northwestern of Suisun Marsh. Suisun Slough itself also experienced low DO events (Schroeter et al. 2006). The DO sags can be persistent and extend several kilometers in slough habitat. These low DO events appear to coincide with the fall flood-up and drain cycles of managed wetlands in Suisun Marsh. The release of drained water from wetlands sent pulses of high DOC and low DO water to the receiving sloughs. A conceptual model of the causes and effects of low DO in small sloughs is presented in Figure 3-1 (based on a schematic previously developed by Siegel et al., 2010a).

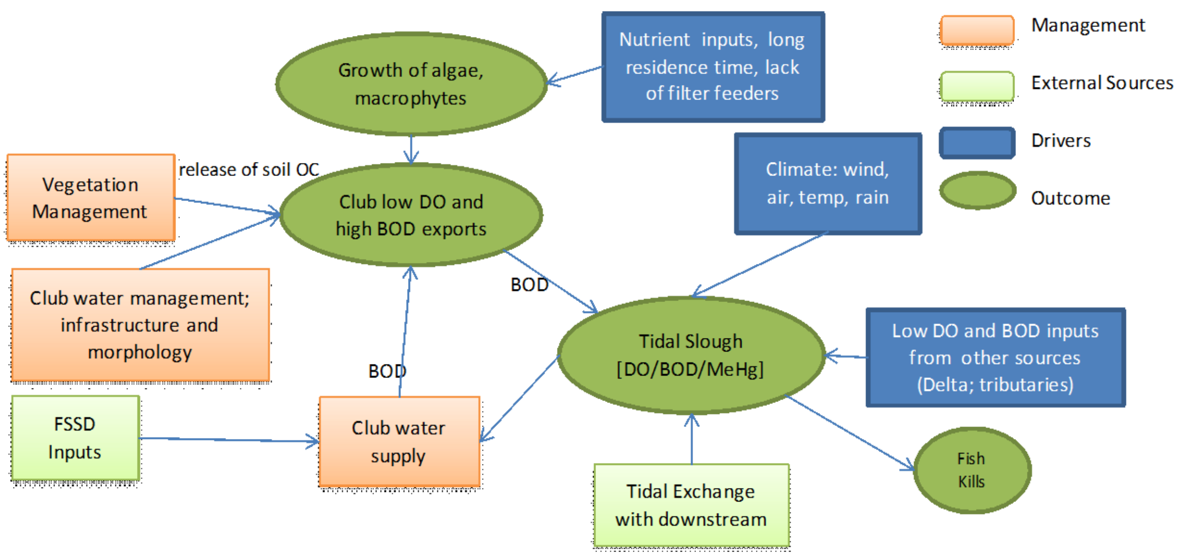


Figure 3-1 Conceptual model of low DO in small tidal sloughs in Suisun Marsh (modified from Siegel et al. 2011).

Potential sources of oxygen-consuming materials (measured as biological oxygen demand, BOD) to Suisun Marsh are storm water runoff from urbanized, agricultural, and grazed open areas, nutrient-enriched wastewater discharge from Fairfield-Suisun Sewer District, wastes from boats in Suisun City marina, and tidal marshlands.

In addition to loads of oxygen consuming materials from various sources, other factors (e.g. geometry, hydrology) contribute to low DO conditions in tributary sloughs of Suisun Marsh and have been summarized in Siegel et al.(2010a; Figure 3-2; Figure 3-3).

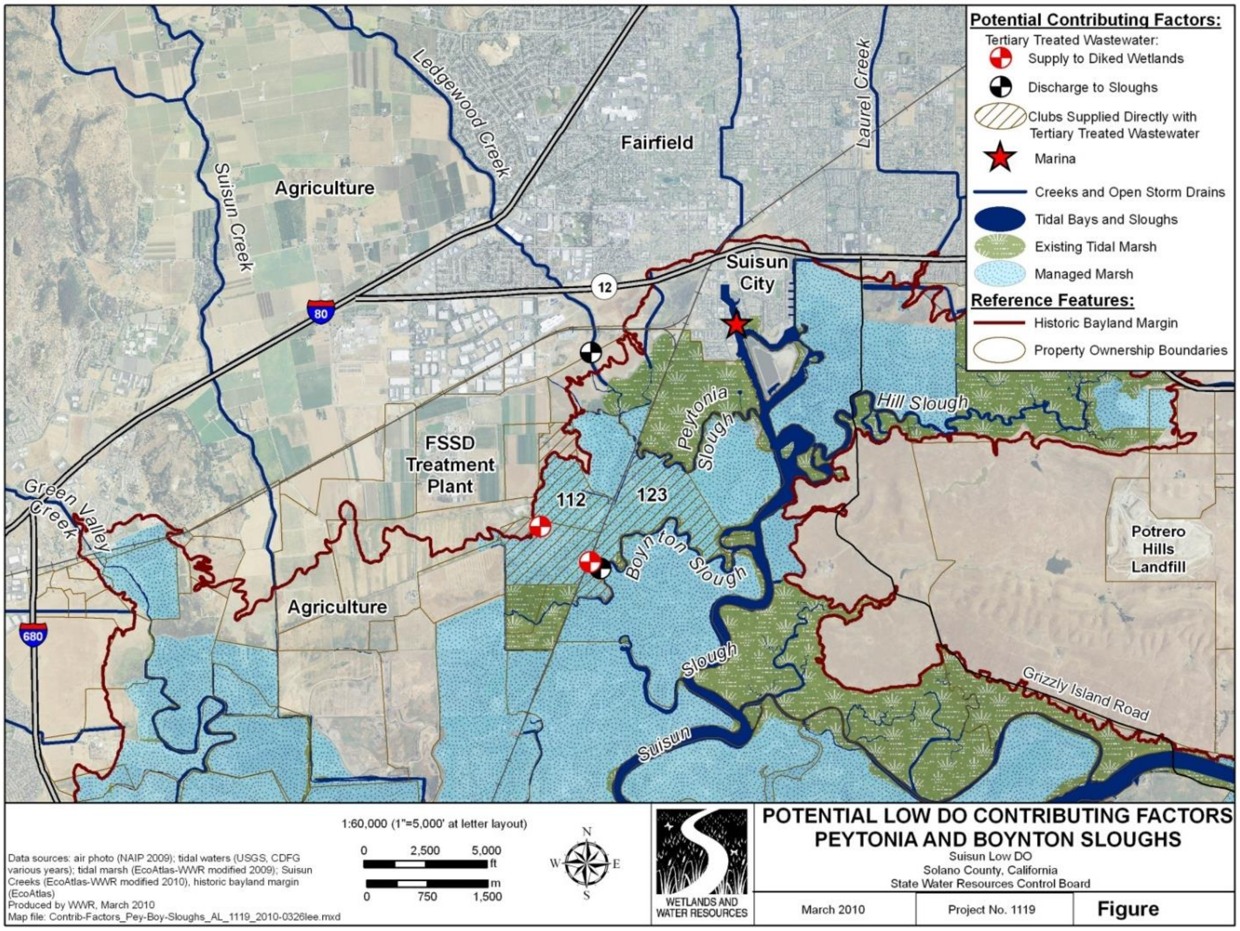


Figure 3-2 Potential low DO contributing factors in Peytonia and Boynton Sloughs (Siegel et al., 2010a).

3.2.1 Slough size

Most of the impacted sloughs are small tributary sloughs. The small width and depth of these sloughs limits the mixing of internal water with external tidal water (poor water circulation), and creates higher potential of low DO conditions (Siegel et al. 2011). The width of the Peytonia Slough is 80 ft narrowing down to 20–30 ft wide, and Boynton Slough is 80 ft wide, compared to the 450 ft width of Suisun Slough. Goodyear Slough is approximately 90 ft wide. Hill Slough is roughly 170 ft wide near the confluence with Suisun Slough and narrows down to 80 ft. Nurse and Denverton Sloughs in the northeast both are well above 100 ft in width. Suisun Slough is about 700 ft wide at the confluence with Goodyear Slough.

3.2.2 Hydrology

Four external hydrological sources that bring BOD to Peytonia, Boynton and other sloughs along Suisun Marsh are: tides (dominant), watershed runoff (seasonally important), the Fairfield –Suisun Sewer District Wastewater Treatment Plant (Boynton Slough), and direct rainfall (Siegel et al, 2010a; Figure 3-2).

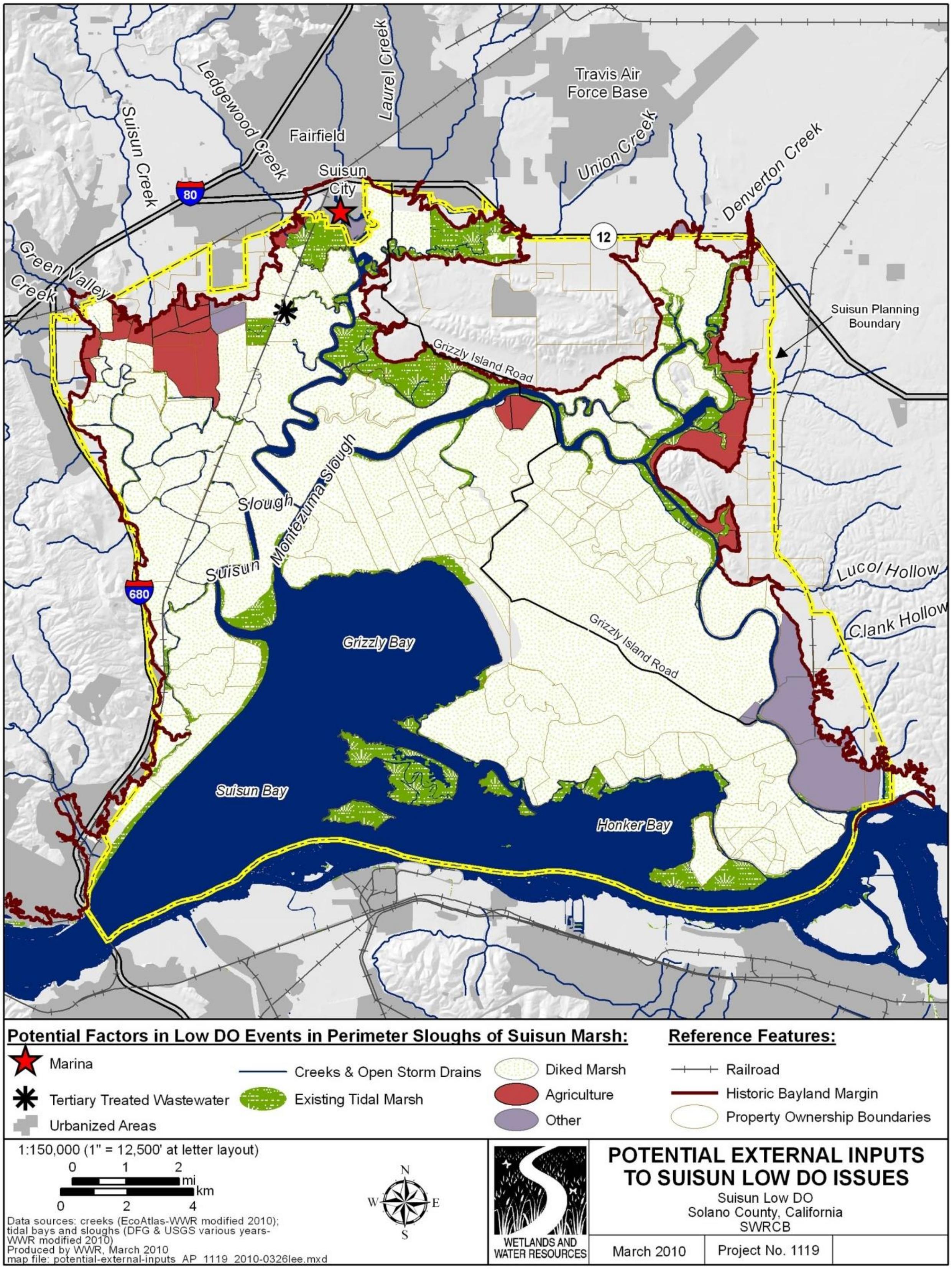


Figure 3-3 Potential External Inputs Contributing to Suisun Low DO (Siegel et al. 2011).

Tides

Tides are the dominant hydrologic force in the tidal sloughs of Suisun Marsh. Suisun and Montezuma sloughs are the two largest sloughs conducting tides throughout Suisun Marsh. The marsh experiences mixed semi-diurnal tides. Water flows into and out of the sloughs twice each day. Boynton Slough tidal flows range between about -800 and +1200 cfs. Peytonia Slough tidal flows range between about -700 and + 800 cfs. The tides are influenced by three components: the daily unequal high and low tides, the biweekly spring neap tides and the quarterly seasonal tide (Schureman 1971). The tides can bring BOD originated from Delta and Suisun Bay to Suisun Marsh.

Surrounding Watersheds

Several creeks drain to Suisun Marsh. These creeks include Green Valley Creek, Suisun Creek, Ledgewood Creek, Laurel Creek, Union Creek, and Denverton Creek. The creeks receive runoff from watersheds that drain agricultural, urban and open land use areas. Runoff from urban and agricultural areas can potentially contribute to pollutant loads to Suisun Marsh sloughs. These include oxygen consuming constituents such as nutrients and organic carbon. As estimated in the previous section, the tributaries can contribute a BOD load of 3776.5 kg/day.

Sewage Treatment Effluent

The FSSD Wastewater Treatment Plant discharges a majority of its effluent to the Boynton Slough. Although the plant is a tertiary treatment plant and low concentrations of nutrients and organic carbon in the effluent are expected, the discharge can still contribute to BOD which consumes oxygen. As estimated in the previous section, the allowable discharge of BOD load to Suisun Marsh is 545 kg/day. Nutrients (primarily nitrogen and phosphorus) can stimulate algae and plant growth, which contribute to BOD upon decomposition.

Managed Wetland Discharges in Peytonia and Boynton Sloughs

Managed wetlands are hydrologically connected to sloughs. Wetlands (112, 113, 123 and 211) with a total area of 980 acres are connected to Peytonia Slough. Six wetlands (122, 123, 131, 124, 130 and 133) with a total area of 3,000 acres are connected to Boynton Slough. The wetlands impact the sloughs during periods when wetlands are flooded or drained. It was found that DOC concentrations were highest at the beginning of the flood events and then decreased. High DOC concentrations can deplete oxygen. Upon release, low DO concentrations were found at the perimeters of the wetlands. The fall drain events resulted in low DO concentrations in export water. These wetlands are representative of the managed wetlands in Suisun Marsh, especially those connected to smaller sloughs with muted tidal exchange.

The impacts of managed wetlands on DO concentrations have been studied recently in detail at Wetland 112 and Wetland 123 (Bachand et al. 2010b). This study suggested that DO concentrations were continuously near or at 0 mg/l at several discharge locations for about 3–5 days at Wetland 123 and for about 5–15 days at Wetland 112. Fall drain events of managed wetlands (Wetland 112 and 123) were also found to affect DO levels in the adjacent sloughs. Fall drain events resulted in DO concentrations in sloughs to drop to near 0 mg/l. During fall drain events, DO levels in sloughs were below their initial concentrations in early spring. Spring drain events also result in decreases in DO concentrations in the sloughs.

The release of organic carbon from managed wetlands to sloughs was estimated in Bachand et al. (2010b) and discussed in the previous chapter. During a wetland drain event, an organic carbon load of 1,981 kg/day and 8,598 kg/day can be released to small sloughs (Peytonia and Boynton Sloughs) from Wetland 112 and 123. Since these two wetlands are only a small fraction of the total managed wetland area in Suisun Marsh, it follows that organic carbon loads from this source category overall are much greater, and the dominant source of organic carbon to the marsh.

Tidal Marshes

Although fully tidal marshes are not common in Suisun Marsh, Peytonia and Boynton Sloughs both have tidal marshes connected to them. Tidal marshes are productive systems that contribute organic matter to the receiving water and increase BOD of the system.

The conceptual model of dissolved oxygen in Suisun Marsh can be summarized as follows (Figure 3-4): 1) nutrients (nitrogen, N, and phosphorus, P) and BOD inputs from external sources including the Delta outflow, tides, surrounding watersheds, and sewage treatment enter Suisun Marsh through large/small sloughs or tidal wetlands; 2) the inputs of nutrients can fuel the growth of phytoplankton, periphyton and macrophytes in different habitats of Suisun Marsh; 3) the flooding and draining of wetlands allows release of organic carbon from soils; and, in addition, vegetation management also allows the release of organic material available; 4) the draining of managed wetlands flushes low DO water and oxygen consuming materials from the managed wetlands to the adjacent sloughs; 5) the lack of mixing in small sloughs worsens the low DO conditions in these sloughs.

3.3. Temporal Variations in DO Concentrations from Stations with Continuous Sampling

DO concentrations in Suisun Marsh sloughs vary seasonally. DO sag events tend to occur in early summer and fall (Siegel et al. 2011). The magnitude of these DO sag events, especially in the fall (DO < 2 mg/l), is sufficient to result in mortality of most fishes, invertebrates and organisms that use the sloughs and waterways of Suisun Marsh.

Continuous DO monitoring was conducted at two managed wetlands in Walnut Creek Gun Club (Wetland 123) and Suisun Farms (Wetland 112) by Siegel et al. (2010a) for two consecutive years. Monitoring stations within Wetland 123 and 112 are shown in Figure 3-5 and Figure 3-6 respectively. During the fall drain events, DO concentrations at perimeter monitoring stations dropped to near 0 mg/l and remained at 0 mg/l for several days (Figure 3-7). DO concentrations at interior monitoring station showed prolonged periods of low concentrations near 0 mg/l throughout the fall period.

The managed wetlands were also drained 2–3 times during spring. During the spring drawdown events, DO concentrations in the wetlands decreased to near 0 mg/l; however, they were able to recover in relatively short period (Figure 3-7; Bachand et al. 2010b). The period of extended DO near 0 mg/l was shorter when compared to the fall. The drop in DO concentrations coincide with water level changes.

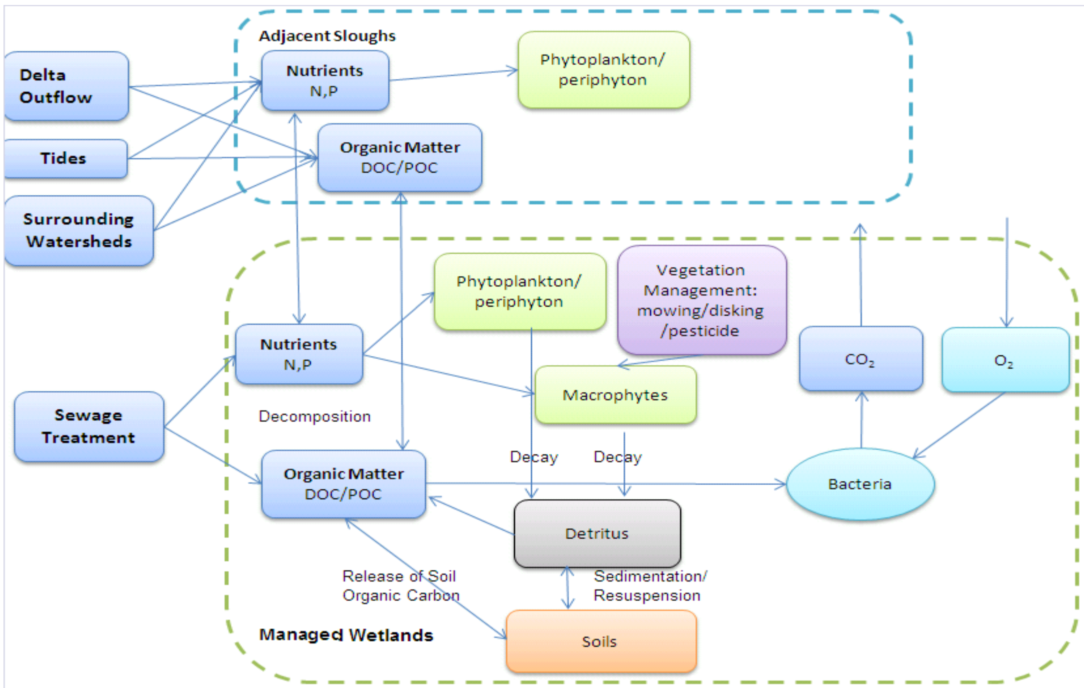


Figure 3-4 Conceptual model of dissolved oxygen in Suisun Marsh

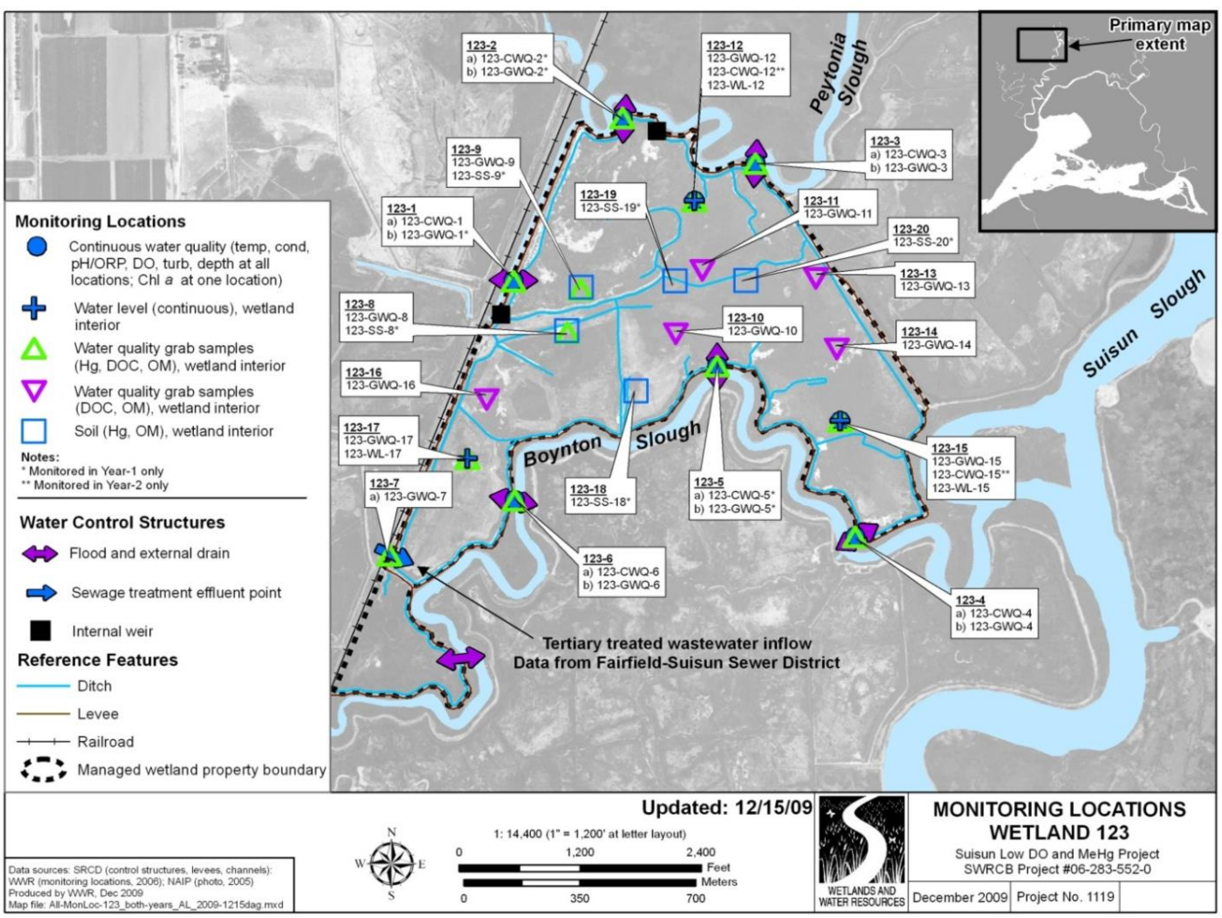


Figure 3-5 Locations of Monitoring Stations for DOC, DO and Hg in Managed Wetland 123 (Siegel et al. 2011).

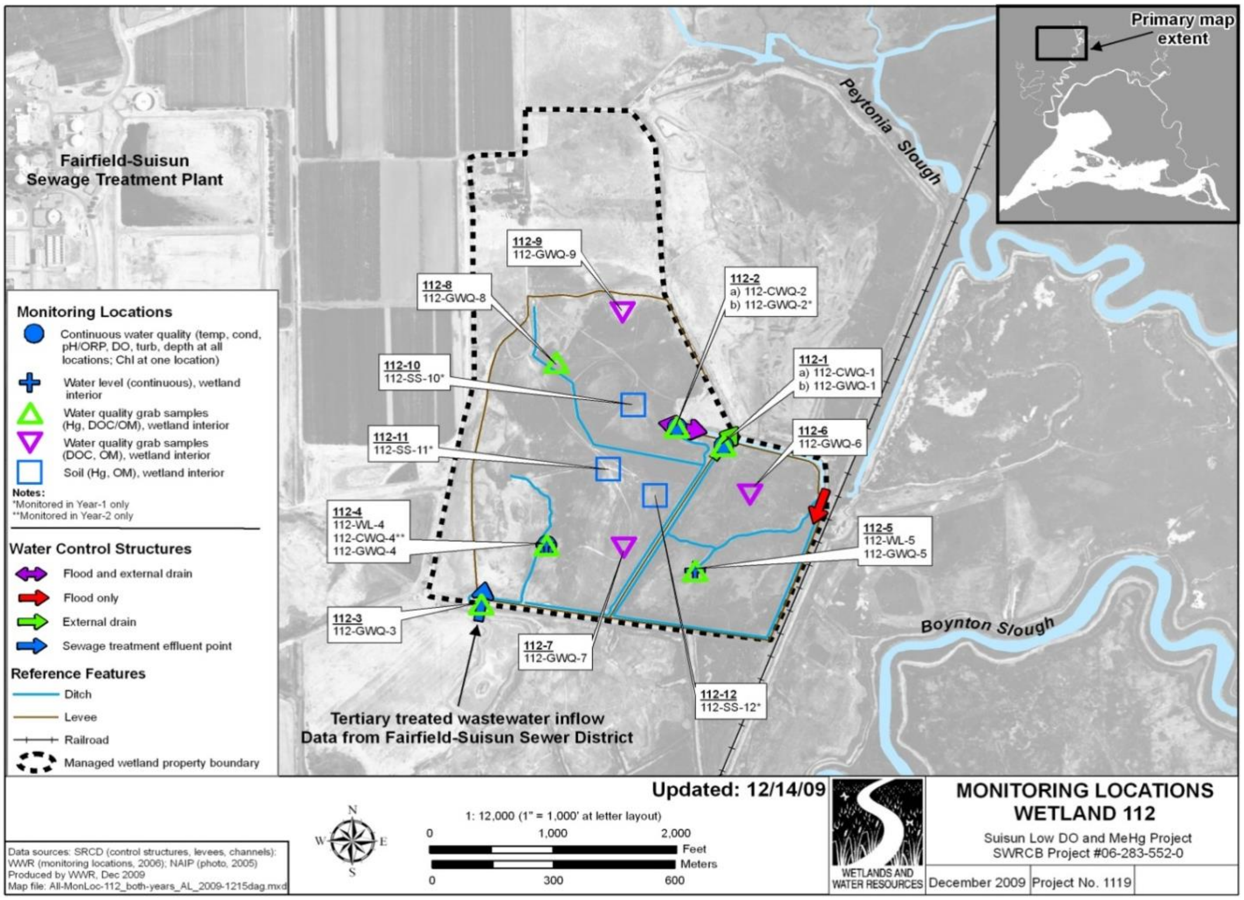
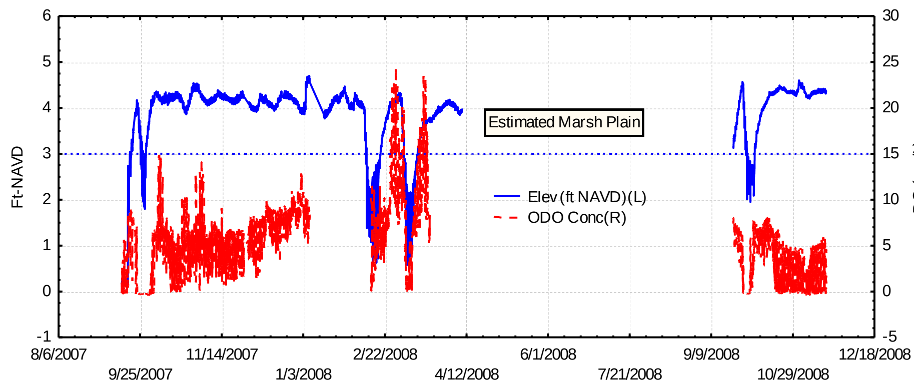
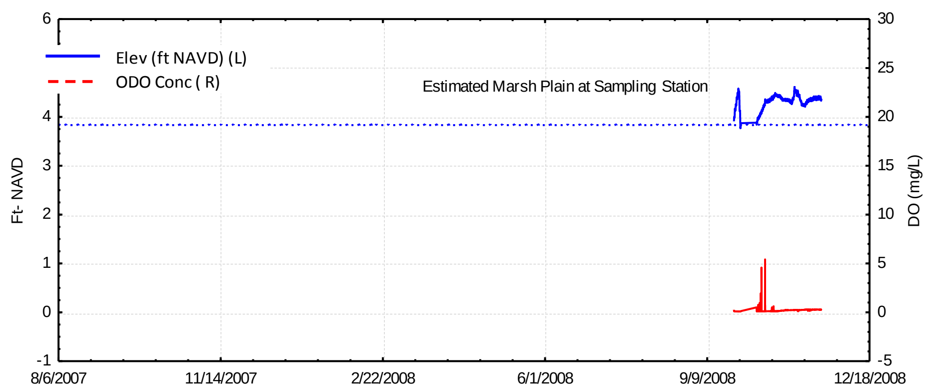


Figure 3-6 Locations of Monitoring Stations for DOC, DO and Hg in Managed Wetland 112 (Siegel et al. 2011).

A) Station 123-4, Perimeter Site



B) Station 123-8, Internal Site



C) Station 112-2, Perimeter Site

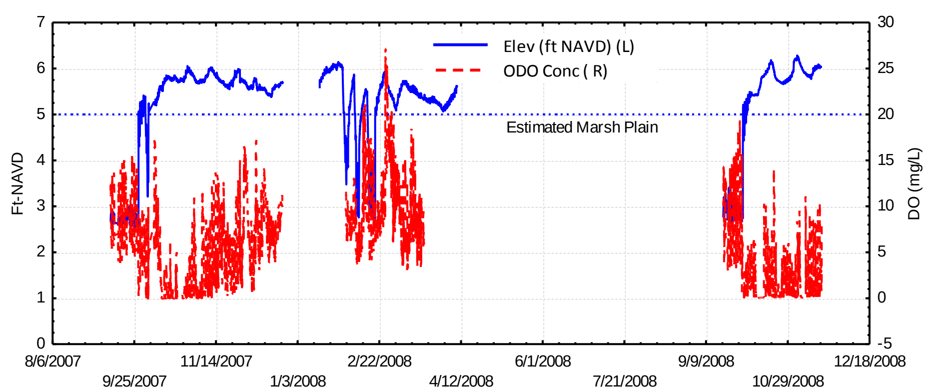


Figure 3-7 DO and Temporal Elevation Changes at Selected Perimeter and Internal Stations for wetland 123 and 112 (Siegel et al. 2011). NAVD: North American Vertical Datum.

Continuous DO monitoring has also been conducted in Peytonia and Boynton Sloughs during 09/07–12/08 (Siegel et al., 2010a). DO concentrations in Peytonia and Boynton Sloughs showed clear seasonal variations (Figure 3-8). Low DO concentrations below the water quality standard of 7 mg/l were observed during the fall (09/07–12/07) when the slough is not being flushed in the downstream direction, and during spring drain period

(04/08–06/08). DO concentrations were above the water quality standard for the time period between 12/07 to 3/08 when the slough starts flowing in the downstream direction.

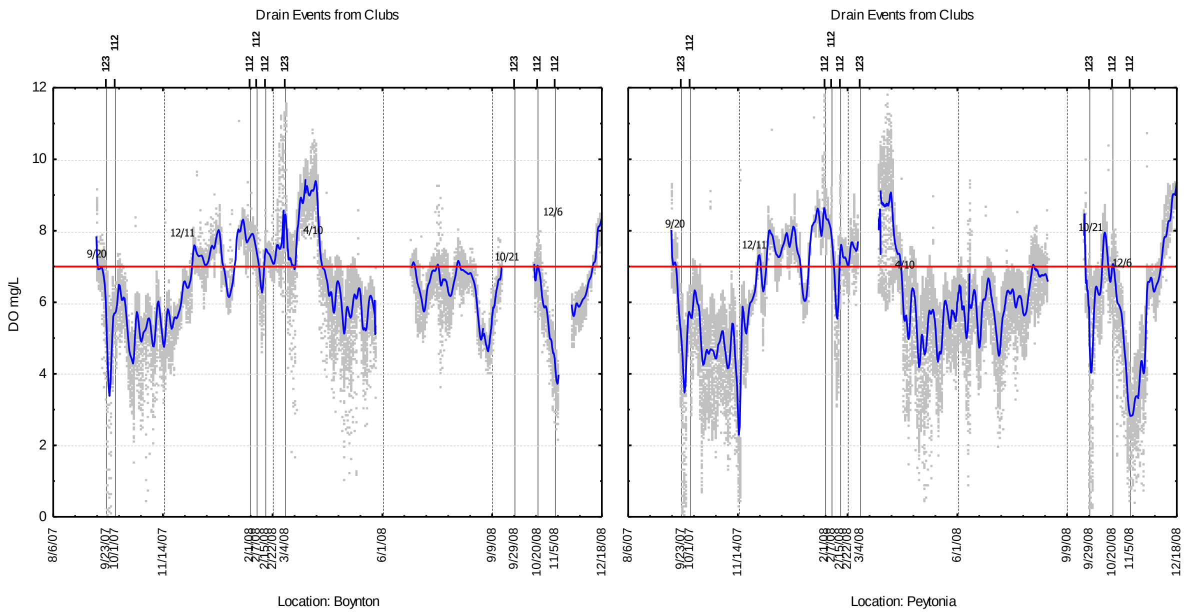


Figure 3-8 DO concentrations in Peytonia and Boynton Sloughs (Siegel et al.2010a).

Peytonia and Boynton Sloughs are considered tidal waters above the Carquinez Bridge from the perspective of the Basin Plan. The applicable water quality objective for DO is 7 mg/l. From the data shown above (Figure 3-8), there are extended periods of low DO concentrations below 7 mg/l. Therefore Peytonia and Boynton Sloughs are considered as impaired by low dissolved oxygen.

Continuous DO monitoring has also been conducted in Goodyear Slough and Denverton Slough for the period of 08/12–01/13 (Figure 3-9). DO concentrations were around 7 mg/l between 08/12–10/12, and started to decrease from middle of October. DO concentrations stay low for the period of 10/12–12/12. DO concentrations started to increase from late December and stay at around 7 mg/l for the period of 12/12–01/13. During the low DO period (10/12–12/12), concentrations in Goodyear Slough reached as low as 1 mg/l and DO in Denverton Slough reached as low as 3 mg/l. Due to lower discharge density, a wider slough channel, and more straight and short connection with Montezuma Slough, Denverton Slough has higher DO concentrations than the Goodyear Slough.

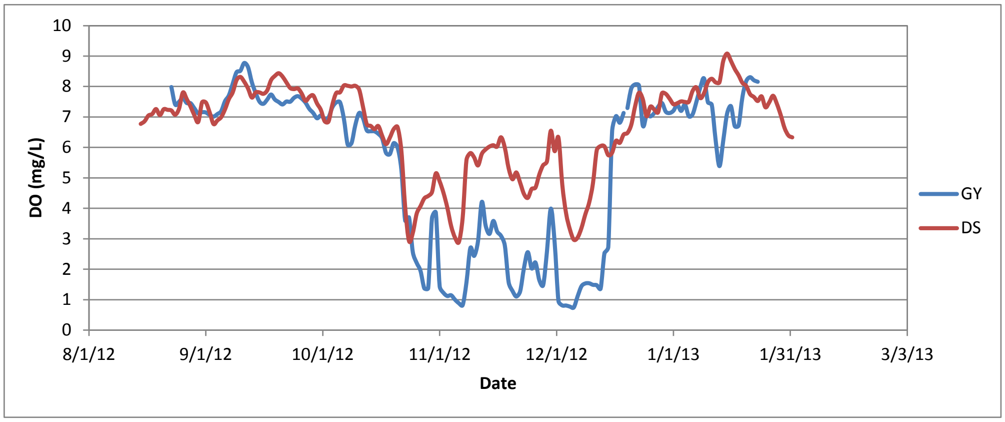


Figure 3-9 DO concentrations in Goodyear and Denverton Sloughs (Regional Water Board, 2013).

3.4. Concentrations of DO Observed at Stations with Grab Samples

DO concentrations have also been monitored at a number of locations in Suisun Marsh by the Environmental Monitoring Program (EMP) and in Suisun Marsh Fisheries Monitoring Project. These data are available from the Bay Delta and Tributaries (BDAT) project website (http://bdat.ca.gov/index.html). DO concentrations were monitored at several locations in Montezuma Slough, Suisun Slough, Goodyear Slough, Boynton Slough, and Peytonia Slough (Table 3-1; Figure 3-10).

Time series data of observed DO concentrations and percent DO saturation were shown in Figure 3-11 to Figure 3-17. DO concentrations measured at stations in Montezuma Slough are mostly above water quality standard of 7 mg/l with a few exceptions (Figure 3-11). Percent dissolved oxygen saturation measured at stations in Montezuma Slough is above criteria of 80% for most of the time (Figure 3-12).

For stations in Suisun Marsh, three stations show DO concentrations above the criterion of 7 mg/l for most of the time (Figure 3-13). Data from station SU1 and SU2 (below Boynton Slough) are often below the DO water quality objective. About half of the measurements for percent oxygen saturation at these two stations were below the criteria of 80% (Figure 3-14). Percent oxygen saturation at SU3 and SU4 was mostly above 80% with a few exceptions.

DO concentrations measured at tributary sloughs are often below the water quality objective, particularly in the upper and middle sections of the Goodyear Slough (Figure 3-15). Percent dissolved oxygen saturation was below 80% at all three stations in Goodyear Slough for most of the time (Figure 3-15). Low DO concentrations usually occurred in late summer and fall months.

A similar pattern of lower DO concentrations was observed for Boynton Slough (Figure 3-16), with dissolved oxygen concentrations generally below the water quality standard of 7 mg/l and median percent oxygen saturation below 80% over a 3-month period. Dissolved oxygen concentrations and oxygen saturation measured at Peytonia Slough showed similar pattern of DO frequently below water quality objectives (Figure 3-17).

When comparing across the sites, Montezuma Slough and part of Suisun Slough have higher DO concentrations, with most of the observations above the water quality objective (Figure 3-20). Goodyear Slough, Peytonia Slough and Boynton Slough showed lower DO concentrations, with DO below the water quality objective for more than 50% of the time (Figure 3-20). Parts of Suisun Slough also showed low DO concentrations.

Table 3-1
Stations with Observed DO Concentrations in Suisun Marsh (Source: BDAT)

Site	Location	Record Period	% of Samples Below 7 mg/l	% of Samples with 3-month Median DO Saturation Below 80%
NZ032	Montezuma Slough, 2nd bend from mouth	1999–2007	3.7%	-
MZ1	Montezuma Slough at Roaring	2000–2011	7.75%	16.7%
MZ2	Montezuma Slough at boat ramp	2000–2011	8.8%	21.2%
SU1	Suisun Slough seining beach	2000–2011	48.2%	83.2%
SU2	Suisun Slough- below Boynton Slough	2000–2011	50.0%	80.7%
SU3	Suisun Slough – above Cordelia Slough	2000–2011	16.2%	22.3%
SU4	Suisun Slough – below Cordelia Slough	2000–2011	14.6%	26.1%
S42	Suisun Slough 300' south of Volanti Slough	1978–1985	11.5%	-
GY1	Goodyear Slough – upper	2000–2011	76.9%	93.8%
GY2	Goodyear Slough - middle	2000–2011	72.1%	90.0%
GY3	Goodyear Slough – lower	2000–2011	31.6%	48.1%
BY1	Boynton Slough - upper	2000–2011	75.7%	95.4%
BY3	Boynton Slough – lower	2000–2011	67.4%	86.9%
PT1	Peytonia Slough – upper	2000–2011	68.1%	92.4%
PT2	Peytonia Slough – middle	2000–2011	66.7%	91.1%
DV2	Denverton Slough – middle	2000–2011	49.26%	67.94%
DV3	Denverton Slough - lower	2000–2011	43.70%	64.34%
NS2	Nurse Slough – middle	2000–2011	24.44%	41.86%
NS3	Nurse Slough – lower	2000–2011	18.94%	37.30%

DO concentrations from Nurse and Denverton Slough were also compared with DO objectives (Figure 3-18 and Figure 3-19). The Nurse Slough showed approximately 20% of time below DO objective of 7 mg/l and 40% of time of 3-month median DO below 80% saturation. The Denverton Slough showed approximately 40% of time below DO objective of 7 mg/l and over 60% of time of 3-month median DO below 80% saturation. Conditions in these two sloughs are better than in other parts of the marsh due to enhanced mixing with Montezuma Slough and limited discharge form duck clubs.

