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Influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay

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Time series of salinity and suspended-solids concentration measured at four locations and vertical profiles of salinity and suspended-solids concentration measured during 48 water-quality cruises from January 1993 to September 1997 are analyzed to describe the influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay, California. Estuarine turbidity maxima form when salinity is present but they are not associated with a singular salinity. Bottom topography enhances salinity stratification, gravitational circulation and estuarine turbidity maxima formation seaward of sills. The spring/neap tidal cycle affects locations of estuarine turbidity maxima. Salinity stratification in Carquinez Strait, which is seaward of a sill, is greatest during neap tides, which is the only time when tidally averaged suspended-solids concentration in Carquinez Strait was less than that observed landward at Mallard Island. Spring tides cause the greatest vertical mixing and suspended-solids concentration in Carquinez Strait. Therefore, surface estuarine turbidity maxima always were located in or near the Strait (seaward of Middle Ground) during spring tide cruises, regardless of salinity. During neap tides, surface estuarine turbidity maxima always were observed in the landward half of the study area (landward of Middle Ground) and between 0–2 practical salinity units.

1. INTRODUCTION

A feature of many estuaries is a longitudinal maximum of suspended-solids concentration (SSC), called an estuarine turbidity maximum (ETM). Several processes can contribute to the formation of ETMs (Jay and Musiak, 1994). Gravitational circulation or tidal asymmetry of velocity and SSC can cause convergent fluxes of suspended solids and form ETMs (Hamblin, 1989; Jay and Musiak, 1994; Wolanski et al., 1995). Schubel and Carter (1984) state that the origin and maintenance of ETMs once was attributed to flocculation, but that nontidal (gravitational) circulation primarily is responsible. A cycle of local deposition, bed storage, and resuspension also can contribute to the formation of ETMs (Hamblin, 1989; Uncles et al., 1994; Wolanski et al., 1995; Grabemann et al., 1997). Suppression of turbulence by salinity stratification increases settling and trapping of fine sediment and may be a more effective trapping mechanism than gravitational circulation (Hamblin, 1989; Geyer, 1993).

Because gravitational circulation and stratification are dependent on the salinity field, ETMs often are located near a particular salinity. In the Tamar Estuary, an ETM is observed at the freshwater-saltwater interface or landward, and in the Weser Estuary an ETM is observed at 6 practical salinity units (psu) (Grabemann et al., 1997). While ETMs typically are located at low salinities, they also can be located at much greater salinities. ETMs in Lorient and Vilaine Bays are at salinities of about 18 psu and 25-30 psu, respectively (Le Bris and Glemarec, 1996). Freshwater flow into an estuary affects the salinity field and, therefore, can affect the position of ETMs (Uncles and Stephens, 1993; Grabemann et al., 1997).

ETMs also may be located at longitudinally fixed locations, independent of salinity. Nonlinear interactions of first-order tides in channels with constrictions or decreasing depth in the landward direction may induce landward residual currents and convergence in part of the water column (Ianniello, 1979), which results in a fixed, topographically controlled ETM (Jay and Musiak, 1994). Wind-wave resuspension in shallow water and ebbtide transport to deeper channels also can create fixed locations for ETMs, such as in the Tay Estuary (Weir and McManus, 1987).

Data from synoptic field measurements confirm the existence of an ETM in Suisun Bay (Figure 1), the most landward subembayment of northern San Francisco Bay (Meade, 1972; Conomos and Peterson, 1977; Arthur and Ball, 1978). Ten synoptic measurements collected at high slack tide during spring and summer from 1974 to 1977 indicate that an ETM typically exists in the surface salinity range of 1-6 psu (Arthur and Ball, 1978). ETM formation was attributed to gravitational circulation and flocculation. The 2-psu bottom isohaline is used as a habitat indicator to regulate freshwater flow to the Bay because it is believed to be an easily measured indicator of the location of the ETM and a salinity preferred by many estuarine species (Jassby et al., 1995).

The purpose of this paper is to describe the influence of salinity, topography, and tides on the locations of ETMs in northern San Francisco Bay. The reasons for revisiting the issue of locations of ETMs in northern San Francisco Bay include availability of large data bases of vertical profiles and time series of salinity and SSC, evaluating the applicability of previously described ETM formation mechanisms, and improving the scientific basis for regulation of freshwater flow to the Bay.