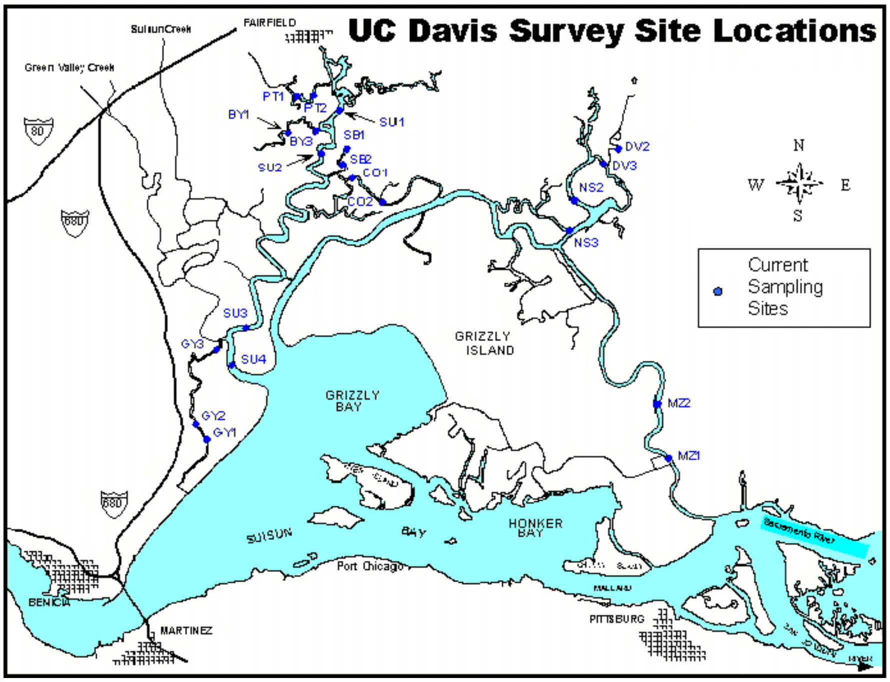


Figure 3-10 **Monitoring locations for DO, salinity, specific conductance in Suisun, Montezuma, Goodyear, Peytonia and Boynton Sloughs (Source: DWR).**

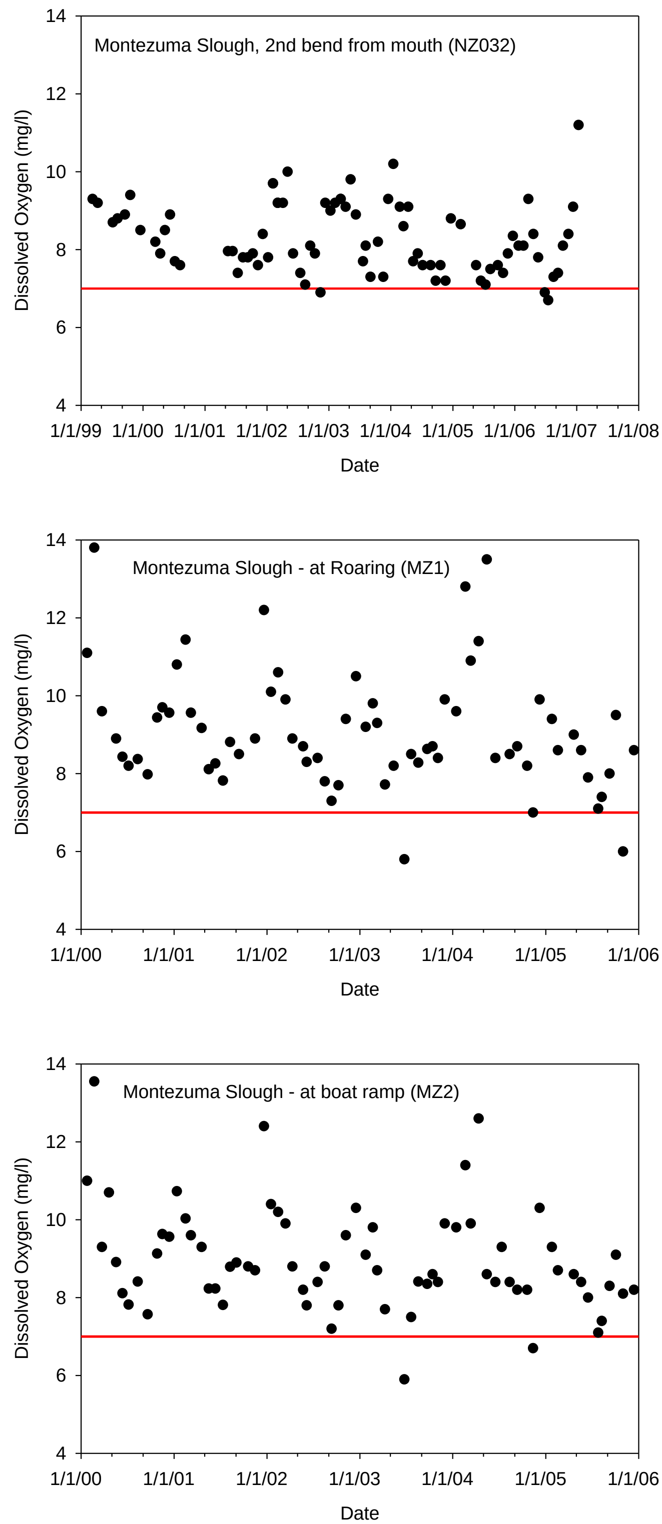


Figure 3-11 Dissolved oxygen concentrations measured at Montezuma Slough (Site NZ032, MZ1 and MZ2; Source: BDAT).

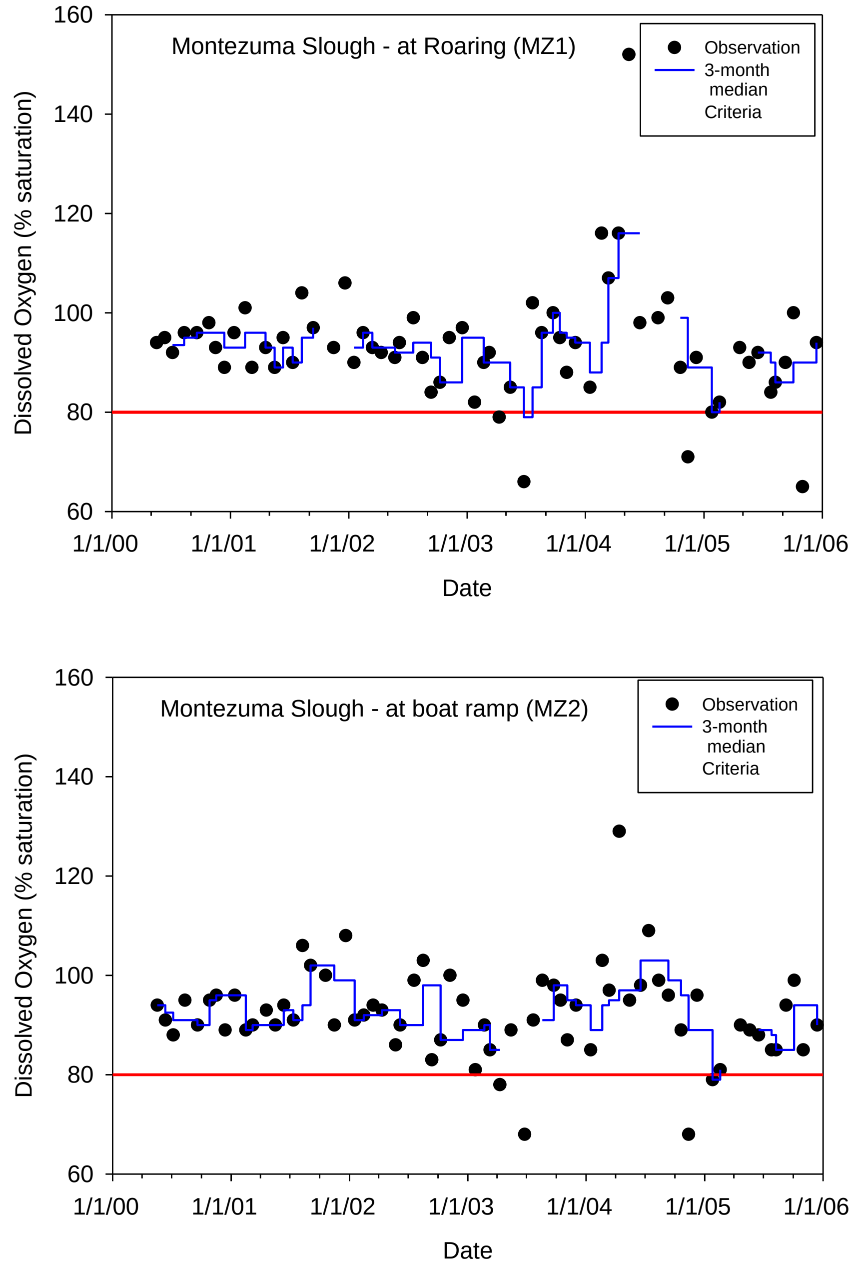


Figure 3-12 Percent dissolved oxygen saturation measured at Montezuma Slough (Site MZ1 and MZ2; Source: BDAT).

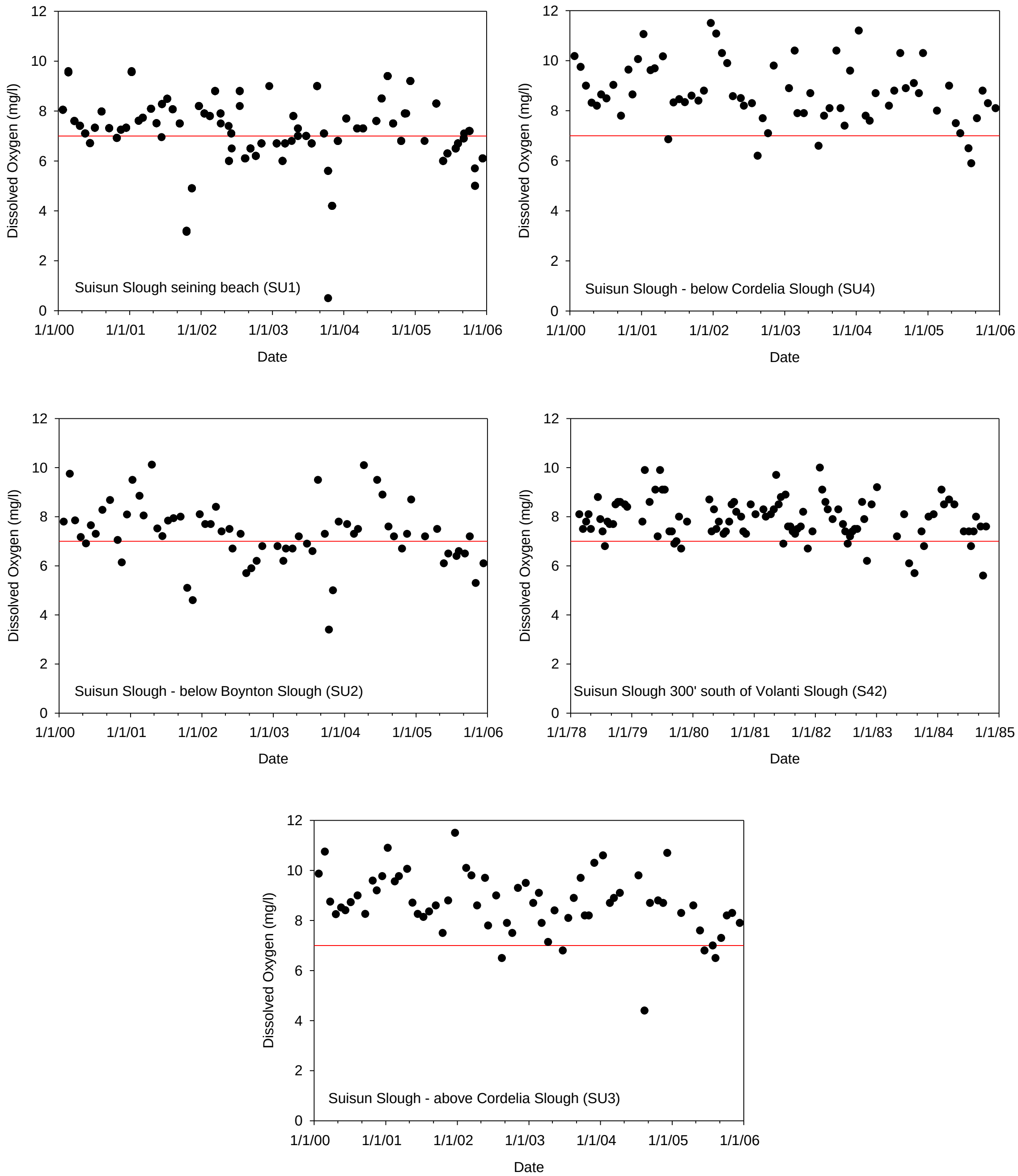


Figure 3-13 Dissolved oxygen concentrations measured at Suisun Slough (Site SU1, SU2, SU3, SU4 and S42; Source: BDAT).

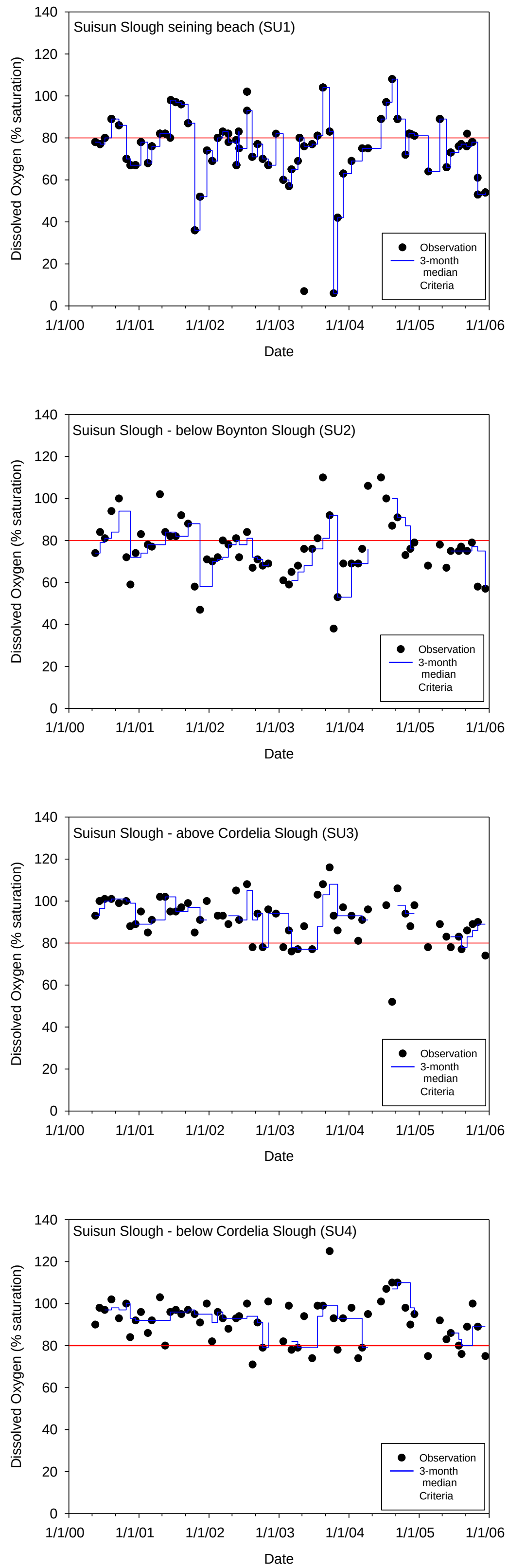


Figure 3-14 Percent dissolved oxygen saturation measured at Suisun Slough (Site SU1, SU2, SU3 and SU4; Source: BDAT).

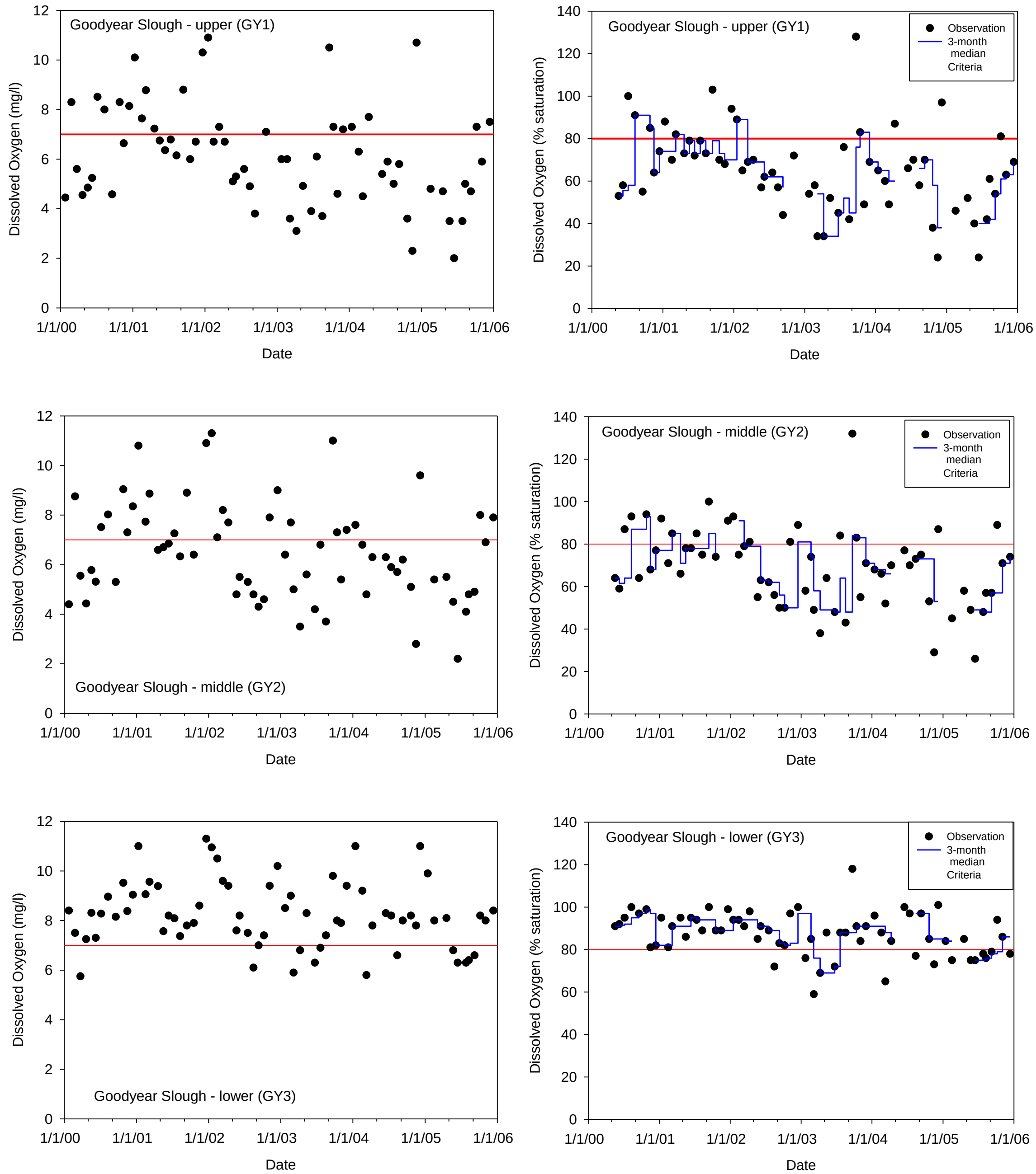


Figure 3-15 Dissolved oxygen concentrations and percent oxygen saturation measured at Goodyear Slough (Site GY1, GY2, and GY3; Source: BDAT).

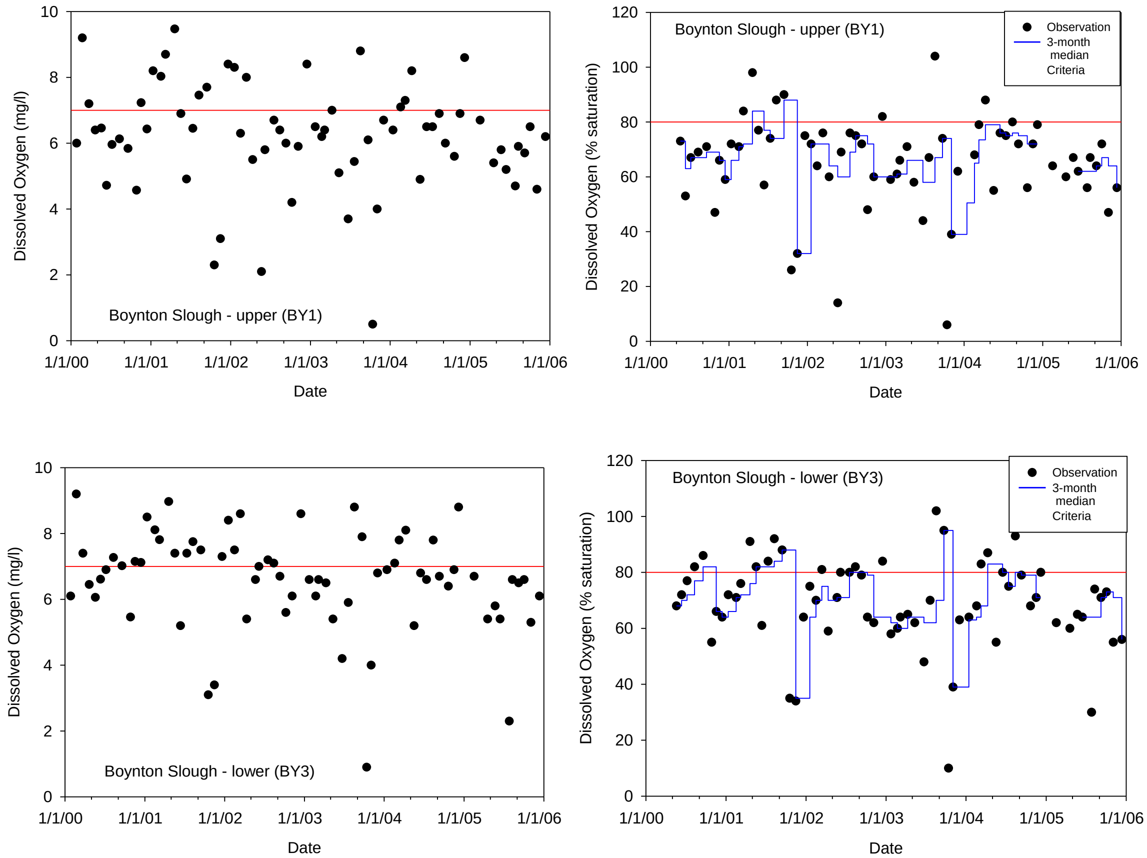


Figure 3-16 **Dissolved oxygen concentrations and percent oxygen saturation measured at Boynton Slough (Site BY1 and BY3; Source: BDAT).**

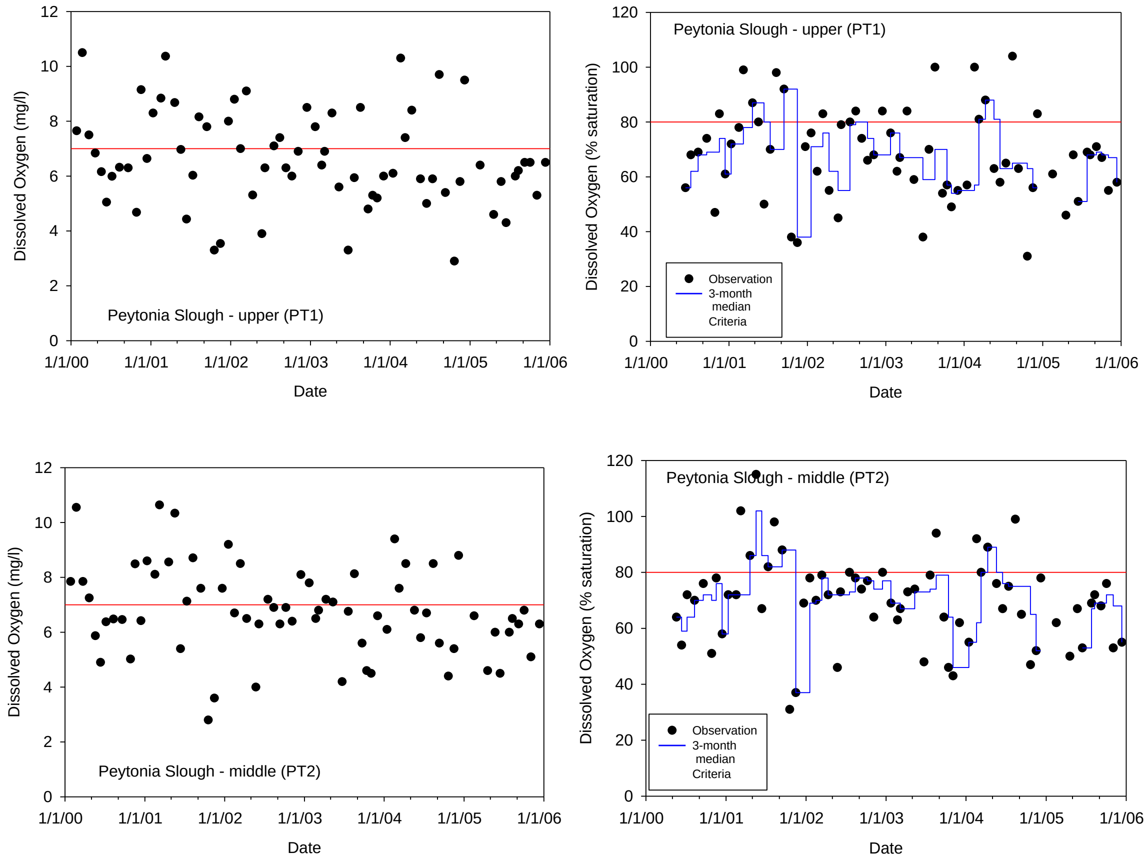


Figure 3-17 Dissolved oxygen concentrations and percent oxygen saturation measured at Peytonia Slough (Site PT1 and PT2; Source: BDAT).

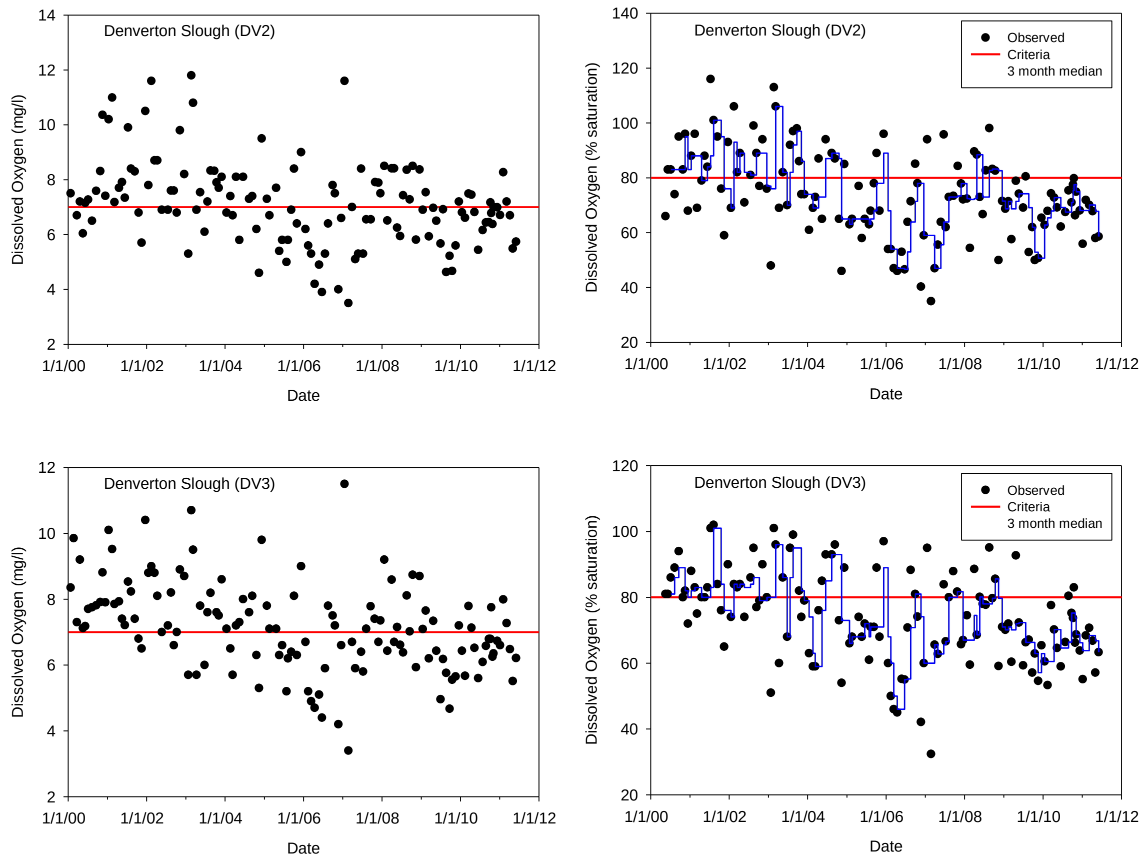


Figure 3-18 Dissolved oxygen concentrations and percent oxygen saturation measured at Denverton Slough (Site DV2 and DV3; Source: Moyle, personal communication).

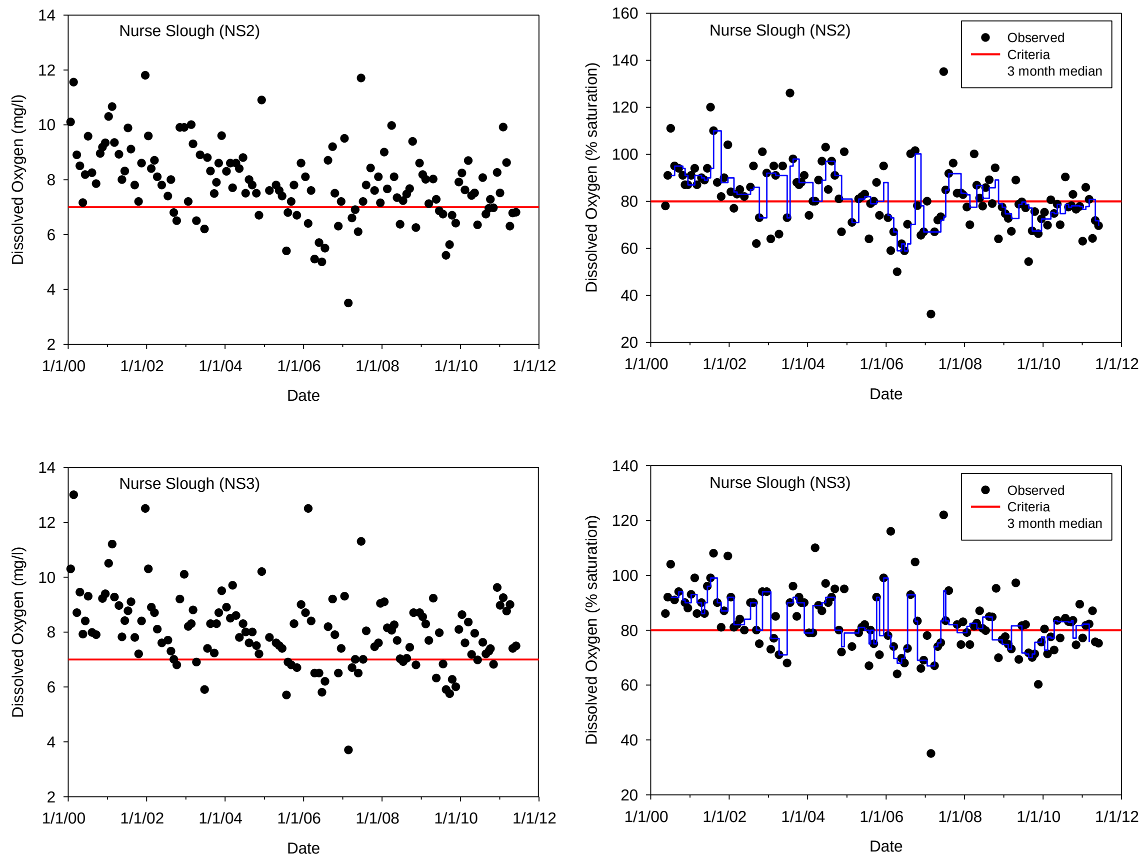


Figure 3-19 Dissolved oxygen concentrations and percent oxygen saturation measured at Nurse Slough (Site NS2 and NS3; Source: Moyle, personal communication).

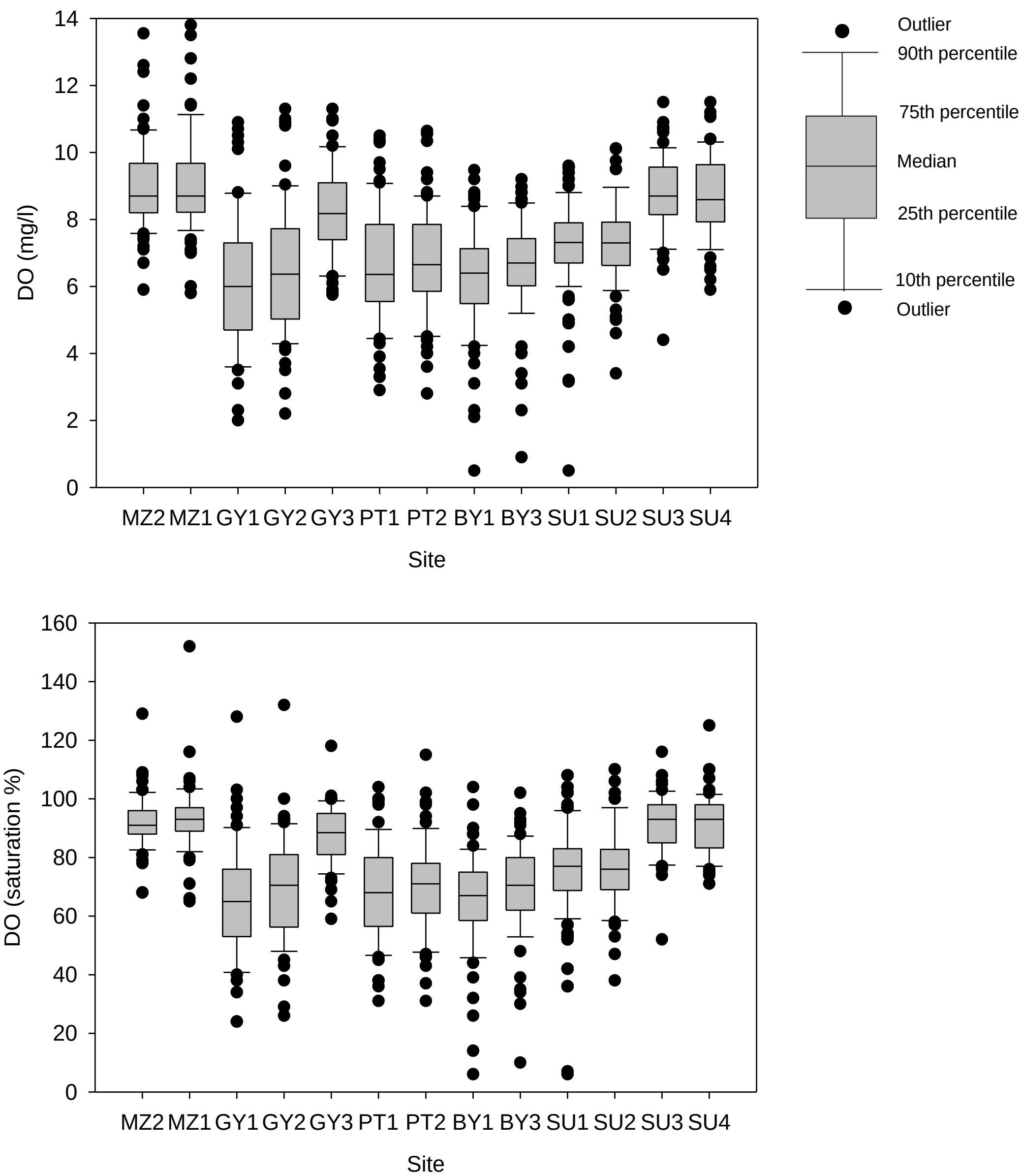


Figure 3-20 Dissolved oxygen concentrations and percent oxygen saturation at stations in Montezuma Slough (MZ), Suisun Slough (SU), Goodyear Slough (GY), Peytonia Slough (PT) and Boynton Slough (BY) (Source: BDAT).

3.5. CONDITIONS AT REFERENCE SLOUGHS

Many sloughs within Suisun Marsh receive discharges from managed wetlands. These sloughs represent conditions that are modified by human activities. Sloughs that are connected to the larger sloughs (Suisun and Montezuma Sloughs) that receive no discharges from managed wetlands can be used to characterize background/reference conditions in the marsh. Two of these sloughs in Suisun Marsh have also been monitored for dissolved oxygen: the First Mallard and Second Mallard Sloughs, located at the intersection of Cutoff Slough. Dissolved oxygen concentrations at two stations in the First Mallard and Second Mallard Sloughs are monitored continuously by NOAA under the National Estuarine

Research Reserve System's (NERRS) National Monitoring Program. These stations drain different regions of the San Francisco Bay National Estuarine Research Reserve. The First Mallard Slough drains the northwestern portion of Rush Ranch, while the Second Mallard Slough drains the southeastern areas (Figure 3-22). The area draining to the First and Second Mallard Sloughs consists mostly of tidal marshes and upland non-tidal wetlands, covered by native vegetation.

DO concentrations in the First Mallard Slough range between 4 to 9 mg/l. DO concentrations in the Second Mallard Slough range between 5 to 10 mg/l. Daily average DO concentrations at these two locations are compared to potential DO objectives of 7 mg/l and 5 mg/l and the 3-month medians of daily average DO saturation were compared to the objective of 80% saturation. The hourly DO concentrations were compared to EPA recommended DO criteria for continuous exposure of saltwater: 1) 2.3 mg/l for criterion minimum concentration (CMC) for juvenile and adult survival; 2) 4.8 mg/l for criterion continuous concentration (CCC) for growth effects, and 3) criteria for episodic exposure based on hours of exposure to adjusted CMC (EPA, 2000). The results are shown in Figure 3-22 to Figure 3-27 and summarized in Table 3-2 and Table 3-3.

For the First Mallard Slough, when compared to a criterion of 7 mg/l, about half of the data are below 7 mg/l, but only a limited number of measurements are below 5 mg/l. The First Mallard Slough is below 80% DO saturation for most of the time. The hourly DO is below continuous exposure criteria CMC occasionally and below CCC for 5% of the time.

For the Second Mallard Slough, when compared to a criterion of 7 mg/l, about 40% of the data are below 7 mg/l, and only a limited number of measurements are below 5 mg/l. The Second Mallard Slough is below 80% DO saturation for over 78% of the time. The hourly DO is below continuous exposure criteria CMC occasionally and below CCC for 2% of the time.

The First and Second Mallard Sloughs are considered to be relatively pristine and can be used to represent background conditions in Suisun Marsh. The fact that about 50% of the time DO levels in the First Mallard Slough and 40% of the time in the Second Mallard Slough were below 7 mg/l suggests that a criterion of 7 mg/l is not met even without discharges from managed wetlands. Both, the First and Second Mallard Slough, and the Cutoff Slough have DO above 5 mg/l more than 95% of the time, Table 3-2 and Table 3-3.

Figure 3-21 Locations of the First and Second Mallard Slough Monitoring Stations.

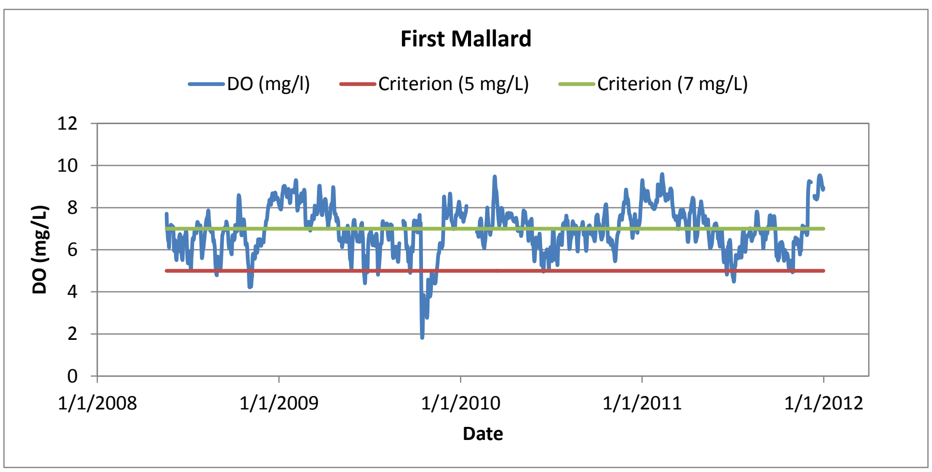


Figure 3-22 Daily average DO concentrations at the First Mallard Slough compared to DO criteria of 5 and 7mg/l.

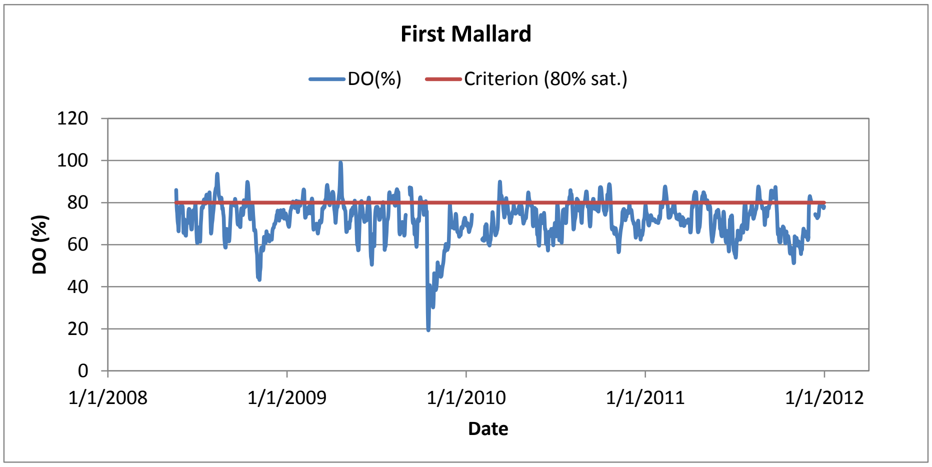


Figure 3-23 **Daily average DO concentrations at the First Mallard Slough compared to 80% of DO saturation.**

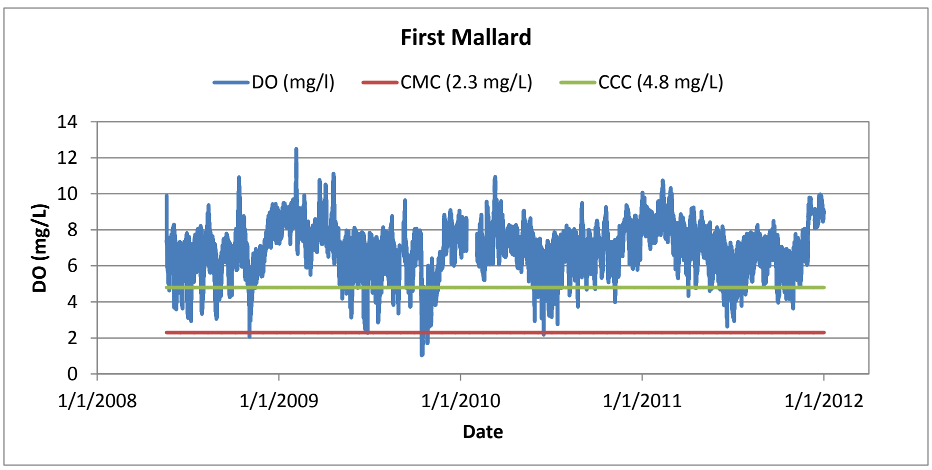


Figure 3-24 **Hourly DO concentrations compared to criterion minimum concentration (CMC) and criterion continuous concentration (CCC) at the First Mallard Slough.**

Table 3-2
Summary of Time Below DO Criterion for the First Mallard Slough

	Days below criterion of 5 mg/l	Days below criterion of 7 mg/l	Number of rolling 3-month median of daily average below 80% saturation	Hours below CMC of 2.3 mg/l*	Hours below CCC of 4.8 mg/l*	Hours below adjusted CMC* (based on hourly duration of exposure)	Hours with cumulative growth reduction >25%*
Number	57	667	1230	54	1647	22	842
Total Data Points	1289	1289	1243	30830	30830	30830	30830
Percent	4.4%	51.7%	95.4%	0.18%	5.34%	0.07%	2.73%

*EPA, 2000

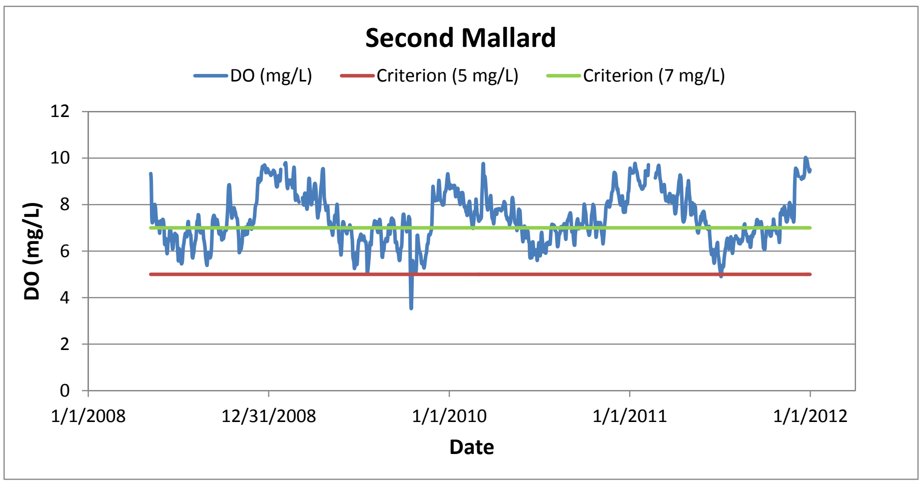


Figure 3-25 **Daily average DO concentrations at the Second Mallard Slough compared to DO criteria of 5 and 7mg/l.**

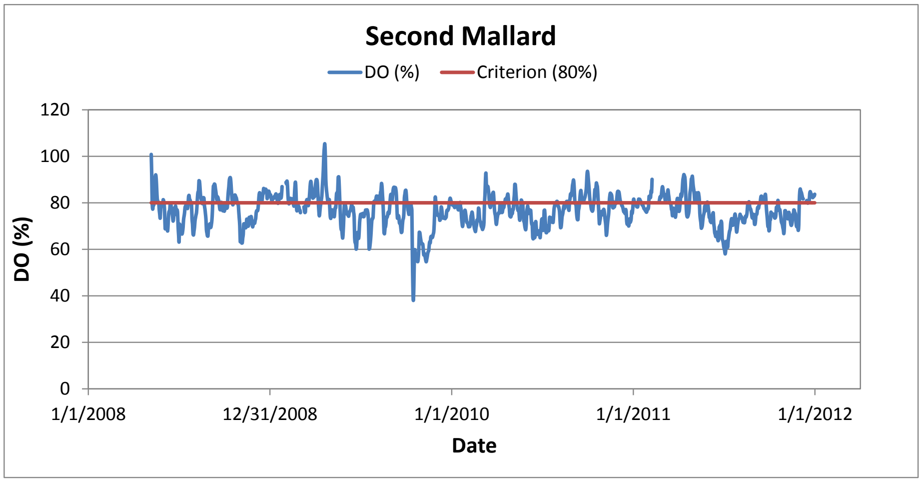


Figure 3-26 **Daily average DO concentrations at the Second Mallard Slough compared to 80% of DO saturation.**

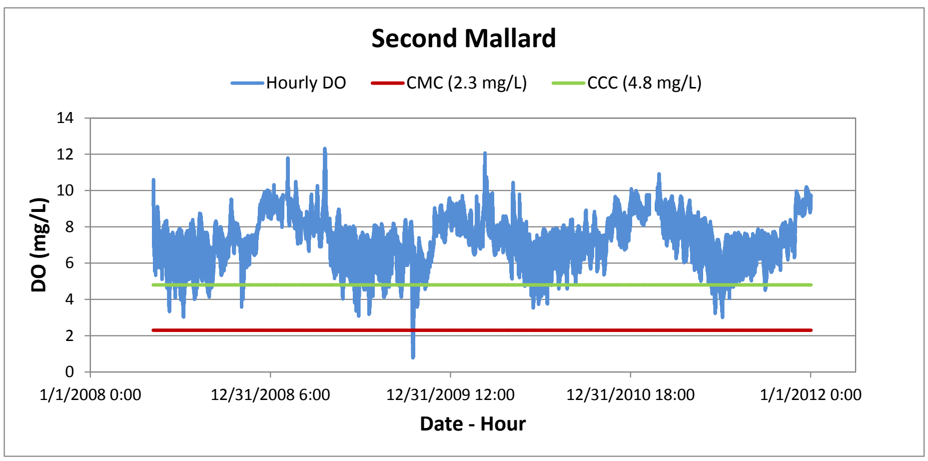


Figure 3-27 **Hourly DO concentrations compared to criterion minimum concentration (CMC) and criterion continuous concentration (CCC) at the Second Mallard Slough.**

Table 3-3
Summary of Time Below DO Criterion for the Second Mallard Slough

	Days below criterion of 5 mg/l	Days below criterion of 7 mg/l	Number of rolling 3-month median of daily average below 80% saturation	Hours below CMC of 2.3 mg/l*	Hours below CCC of 4.8 mg/l*	Hours below adjusted CMC (based on hourly duration of exposure)*	Hours with cumulative growth reduction >25%*
Number	5	513	971	18	662	11	195
Total data points	1305	1305	1243	31206	31206	31206	31206
Percent	0.38%	39.31%	78.12%	0.06%	2.12%	0.04%	0.62%

*EPA, 2000

The cumulative distribution of 1-hour minimum, 4-hour minimum, 6-hour minimum and 24-hour minimum DO concentrations for the First Mallard and Second Mallard Sloughs were estimated to show the frequency of exceedances for DO (Figure 3-28, Figure 3-30). For 20% of the time, the 24-hour minimum DO is less than 5 mg/l. The 1-hour to 6-hour minimum DO is generally less than 6 mg/l for 15-25% of the time.

The DO concentrations at the First Mallard Slough show seasonal variations with lower concentrations during summer months when temperatures are higher (Figure 3-29). However, the lowest DO occurs during the fall, usually in October and November, when 24-hour and 30-day running averages could drop below 5 mg/l. Similar DO patterns were also found for the Second Mallard Slough (Figure 3-30 and Figure 3-31).

The statistics of the 1-hour, 4-hour, 6-hour, and 24-hour minimum DO concentrations are shown in Table 3-4. Mean values of the 1-hour to 24-hour minimum DO concentrations are generally less than 7 mg/l.

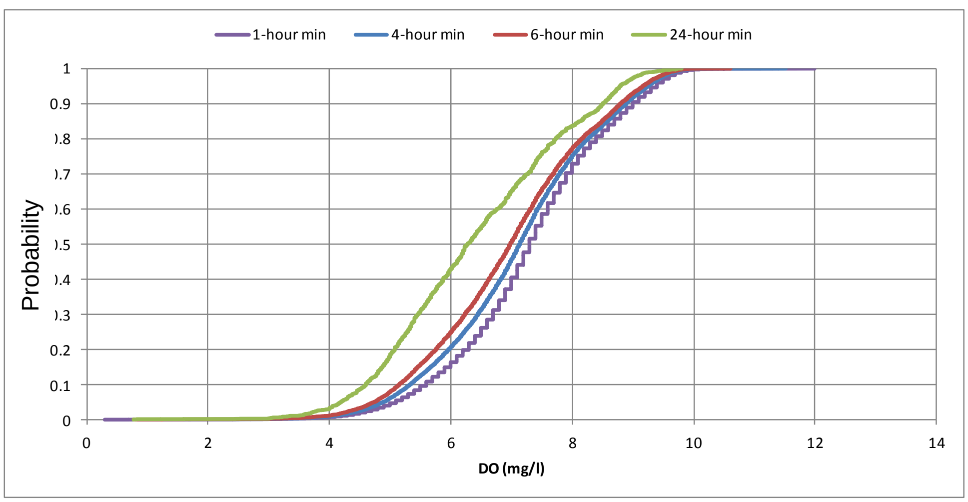


Figure 3-28 Cumulative probability distributions of 1-hour min, 4-hour min, 6-hour min and 24-hour min DO concentrations at the First Mallard Slough.

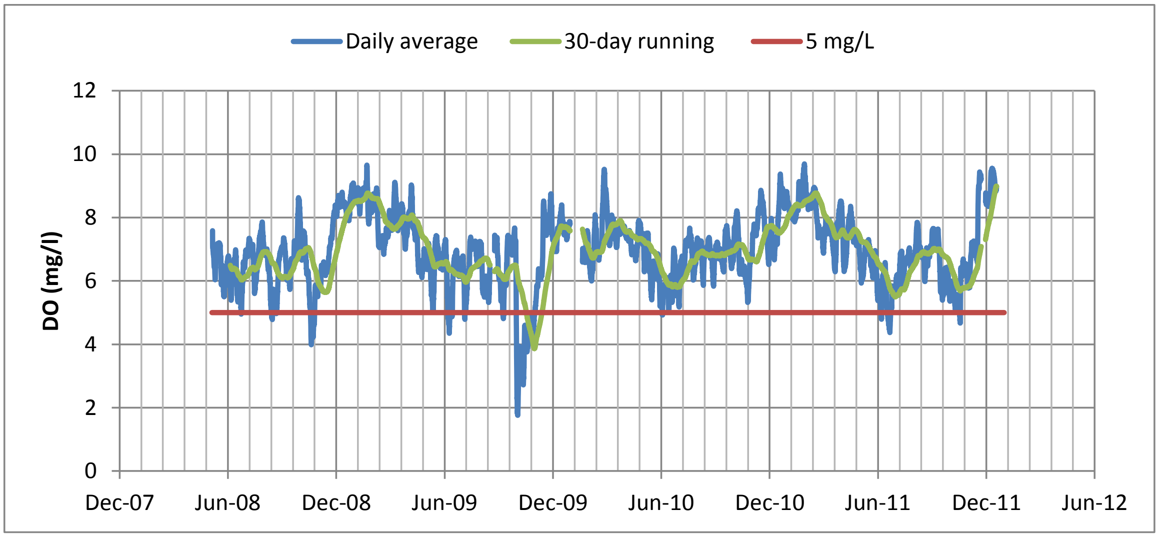


Figure 3-29 **24 hour running average and 30-day running average at the First Mallard Slough compared to a criterion of 5 mg/l.**

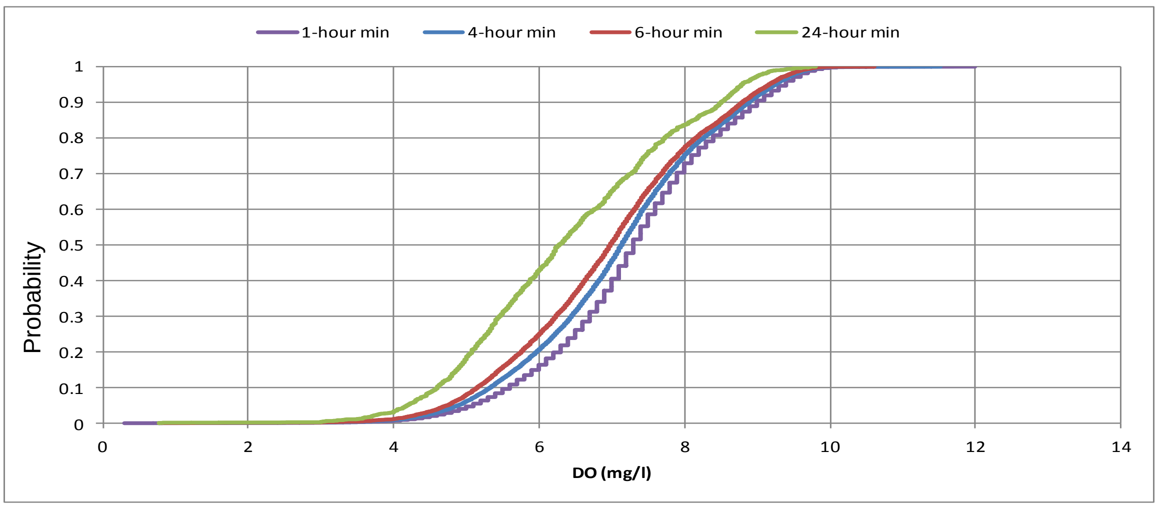


Figure 3-30 **Cumulative probability distributions of 1-hour min, 4-hour min, 6-hour min and 24-hour min DO concentrations at the Second Mallard Slough.**

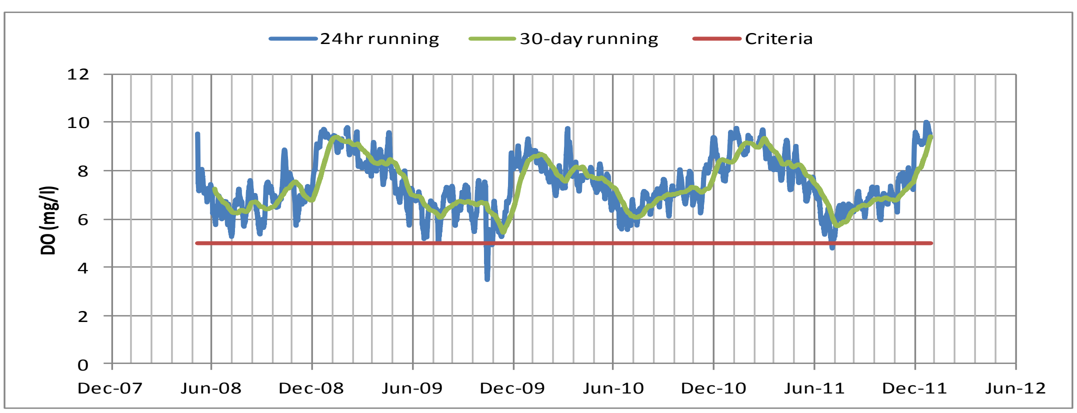


Figure 3-31 **24 hour running average and 30-day running average compared to a criterion of 5 mg/l at the Second Mallard Slough.**

Table 3-4
Statistics of 1-hour Minimum, 4-hour Minimum, 6-hour Minimum and 24-hour Minimum DO at the First and Second Mallard Sloughs

	1 hour min	4 hour min	6 hour min	24 hour min
Second Mallard				
Min	0.3	0.8	0.8	0.8
Max	12.0	11.5	10.6	9.8
mean	7.3	7.1	6.9	6.4
Standard deviation	1.3	1.3	1.4	1.5
95th percentile	9.4	9.3	9.2	8.8
5th percentile	5.1	4.9	4.7	4.2
First Mallard				
Min	0.3	1.0	1.0	1.0
Max	11.8	10.9	10.2	9.2
Mean	6.8	6.6	6.5	6.0
Standard deviation	1.3	1.3	1.3	1.4
95th percentile	8.8	8.6	8.5	8.2
5th percentile	4.5	4.3	4.2	3.6

3.6. Impairment Assessment

For all tidal waters above Carquinez Bridge, the currently applicable water quality objective for DO is 7 mg/l. However, DO concentrations at several sloughs monitored are below 7 mg/l for over 50% of the time (Goodyear, Peytonia and Boynton Sloughs; Figure 3-20), suggesting impairment by low DO. DO concentrations measured at Montezuma and Suisun sloughs also showed DO concentrations of lower than 7 mg/l (for <10% of time and between 10-40% of time, respectively). These two sloughs are also considered as impaired by low DO although to a lesser degree.

When compared to the other water quality objective in the basin plan (3-month median above 80% DO saturation), the Montezuma Slough shows only 2% of samples with 3-month median DO below 80% saturation (Table 3-1). The Suisun Slough showed 60–68% of 3-month median below 80% saturation in the upper slough and 11% in the lower slough. The Goodyear, Peytonia and Boynton showed 73%–94% of measurements below the 80% saturation level, except at lower Goodyear Slough.

The impairment assessment may be modified with updated DO targets, currently under development, that are more representative of natural conditions in wetlands and in small sloughs in Suisun Marsh.

3.7. Summary

The conceptual model/impairment assessment of dissolved oxygen in Suisun Marsh suggests that:

- Causes of low DO in Suisun Marsh sloughs include:
  - External and internal BOD input:
    - Tides (and delta outflow) that bring BOD from the Delta and Suisun Bay
    - Surrounding watersheds that drain agricultural and urban areas
    - Wastewater treatment plant effluent
    - Managed wetlands discharges that are low in DO and rich in BOD
    - Tidal marshes
  - Slough size: narrow slough with limited mixing, resulting in low DO. Low DO is often found in smaller sloughs.
- The preliminary load estimates presented here, given available data, suggest that the most significant driver of low DO are vegetation and water management activities in the managed wetlands that result in releases of low DO water, as well as water containing high concentrations of organic carbon. These can be directly linked to low DO in adjacent small sloughs. Inputs of BOD from tributaries and the wastewater treatment are also contributors, although to a lesser degree than the managed wetlands. Limited mixing in small sloughs further exacerbates the low DO problem.
- DO monitoring conducted at two managed wetlands suggested that during fall drain events, DO concentrations at perimeter monitoring stations decreased to near 0 mg/l and remained at 0 mg/l for several days. DO at interior stations showed prolonged periods of low DO concentrations near 0 mg/l throughout the fall period. Spring drain events lowered DO concentrations to near 0 mg/l but these low Do periods were relatively short-lasting.
- Monitoring at Peytonia and Boynton sloughs showed low DO concentrations below water quality objectives during fall and spring drain periods.
- For all tidal waters above the Carquinez Bridge, the applicable water quality objective for DO is 7 mg/l. DO concentrations at several sloughs monitored are below 7 mg/l for over 50% of the time (Goodyear, Peytonia and Boynton Sloughs). DO concentrations measured at Montezuma and Suisun sloughs showed occasional low concentrations below 7 mg/l and could be considered as impaired by low DO although to a lesser degree.

4. MERCURY

Mercury, particularly in the form of methylmercury (CH_3Hg or MeHg), is a neurotoxin that affects humans and wildlife. The primary route of exposure of mercury is through consumption of methylmercury contaminated fish and other prey items. Pathways of inorganic mercury conversion to methylmercury and subsequent uptake into fish and birds are illustrated conceptually in Figure 4-1. San Francisco Estuary has been listed on the CWA 303(d) list as impaired by mercury (Regional Water Board, 2007). Fish consumption advisories have been issued for the San Francisco Estuary and several tributaries.

The few studies conducted in Suisun Bay and Marsh, have all shown high levels of methylmercury in fish. In a study by Slotton et al. (2002), seven of eight striped bass collected from Suisun Bay have mercury concentrations above the EPA screening level for protection of human health (Siegel et al. 2011). In Suisun Marsh, the same study found that mercury concentrations in inland silversides, although a small fish, are also above the EPA screening level for protection of human health (Siegel et al. 2011).

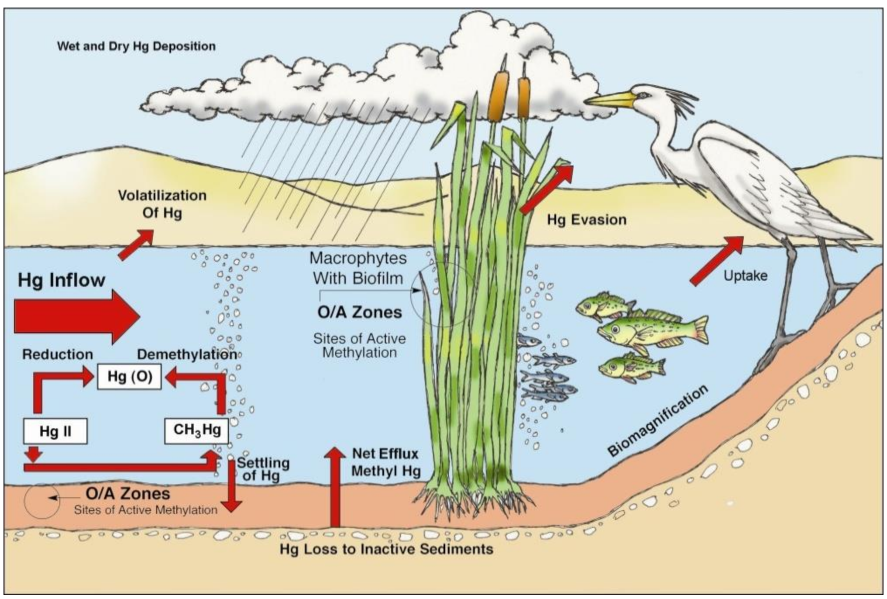


Figure 4-1 Hg cycling and biological uptake pathways in wetlands and sloughs.

4.1. CONCEPTUAL MODEL OF MERCURY METHYLATION IN SUISUN MARSH

A conceptual model of mercury methylation in Suisun Marsh is shown in Figure 4-2. In general, wetlands create ideal biogeochemical conditions for methylmercury production. Various studies spanning different ecosystems have found enhanced methylmercury production in wetlands (Hurley et al., 1995; Rudd, 1995; St. Louis et al., 1994; St. Louis et al., 1996). In the Bay-Delta region, studies have found higher methylmercury concentrations in tidal wetlands than the adjacent channels (Heim, 2003; Marvin-DiPasquale et al. 2003;

Slotton et al. 2002). Key processes of interest include formation and loss of reactive inorganic mercury or Hg(II), and methylation and demethylation, as described below.

4.1.1 Formation and Loss of Reactive Hg(II)

Methylmercury concentrations in water and sediments are not only affected by the methylation potential, but also by the available pool of reactive Hg(II) ready for methylation. Different processes affect the formation and loss of reactive Hg(II) pool. The inputs of Hg to Suisun Marsh from various sources including Delta outflow, tributaries, atmospheric deposition, coastal embayment and internal sources have been summarized previously. Different species of mercury are associated with these sources, with some being more bioavailable for methylation than the others (e.g., Hg-chlorides and Hg sulfates are more bioavailable than Hg(0) and HgS). The formation of reactive Hg(II) includes dissolution of HgS by organic acids or complexation with organic carbon. This process is affected by sediment and water properties such as organic carbon concentrations, redox potential (Fe, S), pH, dissolved oxygen levels, salinity and nutrients. In particular, organic carbon has been found to be important in dissolution of HgS to form reactive Hg(II).

Suisun Marsh is characterized by different habitats/vegetation, including flood plains, seasonally flooded/managed wetlands, saltwater/tidal marsh, and open water/sloughs. Different drying/wetting regimes are associated with these habitats. The managed wetlands are characterized by sporadic wetting/drying episodes. The drying periods replenish oxygen and lead to the subsequent oxidation of Hg(0) to form reactive Hg(II). Therefore, the highest reactive Hg(II) has been found in this type of habitat (Marvin-DiPasquale et al., 2007). The role of habitats in formation of reactive Hg(II) and methylation have been discussed in detail in Alpers et al. 2008.

4.1.2 Methylation and Demethylation

Methylation of Hg is carried out mainly by sulfate-reducing bacteria although recent evidence also points to the contribution of iron-reducing bacteria. Therefore, sediment and water properties that affect activity of these bacteria are important. High organic carbon levels can fuel the microbial activity. Both of these bacterial classes are anaerobic. Methylation mostly occurs at the oxic/anoxic interface and in soils/sediments where these bacteria are present. The reduction of sulfate and iron requires anoxic conditions and in most situations low dissolved oxygen promotes the methylation process.

Demethylation can be carried out both biotically and abiotically through photodemethylation. Biotic demethylation can occur through oxidative pathway (to form CO_2) or through reductive pathway (by using CH_4).

For Suisun Marsh, the important types of habitat are managed wetlands, which are characterized by high organic carbon, low DO and prolonged drying/wetting cycles. These conditions favor the formation of reactive Hg(II) and methylation of Hg(II) to form MeHg. These factors are discussed in detail in Section 4.2.

4.2. Environmental Factors Contributing to High Methylation Rates in Suisun Marsh

4.2.1 Flooding and Drying in Wetlands Creating Oxic-Anoxic Conditions for Methylation

The speciation of mercury affects methylation potential. It was found that the fully oxidized ionic form of mercury ($Hg(II)_R$) is the most bioavailable form for methylation (Alpers et al. 2008). The most abundant form of mercury that occur in mines, such as elemental mercury (Hg^0) and cinnabar (HgS), are less available for methylation. Studies have found inverse relationship between sulfate reduction rate and $Hg(II)_R$ (Yee et al. 2005). The hydrogen sulfide produced by sulfate-reducing bacteria can react with Hg(II) to form relatively insoluble cinnabar (HgS(s)), removing Hg(II) from the reactive mercury pool for methylation and bioaccumulation

Measurements of $Hg(II)_R$ concentrations in sediments of Bay-Delta have indicated that $Hg(II)_R$ concentrations are higher in oxidized environments relative to reduced environments (Marvin-DiPasquale and Cox 2007). The reason for this is that the complexation of Hg(II) with H_2S(aq) in reduced environments forms HgS.

Therefore, an environmental factor that is likely to contribute to increased concentrations of Hg(II)R is episodic wetting and drying. During drying, the oxic conditions enhance the oxidation of Hg^0 to reactive Hg(II)R. It was found that different methylation potentials can result from different frequencies of drying and wetting among habitat types (Alpers et al. 2008). In the Bay-Delta region, low levels of MeHg were found in habitats that are perennially flooded (open water), moderate concentrations were found in habitats that flood frequently and do not fully dry (e.g., tidal marsh), and relatively high MeHg was found in habitats that flood less frequently and are allowed to completely dry (e.g., high tidal marsh) before returning to anoxic conditions.

Wetlands provide extensive oxic/anoxic surfaces for methylation in the sediment-water interface. The flood and ebb of tides result in water levels in the tidal wetlands to fluctuate and create wetting/drying cycles in some areas. The wetting results in anoxic conditions while drying can create oxic conditions. Cycling between oxic/anoxic conditions enhances methylmercury production. Oxic conditions can result in decomposition of marsh litter, oxidation of substances in soils (e.g. Hg^0, sulfide) and lowering pH, while anoxic condition is favorable by sulfate reducing bacteria for methylation.

Drying and wetting in managed wetlands similarly can lead to conditions that enhance methylation. Managed wetlands create extensive oxic/anoxic surfaces for methylation. Unlike tidal marshes, managed wetlands have longer drying and wetting periods due to wetland operation. The prolonged drying of wetland soils accelerates decomposition of marsh litter and oxidation of reduced forms (e.g. Hg^0, sulfide, Fe^{2+}) to oxidized forms (e.g., sulfate, Fe^{3+}). During the prolonged flooding of the managed wetlands, anoxic conditions can develop to reduce sulfate to sulfide, which enhances methylmercury production. As a result, higher MeHg concentrations are expected in managed wetlands than tidal wetlands and open water (channels).

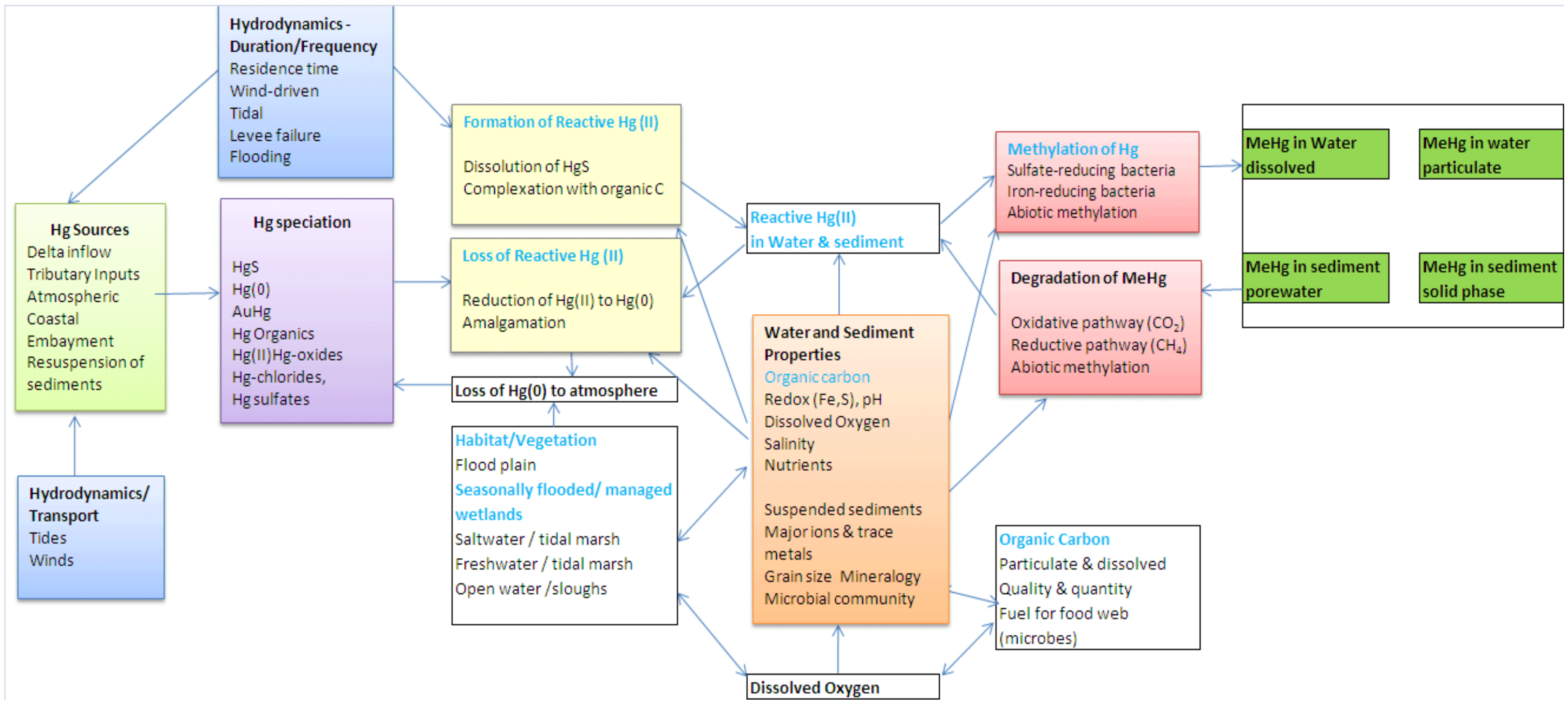


Figure 4-2 Conceptual Model of Mercury Methylation in Suisun Marsh (Modified from Alpers et al. 2008).

The roles of managed wetlands on the production of methylmercury have been described recently in a study at managed wetland 112 and 123 (Bachand et al. 2010b) (see Figure 2-2 for locations). At Wetland 123, drain events have consistently higher unfiltered MeHg concentrations (3–7 times) and higher filtered MeHg (3–20 times). Heim et al. (2007) found MeHg concentrations higher in the marsh interiors than the edge and higher concentrations in marshes than in open water.

4.2.2 High Dissolved Organic Carbon Concentrations in Managed Wetlands

High organic carbon concentrations in managed wetlands are another factor contributing to high mercury methylation potential in Suisun Marsh. During the recent study, elevated dissolved organic carbon concentrations have been found in managed wetlands within a few weeks after flooding (Bachand et al. 2010b). The wetlands are able to support several types of primary production of: 1) macrophytes, 2) benthic algae, and 3) phytoplankton and have soils rich in organic matter. The elevated organic carbon levels in managed wetlands fuel microbial activities that are responsible for methylation. As a result, elevated methylmercury concentrations were observed with high DOC concentrations in managed wetlands 112 and 123 for both sampling years (Figure 2-7).

4.2.3 High Total Mercury Concentrations in Suisun Marsh

As summarized previously in the conceptual model of DWR (2005), relatively high mercury concentrations were present in sediments of Suisun Marsh, ranging from 0.20–0.33 ppm (Slotton et al. 2000; Heim, 2003). Sources of mercury to Suisun Marsh sediments may include: 1) sediment loads from Delta; 2) deposition of sediments eroded from Suisun and San Pablo Bay; 3) inputs from tributaries. The high mercury concentrations in sediments provide a supply for mercury methylation.

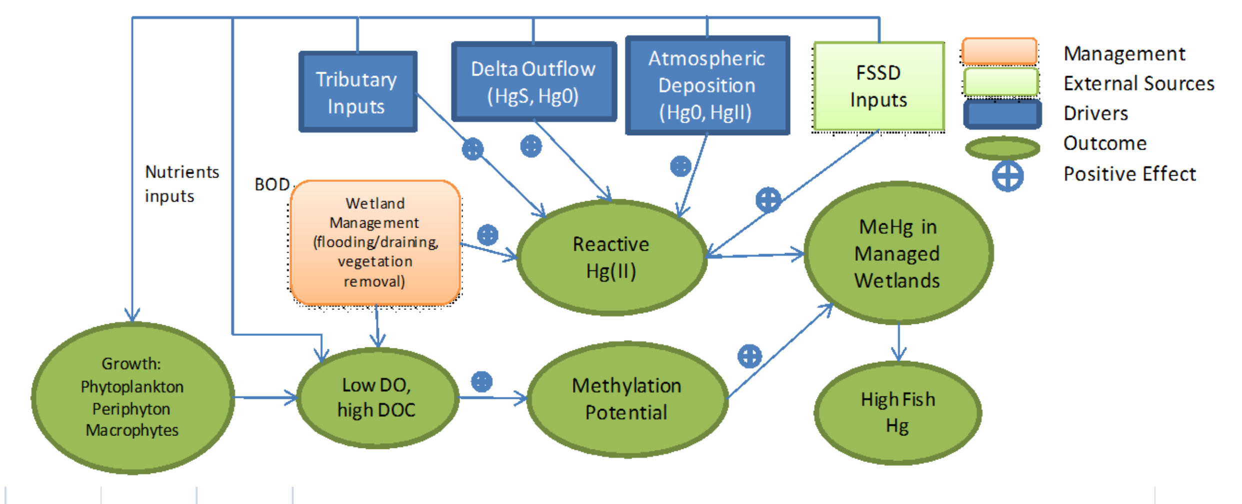


Figure 4-3 Cause and Effect Relationships of Mercury in Suisun Marsh. The blue symbol represents a positive relationship between two quantities.

4.3. SOURCES OF MERCURY TO SUISUN MARSH

Potential sources of mercury to Suisun Marsh include atmospheric deposition, tributary inputs, loads from the Delta, wastewater treatment discharge, internally generated sources and the coastal embayment (DWR, 2005). A summary of the mercury loads to Suisun Marsh is shown in Figure 4-4.

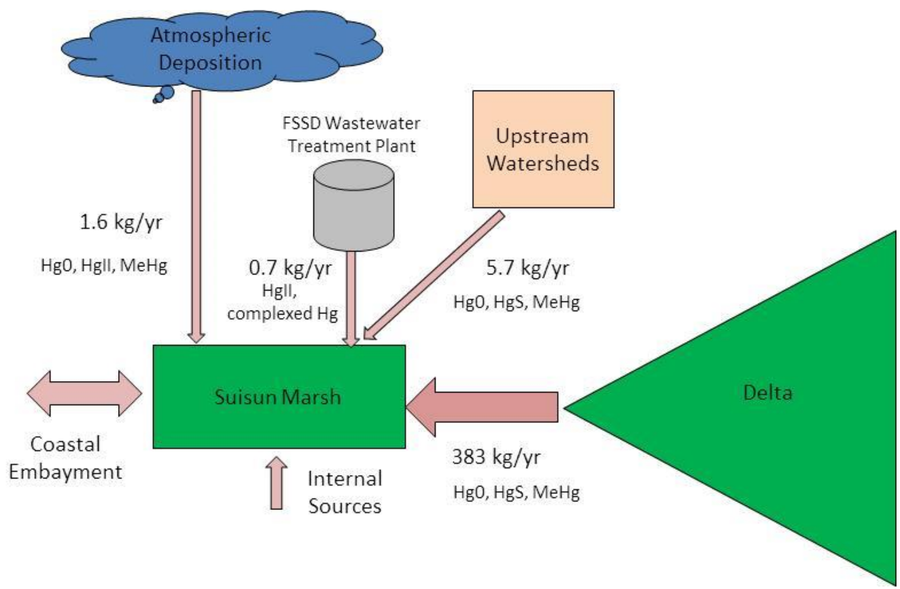


Figure 4-4 Hg loads to Suisun Marsh. Speciation identified in the sources is the best current understanding of sources.

4.3.1 Atmospheric Deposition

Mercury concentrations in wet deposition were measured at three sites in the Bay-Delta region for the period of April 2004 – June 2006 (Gill, 2008). Volume-weighted mercury concentrations observed at the three sites were very similar, ranging from 3.7 to 4.2 ng/l (Table 4-1). Estimated fluxes of wet deposition ranged from 4.1 $ng/m^2/day$ (1.5 $\mu g/m^2/yr$) at Twitchell Island to 16.2 $ng/m^2/day$ (5.9 $\mu g/m^2/yr$) at Pt. Reyes, depending on the precipitation amount. Volume weighted methylmercury concentrations in rainfall sampled at Woodland sampling site averaged at 0.103 ng/l.

The Mercury Deposition Network (MDN) currently has one inactive and four active sites in California (Figure 3.2). One active MDN site is at Moffett Field near San Jose (CA 72), and the other is in the Sierra's Sequoia National Park (CA 75). Volume-weighted mercury concentrations observed at these MDN sites ranged from 4 to 9 ng/l (Table 4-2). Estimated fluxes of wet deposition at these sites ranged from 1.7 to 5.3 µg/m2/yr, similar to values reported by Gill (2008). Dry deposition of mercury was monitored at two sites in the Bay-Delta region: Moss Landing (coastal) for the period of December 2004 to June 2005 and at Woodland (Central Valley) for the period of July 2005 to May 2006. Three species of atmospheric mercury (elemental mercury, Hg^0, reactive gaseous mercury, RGM, and particulate mercury, Hg_p) were measured (Table 4-2). RGM refers to mercury forms that react with surfaces and are an important component of dry deposition.

Table 4-1
Mercury Concentrations in Rainfall Measured at Bay–Delta Region during 04/04–05/06 (Gill, 2008)

Site	Region	Mean (ng/l)	Std	Median (ng/l)	N	Volume-weighted (ng/l)
Twitchell Island	Central Valley	5.78	4.60	3.75	12	4.25
Pt. Reyes	Coastal	5.88	6.46	4.46	16	4.16
Woodland	Central Valley	4.50	2.90	3.94	18	3.74

Table 4-2
Summary of Mercury Wet Deposition Studies in California (Gill, 2008)

Site	Period of Operation	# of Samples	Volume Weighted Hg conc. (ng/l)	Annual Rainfall (cm)	Flux ($\mu g/m^2/yr$)	Reference
MDN site CA72 (Moffett Field, CA)	1/11/2000 to 12/27/2006	124	9.0	~43	3.9	MDN website
MDN Site CA 75 (Sequoia National Park – Giant Forest)	7/22/2003 to present	57	6.0	~89	5.3	
MDN Site CA97 (Covelo)	12/16/1997 to 10/19/2000	58	4.0	~43	1.7	
SF Bay Estuary	8/1999 to 8/2000	59	8.0	53	4.2	Tsai and Hoenicke (2001)
Long Marine Lab	2/23/2000 to 3/3/2001	17	6.0	~67	4.0	Steding and Flegal (2002)
Moffett Field	1/30/2000 to 3/2/2001	26	11.8	~37	4.4	Steding and Flegal (2002)

Table 4-3
Summary of Atmospheric Mercury Speciation Measurements from Central California (Gill, 2008)

	Moss Landing				Woodland			
	Min	Max	Median	Mean ± 1σ	Min	Max	Median	Mean ± 1σ
Hg^0 (ng/m^3)	1.10	11.0	1.64	1.76 ± 0.59	0.96	4.85	1.68	1.74 ± 0.32
RGM (pg/m^3)	0	22.1	0.4	0.8 ± 1.4	0	190	3.0	7.4 ± 16.5
Hg_p(pg/m^3)	0	35.6	0.5	1.4 ± 2.6	0	51.6	4.0	5.3 ± 5.0

Dry deposition fluxes were estimated using median observed concentrations of RGM and Hg_p (Table 4-4). Dry deposition of Hg was greater in winter at Moss Landing, but more significant in summer at Woodland. For the Central Valley site, dry deposition loads are comparable to wet deposition loads (Table 4-5).

Table 4-4
Estimates of Dry Deposition Flux at a Coastal and Central Valley Location for Summer and Winter Periods (Gill, 2008)

Hg Species	Deposition Velocity (cm/s)	Moss Landing (coastal)		Woodland (central valley)	
		[Hg] (pg/m^3)	Flux (ng/m^2/d)/µg/m^2/yr	[Hg] (pg/m^3)	Flux (ng/m^2/d)/ µg/m^2/yr
		Dec–Feb		Dec–Feb	
RGM	1.9	0.6	1.0/0.36	1.7	2.8/1.0
Hg_p	0.092	1.5	0.1/0.036	4.0	0.3/0.11
Total			1.1/0.40		3.1/1.1
		May–Jun		May–Jul	
RGM	1.9	0.2	0.3/0.11	5.3	8.7/3.2
Hg_p	0.092	0.5	0.04/0.014	7.7	0.6/0.22
Total			0.3/0.11		9.3/3.4

Table 4-5
A Comparison of Wet and Dry Aatmospheric Deposition Fluxes of Mercury

Site	Period	Rainfall (cm)	[Hg] (ng/l)	Wet Deposition		Dry Deposition	
				ng/m^2/month	µg/m^2/yr	ng/m^2/month	µg/m^2/yr
Coast	Winter	50	2.5	417	5.0	33	0.40
Coast	Summer	0.75	10	25	0.30	9.2	0.11
Central Valley	Winter	20	2.5	167	2.0	92	1.1
Central Valley	Summer	0.25	10	8	0.10	283	3.4

Atmospheric deposition of mercury to Suisun Marsh was calculated to be about 1.6 kg/yr (Cooke et al. 2004). Atmospheric deposition is the sum of wet and dry deposition falling on water surfaces and indirect deposition on the watershed with subsequent runoff during storms (Cooke et al. 2004).

4.3.2 Tributary Inputs

Other sources of mercury to Suisun Marsh include urban runoff, local watershed runoff, and municipal and industrial effluents (DWR, 2005). The importance of these sources to the mercury loading of the Marsh is unknown, but may be significant. Storm water loading of Hg from small tributaries to San Francisco Bay was estimated to total 200 to 400 kg/yr (Davis et al. 2003; Davis et al. 2001). For the Fairfield-Suisun area, urban stormwater runoff discharges of mercury are estimated at 3.1 kg/yr (Regional Water Board, 2006). The total non-urban stormwater runoff to the San Francisco Bay is at 25 kg/yr. Based on projected stormwater runoff volume estimated by Davis et al. (2000a), non-urban stormwater runoff from the Fairfield-Suisun area is estimated to contribute 1.9 kg/yr. Based on drainage area, non-urban stormwater runoff of mercury from Fairfield-Suisun is estimated at 2.6 kg/yr.

4.3.3 Loads from the Delta

Mercury enters the Delta in the form of contaminated sediment deposit and contaminated runoff from the Coast Ranges and Sierra Nevada. The origin of much of this mercury is historical mining activities in the Coast Ranges and the subsequent use of elemental mercury for gold and silver extraction in the Sierra Nevada (DWR, 2005). Recent studies suggest that about 350–750 kg/yr of mercury is being transported into the Bay-Delta from the Coast Ranges and Sierra Nevada. Foe (2003) estimated that mercury export to Suisun Marsh is about 1,050 g/day total mercury and 5 g/day methylmercury.

Stephenson et al. (2005) summarized transport of mercury and methylmercury in the San Francisco Bay Delta and tributaries. Rainfall contributes about 1 g/day of total mercury to the Bay-Delta. About 520 g/day total mercury reaches the Delta through river inputs under average river flow conditions. This is lower than the export from the Delta to Suisun Marsh, and reflects additional sediment erosion or other inputs within the Delta boundaries. For methylmercury, rainfall contributes 0.05 g/day to Bay-Delta. River inputs contribute a load of 10 g/day.

Within the San Joaquin River Basin, Mud Slough contributes about 50% of MeHg at Vernalis but only 10% of the water volume during non-irrigation season (Stephenson et al. 2005). The three east-side rivers (Merced, Tuolumne, and Stanislaus) discharge 60% of the water but only 38% of the MeHg. MeHg concentrations between Mud Slough and Vernalis are 0.25 ± 0.03 ng/l (mean ± 95% CI).

Sacramento River is the main source of water and external MeHg loading to the Delta. Discharges from the four reservoirs- Shasta, Oroville, Englebright and Folsom account for 75% of the water but only 25% of the MeHg load at Freeport. This is due to low MeHg concentrations in these reservoirs. MeHg concentrations from Shasta are at 0.03 ± 0.01 ng/l. MeHg concentrations increased 2.8 fold between Keswick and Colusa. Sources of Freeport MeHg are: Sacramento River at Colusa (57%), Feather River (29%), American River (12%) and Colusa Basin Drain (10%).

A study by Foe et al. (2008) estimated that 9.8 g/day of methyl mercury is exported from the Delta to the San Francisco Bay. This is an increase from the previously estimated export of 4.7 g/day. Export by SWP and DMC pumping plants accounts for 6 and 7% of total methyl mercury exports, at a rate of 1.5 g/day.

4.3.4 Internally Generated Loads

Bathymetric surveys suggested that between 1867 and 1887, Suisun Bay was depositional and accumulated sediment (Cappiella et al. 2001). These sediments are rich in mercury associated with mining activities. Following the hydraulic mining period, Suisun Bay became erosional and more than 100 million cubic meters of sediment have been eroded. Although currently the deposition pattern of sediments in Suisun Marsh is unknown, some of this sediment- associated mercury could have been deposited in Suisun Marsh.

Slotton et al. (2002) sampled surficial sediments (top 1 cm) throughout Suisun Marsh and the Delta. Mercury concentrations in the Marsh ranged from 0.20 to 0.33 ppm. In comparison, mercury concentrations in sediments in the Delta ranged from 0.15 to 0.20 ppm. Similar mercury concentrations were reported by Heim et al. (2003) for 1999/2000.

4.3.5 Coastal Marine Embayments

Mercury contaminated sediments and water likely enters Suisun Marsh from San Francisco Bay through tidal transport processes. Between 1856 and 1887 more than 250 million cubic meters of sediment from hydraulic gold mining deposited in the San Pablo Bay. From 1951 through 1993 San Pablo Bay was erosional (Jaffe et al. 2001). Erosion and transport of these sediments may contribute to Hg inputs to Suisun Bay and Suisun Marsh.

4.3.6 Wastewater Treatment Plant

Currently, the interim mercury mass-based effluent limitation for FSSD (NPDES CA003802) is 0.060 kg/month or 0.72 kg/year, which is a relatively small load compared to the Delta and tributary inputs. MeHg sampled at the outfall location in Suisun Marsh resulted in an estimate of filtered MeHg of 0.1 ng/l and unfiltered MeHg of 0.2 ng/l (Bachand et al. 2010b).

4.4. CONCENTRATIONS OF MERCURY AND METHYLMERCURY IN SUISUN MARSH

4.4.1 Aqueous THg and MeHg Concentrations in Suisun Marsh (long-term and seasonal pattern)

MeHg concentrations in Suisun Marsh have been measured previously by Heim et al. (2008) at several sloughs including: Boynton Slough, First Mallard, Sheldrake Slough, Suisun Slough, Nurse Slough, and Montezuma Slough. The MeHg fluxes were measured at 0 to 0.03 g/day at First Mallard and 0.03 to 0.7 g/day at Suisun Marsh.

MeHg concentrations have also been measured at various sloughs in Suisun Marsh for a period of over one year (Heim et al. 2010). The concentrations at Boynton, Peytonia, and Suisun Sloughs were found to vary seasonally, ranging from detection level of 0.02 ng/l to over 3 ng/l. Higher concentrations were found during fall and winter than during summer months. Coinciding with the elevated MeHg concentrations were the decreases in oxygen concentrations in upper sloughs.

MeHg concentrations in managed wetlands of Suisun Marsh were monitored for two years during 2007–2008 (Heim et al. 2010). Both the filtered and unfiltered MeHg concentrations were measured. Samples were taken both at the edge and the interior of the wetlands. Locations of the MeHg sampling within Wetland 112 and 123 are shown in Figure 3-5 and Figure 3-6.

The results suggested increases of MeHg concentrations in the direction of fresh water inflow movement at the edge of wetlands (from south to north) and higher concentrations in the interior sites relative to source water, suggesting elevated MeHg concentrations in the wetlands relative to incoming slough water. Unfiltered MeHg concentrations at the edge sites ranged from 0.02 ng/l to 4.8 ng/l at Wetland 112 and at the interior sites ranged from 0.5 ng/l to 6.8 ng/l during the first year of sampling. Measured filtered MeHg concentrations showed similar pattern of increasing in the direction of water movement in the edge sites and higher concentrations in the interior sites (Figure 4-5). Filtered MeHg concentrations ranged from 0.2 to 1.5 ng/l.

The year 2 sampling showed similar patterns for Wetland 112. Unfiltered and filtered MeHg concentrations showed increases in the direction of water movement at the edge sites and higher concentrations at the interior sites relative to source water.

Similarly, at Wetland 123, MeHg concentrations were increasing in the direction of water movement at the edge sites and higher MeHg levels were detected in the interior (Figure 4-6). MeHg concentrations in wetland waters showed large variations ranging from 0 to 15 ng/l (filtered and unfiltered).

In year 1 sampling, Wetland 112 showed increases in MeHg concentrations after the fall flood up and then decreased. Dissolved MeHg concentrations showed clear initial increase after flood-up. For both year 1 and year 2 sampling, wetland 123 showed rapid increases in MeHg concentrations and decreases after the fall flood up. Dissolved MeHg concentrations follow a similar pattern as the unfiltered MeHg (Figure 4-6 and Figure 4-7). The increases in MeHg concentrations after fall flood up coincide with increases in organic carbon and decreases in dissolved oxygen.

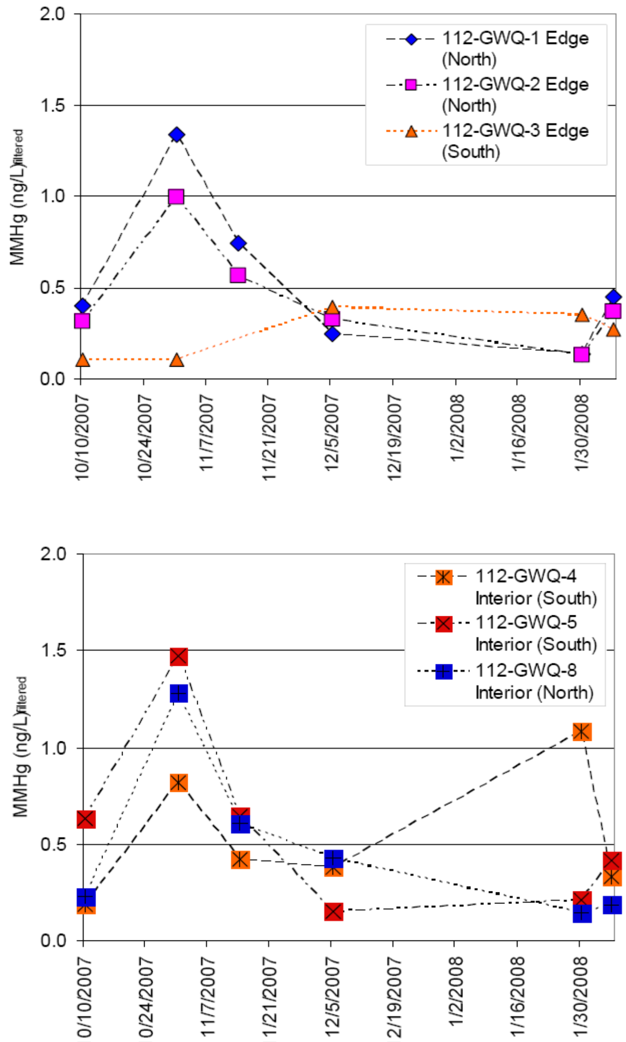


Figure 4-5 **MeHg concentrations in filtered water collected in year one (2007–2008) from the edge and interior at Club 112. The data show MeHg concentrations initially increasing in the direction of water movement at the edge locations (south to north) with higher concentrations at the interior sites relative to source water (from Heim et al. 2010).**

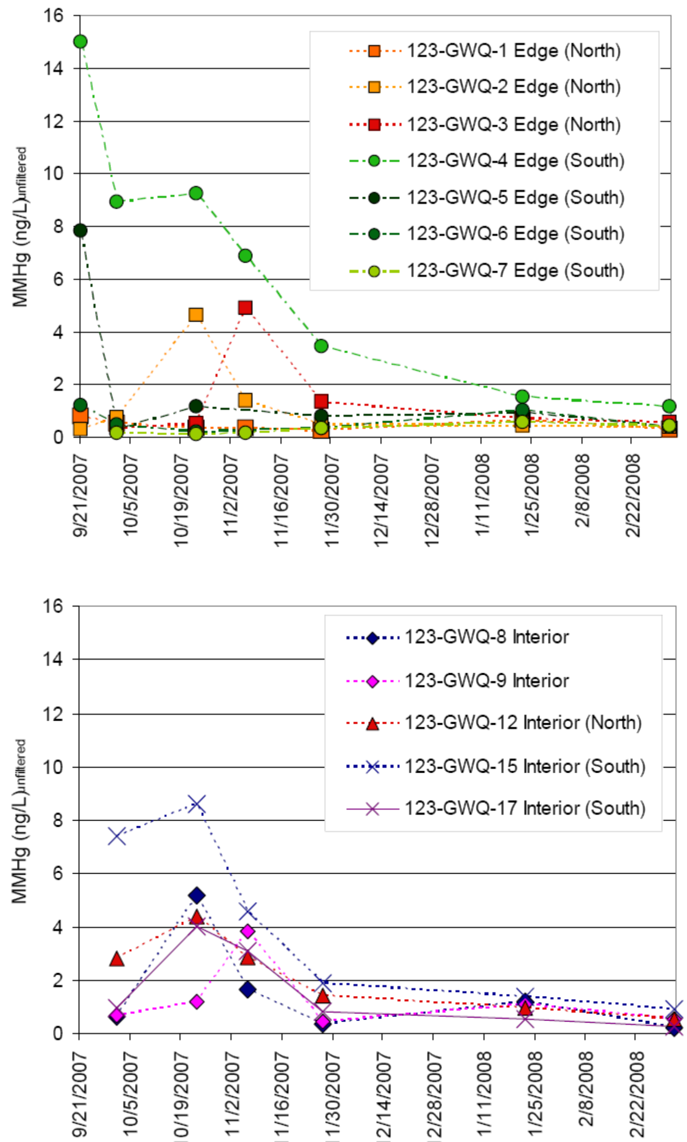


Figure 4-6 **MeHg concentrations in filtered water collected in year one (2007–2008) from the edge (upper panel) and interior (lower panel) at Club 123. The data show the freshwater source GWQ-7 is low in concentration, GWQ-4 at the southeast is the high in concentration, and interior sites have an initial peak in MeHg concentration and then decrease over time (from Heim et al. 2010).**

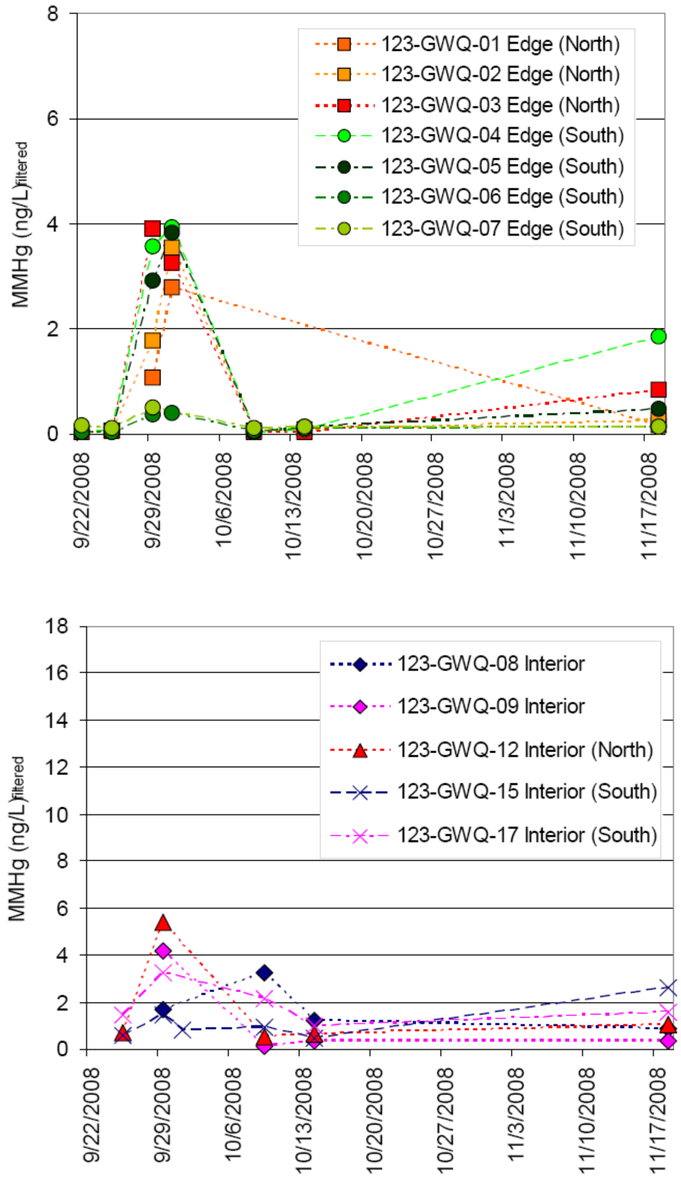


Figure 4-7 **MeHg concentrations in filtered water collected in year two (2008–2009) from the edge (upper panel) and interior (lower panel) at Club 123. The data show MeHg concentrations increasing and decreasing rapidly after flood up.**

4.4.2 Aqueous THg and MeHg Concentrations (spatial patterns)

Water samples were collected from managed wetlands for MeHg in filtered and unfiltered water from October to November 2007 (Heim et al. 2010). Samples were collected from wetlands 525, 529 and 530 (Figure 4-8) and Montezuma slough (MS; Figure 4-9) for THg and MeHg. In addition, SSC concentrations were also measured. Concentrations of MeHg at Montezuma Slough were lower than the managed wetlands (wetland 525, 529 and 530). Several months after fall flood up MeHg concentrations at channel sites are similar to managed wetlands.

THg and MeHg concentrations in unfiltered water were also collected from several channel locations within Suisun Marsh for 2005–2006 (Suisun Slough, First Mallard, Peytonia Slough, and Boynton Slough). Total mercury concentrations ranged from ~7 to 37 ng/l. Concentrations of MeHg ranged from 0.08 to 0.4 ng/l (Figure 4-10). Limited data in Montezuma Slough suggested MeHg concentrations of 0.15 ng/l (Bachand et al. 2010b).

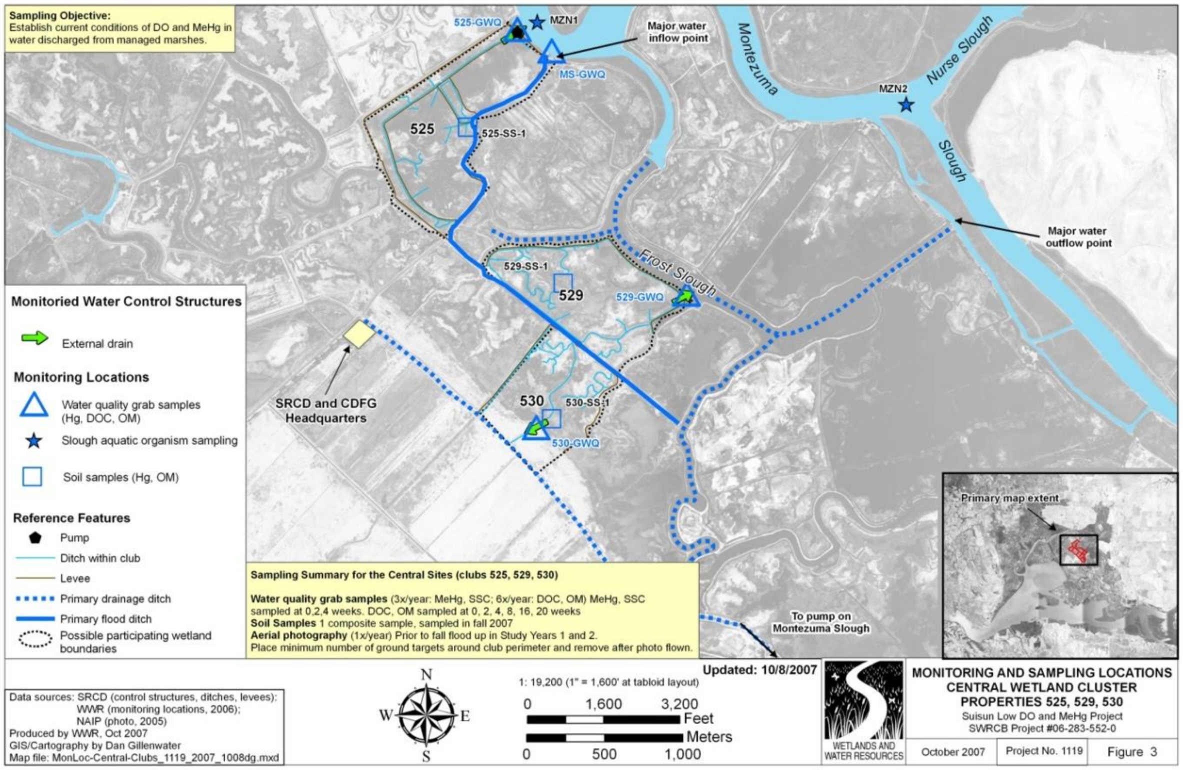


Figure 4-8 Water quality sampling stations within Wetland 525, 529 and 530 (Siegel et al. 2011).

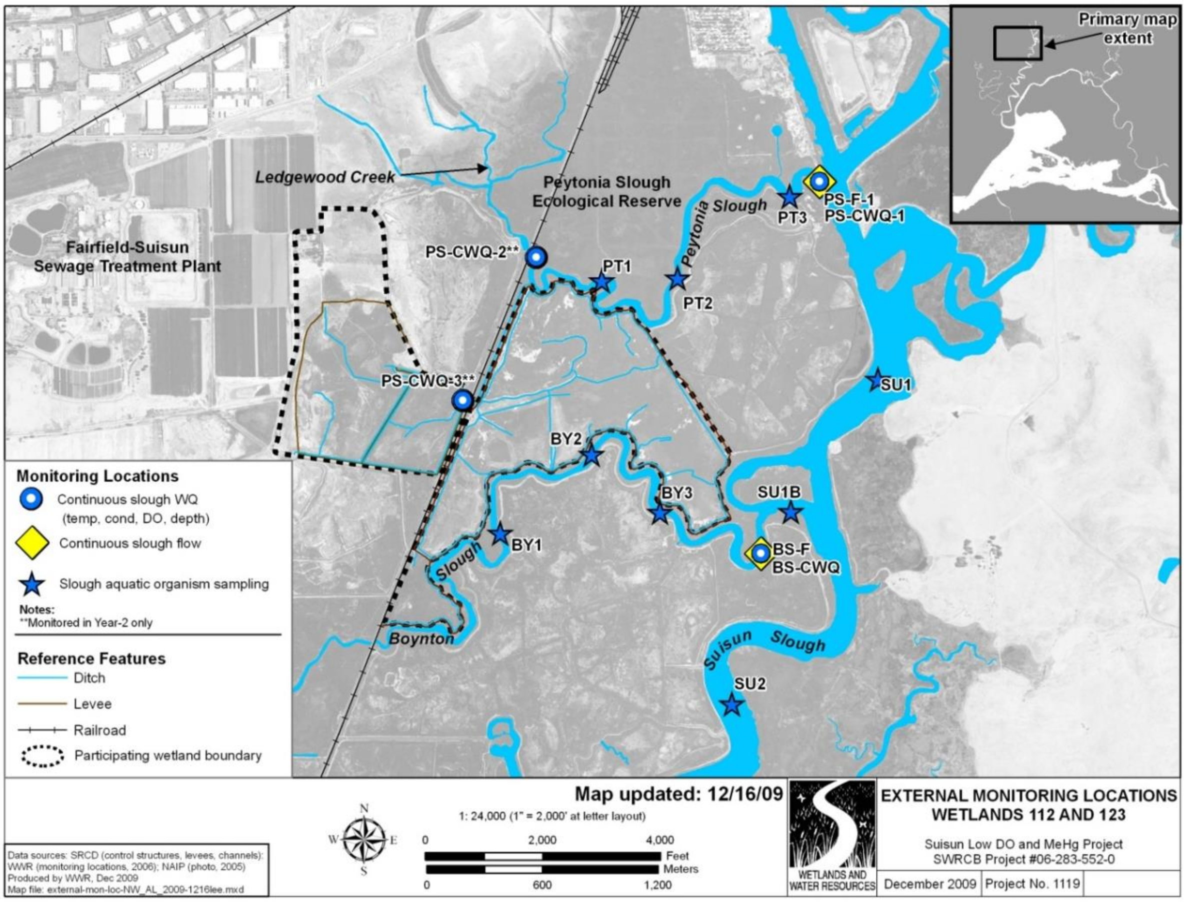


Figure 4-9 Water quality monitoring stations within Boynton, Peytonia and Suisun Sloughs (Siegel et al. 2011).

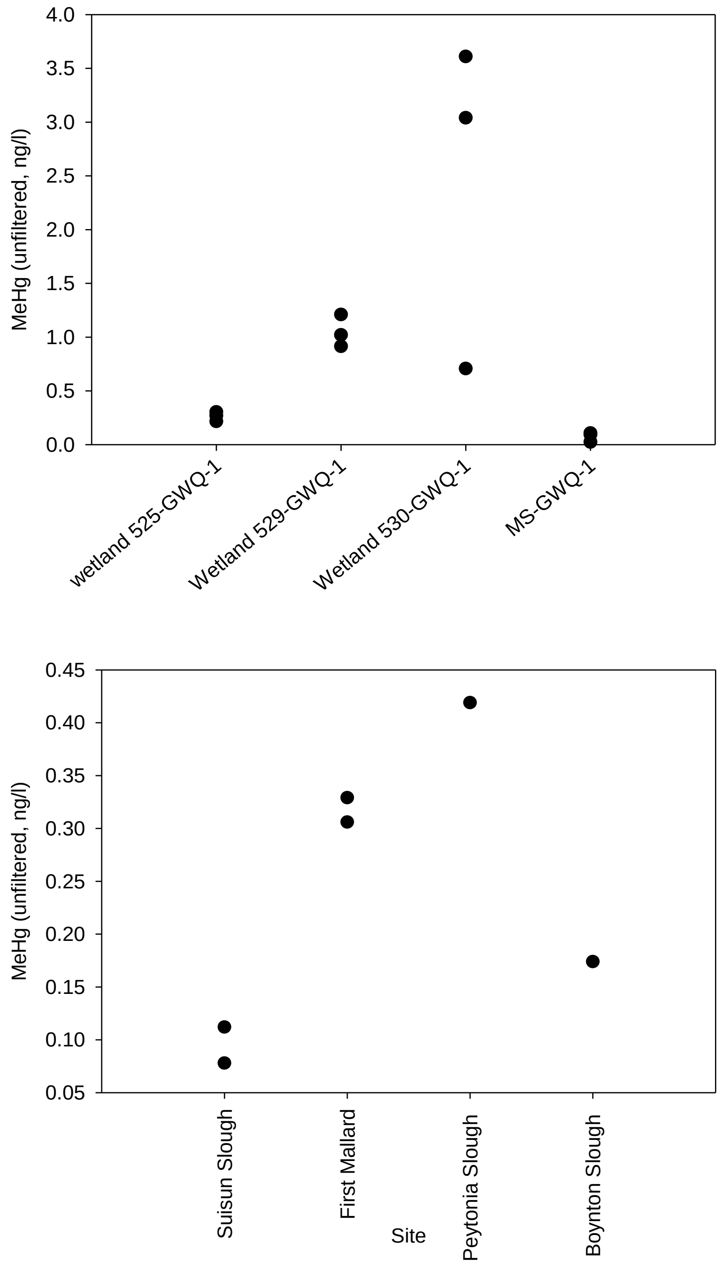


Figure 4-10 MeHg concentrations in unfiltered water collected at managed wetlands and channel sites in Suisun Marsh (Source: Heim et al. 2010).

4.4.3 Sediment THg Concentrations

Soil samples were collected from five managed wetlands within Suisun marsh (Heim et al. 2010; wetland 112, 123, 525, 529 and 530; Figure 4-11). Locations of sampling within Wetland 112, 123, 525, 529 and 530 are shown in Figure 3-5, Figure 3-6, and Figure 4-8. The average THg concentrations in soils are 0.11 ± 0.01 µg/g dw. Concentration of MeHg averaged at 2.50 ± 0.97 ng/g dw. Average THg concentrations of surface soils in the northern wetlands (wetlands 112 and 123) were 0.097 ± 0.01 µg/g dw compared to 0.148 ± 0.02 µg/g dw at the central wetlands (wetlands 525, 529, 530). Average MeHg concentrations are similar at northern (1.835 ± 0.515 ng/g dw) and central (4.374 ± 3.540 ng/g dw) sites, given the large variability between sites.

The mercury methylation potential was measured as percent MeHg to THg. The percent MeHg to THg ratios range from 0.08 to 8.04% (Heim et al. 2010). Wetland 112 (percent MeHg/THg = 0.73 ± 0.207) and 123 (percent MeHg/THg = 2.42 ± 0.732) show similar potential for mercury methylation given the uncertainties in the ratios.

Mercury concentrations in sediments from other habitat types were also collected from Suisun Marsh. Sediment samples were collected from channel locations within Suisun Marsh during 2007(Figure 4-12). Sediment THg concentrations were higher in the tidal sloughs (0.2 – 0.5 μg/g) than the managed wetlands (~0.1 μg/g). However, the MeHg concentrations in sediments were higher in managed wetlands than in tidal sloughs (Figure 4-11 and Figure 4-12), suggesting higher methylation potential in the managed wetlands.

4.4.4 Fish Hg Concentrations

Fish Hg concentrations in Suisun Marsh have been sampled by Darrell Slotton of U.C. Davis for Silversides (S. Siegel, personal communication). The data were shown for a few locations in the Bay Delta for the Fall of 2005 and Fall of 2006 (Figure 4-13 and Figure 4-14). For Suisun Marsh, Hg concentrations in Silversides were higher during the Fall of 2006 (Figure 4-15). This is likely due to the sampling event in 2006 happening after high runoff and winter flooding. The seasonal sampling in Suisun Marsh during winter 2006 suggested elevated silverside Hg concentrations during winter/spring compared to fall season, following winter high runoff/flooding events (Figure 4-16).

Hg concentrations were determined by D. Slotton for other species besides Silversides (Threadfin Shad, Yellowfin Goby, Golden Shiner, and Grangon Shrimp) during 1998–2000 (Slotton et al. 2002; Table 4-6). Hg concentrations in Silversides sampled in Suisun Slough showed the highest concentrations, although high concentrations were noted in other species as well.

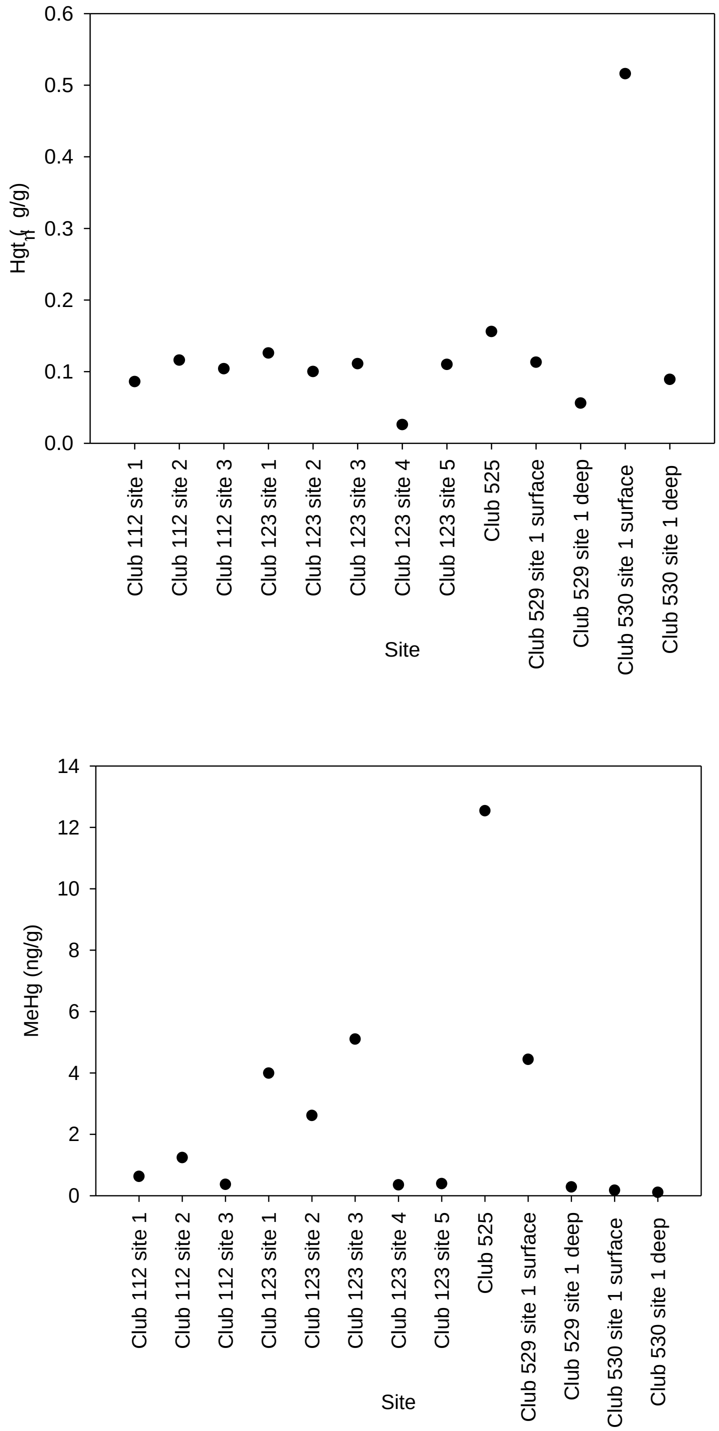


Figure 4-11 THg and MeHg concentrations in sediments collected at managed wetlands in Suisun Marsh (Heim et al. 2010).

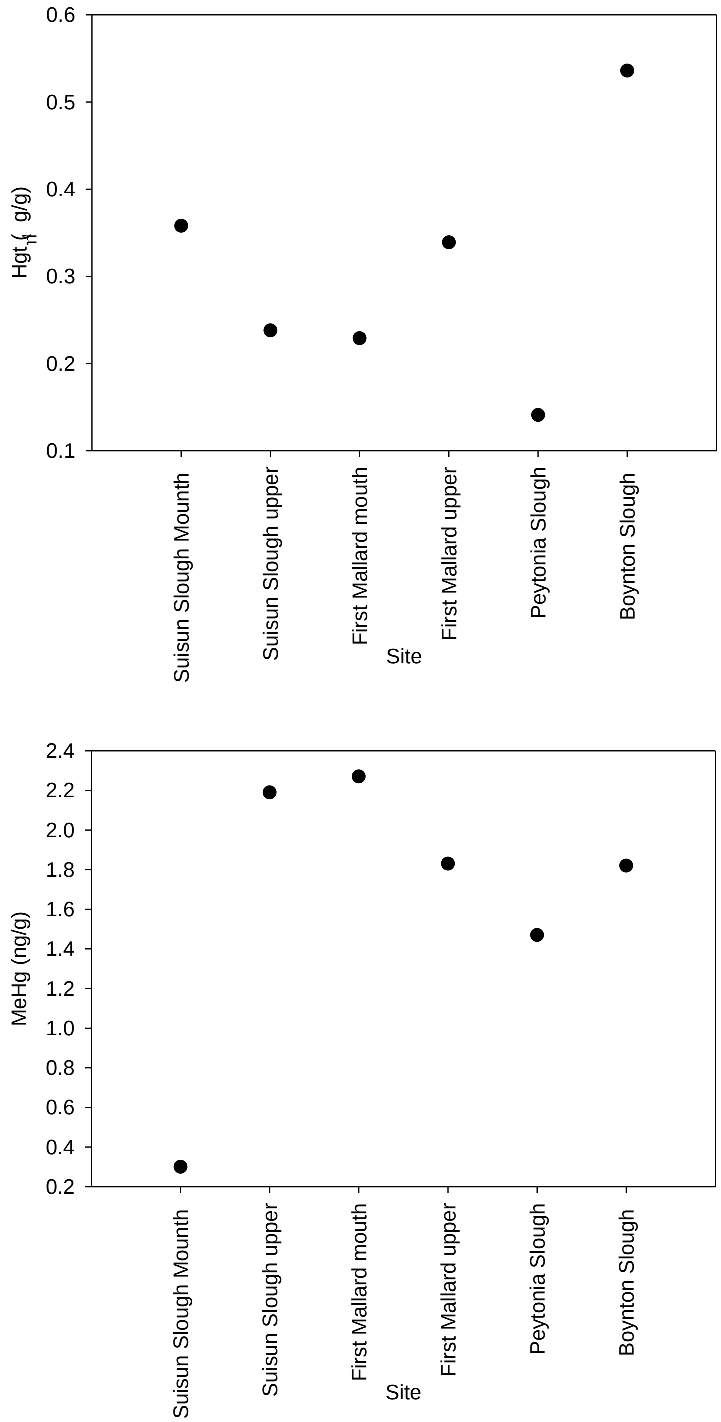


Figure 4-12 THg and MeHg concentrations in sediments collected at channels sites in Suisun Marsh (Heim et al. 2010).

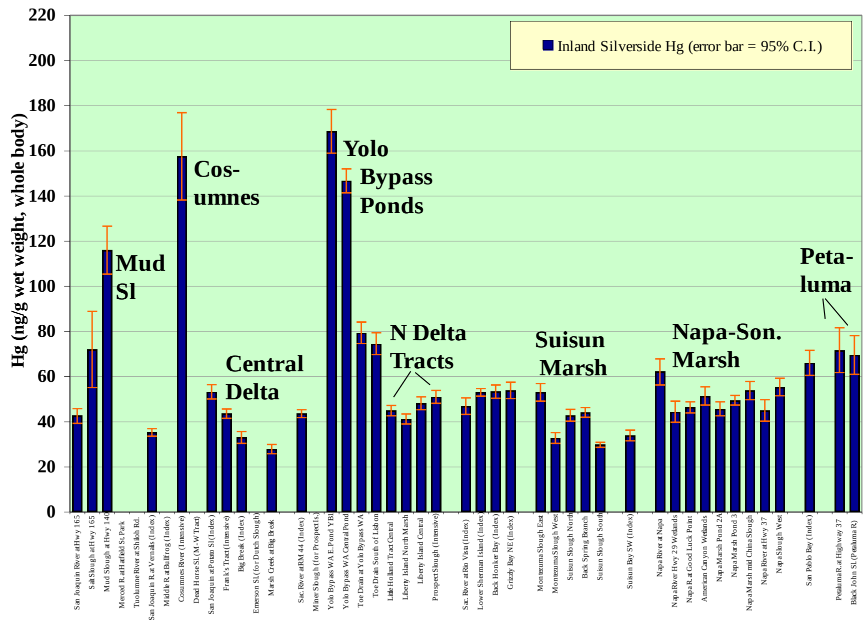


Figure 4-13 **Inland Silverside Hg concentrations (wet weight) for Fall 2005 sampled by D. Slotton (S. Siegel, personal communication).**

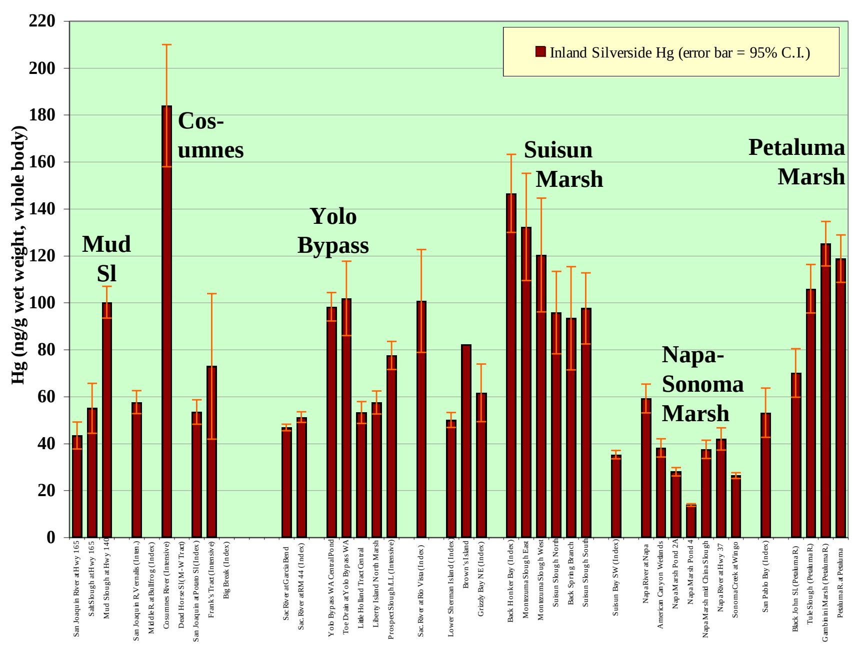


Figure 4-14 **Inland Silverside Hg concentrations (wet weight) sampled by D. Slotton for Fall 2006 following high runoff and flooding winter and spring (S. Siegel, personal communication).**

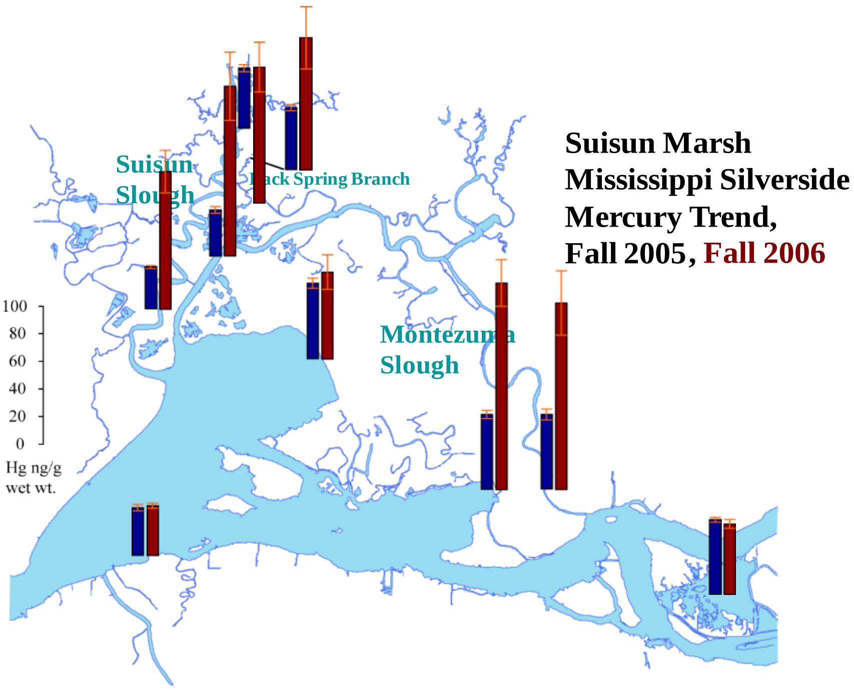


Figure 4-15 **Suisun Marsh Mississippi Silverside Mercury Trend, Fall 2005 and Fall 2006 (D. Slotton, unpublished data).**

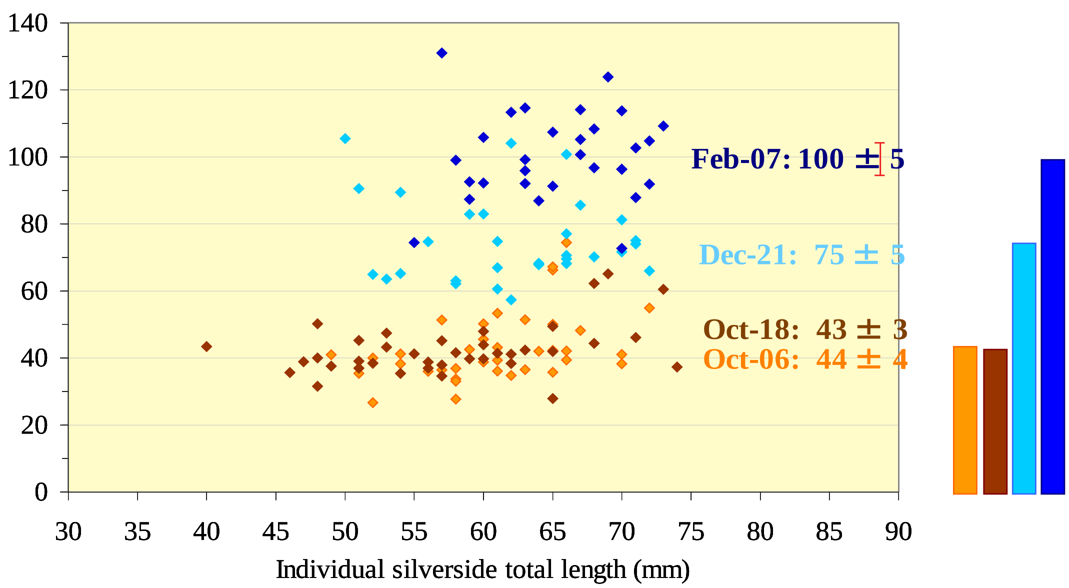


Figure 4-16 **Seasonal variations in silverside Hg concentrations in Suisun Slough North between Oct-2005–Feb-2006 (D. Slotton and S. Siegel, personal communication). Y-axis concentrations in ng/g.**

Table 4-6
Fish Mercury Concentrations in In-land Water of Suisun Marsh (Slotton et al. 2002)

Inland Silversides Total Mercury		
* multi-individual composites		
* whole-body, dry wt ppm Hg		
*(dry wt ppm = app. 5x wet wt ppm)		
Suisun Slough	0.31	µg/g
Cutoff Slough	0.13	µg/g
Inter-annual Variability, Inland Silversides THg		
* multi-individual composite		
* whole-body, dry wt ppm Hg		
* (dry wt ppm = app. 5x wet wt ppm)		
Suisun Slough		
Fall 1998	0.27	µg/g
Fall 1999	0.31	µg/g
Fall 2000	0.31	µg/g
Threadfin Shad		
composite: mean size 41–97 mm, 0.3–10.2 g		
Suisun Slough	0.1	dry wt µg/g = ppm
	0.23	Sep–Dec
Cutoff Slough	0.13	
Montezuma Slough	0.08	
Yellowfin Goby		
small composites: mean size 52–88 mm, 1.0–5.6 g		
large composites: mean size 90–130 mm, 5.6–16.8 g		
Suisun Slough	0.08	dry wt µg/g = ppm
Cutoff Slough	0.1	
Montezuma Slough	0.14	
	0.22	
Golden Shiner		
(composite: mean size 57–91 mm, 1.2–6.2g)		
Suisun Slough		
Cutoff Slough	0.07	dry wt µg/g
Grangon Shrimp		
composite: mean size 42–63 mm, 0.1–1.6 g		
Suisun slough	0.13	dry wt µg/g
Cutoff Slough	0.26	dry wt µg/g

4.4.5 Data Summary

A summary of the mercury data in different compartments in Suisun Marsh is shown in Table 4-7.

4.5. Impairment Assessment

The water quality objectives for mercury are established for protection of human health, and aquatic organisms and wildlife. For example, Mercury TMDL for San Francisco Bay (Regional Water Board, 2009) established several numeric criteria for Hg to protect people consuming the bay fish and birds feeding on aquatic organisms.

Established numeric mercury water quality objectives for all segments of San Francisco Bay include:

- 0.2 mg/kg (ppm) fish muscle tissue in trophic level 3&4 fish consumed by humans (wet weight concentrations)
- 0.03 mg/kg small fish (3–5 cm, whole) to protect wildlife (California least tern), wet weight concentrations.

The fish targets for protecting human health in San Francisco Bay:

- Comply with the EPA procedures used to determine a human health criterion of 0.3 mg methylmercury per kg of fish tissue (ppm) (μg/g)
- Use fish consumption rates specific to the Bay Area to protect people consuming local fish
- Water quality objectives apply to the five most commonly consumed bay fish: striped bass, California halibut, jacksmelt, white sturgeon, and white croaker
- Compliance with the target is evaluated by comparison to the average measured mercury concentrations in the edible portion of the above five fish

For Suisun Marsh, the observed Hg concentrations in silversides were compared to the San Francisco Bay criteria of 0.03 mg/kg for small fish to protect wildlife. Observed silverside Hg concentrations in 2005 and 2006 from Suisun Marsh shown in Figure 4-13, Figure 4-14 and Figure 4-16 are generally above 0.03 mg/kg, suggesting water quality impairment. Earlier sampling by Slotton et al. (2002) in 1998–2000 as shown in Table 4-6 also indicates concentrations above 0.03 mg/kg.

Table 4-7
Summary of Hg and MeHg Concentrations Sampled in Water, Sediments and Fish in Suisun Marsh

	THg (ng/l, unfiltered)	THg (ng/l, filtered)	MeHg (ng/l, unfiltered)	MeHg (ng/l, filtered)	Sampling Date	Water Quality Objectives (THg, µg/l)	Reference
Water							
Sloughs							
Suisun Slough	36.62		0.112		6/28/2005	2.1	Heim et al. (2010)
First Mallard	26.33		0.329		6/28/2005	2.1	
Suisun Slough	6.7		0.078		5/2/2006	2.1	
First Mallard	13.31		0.306		5/2/2006	2.1	
Peytonia Slough	11.13		0.419		9/5/2006	2.1	
Boynton Slough	10.81		0.174		9/5/2006	2.1	
Montezuma Slough			0.023–0.107	<MDL – 0.05	10/17/2007 – 11/19/2007		
Wetlands							
Wetland 525			0.22–0.30	0.17–0.23	10/17/2007 – 11/19/2007		
Wetland 529			0.91–1.21	0.12–0.32	10/17/2007 – 11/19/2007		
Wetland 530			0.71–3.61	0.25–0.85	10/17/2007 – 11/19/2007		
Sediment	THg (µg/g) range	THg (µg/g) median	MeHg (ng/g) range	MeHg (ng/g) median	Sampling Date	Water Quality Objectives (THg, mg/kg)	Reference
Wetlands							
Wetland 112	0.09 – 0.12	0.10	0.37–1.24	0.63	9/10/2007	1.06	Heim et al. (2010)
Wetland 123	0.03 – 0.13	0.11	0.35–5.1	2.61	9/10/2007	1.06	
Wetland 525	0.16	0.16	12.54	12.54	9/10/2007	1.06	
Wetland 529	0.06 – 0.11	0.085	0.28 – 4.44	2.36	9/10/2007	1.06	
Wetland 530	0.09 – 0.52	0.30	0.11 – 0.18	0.14	9/10/2007	1.06	

Table 4-7 (continued)
Summary of Hg and MeHg Concentrations Sampled in Water, Sediments and Fish in Suisun Marsh

	THg (ng/l, unfiltered)	THg (ng/l, filtered)	MeHg (ng/l, unfiltered)	MeHg (ng/l, filtered)	Sampling Date	Water Quality Objectives (THg, µg/l)	Reference
Slough							
Suisun Slough (mouth)	0.21 – 0.36	0.36	0.24 – 0.48	0.3	3/29/2007	1.06	
Suisun Slough (upper)	0.20 – 0.26	0.24	1.8 – 2.51	2.19	3/28/2007	1.06	
First Mallard (mouth)	0.17 – 0.29	0.23	1.53 – 2.78	2.27	3/29/2007	1.06	
First Mallard (upper)	0.29 – 0.37	0.34	1.16 – 1.99	1.83	3/29/2007	1.06	
Peytonia Slough	0.08 – 0.44	0.14	0.29 – 2.02	1.47	3/28/2007	1.06	
Boynton Slough	0.28 – 0.61	0.54	1.53 – 3.16	1.82	3/28/2007	1.06	
Fish							
Inland Silversides	Fish Hg (ppm) dry wt					Fish Hg criteria (ppm) wet wet	
Suisun Slough	0.31					0.03	
Cutoff Slough	0.13					0.03	
Suisun Slough	0.27– 0.31				Fall 1998, Fall 1999, Fall 2000	0.03	Slotton et al. (2002)

The Basin Plan water quality objective for mercury in Suisun Marsh is a 1-hour average of 2.1 µg/l. Total mercury concentrations in the sloughs of Suisun Marsh ranged from ~7 to 37 ng/l or 0.007 to 0.037 µg/ l (Heim et al. 2010). The ambient water quality criteria for mercury have not been exceeded.

Another possible criterion for assessing the Hg impairment is comparison of mercury concentrations in sediments. The CTR criterion for total recovered mercury in sediments is 1.06 mg/kg. Based on the observed THg concentrations in sediments of wetlands and channels in Suisun Marsh, this criterion has not been exceeded.

The Central Valley Regional Water Quality Control Board (CVRWQCB) has also proposed numeric fish Hg criteria for the Sacramento-San Joaquin Delta Estuary region (CVRWQCB, 2008). Three numeric targets are recommended for the protection of human and piscivorous wildlife: 0.24 mg/kg (wet weight) in muscle tissue of large Trophic Level four (TL4) fish such as bass and catfish; 0.08 mg/kg (wet weight) in muscle tissue of large Trophic Level three (TL3) fish such as carp and salmon; and 0.03 mg/kg (wet weight) in whole Trophic Level two (TL2) and TL3 fish less than 50 mm in length. Based on the regression between methylmercury concentrations in water and mercury concentrations in standard 350-mm largemouth bass in Delta, the criteria of 0.24 mg/kg concentration in largemouth bass corresponds to methylmercury concentrations of 0.066 ng/l in the ambient water.

The ambient methylmercury target of 0.066 ng/l for protection of human and wildlife, derived from the Sacramento-San Joaquin Delta region Hg TMDL, if compared to methylmercury concentrations measured in Suisun Marsh (0.08–0.4 ng/l) has been exceeded at multiple locations.

4.6. SUMMARY

The conceptual model and impairment assessment of mercury in Suisun Marsh can be summarized as follows:

- Sources of mercury to Suisun Marsh include: delta inflow, tributary inputs, atmospheric deposition, coastal embayment and internal sources of Hg. High Hg concentrations have been found in sediments of Suisun Marsh wetlands. The Delta and tributaries are the primary mercury inputs.
- Higher MeHg concentrations are found in managed wetlands than other habitats. The managed wetlands are characterized by the highest level of reactive Hg(II) and methylation potential (Table 4-7). The drying and wetting regime, high organic carbon and low DO concentrations in managed wetlands promote formation of reactive Hg(II) and methylmercury production.
- MeHg concentrations in managed wetlands increase after fall flood-up, then decrease. Higher MeHg concentrations are found in the interior than the edge of managed wetlands. MeHg concentrations are correlated to DOC.
- Higher total mercury concentrations are found in the sediments of sloughs than wetlands, while higher MeHg concentrations dominate in managed wetlands, suggesting higher methylation potential in managed wetlands.
- Elevated Hg concentrations in silversides are found in Suisun Slough and Cutoff Slough, suggesting impairment of Suisun Marsh by mercury.

5. SALINITY

The Suisun Ecological Workgroup (SEW) concluded that fish species native to Suisun Marsh require low salinities during the spawning and rearing periods, stating that salinities exceeding 8 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 the 14-year period due to decreases in freshwater outflow and increases in salinity. Currently Suisun Marsh wetlands are listed for impairment of salinity/TDS/chlorides (303(d) list). More broadly, the position of the low salinity zone in San Francisco Bay, defined as the distance from Golden Gate where the bottom salinity is 2 parts per thousand (ppt) (termed as X2), has been identified as a metric that can be related to the health of several species (Jassby et al., 1995; Kimmerer et al., 1992). This zone is associated with the greatest abundance of pelagic organisms of the upper estuary, including the threatened delta smelt (Hypomesus transpacificus), the state-listed longfin smelt (Spirinchus thaleichthys) and juvenile striped bass (Morone saxatilis). The X2 position is also associated with the abundance of undesirable species such as the invasive Asian clam (Corbula amurensis). Specific mechanisms associated with the location of the low salinity zone and the responses of individual species are a topic of continued research (Feyrer et al., 2007; 2011; Kimmerer et al., 2009). The position of the X2 isohaline during the months of February through June is used as the basis of freshwater inflow management in the estuary (US EPA, 1995). The outflow standard was intended to represent the relationship between springtime precipitation and the extent of estuarine habitat as had occurred in the late 1960s and early 1970s (US EPA, 2012). The standard does not define X2 requirements at other times of the year.

Although potential salinity concerns in the Suisun Bay region are largely driven by factors that are outside of the purview of the proposed Suisun Marsh TMDL, and related to flows and exports from the Delta, an examination of the data and potential impairments is still useful because local-scale effects related to managed wetlands within Suisun Marsh also have an impact on salinity, especially in smaller sloughs. The evaluation of salinity for the purpose of the conceptual model/impairment assessment is discussed from the perspective of local drivers as well as larger-scale Delta outflows.

5.1. SUISUN MARSH CHANNEL WATER SALINITY STANDARDS

Suisun Marsh channel water salinity standards are listed under State Water Resources Control Board (SWRCB) Decision 1641 (SWRCB, 2000). Current salinity standards are listed in Table 5-1. Locations of salinity monitoring stations in Suisun Marsh are shown in Figure 5-1. The salinity standards are for the protection of fish and wildlife beneficial uses in Suisun Marsh.

Table 5-1
Water Quality (Salinity) Objectives for Suisun Marsh

Compliance Location	Interagency Station	Parameter	Description (unit)	Water Year Type	Time Period	Value
Eastern Suisun Marsh Salinity						
Sacramento River at Collinsville Montezuma Slough at National Steel Montezuma Slough near Beldon Landing	C-2 (RSAC081) S-64 (SLMZU25) S-49 (SLMZU11)	EC (Electric Conductivity)	Maximum monthly average of both daily high tide EC values (mmhos/cm1[1]), or demonstrate that equivalent or better protection will be provided at the location	All	Oct Nov–Dec Jan Feb–Mar Apr–May	19.0 15.5 12.5 8.0 11.0
Western Suisun Marsh Salinity						
Chadbourne Slough at Sunrise Duck Club Suisun Slough, 300 feet south of Volanti Slough	S-21 (SLCBN1) S-42 (SLSUS12)	EC	Maximum monthly average of both daily high tide EC values (mmhos/cm) or demonstrate that equivalent or better protection will be provided at the location	All but deficiency period*	Oct Nov Dec Jan Feb–Mar Apr–May	19.0 16.5 15.5 12.5 8.0 11.0
				Deficiency period*	Oct Nov Dec–Mar Apr May	19.0 16.5 15.6 14.0 12.5

*A deficiency period is: 1) the second consecutive dry water year following a critical year; 2) a dry water year following in which the Sacramento River Index was less than 11.35 MAF; or 3) a critical water year following a dry or critical water year.

[1] Specific electrical conductance units: milliSiemens/cm = mmhos/cm = 1000 µmhos/cm. millimhos and milliSiemens are equivalent.

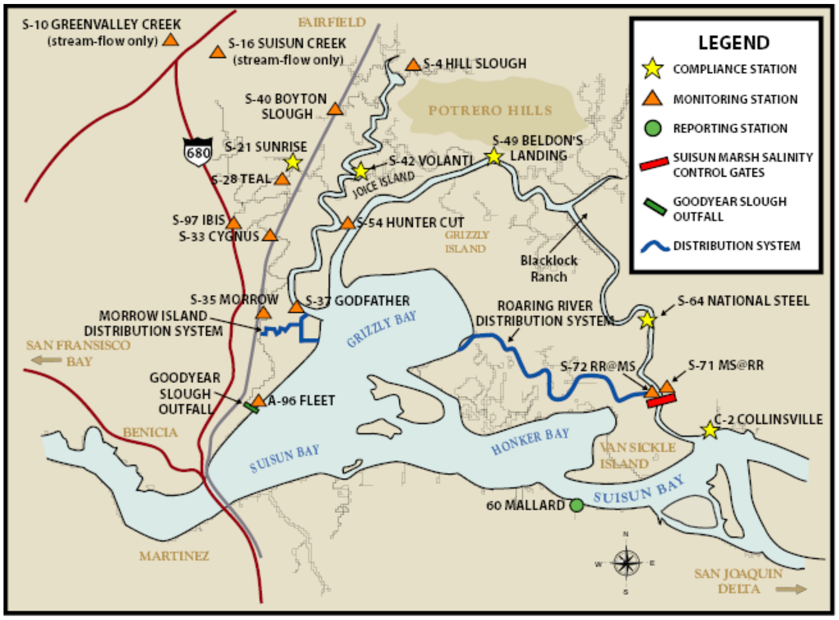


Figure 5-1 Monitoring locations for salinity within Suisun Marsh (Source: DWR).

5.2. DRIVERS OF SALINITY VARIATION IN SUISUN MARSH

The salinity of Suisun Marsh is affected by many factors including (DWR, 2001):

- Tides
- Delta outflow
- Suisun Marsh Salinity Control Gates operations
- Creek inflows
- Managed wetland operations
- Urban runoff
- Climate: precipitation, wind, evaporation, and barometric pressure
- Fairfield-Suisun Sewer District Treatment Plant effluent inflows

Many studies have demonstrated the significant influence of Delta outflow on water salinity in Suisun Marsh (DWR, 2001). Over the long term, starting in the first quarter of the 20th century, salinity in Suisun Marsh has increased due to out-of-basin diversion of freshwater from the Delta. Over more recent time frames there is a negative relationship between Delta outflows and salinity in the marsh. During high Delta outflows, water salinity in Suisun Marsh is lower. During low Delta outflow, high salinity water from Suisun Bay can enter Suisun Marsh, raising the salinity in Suisun Marsh and threatening aquatic life support. The salinity shows a gradient increasing from east to west because the east side of the channel is the closest to the Delta outflow. Suisun Marsh Salinity Control Gates (SMSCG) were installed in Montezuma Slough (Figure 5-1). The gate is operated during the months of

October to May when salinity standards are in place. The typical operation of the gates is between 10–20 days/year.

Water quality monitoring in Suisun Marsh has been focused primarily on the salinity effects on Delta outflow, operation of Suisun Marsh Salinity Control Gates and creek inflows.

5.2.1 Tidal Exchange with Suisun Bay

The influence of tides on salinity in Suisun Marsh varies by location (DWR, 1999). For tidal sloughs that are more directly connected to Suisun Bay, the influence is more significant. For sloughs that are further interior, the effect is less significant. Salinity monitoring in Suisun Marsh suggested that in certain regions tides have a significant impact on channel water salinity, while in other regions this impact is less significant. The salinity in the sloughs affects survival of fish and wildlife and therefore affects fish and wildlife beneficial uses. Salinity usually increases with high tide and decreases at low tide.

5.2.2 Delta Outflow

The Delta outflow is the primary source of fresh water to Suisun Bay and Marsh. The salinity of channels in Suisun Marsh varied considerably with the time of the year. During periods of low delta outflow, saline water from Suisun Bay enters Suisun Marsh, resulting in high salinity. Salinity starts to decrease when Delta outflow increases. In southwestern Suisun Marsh, it requires a long period of time to achieve a reduction in salinity. Northwestern Suisun Marsh salinity is primarily affected by inflow from the watersheds to the north and northwest.

The effect of Delta outflow on Suisun Marsh channel water salinity can be illustrated through monitoring data (Figure 5-2; DWR, 2003). During water year 2000, Suisun Marsh channel water salinity conditions were primarily a function of Delta outflow. At the beginning of the water year, net delta outflow is low, and EC levels at two compliance stations (S-42 and S-21) and one monitoring station (S-97) in Suisun Marsh are moderately high. (Locations of S-42, S-21 and S-97 were shown in Figure 5-1.) With the increases in delta outflow, EC levels at all three stations decreased dramatically and remained low until May.

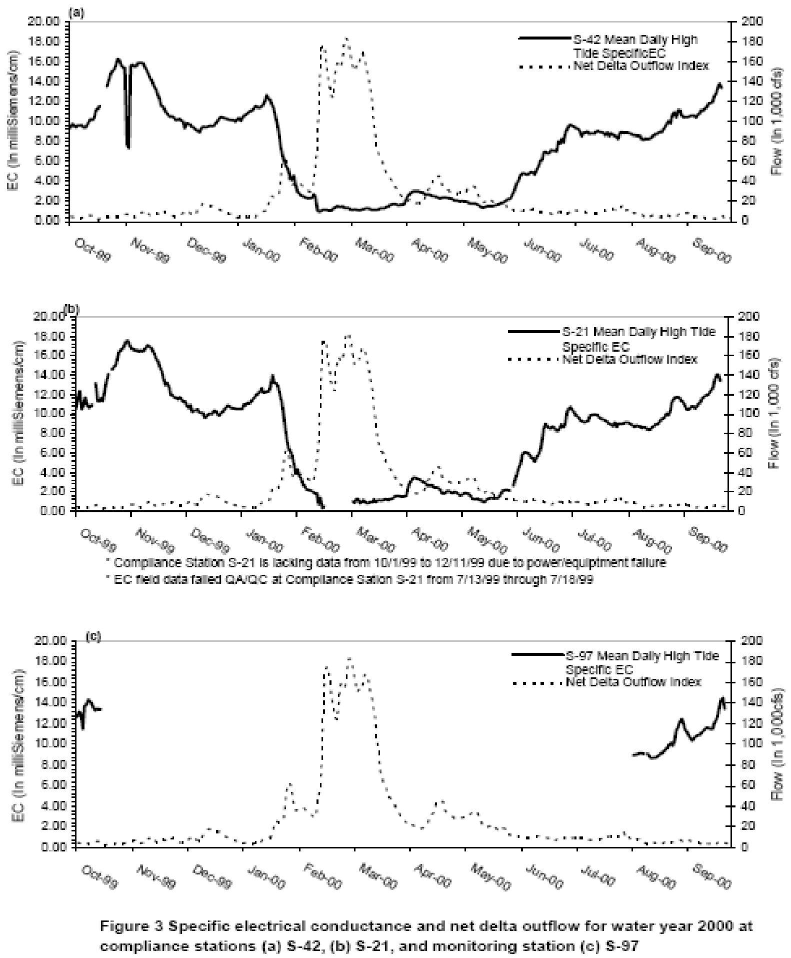


Figure 5-2 Specific electrical conductance and net delta outflow for water year 2000 at compliance stations (1) S-42, (b) S-21, and monitoring station (c) S-97 (DWR, 2003).

The relationship between precipitation, delta outflow and salinity in Suisun Marsh is further complicated by water projects and construction of SMSCG. Salinity at three locations in Suisun Bay and Marsh: Collinsville (C-2), Beldon's Landing (S-49) and Port Chicago was reconstructed by Enright and Culberson (2009; Figure 5-3). Following the construction of the water export projects, total diversions from the Delta have increased over the latter half of the 20th century. As a result, the Delta outflow decreased for the period of 1968–2006. Table 5-2 lists the Delta exports and outflow for the pre-project and post project time periods. Delta outflow is 22% less than it would be if the water projects were not operational. It was suggested that seasonality in Delta outflow has been changed due to water projects, with increased flow in August, September, and October and decreased outflow in April, May, and June. Generally the long-term trends in Delta outflow and salinity are very small (Table 5-3), compared to seasonal and tidal variability (Enright, 2004). Salinity is negatively-correlated with outflow except at Beldon's Landing. As a result, due to the increased Delta export from water projects, Delta outflow decreased for the period of 1968–2006 (although not significantly), salinity at Collinsville and Port Chicago increased.

The long-term precipitation, delta outflow and salinity data show no significant trends in precipitation for the post-SMSCG (1988–2006) years (Enright and Culberson, 2009). Delta outflow for the same period has increased at a rate of 25 cubic meters per second per year ($p = 0.03$). Corresponding specific conductivity at Belden's Landing has decreased at a rate of 0.3 mmhos/yr ($p = 0.03$) (The location of Belden's Landing is shown in Figure 5-1.). This trend is consistent with the historical trends prior to the State Water Project (1921–1967). During the historical period of 1921–1967, Delta outflow increased (although not significantly) and correspondingly specific conductivity at Belden's Landing decreased.

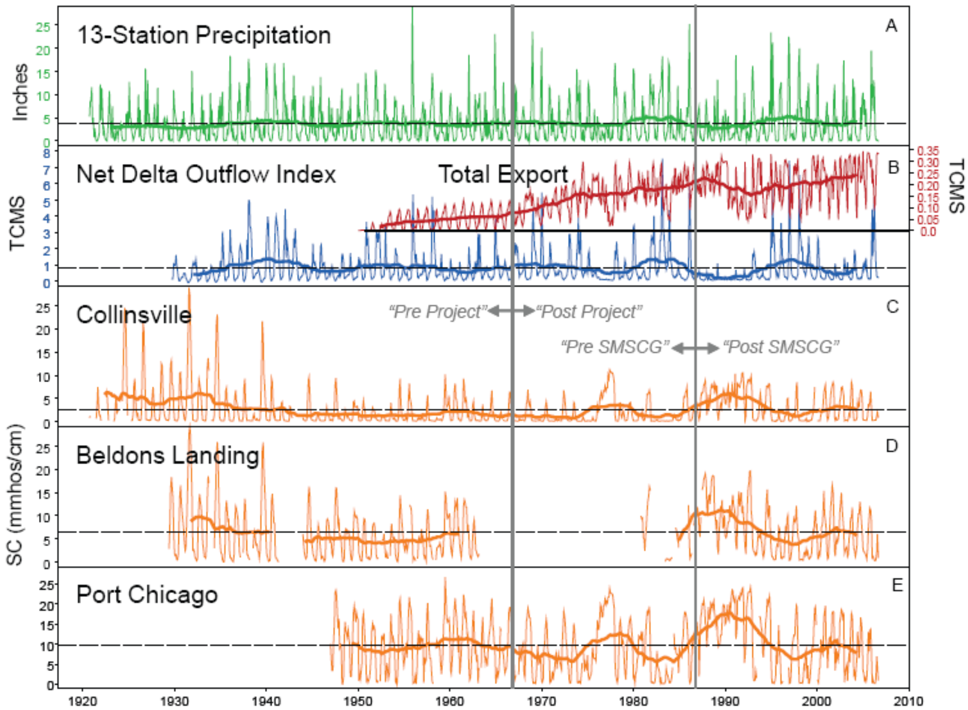


Figure 5-3 **Suisun Marsh Salinity in 1920–2006 (from: Enright and Culberson, 2009). Locations of these stations were shown in Figure 5-1. TCMS: thousand cubic meters per second.**

Table 5-2
Amount of Delta Outflow and Export for the Pre- and Post-project Time Periods (Enright, 2004)

	Mean	Pre 1968	Post 1968
Delta Outflow (CMS)	818	838	795
Delta Export (CMS)	130	43	176

Table 5-3
Trends in Annual Data for 13-station Precipitation, Delta Outflow, and Collinsville, Beldon's Landing, and Port Chicago Specific Conductivity Using Kendall Tau Test (Enright and Culberson, 2009)

	Units	All data (1921–2006)	Pre-project (1921–1967)	Post-Project (1968–2006)	Pre-SMSCG (1921–1987)	Post SMSCG (1988–2006)
Precipitation	Inches/yr	0.09 (p = 0.18)	0.12 (p =0.34)	0.14 (p = 0.61)	0.12 (0.19)	0.76 (p = 0.16)
Delta outflow	cms/yr	-1.9 (p = 0.45)	1.8 (p = 0.76)	-3.1 (p = 0.75)	-6.2 (0.98)	30 (p = 0.03)
Collinsville SC	mmhos/yr	-0.0058 (p = 0.39)	-0.072 (p <0.000)	0.04 (p = 0.082)	-0.032 (p = 0.001)	-0.2 (p = 0.042)
Belden's Landing SC	mmhos/yr	0.0085 (p = 0.59)	-0.076 (p = 0.073)	-0.29 (p = 0.007)	-0.036 (p = 0.51)	-0.3 (p = 0.03)
Port Chicago SC	mmhos/yr	0.008 (p = 0.65)	-0.044 (p = 0.65)	0.035 (p = 0.6)	-0.058 (p = 0.25)	-0.64 (p = 0.006)

5.2.3 Suisun Marsh Salinity Control Gates (SMSCG)

The SMSCG control salinity by closing during low Delta outflow period to limit flow from Grizzly Bay into the Montezuma Slough (DWR, 2003). The gate opens during outgoing tides to allow freshwater to enter Montezuma Slough. The gate closes on flood tide to prevent ocean water intrusion into the Montezuma Slough. Operation of the gate results in lower salinity in Montezuma Slough and maintains the east to west salinity gradient in Montezuma Slough. Without the operation of the gate, salinity in Montezuma Slough would increase.

The gate operation has been demonstrated to be effective in altering salinity in Montezuma Slough. Salinity at station S-64 (National Steel) and S-49 (Belden's Landing) (Figure 5-1) which are close to the Gates was seen to decrease immediately after the gate operation. The operation of SMSCG reduces Suisun Marsh salinity in the fall (Enright, 2004). From east to west, salinity decreased by several mmhos/cm at monitoring stations (Table 5-4).Salinity at two locations in Suisun Bay and Marsh: Collinsville (C-2), and Belden's Landing (S-49) showed significant declines after the operation of SMSCG (Table 5-2). Seasonal trends at these stations for the pre-SMSCG and post SMSCG showed clear lower salinity due to the operation of SMSCG (Figure 5-4). Salinity in the marsh without SMSCG ranged from 1 ppt to 25 ppt, with the gate operation, the salinity variability in the eastern marsh has been dampened (Siegel et al. 2011).

Table 5-4
Amount of Salinity Decreases Due to Operation of SMSCG at Stations from East to West Suisun Marsh (Enright, 2004)

Station	Name	Salinity Decrease (mmhos/cm)
S-64	National Steel	6–8
S-49	Beldons Landing	5–7
S-42	Volanti	4–5
S-21	Sunrise	3–4
S-35	Morrow	1–2

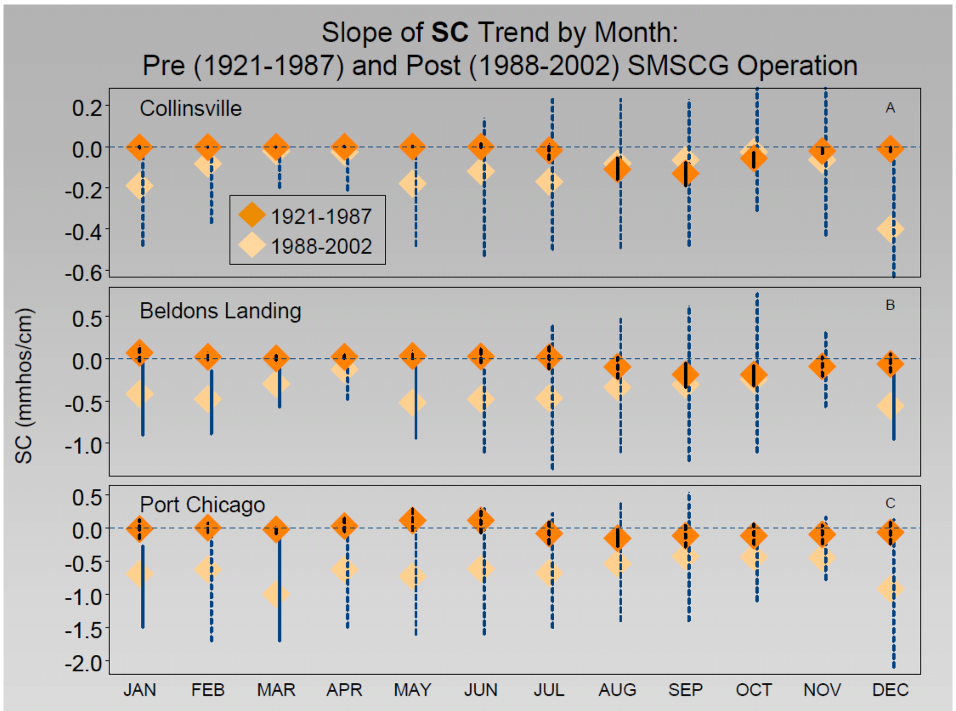


Figure 5-4 Seasonal specific conductivity trends at Collinsville (C-2), Beldon's Landing (S-49), and Port Chicago for the pre-SMSCG (1921–1987) and post-SMSCG (1988–2002) periods (from Enright, 2004).

5.2.4 Local Creek Inflows

Several creeks contribute freshwater to Suisun Marsh (DWR, 1999). These creeks include Green Valley, Suisun, Dan Wilson, Ledgewood, McCoy, and Denverton Creeks. The influence of creek inflow on salinity is most significant during the rainy season and in the northwestern marsh. The sloughs in the northwestern marsh are smaller and influences of Delta outflow and SMSCG operation are less pronounced.

5.2.5 Results of Water Management in Suisun Marsh

Potential problems are associated with managed wetlands. The building of levees around wetlands isolated the wetlands from daily tidal exchange and leaching during winter freshwater flooding. This could potentially cause salinity to build up in the wetlands over the long term. Typical wetland management includes initial flood up in the fall and drainage after the end of the waterfowl season, and leaving the ponds dry in the summer. The dry conditions during summer cause salinity in the soil water to increase due to evaporation and drawing of salinity from lower soil layers.

Suisun Marsh soils are saline due to historical inundation by the brackish tides (DWR, 2001). The presence of water in the soil and the flushing of tides keep salt concentrations in soils at constant levels. The influence of water management on pond water salinity depends on the water management cycle (DFG and SRCD, 2005). During flood-up, the pond water salinity is more dependent on pond soils, as salts accumulated on/or near the surface of the soils during summer dry periods, resulting in elevated salinity in pond water. During the period of December through February, pond water salinity is closer to the slough water salinity, as circulation of the pond water with slough water removes salts from the pond with less saline slough water (DWR, 2001). During the leaching cycles from February to May, pond water salinity is usually similar to slough water.

A conceptual model for salinity in Suisun Marsh is presented in Figure 5-5. The State Water Project, Central Valley Water Project, and precipitation all affect Delta outflow, which is a major driver of salinity in Suisun Marsh. The operation of SMSCG is another major driver in affecting salinity in Suisun Marsh sloughs. Salinity in Suisun Marsh sloughs in turn affects salinity in managed wetlands, as the slough water is used to flood managed wetlands. Draining of managed wetlands has impacts on salinity in sloughs as well. Wetland management activities such as drying during summer time raise soil salinity. High salinity in sloughs and wetlands can affect fish abundance and species diversity. Other factors such as FSSD discharge, surrounding watersheds, geometry/bathymetry of the sloughs, and climate change such as sea level rising and coastal upwelling, may also affect salinity in Suisun Marsh sloughs.

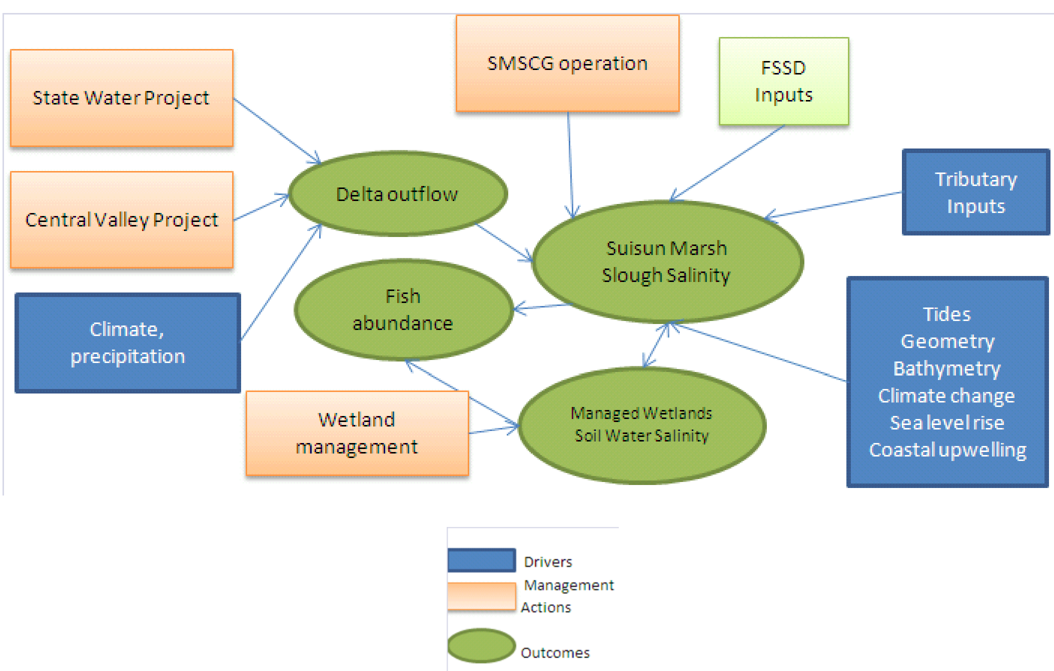


Figure 5-5 Conceptual model (cause and effect relationships) of salinity in Suisun Marsh.

5.3. SALINITY OBSERVED IN SUISUN MARSH

5.3.1 Spatial Variations

Suisun Marsh channels showed an east to west gradient in salinity, with lower salinity in eastern marsh and increasing towards the western marsh, due to closer proximity of eastern marsh to the freshwater inputs from Sacramento River and the Delta (DWR, 2003). The monitoring station closest to the Delta C-2 (as shown in Figure 5-1) typically has lowest monthly mean salinity throughout the region. Salinity measured at the westernmost station along the eastern portion of the marsh (at S-49) is consistently higher than those measured at C-2.

Salinity was also measured at various slough locations including the main and tributary sloughs (Figure 5-6 and Figure 5-7). Salinity data from the sloughs are available from BDAT. The results showed lowest salinity in Montezuma Slough, Peytonia Slough, Boynton Slough and part of Suisun Slough (SU1 and SU2, upper Suisun Slough; Figure 5-8). Goodyear Slough and portions of the Suisun Slough (SU3 and SU4, lower Suisun Slough) have consistently higher salinity (Figure 5-8).

With all the stations considered, salinity was lowest in some of the Montezuma Slough stations (MZ5), Cordelia Slough, and part of Suisun Slough (SU1L-SU3L; Figure 5-9). Salinity in Goodyear Slough, Boynton Slough, and part of the Suisun Slough (SU3 and SU4) and Montezuma Slough (MZ7 and MZ8) are significantly higher. The reason for the high salinity in some tributary sloughs is currently unknown. For parts of the Suisun Slough and Montezuma Slough that show higher salinity, this may reflect input from Grizzly Bay.

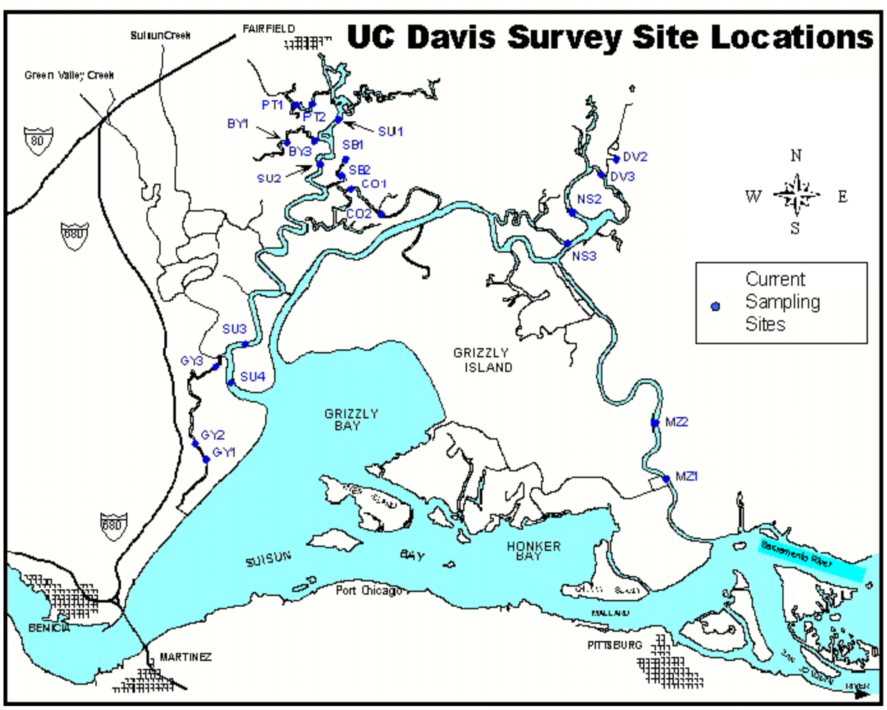


Figure 5-6 **Current salinity/specific conductance monitoring locations within Suisun Marsh (Source: DWR).**

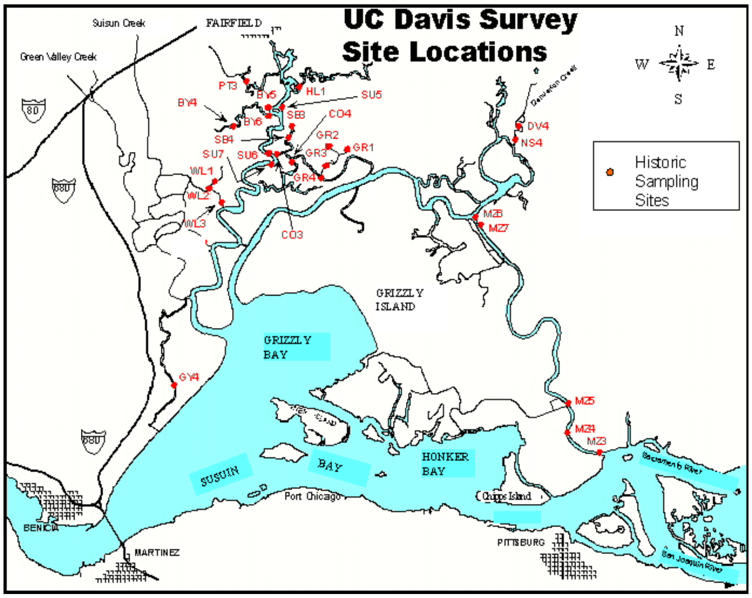


Figure 5-7 **Historical salinity/specific conductance monitoring locations within Suisun Marsh (Source: DWR).**

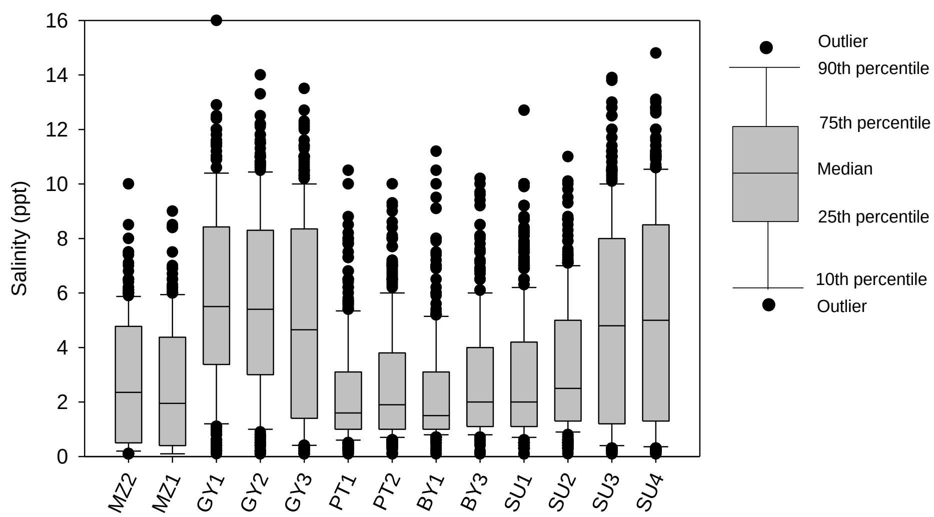


Figure 5-8 **Observed salinity at Montezuma Slough (MZ), Goodyear Slough (GY), Peytonia Slough (PT), Boynton Slough (BY) and Suisun Slough (SU) (Source: BDAT).**

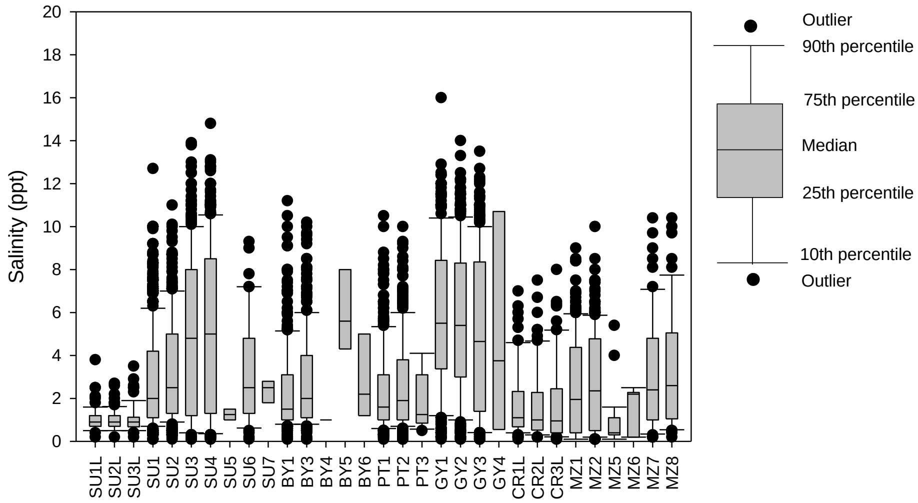


Figure 5-9 Observed salinity at all stations at Suisun Slough (SU), Boynton Slough (BY), Peytonia Slough (PT), Goodyear Slough (GY), Cordelia Slough (CR), and Montezuma Slough (MZ) (Source: BDAT).

5.3.2 Temporal Variations

As shown in the previous section (5.1.2), salinity in Suisun Marsh is significantly influenced by Delta outflow. Temporal variations in salinity therefore largely correspond with temporal variations in Delta outflow, with higher salinity during low Delta flow season and lower salinity during high Delta outflow season (Figure 5-2).

Salinity observed at Montezuma and Suisun Slough and the tributary sloughs (Goodyear, Peytonia and Boynton Slough) showed large temporal variations (inter-annual and seasonal; Figure 5-10 to Figure 5-14) with Delta outflow. Salinity at Montezuma Slough ranged from 0 to 9 ppt (Figure 5-10). Salinity in Suisun Marsh ranged from 0 to 14 ppt (Figure 5-11). Lower salinity is most likely associated with periods of high Delta outflow.

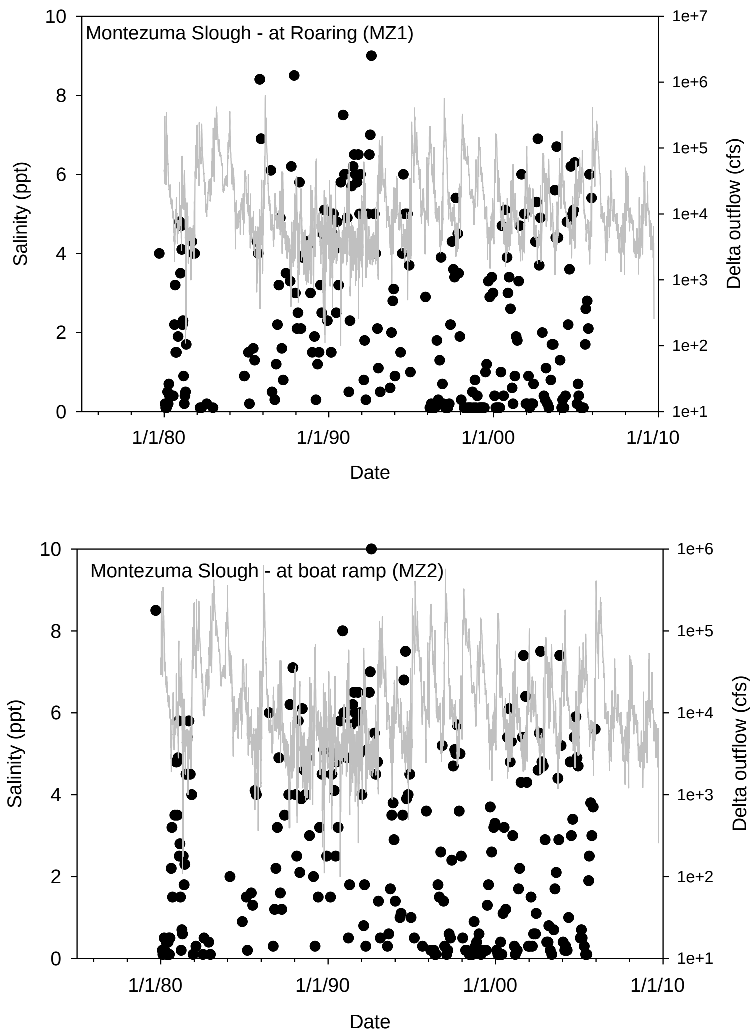


Figure 5-10 Observed salinity at Montezuma Slough (Site MZ1 and MZ2; Source: BDAT).

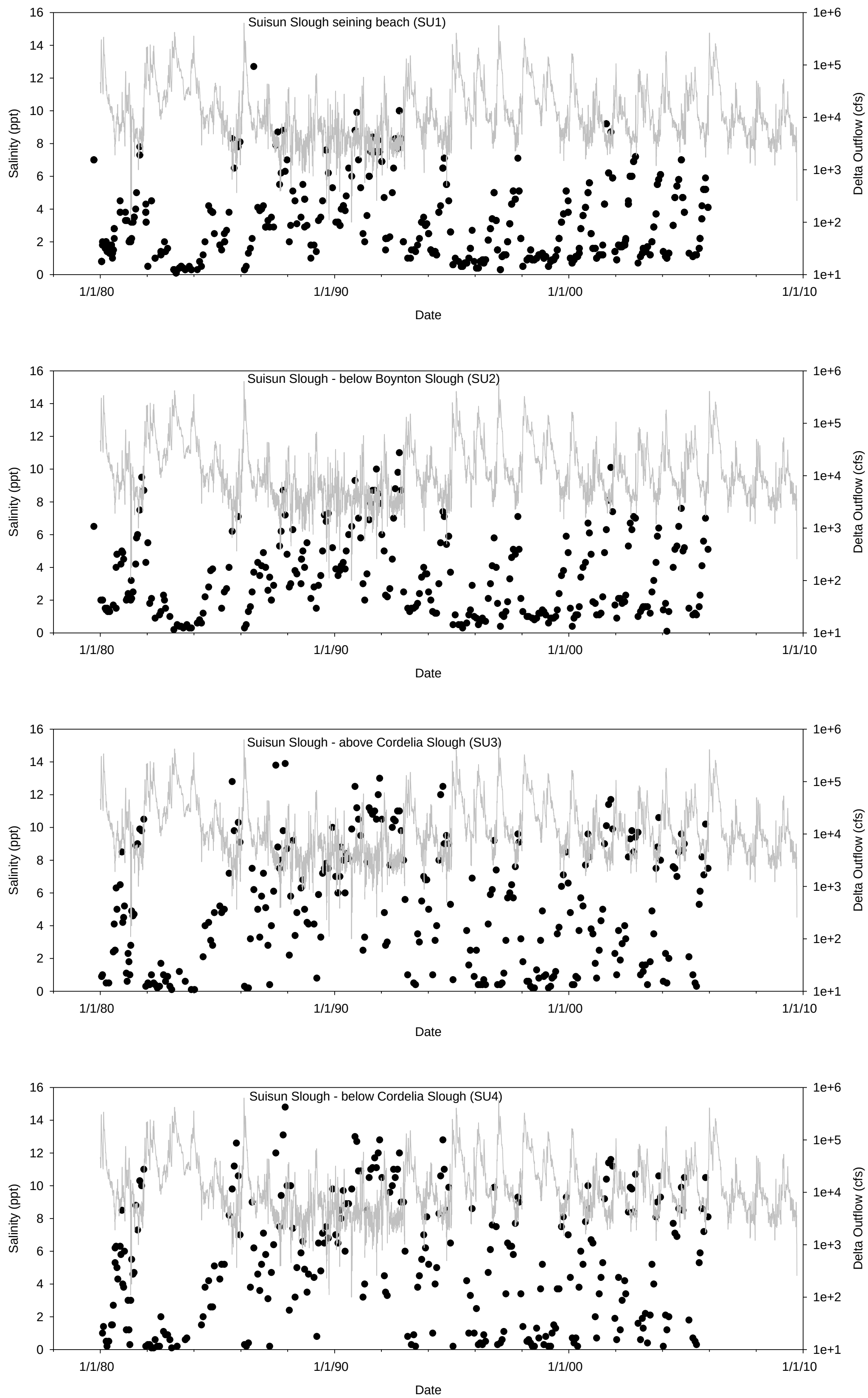


Figure 5-11 Observed salinity at Suisun Slough (SU1, SU2, SU3 and SU4; Source: BDAT).

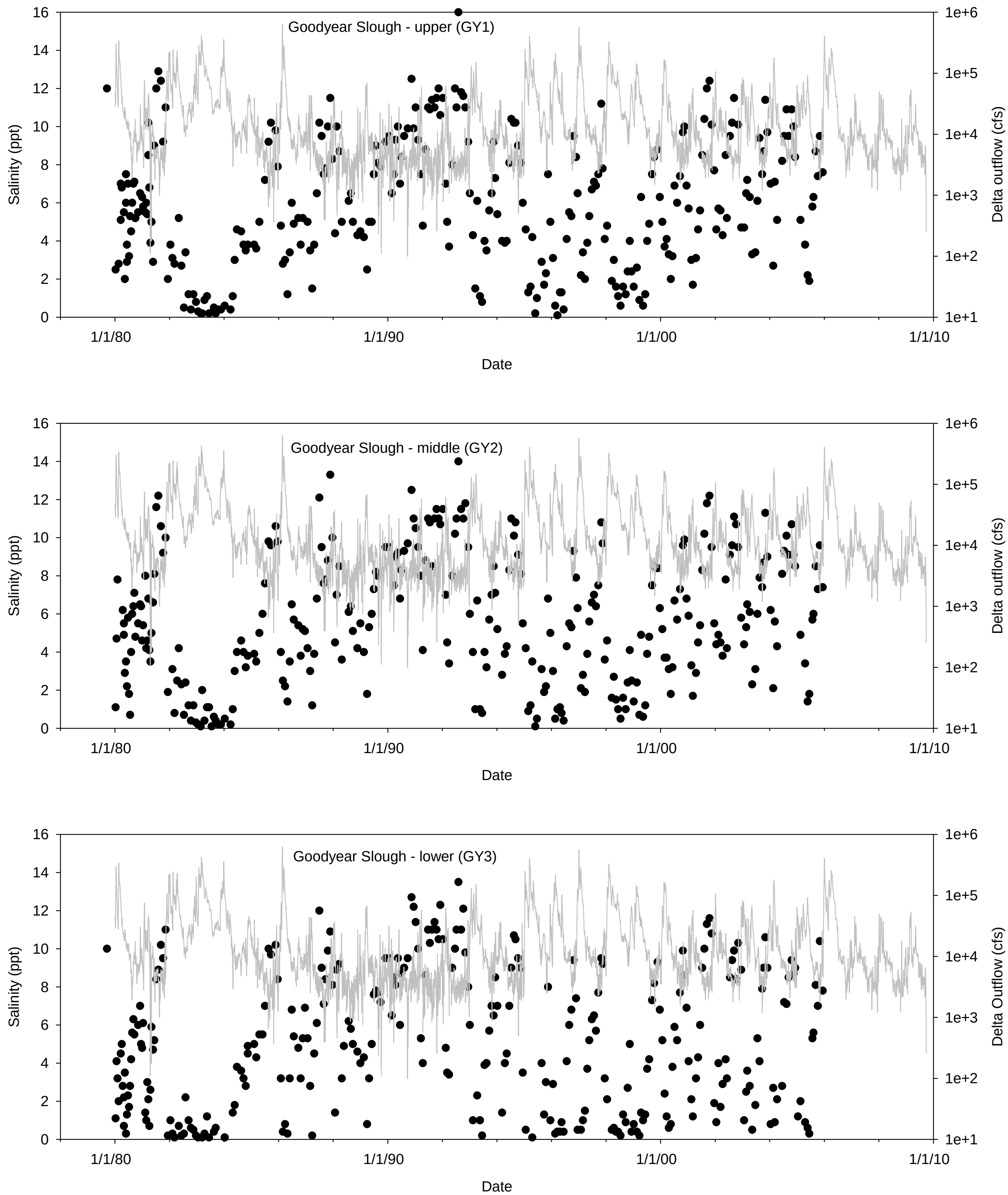


Figure 5-12 Observed salinity at Goodyear Slough (Site GY1 and GY3; Source: BDAT).

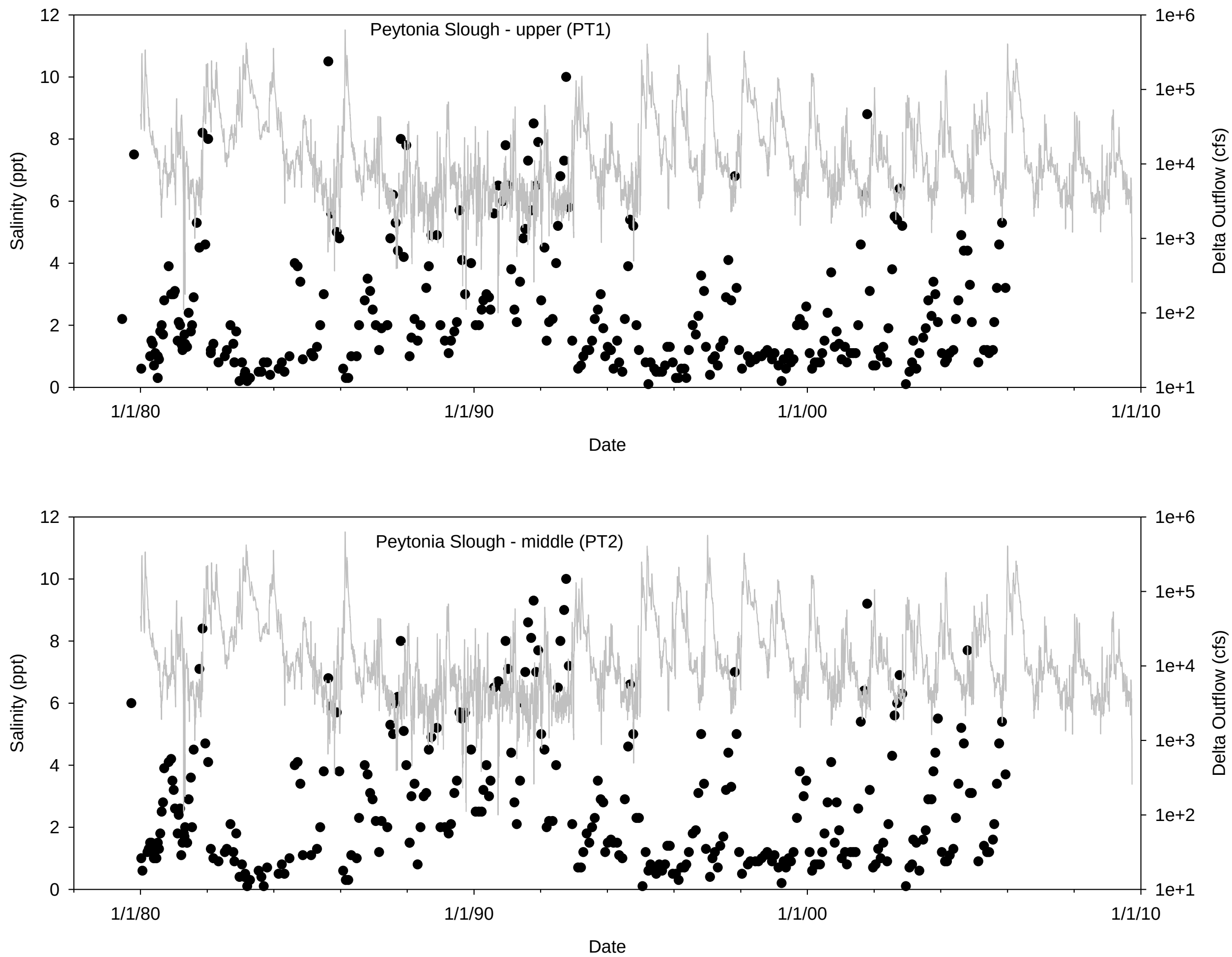


Figure 5-13 Observed salinity at Peytonia Slough (Site: PT1 and PT2; Source: BDAT).

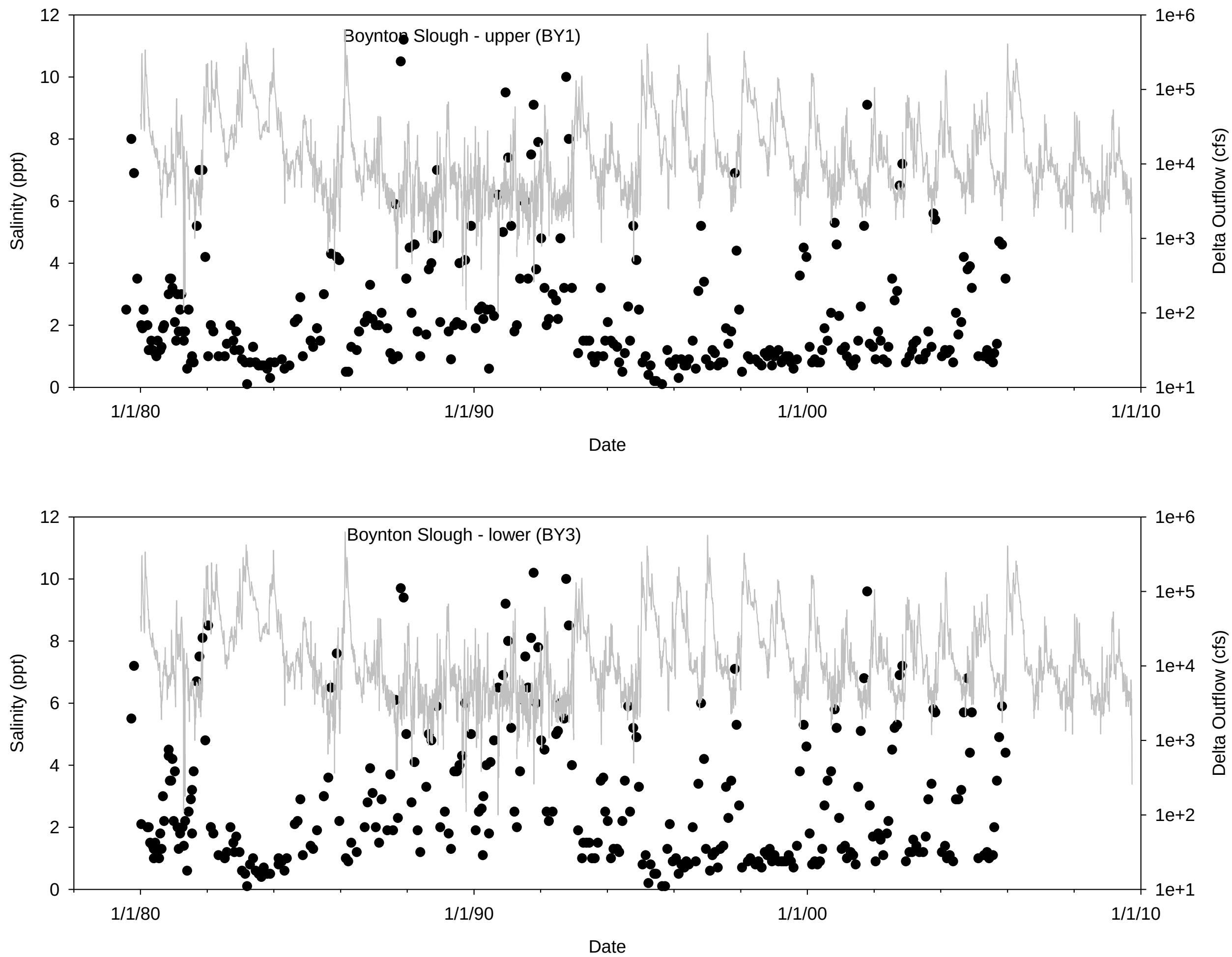


Figure 5-14 Observed salinity at Boynton Slough (Site BY1 and BY3; Source: BDAT).

5.4. SALINITY IMPAIRMENT ASSESSMENT IN SUISUN MARSH

Current salinity standards for Suisun Marsh were compared to the observed specific conductance at Montezuma Slough, Suisun Slough, Goodyear Slough, Peytonia Slough, and Boynton Slough (Figure 5-15 to Figure 5-20). The specific conductance at stations in Suisun Slough showed 0.43–6.09% of observations greater than salinity standards (Table 5-5). Montezuma Slough showed 0–0.43% of observations above salinity standards. In the tributary sloughs, Goodyear Slough shows 4.66–10.43% of observations above salinity standard. Overall, salinity appears to be within range in the larger sloughs, with occasional exceedances limited to smaller sloughs. The frequency of exceedances where they occur is relatively small. For the purpose of the current TMDL, given the larger-scale efforts at managing salinity in Suisun Bay by the State Water Resources Control Board, the salinity appears to not be a significant impairment under current targets.

Table 5-5
Specific conductance measured at Montezuma and Suisun Sloughs, Goodyear, Peytonia and Boynton Sloughs

Site	Name	# of Observations	# of Observations Above Standard	% of Observations Above Standard
SU1	Suisun Slough seining beach	303	3	0.43
SU2	Suisun Slough- below Boynton Slough	984	4	1.32
SU3	Suisun Slough- above Cordelia Slough	291	15	3.84
SU4	Suisun Slough – below Cordelia Slough	288	19	6.09
MZ1	Montezuma Slough – at Roaring	292	2	0.43
MZ2	Montezuma Slough – at boat ramp	278	1	0.00
GY1	Goodyear Slough – upper	271	31	10.43
GY2	Goodyear Slough – middle	306	22	6.09
GY3	Goodyear Slough – lower	302	19	4.66
PT1	Peytonia Slough – upper	300	1	0.43
PT2	Peytonia Slough – middle	305	0	0
BY1	Boynton Slough – upper	306	1	0.43
BY3	Boynton Slough – lower	312	0	0

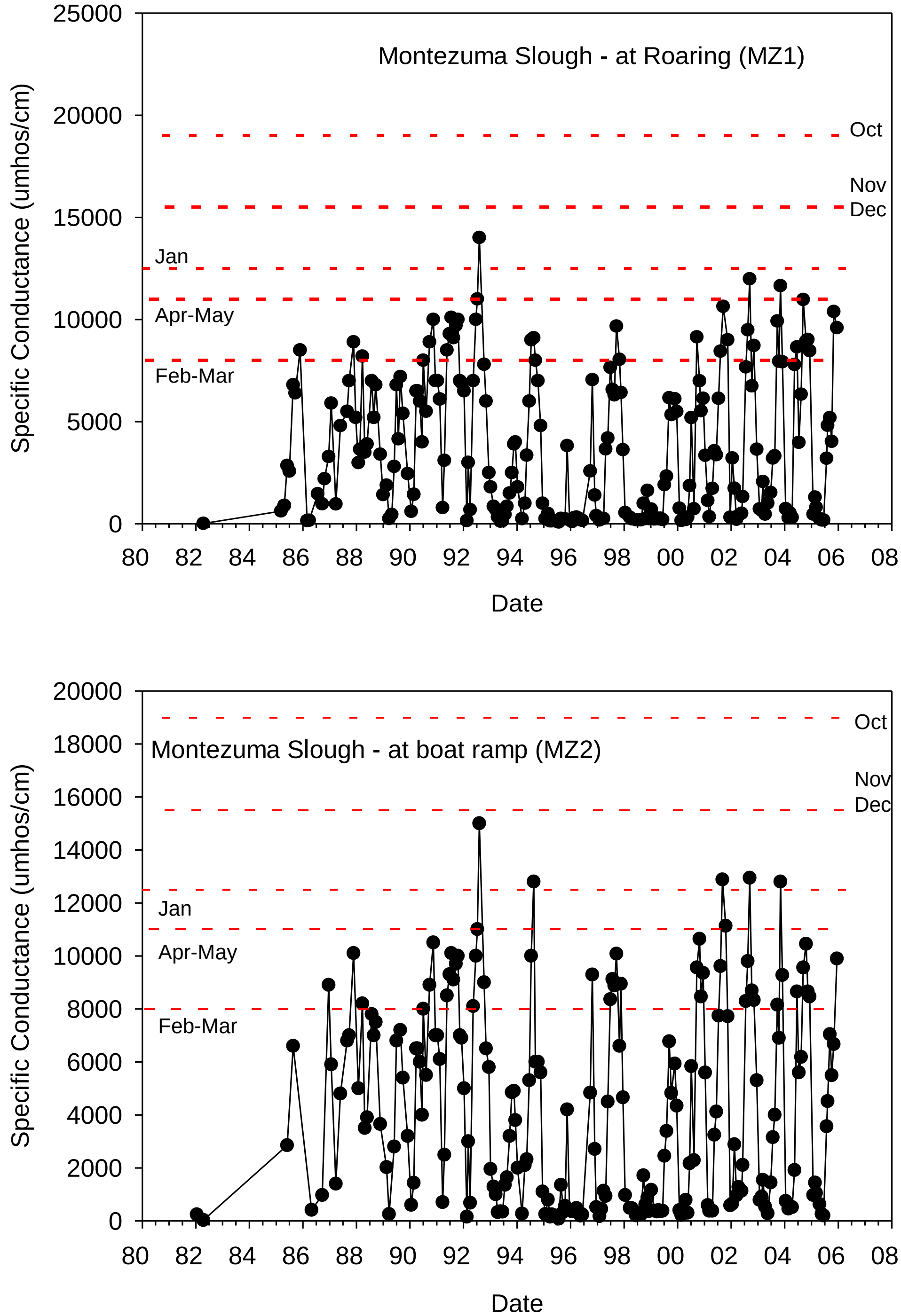


Figure 5-15 **Observed specific conductance at Montezuma Slough (Site MZ1 and MZ2; Source: BDAT). The red lines are monthly salinity standards.**

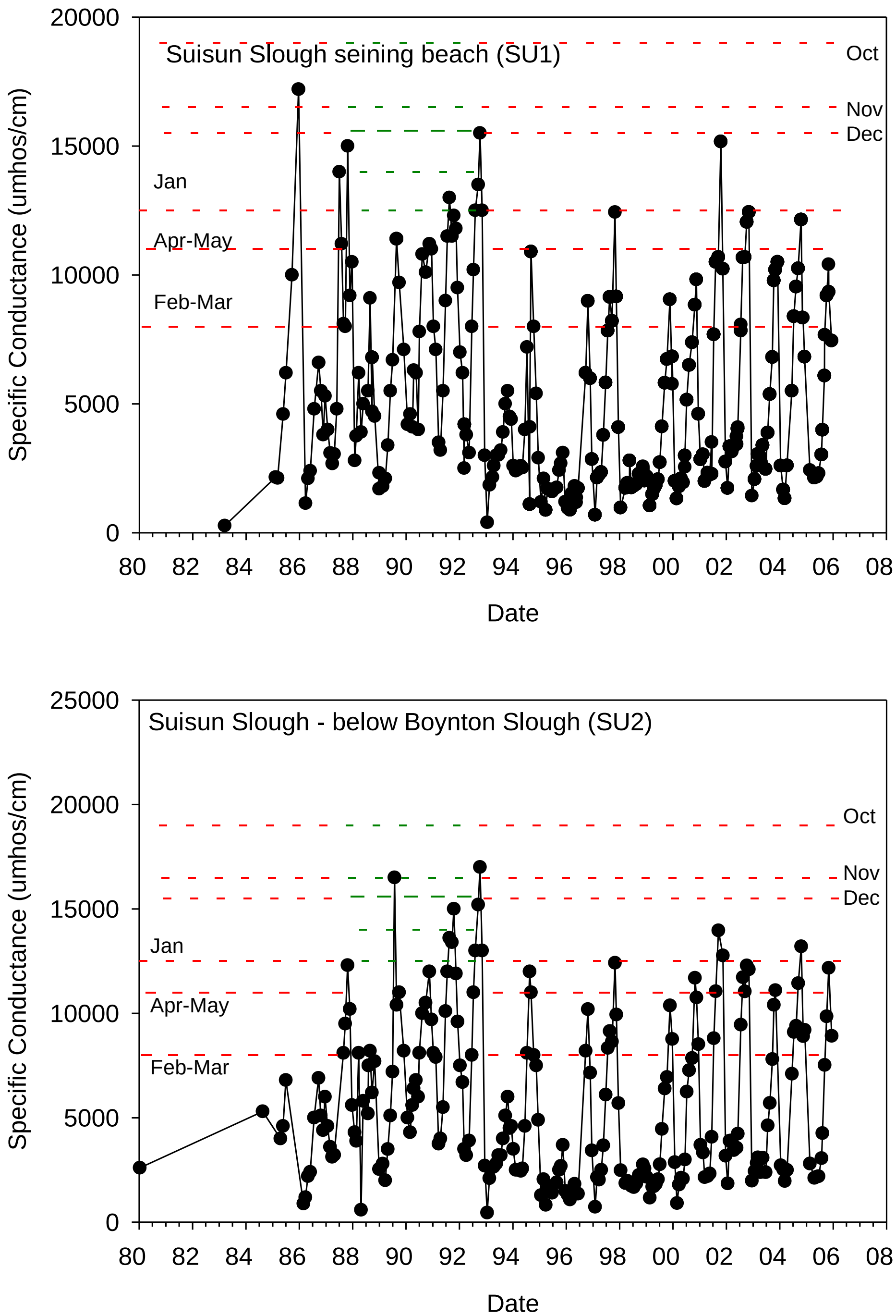


Figure 5-16 Observed specific conductance at Suisun Slough (Site SU1 and SU2; Source: BDAT). The red lines are monthly salinity standards. Green lines are salinity standards for deficiency periods.

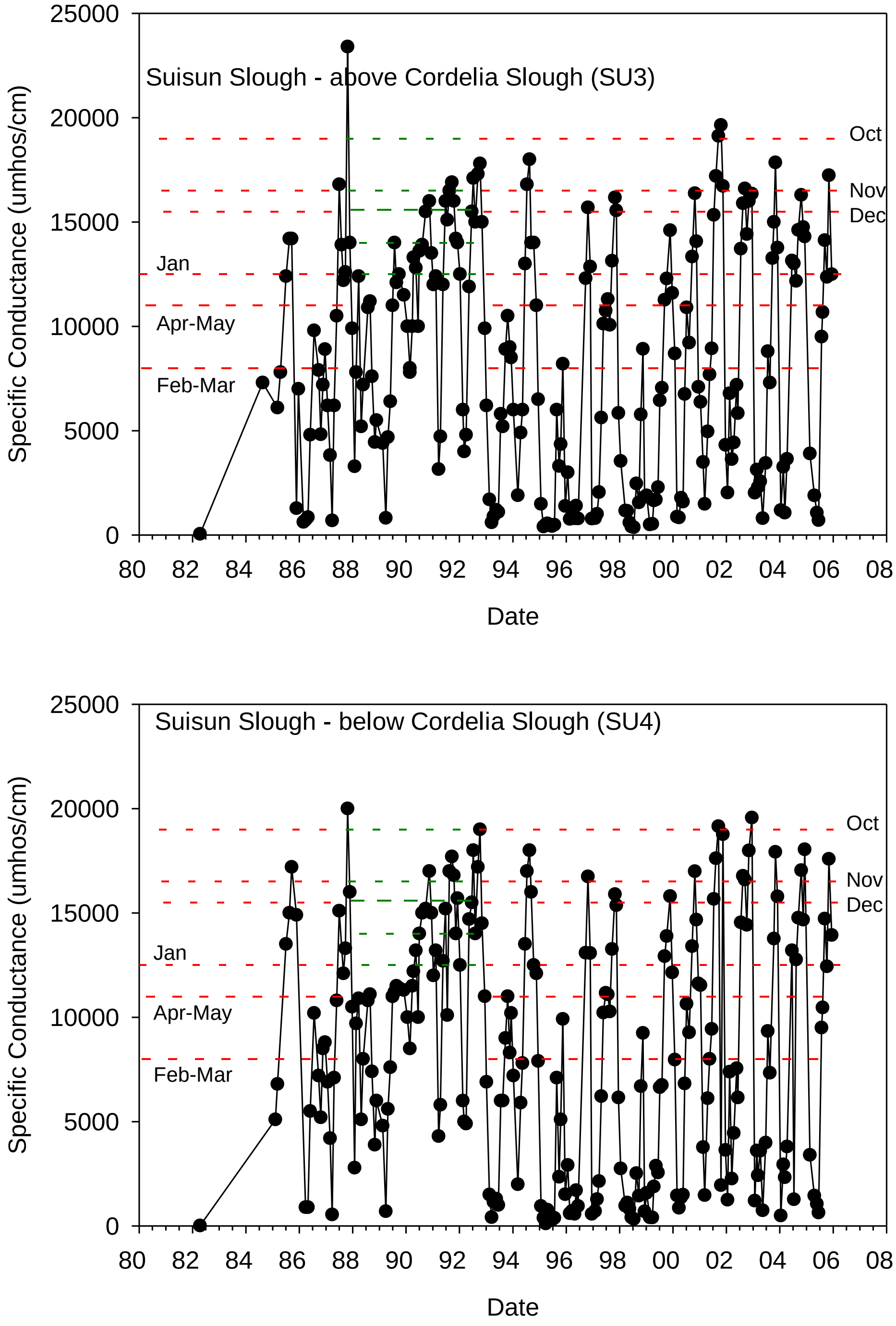


Figure 5-17 Observed specific conductance at Suisun Slough (Site SU3 and SU4; Source: BDAT). The red lines are monthly salinity standards. Green lines are salinity standards for deficiency periods.

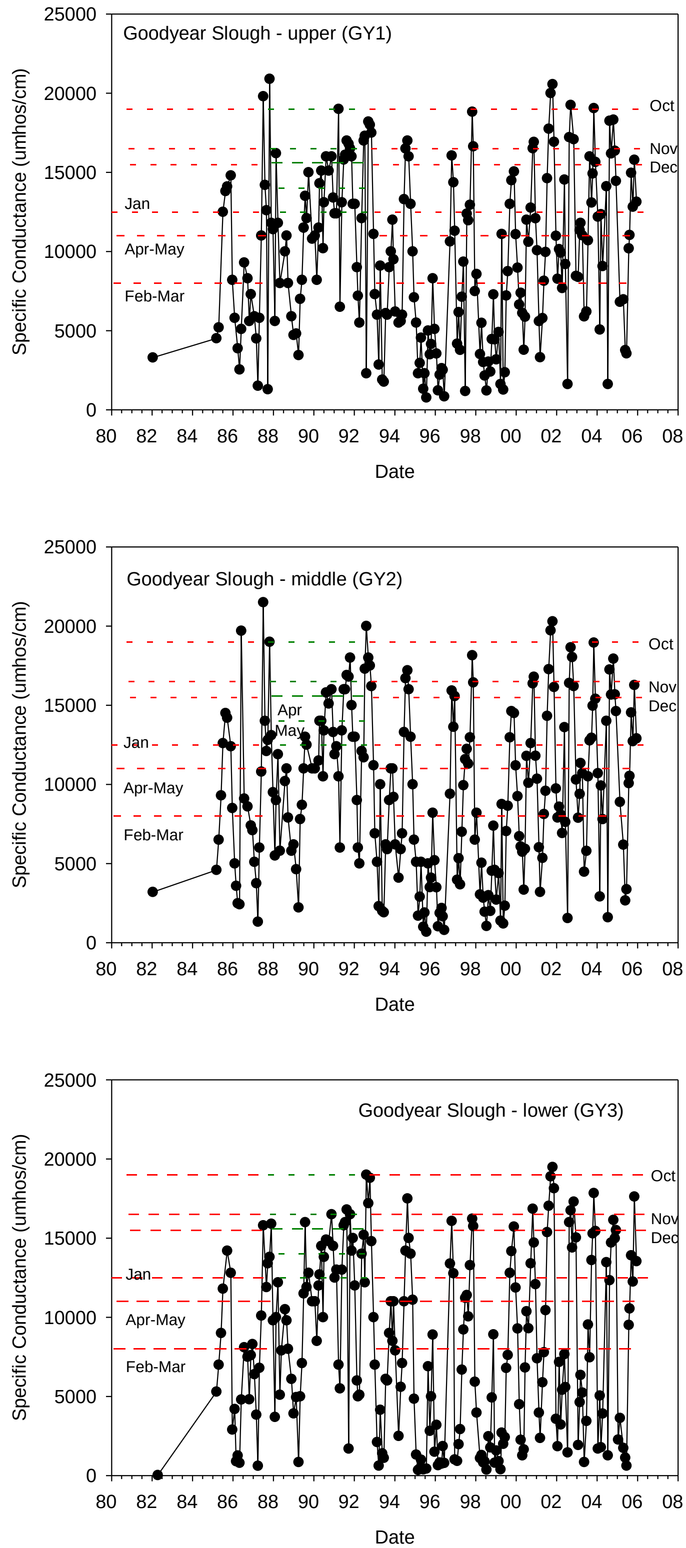


Figure 5-18 Observed specific conductance at Goodyear Slough (Site GY1, GY2, and GY3; Source: BDAT). The red lines are monthly salinity standards. Green lines are salinity standards for deficiency periods.

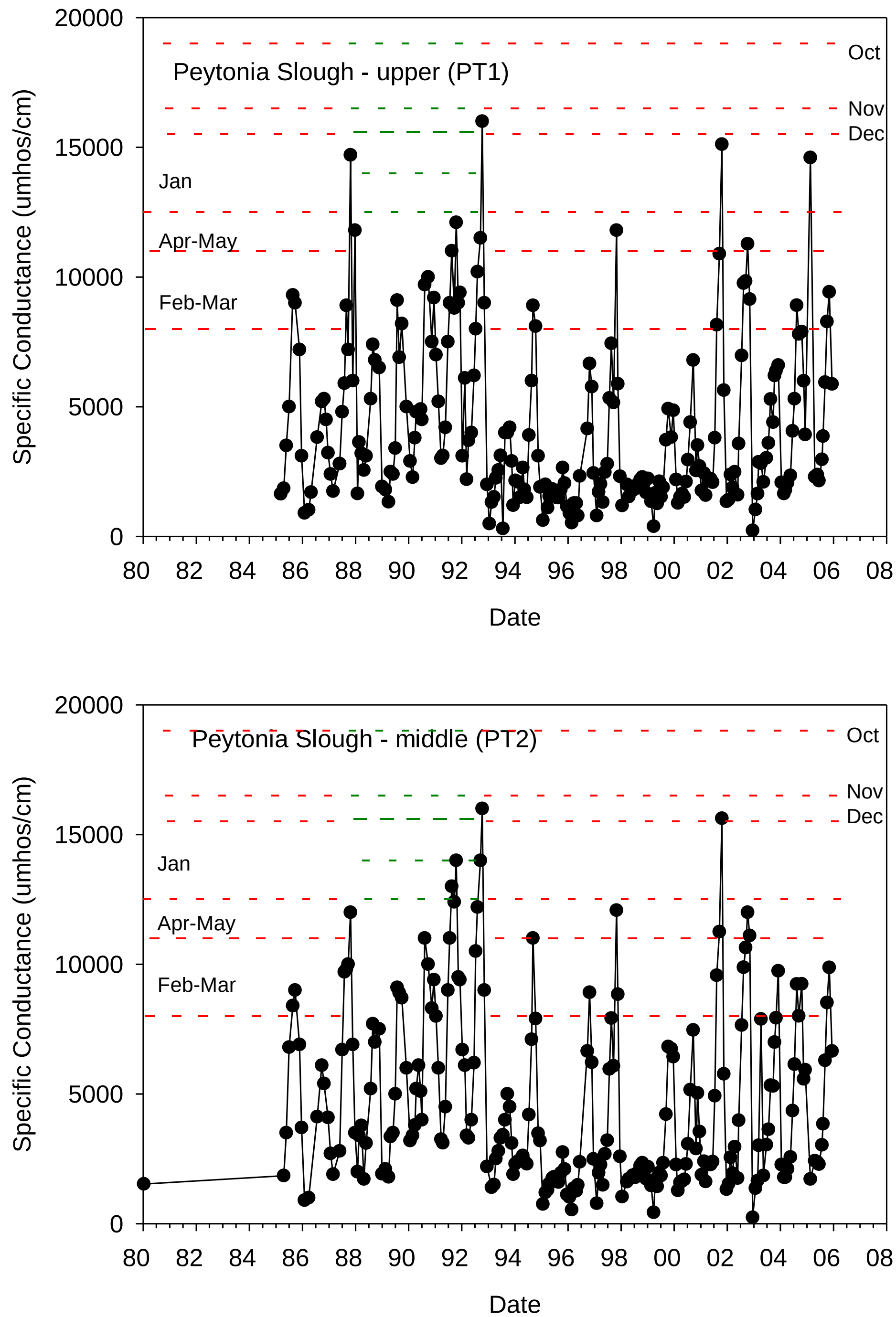


Figure 5-19 Observed specific conductance at Peytonia Slough (Site: PT1 and PT2; Source: BDAT). The red lines are monthly salinity standards. Green lines are salinity standards for deficiency periods.

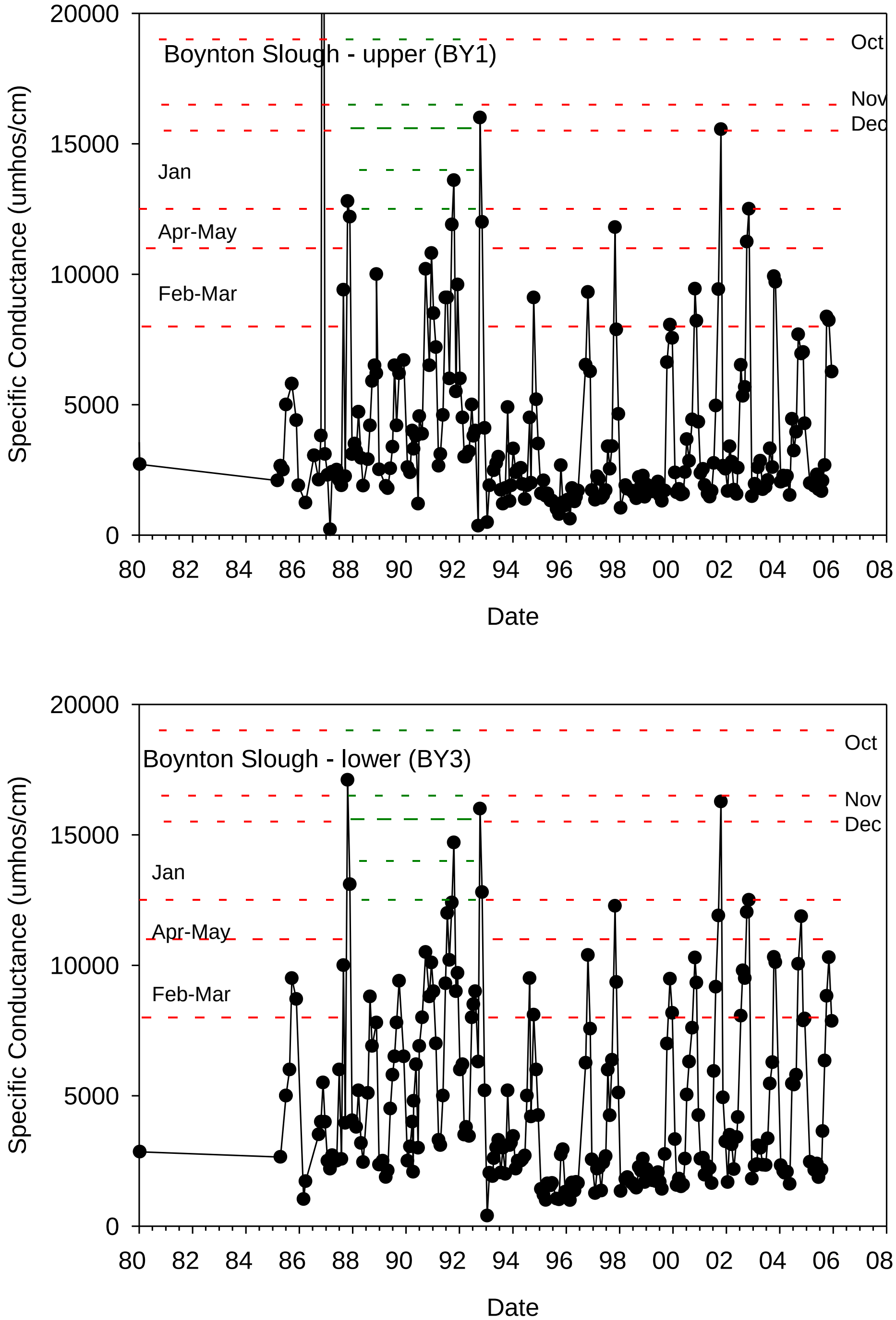


Figure 5-20 Observed specific conductance at Boynton Slough (Site: BY1 and BY3; Source: BDAT). The red lines are monthly salinity standards. Green lines are salinity standards for deficiency periods.

5.5. SUMMARY

The conceptual model/impairment assessment of salinity in Suisun Marsh can be summarized as follows:

- Salinity in Suisun Marsh is strongly affected by Delta outflow, Suisun Marsh Salinity Control Gates, tidal exchange with Suisun Bay, local creek inflows and the managed wetlands.
- Temporal variations in Suisun Marsh salinity are regulated by Delta outflow. Increases in delta outflow resulted in lower salinity in Suisun Marsh. Suisun Marsh salinity showed a spatial gradient of increasing salinity from the east to west, due to proximity to the Delta outflow in the eastern marsh.
- The operation of Suisun Marsh Salinity Control Gates is effective in regulating salinity in Suisun Marsh (Enright and Culberson, 2009; Siegel et al. 2011).
- The tributary inflows have impacts on salinity most significantly during winter storm events and in the northwest corner of Suisun Marsh.
- The management of wetlands alters salinity by flushing saline water from wetland soils to sloughs.
- Overall, salinity appears to be within range in the larger sloughs, with occasional exceedances limited to smaller sloughs. The frequency of exceedances where they occur is relatively small. For the purpose of the current TMDL, given the larger-scale efforts at managing salinity in Suisun Bay by the State Water Resources Control Board, the salinity appears to not be a significant impairment under current targets.

6. NUTRIENTS

Nutrients, defined here as different chemical forms of nitrogen and phosphorus, can enter Suisun Marsh through tributaries draining agricultural and urban areas, the Delta, atmospheric deposition, and the discharge from the FSSD wastewater treatment plant. Elevated nutrient concentrations can potentially result in excess growth of phytoplankton and macrophytes, the subsequent decay of which results in the lowering of DO levels and increasing turbidity in wetlands and sloughs, conditions that could harm the health of aquatic organisms including fish. Suisun Marsh wetlands are 303(d) listed for impairment by nutrients (Regional Water Board, 2007). A conceptual representation of the cause and effect relationships of nutrients in Suisun Marsh is presented in Figure 6-1.

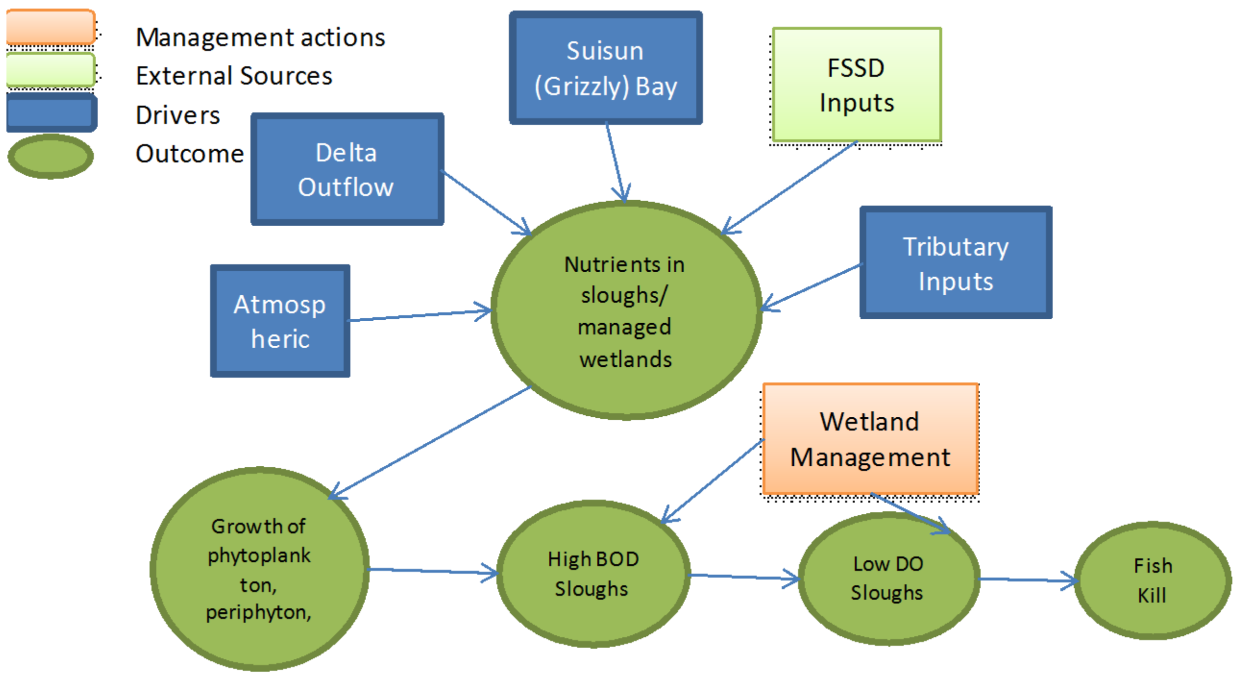


Figure 6-1 Conceptual model (cause-effects relationship) of nutrients in Suisun Marsh.

6.1. SOURCES OF NUTRIENTS TO SUISUN MARSH

Sources of nutrients to Suisun Marsh include Delta outflow which receives nutrients from the Sacramento and San Joaquin River, exchange with the nutrient rich Suisun Bay, tributary inflow that drains urban and agricultural areas, discharge from wastewater treatment plant, atmospheric deposition, and internal releases from wetland soils. During winter time, water quality in Suisun Marsh can be influenced by stormwater runoff from tributaries. Some of these tributaries drain livestock grazing areas, and urban and agricultural areas. In general, very little data has been reported on nutrients to quantify the nutrient sources to Suisun Marsh. The discussion in this chapter is based on the limited information available, primarily from regional sources, and highlights the need for a systematic sampling at key locations in the marsh (major tributaries, sloughs, selected managed wetlands, and the wastewater treatment plant). Such sampling will provide the basis for a quantitative assessment of nitrogen and phosphorus loads to the marsh. A receiving water nutrient sampling station downstream of the FSSD discharge was ongoing since 2005.

Based on a previous study by Davis et al. (2000) for upland watersheds of San Francisco Bay, tributary inputs from the Fairfield sub-watersheds are estimated to be 112 N kg/day and 103 kg P/day. More recently nutrient concentrations were measured in Laurel Creek, Ledgewood Creek and Suisun Creek during spring season following rain events (Regional Water Board, 2013; Table 6-1). Estimated loads from the recent sampling ranged from 1.2 kg N/ha/yr in Suisun Creek to 4.6 kg N/ha/yr in Ledgewood Creek and 0.02 kg P/ha/yr in Suisun Creek to 0.17 kg P/ha/yr in Laurel Creek. The estimated loads from Davis et al. (2000) (expressed on a unit area basis) are in agreement with the recent sampling.

Table 6-1
Concentrations of Total Nitrogen, BOD and TOC in Suisun Marsh Creeks, Sampled During Spring 2013 (2/19/2013–3/4/2013) and Estimated Loads (Regional Water Board, 2013)

Constituents	Laurel Creek 1	Laurel Creek 2	Ledgewood Creek 1	Ledgewood Creek 2	Suisun Creek 1	Suisun Creek 2	Suisun Creek 3
Nitrite as N (mg/l)	ND	ND	ND	ND	ND	ND	ND
Nitrate as N (mg/l)	0.59	0.983	1.19	1.59	0.34	0.33	0.33
Ammonia as N (mg/l)	0.23	0.12	0.15	0.115	ND	ND	ND
Total Kjeldahl Nitrogen (TKN; mg/l)	1.13	1.18	1.04	1.24	0.36	0.34	0.53
DON as N (mg/l)	0.9	1.06	0.89	1.13	0.36	0.34	0.53
Orthophosphate as P (mg/l)	0.088	0.057	0.062	0.061	ND	ND	ND
Total Phosphorus (mg/l)	0.094	0.075	0.094	0.071	0.021	0.009	0.019
Total nitrogen (kg/ha/yr)	2.4	3.5	3.4	4.6	1.2	1.2	1.6
Total phosphorus (kg/ha/yr)	0.17	0.14	0.17	0.13	0.04	0.02	0.03

A large input of ammonium (NH_4) was documented to enter the Delta from agricultural fertilizer runoff, livestock operations and municipal sewage treatment plan outflows (CDFG, 2008). In a nutrient-rich estuary, the tidal/freshwater marsh zone has the ability to transform or retain up to 40% of the NH_4 entering the marsh during a single tide (Gribsholt et al. 2005). A portion (30%) of the NH_4 can be transformed through nitrification (Gribsholt et al. 2005). As a result, a substantial portion of the NH_4 inputs from the Delta can be retained in Suisun Marsh.

Ammonia (NH_3) refers to the dissolved gas form of ammonium (NH_4) in the aquatic environment which is toxic to fish. The existence of the two forms is dependent on the pH of the water column. The primary concern relating to ammonia is its chronic and acute toxicity to fish. Primary concerns due to ammonium inputs to the Bay-Delta ecosystem are the toxicity of ammonium to pelagic organisms and impacts on phytoplankton. Ammonium can inhibit the uptake of nitrate by phytoplankton. At relatively low concentrations, ammonium has been shown to inhibit uptake of nitrate by phytoplankton in the bay, causing low productivity (Wilkerson et al. 2006; Dugdale et al.2007). When ammonium concentrations are below 4 µmol/L (or 0.072 mg/l[2]), phytoplankton blooms can occur due to the uptake of nitrate. Tidal marshes in Suisun Marsh may offer retention of this ammonium and mitigate the adverse impacts.

The inputs of nutrients from the FSSD wastewater treatment plant also need to be considered. Ammonia concentrations in wastewater treatment plant effluent are typically below 0.1 mg/l, although there are occasional spikes greater than 0.5 mg/l (Figure 6-2). Based on the discharge rate of 14.4 mgd to Suisun Marsh and a concentration of 0.1 mg/l for ammonia as nitrogen, the estimated effluent ammonia load from FSSD is 5.4 kg N/day. In 2011 the average daily maximum concentration was approximately 0.07 mg N/l and most recently the measured ammonia load was approximately 1.75 kg N/day. Other species of nitrogen discharged from FSSD reported include organic nitrogen, nitrite and nitrate. Organic nitrogen concentrations in FSSD effluent are normally 0.05–1 mg/l. Nitrite and nitrate concentrations are generally at 12–33 mg/l, and constitute the largest fraction of nitrogen in the discharge. Estimated mean TN load for the period of 2012–2013 is 1,332 kg N/day.

Atmospheric deposition of nutrients to Suisun Marsh could be an important source, especially for nitrogen, which has a significant atmospheric cycle. The nearest station from National Atmospheric Deposition Program (NADP) network (CA88) near Suisun Marsh is located at Davis, CA. Inorganic nitrogen (NH_4 + NO_3) wet deposition loads measured at this station for the last 10 years (2000–2010) averaged 2.45 kg N/ha/yr. This represents an inorganic nitrogen wet deposition load of 315.5 kg/day to Suisun Marsh. Dry to wet N deposition ratios at a nearby station (YOS404) from a Clean Air Status and Trends Network (CASNET) averaged at 0.67 for the period of 2000–2008. This suggests a dry N deposition load of 210.5 kg/day to Suisun Marsh.

[2] 1 µmol/L of ammonium corresponds to 0.018 mg/l.

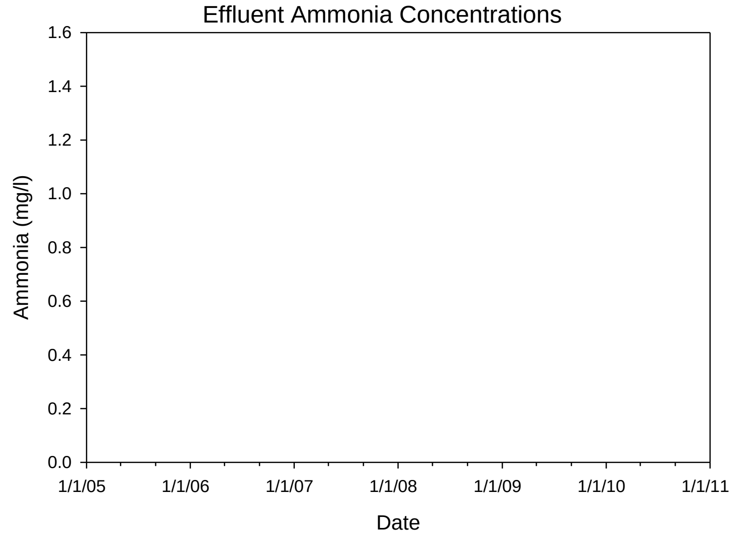
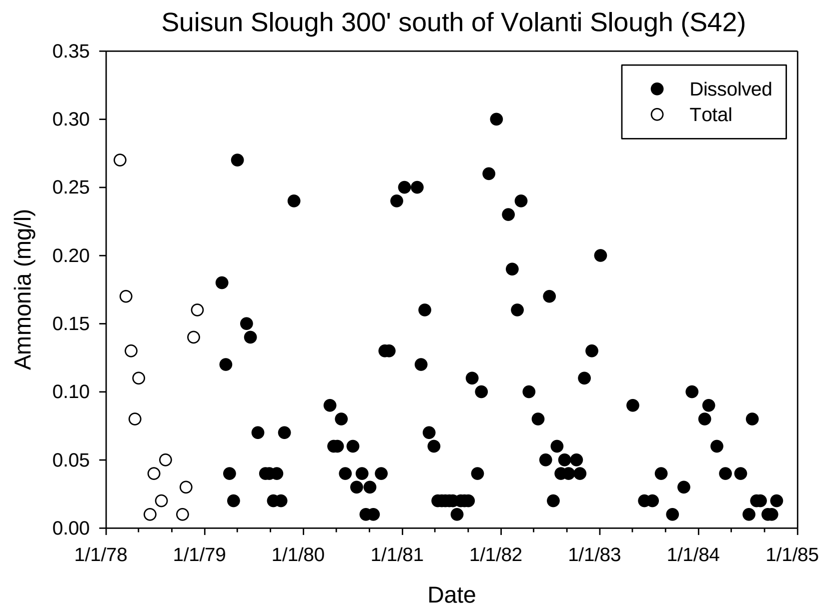


Figure 6-2 Effluent ammonia concentrations from Fairfield-Suisun Sewer District Waste Water Treatment Plant.

6.2. CONCENTRATIONS OF NUTRIENTS (NO_3, PO_4, TN, TP) OBSERVED IN SUISUN MARSH (SPATIAL AND SEASONAL VARIATION)

Limited nutrient data are available in Suisun Marsh from approximately three decades ago. Nutrient concentrations in terms of ammonia, total Kjeldahl nitrogen (TKN), nitrite + nitrate, organic nitrogen, ortho-P and TP concentrations were measured at Suisun Slough at station S42 for the period of 1978–1985 (Figure 6-3 to Figure 6-5). Observed ammonia concentrations for this period ranged from 0 to 0.30 mg/l (Figure 6-3). Organic nitrogen concentrations ranged from 0.1 to 1.5 mg/l. Observed TKN ranged from 0.5 to 1.8 mg/l. Observed NO_2 + NO_3 concentrations ranged from 0 to 0.9 mg/l (Figure 6-4). The organic nitrogen and NO_2 + NO_3 concentrations are relatively high. Orthophosphate concentrations in Suisun Slough ranged from 0.02 to 0.19 mg/l (Figure 6-5). TP concentrations range from 0.1 to 0.35 mg/l. Observed TN/TP ratios are mostly below 16, suggesting nitrogen is more likely to be limiting algal growth.



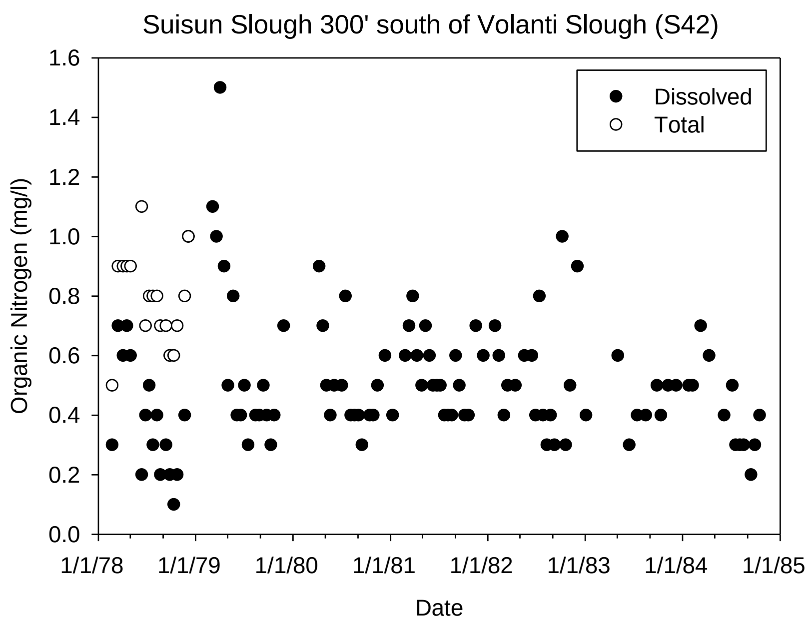


Figure 6-3 **Observed total and dissolved ammonia and organic nitrogen concentrations in Suisun Slough (Source: BDAT).**

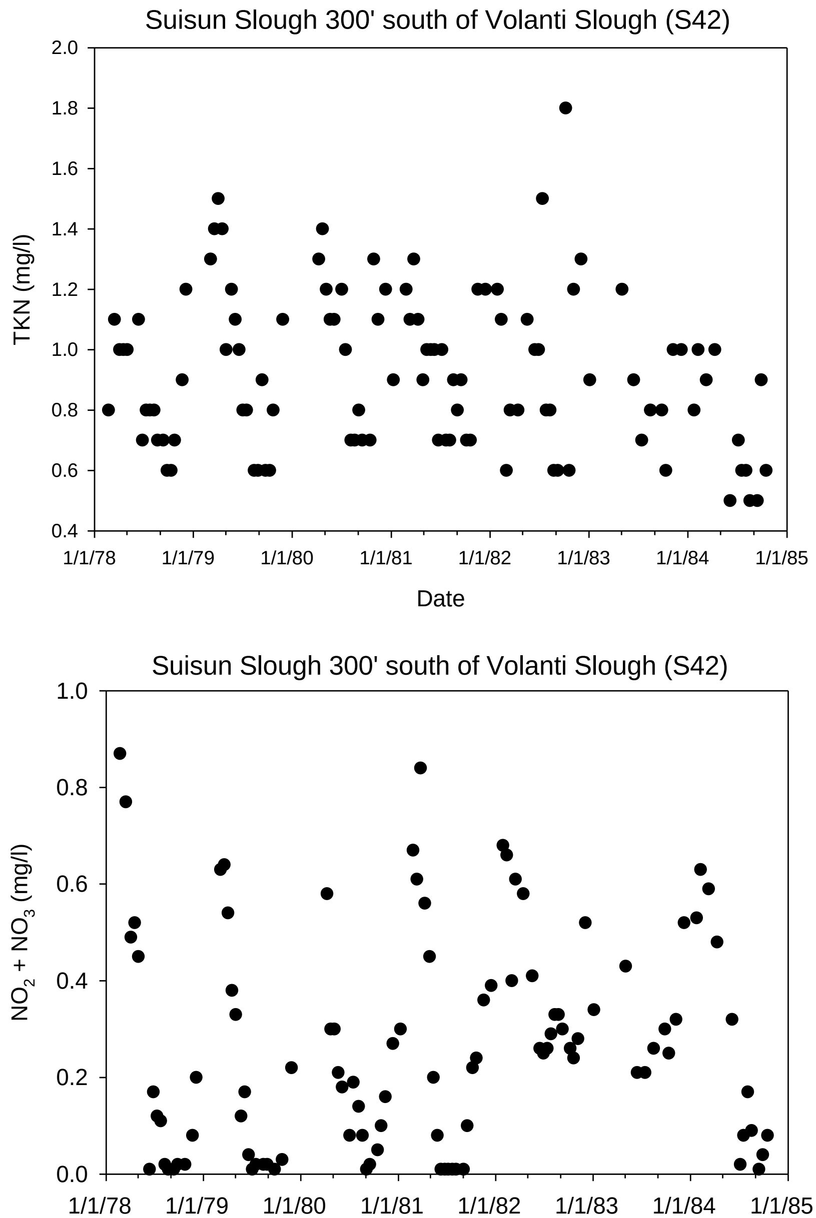


Figure 6-4 Observed TKN and NO_2+NO_3 concentrations in Suisun Slough (Source: BDAT).

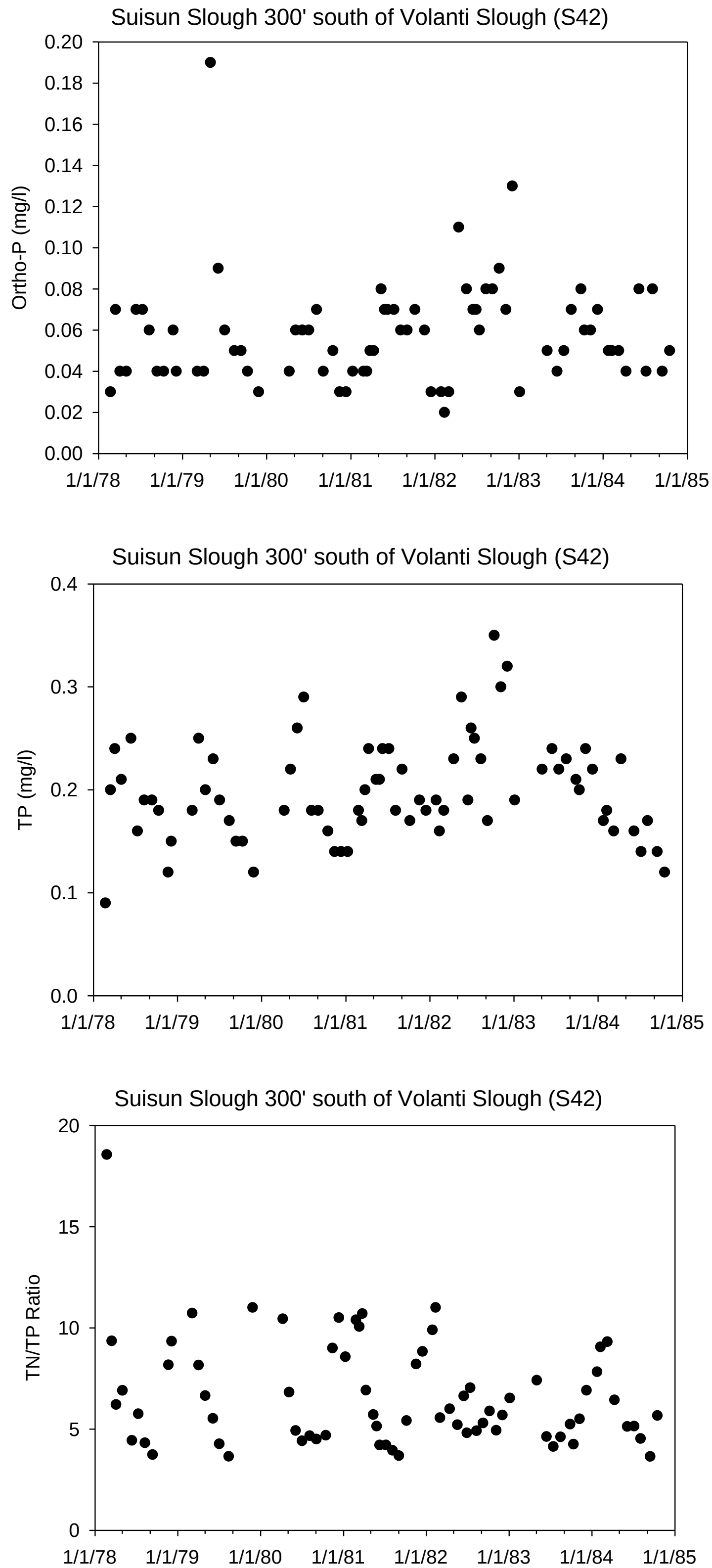


Figure 6-5 Observed orthophosphate, total phosphorus concentrations and TN/TP ratios in Suisun Slough (Source: BDAT).

More recently, over 2000–2011, nutrient concentrations have also been measured in the receiving waters of the FSSD discharge in several tributary sloughs within Suisun Marsh. These include a total of 8 stations, located in Boynton Slough (4 stations), Peytonia Slough (2 stations), Sheldrake Slough (1 station) and Chadbourne Slough (1 station; Table 6-2). Concentrations at these stations are discussed below and compared to the previous measurements collected during the 1978–1985 period in Suisun Slough.

The observed ammonia data in the receiving waters of Boynton Slough generally showed concentrations of 0–0.4 mg/l (Figure 6-6). The concentrations were slightly higher than previously observed in Suisun Slough (0–0.3 mg/l). Ammonia concentrations in Peytonia, Sheldrake and Chadbourne Sloughs are generally similar to concentrations in Boynton Slough with a range of 0–0.4 mg/l, with values over 0.4 mg/l occurring in a few instances.

Organic nitrogen concentrations are generally in the range of 0.5–2.0 mg/l in Boynton and Peytonia Sloughs (Figure 6-6). Concentrations in Sheldrake and Chadbourne Slough are slightly lower, in the 0.3–1.5 mg/l range. The range of organic nitrogen concentrations in these sloughs is higher than previously observed in Suisun Slough (0.2–1.0 mg/l).

TKN concentrations generally range from 1–2 mg/l in Boynton Slough and Peytonia Slough and showed a trend of increase in recent years (2000–2011; Figure 6-6). TKN concentrations in Sheldrake and Chadbourne Sloughs are slightly lower, at 0.3–1.5 mg/l. The range of TKN concentrations in Sheldrake and Chadbourne Sloughs are similar to those previously observed in Suisun Slough (0.5–1.4 mg/l).

Relatively high NO_3 concentrations were observed in Boynton Slough at 0–18 mg/l, particularly for stations above and below the FSSD and managed wetland discharges (Figure 6-6). Stations near the mouth showed the lowest concentrations. Nitrate concentrations in other sloughs are somewhat lower (generally below 2 mg/l). Overall, however, nitrate concentrations observed in these tributary sloughs are much higher than previously observed in Suisun Slough (0–0.8 mg/l).

Relatively high ortho-P concentrations of 0.5–4 mg/l were observed in Boynton Slough (Figure 6-7). Concentrations in Peytonia Slough are generally below 1 mg/l. Sheldrake and Chadbourne Slough showed lower concentrations, ranging from 0–0.6 mg/l. Concentrations observed in these sloughs are higher than previously observed in Suisun Slough (0.1–0.35 mg/l).

The observed NO_3 concentrations in sloughs that could be impacted by discharges from FSSD were compared to concentrations at reference sites at First Mallard and Second Mallard (Figure 6-8). The results suggested higher NO_3 concentrations in the receiving water sloughs particularly in Boynton Slough and to a lesser degree in Peytonia Slough than the reference sites. The NO_3 concentrations were highest in Boynton Slough, followed by Peytonia Slough and were lowest in Chadbourne Slough. Higher concentrations in the receiving water sloughs could be due to discharge from FSSD and managed wetlands.

The observed NH_4 concentrations in the receiving water sloughs of Suisun Marsh were compared to concentrations at reference sites. The results suggested higher NH_4

concentrations in the receiving waters than at First Mallard and Second Mallard (Figure 6-9). The higher NH_4 concentrations in the receiving waters can be due to discharge from FSSD and managed wetlands.

The comparison of PO_4 concentrations in the receiving water sloughs to First and Second Mallard similarly suggested higher concentrations in receiving water sloughs than the reference sites (Figure 6-10). PO_4 concentrations were highest in the Boynton Slough, followed by the Peytonia Slough. The PO_4 concentrations in the Sheldrake and Chadbourne Sloughs were similar to the reference sites.

The results suggested that higher nutrient concentrations in the receiving waters could be attributed to discharge from FSSD and the managed wetlands. The lower nutrient concentrations in the Chadbourne Slough are consistent with the observed higher DO concentrations in the Chadbourne Slough.

Table 6-2
Monitoring Stations in Receiving Water of FSSD Discharge in Suisun Marsh
(Source: Regional Water Board, 2011)

Station	Description
C-1(RW1)	Boynton Slough, about 100 feet downstream from the discharge outfall
C-2 (RW2)	Boynton Slough, about 100 feet downstream from Southern Pacific Railroad crossing
C-3 (RW3)	Boynton Slough, 1800 feet downstream from discharge outfall
C-4 (RW4)	Boynton Slough, in the mouth where it enters Suisun Slough
C-5 (RW5)	Mouth of Sheldrake Slough as it enters Suisun Slough
C-6 (RW6)	Peytonia Slough, in the mouth where it enters Suisun Slough
CR1 (RW7)	Peytonia Slough, about 100 feet downstream from railroad crossing
CR2 (RW8)	Chadbourne Slough, about 100 feet downstream from railroad crossing

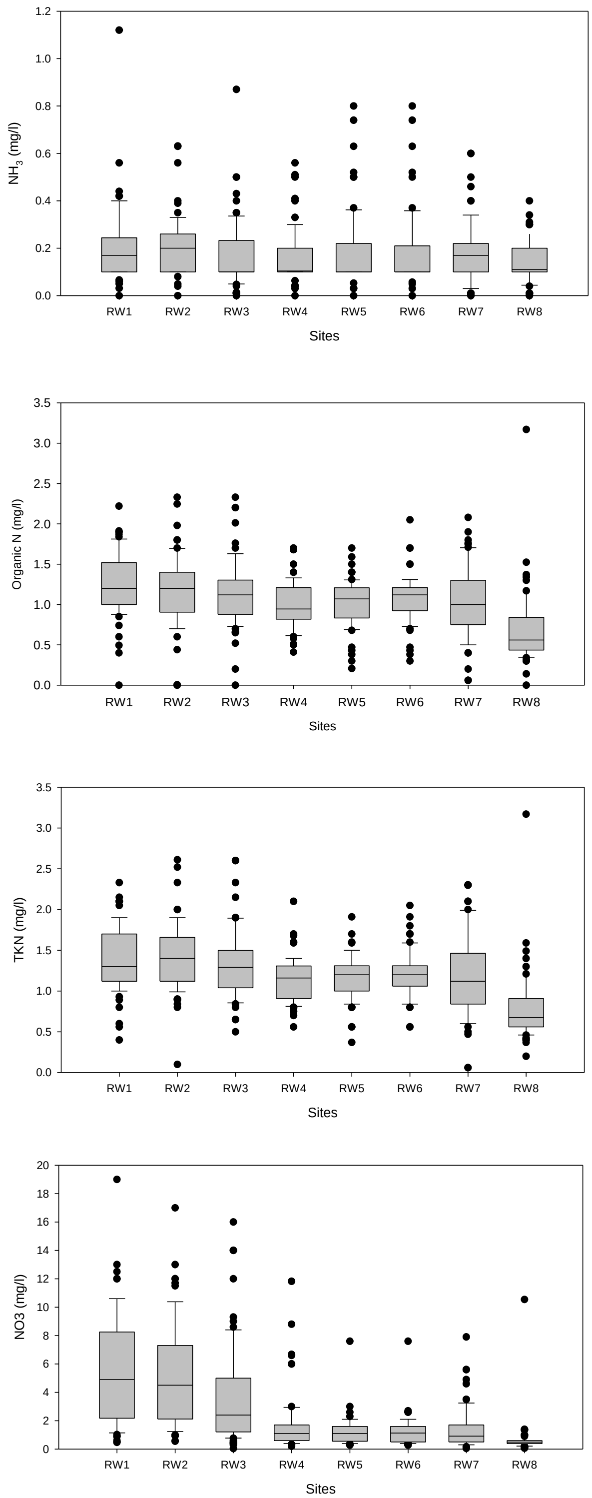


Figure 6-6 **Box plots of observed nitrogen concentrations in the waters of Suisun Marsh that receive discharges from FSSD (Source: Regional Water Board, 2011). The upper and lower ends of the box represent the 75th and 25th percentiles of the data, the line represents the median, and the whiskers represent the 10th and 90th percentiles.**

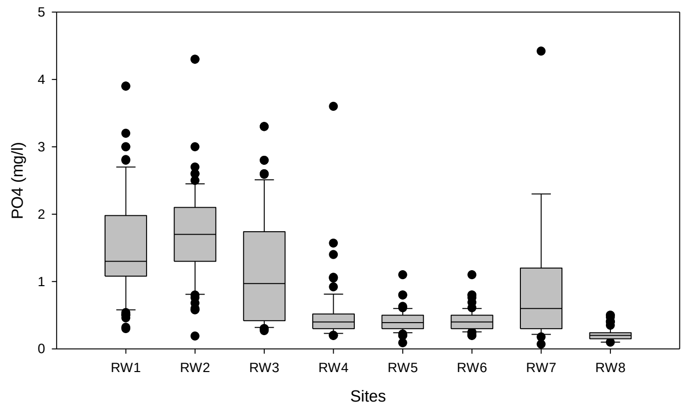


Figure 6-7 **Box plot of observed ortho-P (PO_4) concentrations in the waters of Suisun Marsh that receive discharges from FSSD (Source: Regional Water Board, 2011).**

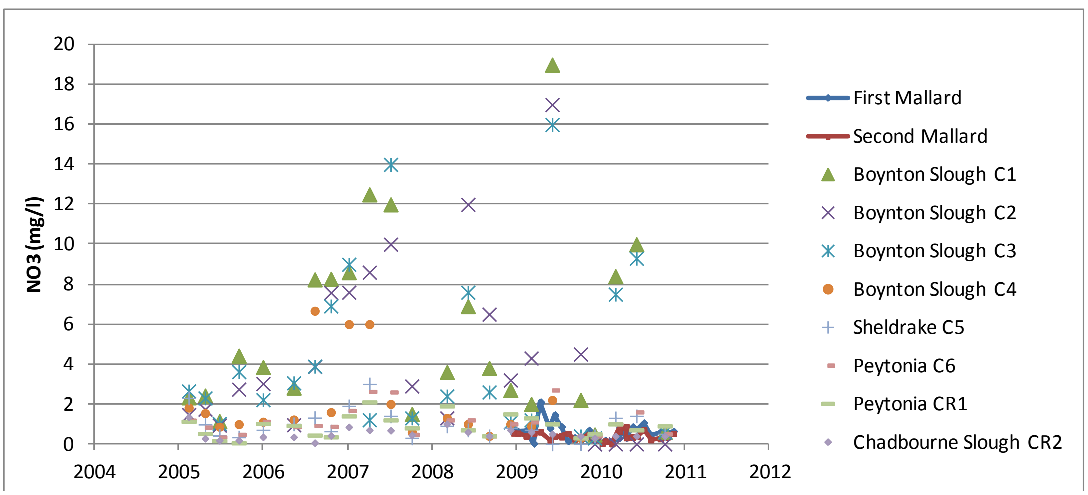


Figure 6-8 **Observed nitrate (NO_3) concentrations in the waters of Suisun Marsh that receive discharges from FSSD compared to concentrations at the First and Second Mallard Sloughs (Source: Regional Water Board, 2012).**

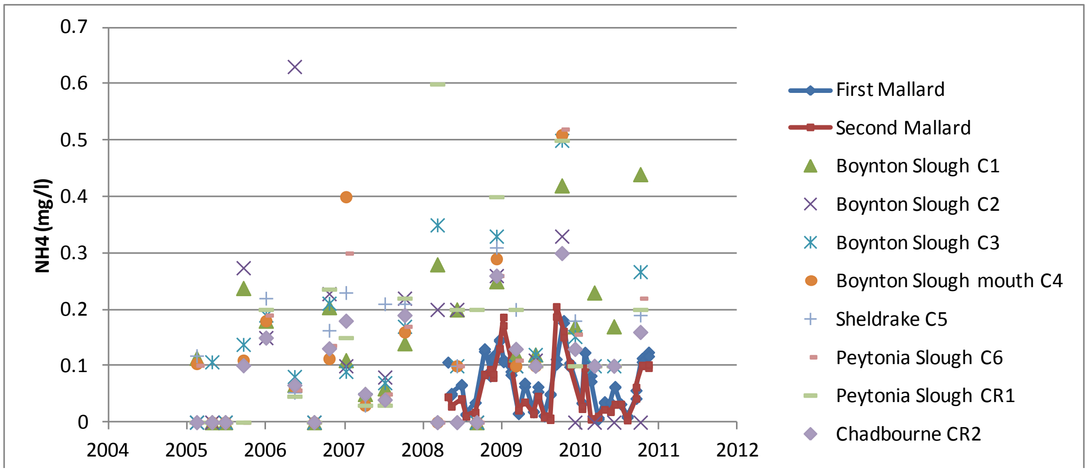


Figure 6-9 **Observed ammonia (NH_4) concentrations in the waters of Suisun Marsh that receive discharges from FSSD compared to concentrations at the First Mallard and Second Mallard Sloughs (Source: Regional Water Board, 2012).**

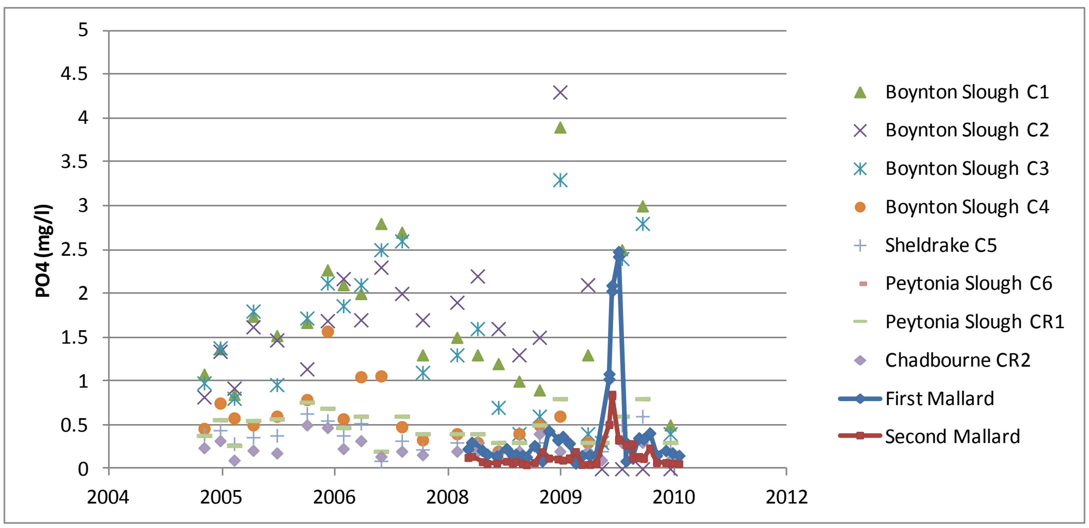


Figure 6-10 **Observed phosphate (PO_4) concentrations in the waters of Suisun Marsh that receive discharges from FSSD compared to concentrations at the First and Second Mallard Sloughs (Source: Regional Water Board, 2012).**

6.3. CONSEQUENCES OF HIGH NUTRIENT CONCENTRATIONS

High nutrient concentrations potentially result in excess growth of phytoplankton, which in turn supports production of OC and could result in low DO concentrations, increasing turbidity, or decrease in water clarity and Secchi depth.

Limited chlorophyll a concentration data are available in Montezuma Slough (station NZ032; Figure 6-11). Since 1998, observed chlorophyll a concentrations at NZ032 have been relatively constant, ranging between 2–5 µg/l, with some elevated concentrations above 5 µg/l (Figure 6-12). Observed chlorophyll a concentrations were higher in the tributary sloughs than the larger slough: Montezuma Slough.

Chlorophyll a concentrations have been measured in the receiving waters of Boynton and Peytonia Sloughs and two other sloughs (Sheldrake and Chadbourne Slough).Chlorophyll a concentrations measured at these sloughs are similar to concentrations measured at the reference sites: the First and Second Mallard Sloughs in the Cutoff Slough region (Figure 6-12). Chlorophyll a concentrations showed a seasonal pattern of higher concentrations in the summer and lower concentrations in winter, and generally range between 2–40 µg/l. These concentrations in the sloughs are considered to be relatively high. Although nutrient concentrations were higher in the receiving water sloughs than the reference sites (First and Second Mallard Sloughs), the observed chlorophyll a concentrations in the receiving water sloughs are within the similar range as in the reference sites. This suggested that nutrient concentrations at the reference sites are sufficient to produce relatively high chlorophyll a concentrations.

Secchi depth measurements are available in the main and tributary sloughs of Suisun Marsh (Figure 6-13). The median values range from 20–30 cm. Montezuma Slough and part of Suisun Slough have higher Secchi depth, at the higher end of this range. Secchi depth in the tributary sloughs (Goodyear, Peytonia, and Boynton Slough) is generally at the lower end (around 20 cm).

Chlorophyll a concentrations have also been measured at the managed wetlands: Wetland 112 and Wetland 123 (Figure 6-14; Bachand et al. 2011). Managed wetlands show extremely high chlorophyll a concentrations of 100–400 µg/l during phytoplankton blooms. For Wetland 123, phytoplankton blooms occurred during September to November and again in February to April. In Wetland 112, phytoplankton blooms lasted for prolonged periods of time. The high observed chlorophyll a concentrations in managed wetlands strongly suggest conditions that favor algae growth such as nutrient enrichment, long residence times and lack of the filter-feeding clams (*Corbula amurensis).*

Periphyton and macrophytes have not been sampled in Suisun Marsh for an evaluation of their spatial and temporal trends to be made.

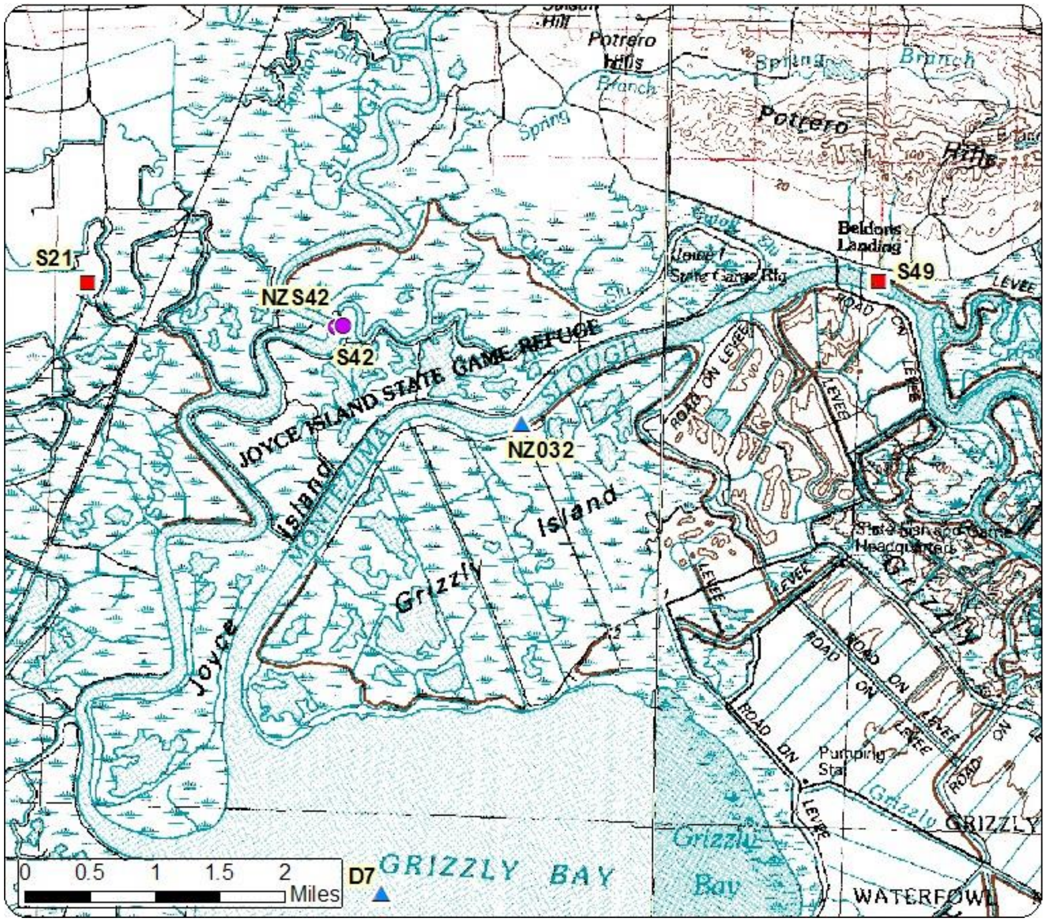


Figure 6-11 Locations of monitoring station NZ032 in Montezuma Slough and S42 in Suisun Slough (Source: BDAT).

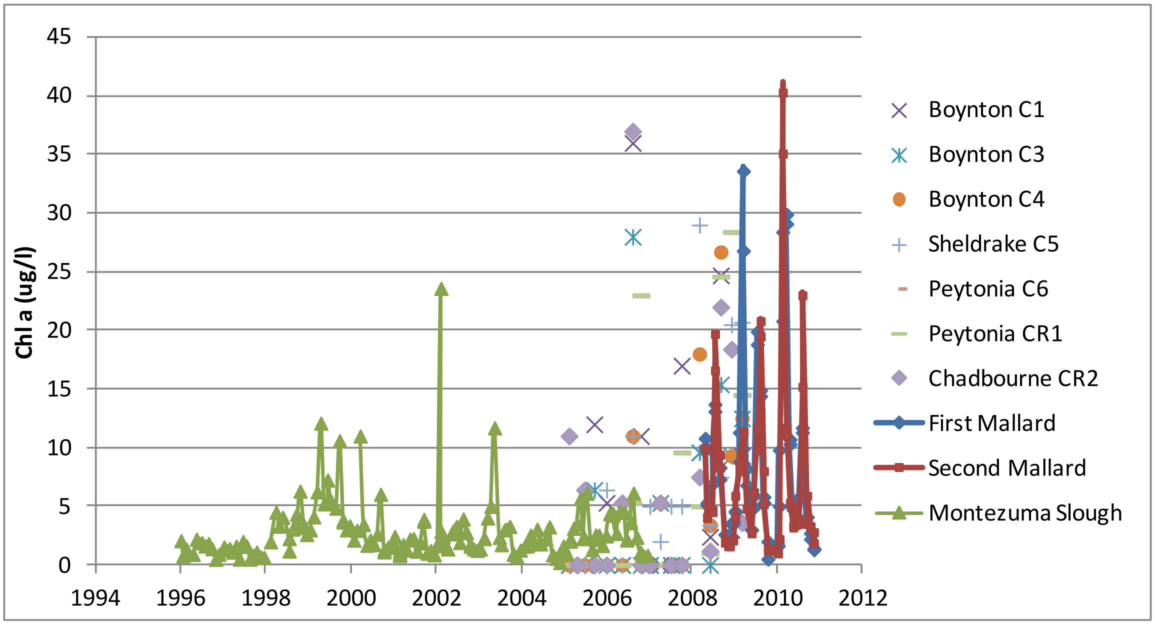


Figure 6-12 **Observed Chlorophyll a concentrations in receiving water sloughs compared to reference sites at First Mallard and Second Mallard and Montezuma Slough.**

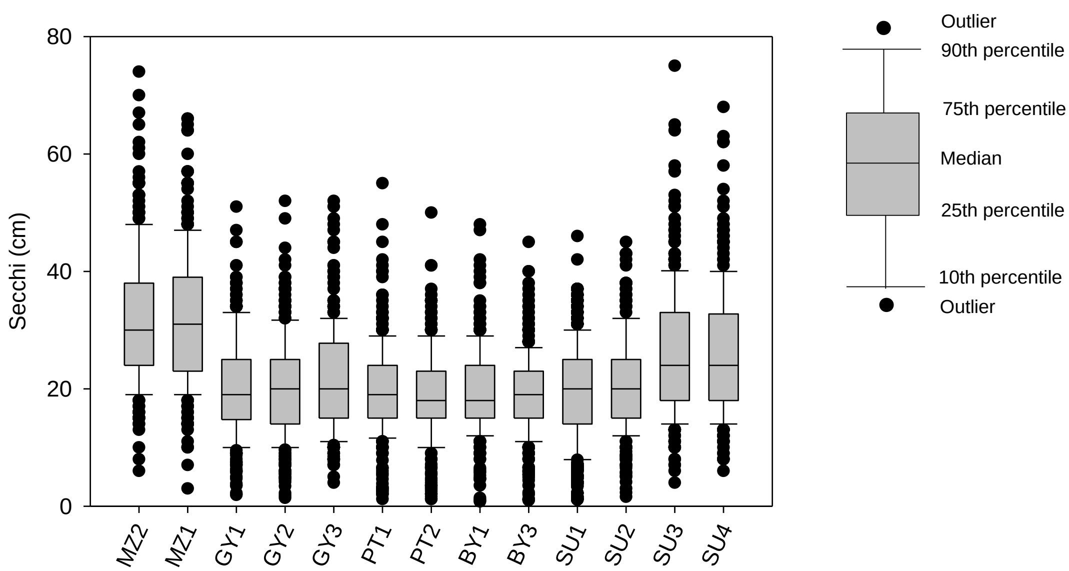


Figure 6-13 **Secchi depth at Montezuma Slough, Goodyear slough, Peytonia Slough, Boynton Slough and Suisun Slough (Source: BDAT).**

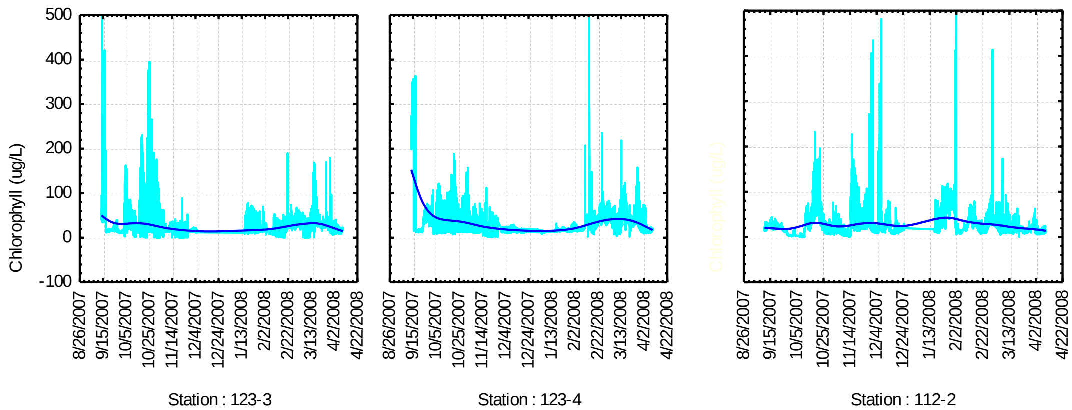


Figure 6-14 Temporal chlorophyll a trends a perimeter stations for wetlands 112 and 123 (Source: Bachand et al., 2010b).

6.4. IMPAIRMENT ASSESSMENT

The only nutrient constituent with a presently established numeric water quality objective in the San Francisco Bay region is ammonia, where the median concentrations are to be below 0.025 mg/l as nitrogen, with maximum values in Central Bay receiving waters not to exceed 0.16 mg/l as nitrogen. The acute ammonia limits for waters where salmonids are absent and chronic ammonia limits for waters with fish in early life stages present can be calculated from the USEPA's 1999 freshwater ammonia criteria document. The acute toxicity limit for total ammonia expressed as nitrogen is calculated based on pH and the chronic toxicity limit is calculated based on pH and temperature. The ammonia concentrations observed in the tributary sloughs are compared to the calculated criterion, and no exceedances of either the acute or chronic toxicity criteria were found.

Although there are no numeric criteria for nitrogen and phosphorus in Suisun Marsh, the high chlorophyll a levels and low dissolved oxygen levels may be indicative of nutrient-related indirect effects. The narrative criteria in the Basin Plan state that waters shall not contain biostimulatory substances in concentrations that promote aquatic growths to the extent that such growths cause nuisance or adversely affect beneficial uses. Irregular and extreme levels of chlorophyll a or phytoplankton blooms may indicate exceedances of this objective and require investigation. Dodds et al. (1998) suggested a concentration of 1.5 mg N/L and 0.075 mg P/L to be the mesotrophic-eutrophic boundary for freshwater streams. A boundary for impaired and potentially impaired water bodies due to nutrients was found to be 10–25 µg/l of planktonic chlorophyll a in freshwater lakes and reservoirs, and 100–150 mg Chl-a/m^2 in benthic algal biomass in streams (Tetra Tech, 2006). For an estuarine setting, the Florida Department of Environmental Protection (FDEP) used a criterion of chlorophyll a concentrations exceeding 20 µg/l for more than 20% of the measurements each year as the level at which a water body would be considered to be impaired by nutrients (EPA 2012). The observed chlorophyll a concentrations of 0–40 µg/l in receiving waters of FSSD, although high, are also in the range observed in the designated reference sites. Given all of this information, impairment by nutrients is not clearly established and needs to be assessed through further data collection and evaluation, and is underway as part of this TMDL.

6.5. SUMMARY

The conceptual model/impairment assessment of nutrients in Suisun Marsh suggests the following:

- Various sources of nutrients may contribute to Suisun Marsh including: Delta outflow which receives nutrients from the Sacramento and San Joaquin Rivers that drain agricultural areas, exchange with nutrient-rich Suisun Bay, inflow from tributaries that drains urban and agricultural areas, atmospheric deposition, discharge from wastewater treatment plant and internal releases from wetland soils.
- Secondary impacts associated with nutrients, such as chlorophyll a, are somewhat elevated in some locations, but are not higher than in designated reference stations. Using current data, impairment by nutrients is not clearly established and needs to be assessed through further data collection and evaluation.
- The only nutrient constituent with a presently established numeric water quality objective in the San Francisco Bay region is ammonia, where the median concentrations are to be below 0.025 mg/l as nitrogen, with maximum values in Central Bay receiving waters not to exceed 0.16 mg/l as nitrogen. The ammonia concentrations observed in the tributary sloughs are compared to the calculated criterion, and no exceedances of either the acute or chronic toxicity criteria were found.
- Evidence of elevated organic carbon and impacts on DO and mercury methylation suggest that excess algal growth in managed wetlands, supported by nutrients, may constitute an impairment of narrative criteria for nutrients in Suisun Marsh.

7. SUMMARY

Suisun Marsh wetlands are listed for impairment for metals, nutrients, organic enrichment/Low DO, and salinity/TDS/chloride (Table 7-1).

Table 7-1
2010 CWA Section 303(d) List of Water Quality Limited Segments (Regional Water Board, 2010)

Type	Name	Pollutant/ Stressor	Potential Sources	TMDL Requirement*	Estimated Size Affected (acres)
Wetland, Tidal	Suisun Marsh Wetlands	Mercury	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Nutrients	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Organic enrichment/ Low DO	Flow regulation/modification Urban runoff/storm sewers	A	66339
		Salinity/TDS/ chloride	Flow regulation/modification Urban runoff/storm sewers	A	66339
River and Stream	Suisun Creek	Low Dissolved Oxygen	Habitat modification Removal of riparian vegetation Stream bank modification/destabilization	A	19 miles
		Temperature, water	Habitat modification Removal of riparian vegetation	A	19 miles

*Those requiring TMDLs (A), being addressed by USEPA approved TMDLs (B), and being addressed by action other than TMDLs (C).

The work presented in this document included an evaluation of site-specific data, scientific literature, and applicable standards to develop a conceptual model of each constituent of interest. Important findings pertaining to each constituent are summarized below.

Organic Carbon

- The managed wetlands are characterized by higher organic carbon concentrations than the adjacent sloughs (2.5–7 times). Sources of organic carbon in managed wetlands include releases from wetland soils, in-situ primary production and organic carbon inputs from sloughs.

- Organic carbon concentrations in managed wetlands increased after fall flood-up and then decreased. Upon release, the managed wetlands discharge sent pulses of high organic carbon water to the adjacent sloughs.
- Although data across wetlands are limited, the nature of vegetation management may affect organic carbon export to sloughs.
- Given the extent of quantification that could be performed with available data, the release from managed wetlands appears to be a dominant pathway of organic carbon loads to the sloughs

Dissolved oxygen:

- The preliminary load estimates presented here, given available data, suggest that the most significant driver of low DO are vegetation and water management activities in the managed wetlands. Discharges from the managed wetlands result in releases of low DO water, as well as water containing high concentrations of organic carbon. These can be directly linked to low DO in adjacent small sloughs. Inputs of BOD from tributaries and the wastewater treatment are also contributors, although to a lesser degree than the managed wetlands. Limited mixing in small sloughs further exacerbates the low DO problem.
- For all tidal waters above the Carquinez Bridge, the applicable water quality objective for DO is 7 mg/l. DO concentrations at several sloughs monitored are below 7 mg/l for over 50% of the time (Goodyear, Peytonia and Boynton Sloughs) and are impaired by low DO. DO concentrations measured at Montezuma and Suisun sloughs showed occasional low concentrations below 7 mg/l and are also considered as impaired by low DO although to a lesser degree.
- The current DO standard in the Basin Plan may be updated to reflect hydrologic conditions in the wetlands and sloughs of Suisun Marsh because it is known that even relatively undisturbed sloughs in the interior of the marsh do not attain this target all of the time.

Mercury:

- Higher MeHg concentrations were found in managed wetlands than other habitats. The managed wetlands are characterized by the highest level of reactive Hg(II) and methylation potential. The drying and wetting regime, high organic carbon and low DO concentrations in managed wetlands promote formation of reactive Hg(II) and methylmercury production.
- Elevated Hg concentrations in silversides above wildlife criteria of fish tissue Hg were found in the Suisun Slough and Cutoff Slough, suggesting impairment of Suisun Marsh by mercury.

Salinity:

- Salinity in Suisun Marsh is strongly affected by Delta outflow, Suisun Marsh Salinity Control Gates, tidal exchange with Suisun Bay, local creek inflows and the managed wetlands.
- The management of wetlands alters salinity through flushing saline water from wetland soils to sloughs.
- Overall, salinity appears to be within range in the larger sloughs, with occasional exceedances limited to smaller sloughs. The frequency of exceedances where they occur are relatively small. For the purpose of the current TMDL, given the larger-scale efforts at managing salinity in Suisun Bay by the State Water Resources Control Board, the salinity appears to not be a significant impairment under current targets.

Nutrients:

- Observed data in the receiving water of FSSD suggested elevated concentrations above reference sites of First and Second Mallard, and similar concentrations of chlorophyll a to the reference sites. The observed chlorophyll a concentrations of 0–40 µg/l in receiving water of FSSD and the reference sites suggested possible impairments by the nutrients.
- The review of data for the nutrient conceptual model highlights the need for a systematic sampling at key locations in the marsh (major tributaries, sloughs, and selected managed wetlands). Such sampling will provide the basis for a quantitative assessment of nitrogen and phosphorus loads to the marsh.
- The only nutrient constituent with a presently established numeric water quality objective in the San Francisco Bay region is ammonia, where the median concentrations are to be below 0.025 mg/l as nitrogen, with maximum values in Central Bay receiving waters not to exceed 0.16 mg/l as nitrogen. The ammonia concentrations observed in the tributary sloughs are compared to the calculated criterion, and no exceedances of either the acute or chronic toxicity criteria were found.
- Evidence of elevated organic carbon and impacts on DO and mercury methylation suggest that excess algal growth in managed wetlands, supported by nutrients, may constitute an impairment of narrative criteria for nutrients in Suisun Marsh.

8. REFERENCES

Alpers, C., C. Eagles-Smith, C. Foe, S. Klasing, M. Marvin-DiPasquale, D. Slotton, and L. Windham-Myers. 2008. Mercury conceptual model. Sacramento (CA): Delta Regional Ecosystem Restoration Implementation Plan.

Alpine, A.E., and J.E. Cloern,.1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary: Limnology and Oceanography37:946–955.

Bachand, P.A.M., D. Gillenwater, S. Siegel and S. Prentice. 2010a. Recommendations to reduce the hydrologic impacts of managed wetlands in Suisun Marsh, CA.

Bachand, P.A.M., S.W. Siegel, D. Gillenwater, J. Fleck, B. Bergamaschi, W. Horwath. 2010b. Water quality impacts of wetlands managed for waterfowl on Suisun Marsh, CA and recommended management practices to reduce the impacts.

Cappiella K, Malzone C, Smith R, Jaffee B. 2001. Historical Bathymetric Change in Suisun Bay 1867–1990. Available at: http://sfbay.wr.usgs.gov/access/suisunbay/bathy/introduction.html

California Department of Fish and Game (CDFG). 2008. Ecosystem Restoration Program (ERP) Conservation Strategy for Stage 2 Implementation. Sacramento-San Joaquin Delta and Suisun Marsh and Bay Planning Area.

Central Valley Regional Water Quality Control Board (CVRWQCB). 2008. Amendments to the water quality control plan for the Sacramento River and San Joaquin River basins for the control of Methylmercury and total mercury in the Sacramento-San Joaquin Delta estuary. Staff report. Draft report for public review.

Cooke, J., C. Foe, S. Stanish, P. Morris. 2004. Cache Creek, Bear Creek, and Harley Gulch TMDL for Mercury. Regional Water Quality Control Board Central Valley Region staff report. Rancho Cordova, CA. 120 p.

Davis, J.A., L.J. McKee, J.E. Leatherbarrow, and T.H. Daum. 2000. Contaminant loads from stormwater to coastal waters in the San Francisco Bay Region. Comparison to other pathways and recommended approach for future evaluation. San Francisco Estuary Institute, Richmond, CA.

Davis, J.A., K. Abu-Saba, A.J. Gunther. 2001. Technical report of the sources, pathways, and loadings workgroup. San Francisco Estuary Institute, Richmond, CA.

Davis, J.A., D. Yee, J.N. Collins ,S.E. Schwarzbach, and S.N. Luoma. 2003. Potential for increased mercury accumulation in the estuary food web. San Francisco Estuary 13 and Watershed Science [online serial]. Vol 1, Issue 1 (October 2003), Article 2. *http://respositories.cdlib.org/jmie/sfews/vol1/iss1/art4*

Department of Fish and Game (DFG) and Suisun Resource Conservation District (SRCD). 2005. Conceptual Model for Managed Wetlands in Suisun Marsh. Initial Draft.

Downing, B.D., B.A. Bergamaschi, T.E.C. Kraus, E. Beaulieu and F. Anderson. 2010. Appendix F. Suisun Marsh DOM Report. in Strategy for Resolving MeHg and Low Dissolved Oxygen Events in Northern Suisun Marsh. SWRCB #06-283-552-0. Association of Bay Area Governments.

Department of Water Resources (DWR). 1999 Suisun Marsh Monitoring Program Reference Guide.

Department of Water Resources (DWR). 2001. Comprehensive Review Suisun Marsh Monitoring Data 1985–1995. Submitted in fulfillment of Suisun Marsh Preservation Agreement and Suisun Marsh Monitoring Agreement.

Department of Water Resources (DWR). 2001. Suisun Ecological Workgroup. Final Report to the State Water Resources Control Board.

Department of Water Resources (DWR) Environmental Services Office. 2003. Suisun Marsh monitoring program annual data summary. Water year 2000.

Department of Water Resources (DWR). 2005. Mercury Water Quality Conceptual Model. *http://podium.water.ca.gov/suisun/dataReports/SMTCmodel/MeHgCMNarrativeV2.pdf*

Department of Water Resources (DWR) Division of Environmental Services. 2007. Restoration plan for the Blacklock restoration project. Suisun Marsh, Solano County, California SRCD Ownership #635.

Dugale, R.C., F.P. Wilkerson, V.E. Hogue, and A. Marchi. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuarine Coastal and Shelf Science 73: 17–29. Enright, C., and S. D. Culberson. 2009. Salinity trends, variability, and control in the northern reach of the San Francisco Estuary. San Francisco Estuary and Watershed Science. 7(2): 1–28.

Enright, C., C. Enos, A. Mueller, and B.A. Bergamaschi. 2009. Suisun Marsh Water Quality: Mercury, Organic Matter, and Scalar Transport.

Feyrer, F., Nobriga, M. L., & Sommer, T. R. (2007). Multidecadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. Canadian Journal of Fisheries and Aquatic Sciences, 64(4), 723–734.

Feyrer, F., Newman, K., Nobriga, M., & Sommer, T. (2011). Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. Estuaries and Coasts, 34(1), 120–128.

Foe, C. 2003. Mercury mass balance for the freshwater Sacramento-San Joaquin Bay-Delta estuary (Task 1A). 35 p. Available at: *http://Loer.tamug.tamu.edu/calfed/Report/DraftFinal/Task%201A.pdf*

Foe, C., S. Louie, and D. Bosworth. 2008. Task 2. Methyl mercury concentrations and loads in the Central Valley and Freshwater Delta.

Gill, G. 2008. Calfed Mercury Project Task 3- Atmospheric Mercury Deposition Studies.

Gribsholt, B., H. T. S. Boschker, E. Struyf, M. Andersson, A. Tramper, L. De Brabandere.2005. Nitrogen processing in a tidal freshwater marsh: A whole-ecosystem 15 N labeling study. *Limnology and Oceanography* 50:1945–1959.

Heim, W.A., K. Coale, and M. Stephenson. 2003. Assessment of Ecological and Human Health Impacts of Mercury in the Bay-Delta watershed. CALFED Bay-Delta Mercury Project Draft Final Report. 36 p.

Heim, W.A., M. Stephenson, B. Hughes, A. Bonnema, and K. Coale. 2008a. Calfed Mercury Project. Task 5.3a. Methylmercury loading studies in Delta Wetlands. Sycamore Slough and Suisun Marsh.

Heim, W.A., K. Coale, and M. Stephenson. 2008b. Methyl and total mercury spatial and temporal trends in surficial sediments of the San Francisco Bay-Delta. Assessment of Ecological and Human Health Impacts of Mercury in the Bay – Delta Watershed. Calfed Bay-Delta Mercury Project Final Report.

Heim, W.A., M. Stephenson, W. Piekarski, A. Byington, and A. Newman. 2010. Appendix E. in Strategy for resolving MeHg and low dissolved oxygen events in northern Suisun Marsh. SWRCB agreement #06-283-552-0. Association of Bay Area Governments.

Hurley, J.P., J.M. Benoit, C.L. Babiarz, M.M. Shafer, A.W. Andren, J.R. Sullivan. 1995. Influences of Watershed Characteristics on Mercury Levels in Wisconsin Rivers. Environmental Science and Technology 29: 1867–1875.

Jaffe B., R. Smith, and L. Zink. 2001. Introduction to sedimentation changes in San Pablo Bay 1856–1983. Available at: *http://sfbay.wr.usgs.gov/access/sanpablobay/bathy/intro.html.*

Jaffe, R., D.M. McKnight, N. Maie, R. Cory, W.H. McDowell, and J.L. Campbell. 2008. Spatial and temporal variations in DOM composition in ecosystems: The importance of long-term monitoring of optical properties. Journal of Geophysical Research, 113:G04032, doi:10.1029/2008JG000683.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel and T. J. Vendlinski. (1995). Isohaline position as a habitat indicator for estuarine populations. Ecological Applications, 5: 272–289.

Kimmerer, W. and S. Monismith. (1992). An Estimate of the Historical Position of 2PPT Salinity in the San Francisco Bay Estuary. Issue Paper prepared for the fourth technical workshop on salinity, flows, and living resources of the San Francisco Bay/Delta Estuary. August 1992. Available online at: http://www.calwater.ca.gov/Admin_Record/C047938.pdf.

Kimmerer, W. J., Gross, E. S., & MacWilliams, M. L. (2009). Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume?. Estuaries and Coasts, 32(2), 375–389.

Marvin-DiPasquale, M., and M.H. Cox. 2007. Legacy mercury in Alviso Slough, South San Francisco Bay, California: Concentration, speciation and mobility. U.S. Geological Survey, Open-File Report 2007–1240, 98p.

Marvin-DiPasquale M.C., and J.L. Agee. 2003. Microbial mercury cycling in sediments of the San Francisco Bay-Delta. Estuaries. 26(6): 1517–1528.

Marvin – DiPasquale, M.C., J.L. Agee, R.M. Bouse, and B.E. Jaffe. 2003. Microbial cycling of mercury in contaminated pelagic and wetland sediments of San Pablo Bay, California. Environmental Geology. 43: 260–267.

Massera, P. 2008. Suisun Marsh Program Overview. Prepared for: State Water Resources Control Board.

Matern, Scott A., L. Meng, and P. B. Moyle. 1999. Trends in fish populations of Suisun Marsh, January 1998–December 1998. Annual report prepared for Contract 94-6036494 B-81568, California Department of Water Resources, Sacramento, California. 53pp.

McKnight, D.M., E.W. Boyer, P.K. Westerhoff, P.T. Doran, T. Kulbe, and D.T. Andersen. 2001. Spectrofluorometric characterization of dissolved organic matter for indication of precursor organic material and aromaticity. Limnology and Oceanography, 46:38–48.

Meng, Lesa, P.B. Moyle, and B. Herbold. 1994. Changes in abundance and distribution of native and introduced fishes of Suisun Marsh. Transactions of the American Fisheries Society. 123: 498–507.

Mueller-Solger, A., and B. Bergamaschi. 2005. Conceptual Model: Organic Matter in Suisun Marsh.

O'Rear, T.A., and P.B. Moyle. 2010. Trends in fish populations of Suisun Marsh January 2009 – December 2009. California Department of Water Resources.

Raymond, P. A. and J.E. Bauer. 2001. DOC cycling in a temperate estuary: A mass balance approach using natural ^{14}C and ^{13}C isotopes. Limnology and Oceanography 46(3): 655–667.

Rudd, J.W.M. 1995. Sources of methylmercury to freshwater ecosystems. A review. Water Air and Soil Pollution 80: 697–713.

RWQCB, 2007. San Francisco Bay Basin (Region 2) Regional Water Quality Control Plan (Basin Plan). California Regional Water Quality Control Board, San Francisco Bay Region. Oakland, CA. January.

Schroeter, R., A. Stover, and P.B. Moyle. 2006. Trends in fish populations of Suisun Marsh January 2005–December 2005. California Department of Water Resources.

Schureman , P. 1971. Manual of dissolved organic carbon, harmonic analysis and prediction of tides. US Coast and Geodetic Survey, Washington DC.

Suisun Ecological Workgroup (SEW). 2001. Final Report to the State Water Resources Control Board.

San Francisco Bay Regional Water Quality Control Board (Regional Water Board). 2006. Mercury in San Francisco Bay. Proposed Basin Plan amendment and staff report for revised total maximum daily load (TMDL) and proposed mercury water quality objectives.

San Francisco Bay Regional Water Quality Control Board (Regional Water Board). 2007. 2006 CWA Section 303(d) list of water quality limited segments. *http://www.waterboards.ca.gove/water_issues/programs/tmdl/docs/303dlists2006/epa/state_usepa_combined.pdf.*

San Francisco Bay Regional Water Quality Control Board (Regional Water Board). 2009. Staff Report: Evaluation of water quality conditions for the San Francisco Bay Region. Proposed Revisions to Section 303(d) list.

Siegel, S., P. Bachand, D. Gillenwater, S. Chappell, B. Wickland, O.Rocha, M. Stephenson, W. Heim, C. Enright, P. Moyle, P.Crain, B. Downing, B. Bergamaschi. 2011. Final evaluation memorandum, Strategies for resolving low dissolved oxygen and methylmercury events in northern Suisun Marsh. Prepared for the State Water Resources Control Board, Sacramento, California. SWRCB Project Number 06-283-552-0. May.

Slotton, D.G., S.M. Ayers, T.H. Suchanek, R.D. Weyand, A.M. Liston, C. Asher, D.C. Nelson, and B. Johnson. 2002. The effects of wetland restoration on the production and bioaccumulation of methyl mercury in the Sacramento- San Joaquin Delta, California. CALFED Bay-Delta Program Draft Report. 49p. Available at: *http://Loer.tamug.tamu.edu/calfed/Report/DraftFinal/UCD_Delta_Report. pdf.*

Solano Transportation Authority (STA). 2002. Chapter 8: hydrology and water quality. In Draft Programmatic EIR for the County Transportation Expenditure Plan. J&S 02-176.

Sobczak, W.V., J.E. Cloern, A.D. Jassby, B.E. Cole, T.S. Schraga, and A. Arnsberg. 2005. Detritus fuels ecosystem metabolism but not metazoan food webs in San Francisco Estuary's Freshwater Delta. Estuaries 28 (1): 124 – 137.

Sobczak, W.V. J.E. Cloern, A.D. Jassby, and A.B. Muller-Solger. 2002. Bioavailability of organic matter in a highly disturbed estuary: The role of detrital and algal resources. Proceedings of the National Academy of Sciences 99 (12): 8101–8105.

Stephenson M., C. Foe, G. A. Gill, and K.H. Coale. 2005. Transport, Cycling, and Fate of Mercury and Monomethyl Mercury in the San Francisco Delta and Tributaries: An Integrated Mass Balance Assessment Approach.

St. Louis, V.L., J.W.M. Rudd, C.A. Kelly, K.G. Beaty, N.S. Bloom, and R.J. Flett. 1994. Importance of wetlands as sources of methyl mercury to boreal forest ecosystems. Canadian Journal of Fishery and Aquatic Science 51: 1065–1076.

St. Louis, V.L., J.W.M. Rudd, C.A. Kelly, K.G. Beaty, R.J. Flett, and N.T. Roulet. 1996. Production and loss of methylmercury and loss of total mercury from boreal forest catchments containing different types of wetlands. Environmental Science & Technology 30: 2719–2729.

State Water Resources Control Board (SWRCB). 2000. Revised Water Right Decision 1641.

Steding, D. J. and A.R. Flegal. 2002. Mercury concentrations in coastal California precipitation: Journal of Geophysical Research 107(D24): 4764, doi: 10.1029/2002JD002081.

Tsai, P. and R. Hoenicke. 2001. San Francisco Bay Atmospheric Deposition Pilot Study. Part 1. Mercury. San Francisco Estuary Institute. Report is available at: *http://www.sfei.org/rmp/reports/air_dep/mercury_airdep/ADHg_FinalRpt.pdf.*

Yee, D., J.E. Leatherbarrow, and J.A. Davis. 2001. Fairfield-Suisun/South S.F. Bay Trace Organic Contaminants in Effluent Study. SFEI, Richmond, CA.

Yee, D., J. Collins, L. Grenier, J. T. Akekawa, S. Schwarzbach, M. Marvin-DiPasquale, D. Krabbenhoft, and J. Evens. 2005. Mercury and methylmercury processes in North San Francisco Bay tidal wetland ecosystems. Annual report project #ERP-02D-P64, California Bay-Delta Authority. *http://www.calwater.ca.gov/content/erp_calfed_mercury_2005_project_annual_reports_content.asp.*

Wilkerson, F.P., R. C. Dugdale, V.E. Hogue, and A. Marchi. 2006. Phytoplankton blooms and nitrogen productivity in San Francisco Bay. Estuaries and Coasts 29(3): 401–416.

U.S. Environmental Protection Agency (USEPA) (1995) Water Quality Standards for Surface Waters of the Sacramento River, San Joaquin River, and San Francisco Bay and Delta of the State of California, Federal Register, Volume 60, No. 15.

U.S. Environmental Protection Agency (USEPA) (2012) Water Quality Challenges in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary: EPA’s Action Plan.