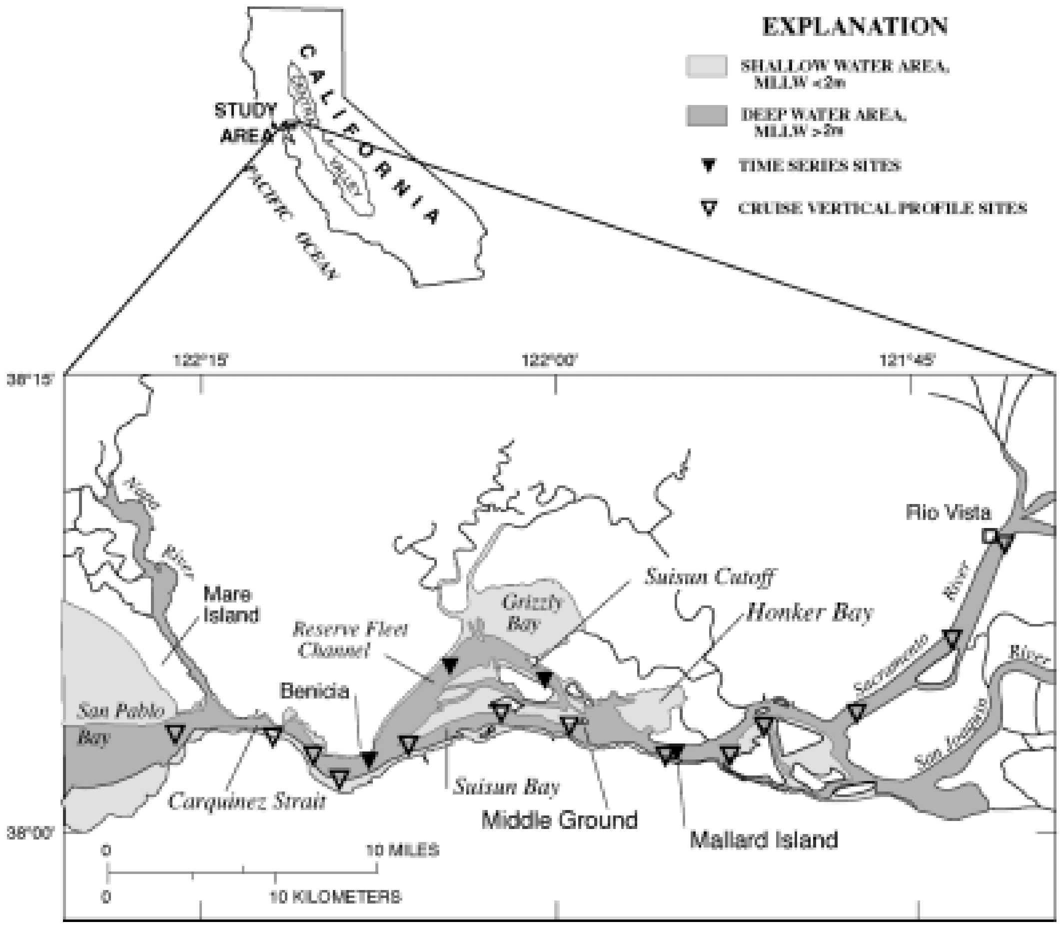

Figure 1. Northern San Francisco Bay, study area. MLLW, mean lower low water.

2. STUDY AREA

The region containing ETMs in northern San Francisco Bay is shown in Figure 1. Suisun Bay is the most landward subembayment of northern San Francisco Bay. The Sacramento and San Joaquin Rivers deliver freshwater to Suisun Bay, primarily during the winter rainy season and during the spring snowmelt and reservoir releases. The annual discharge of the Sacramento River is about six times greater than that of the San Joaquin River. Precipitation is negligible during late spring and summer. Suisun Bay is a partially mixed estuary that has extensive areas of shallow water that are less than 2 m deep at mean lower-low water (MLLW), including the subembayments of Grizzly and Honker Bays. Channels that are about 9-11 m deep are parallel to the southern and northwestern shores and are between Grizzly and Honker Bays. Carquinez Strait is a narrow channel about 18 m deep that connects Suisun Bay to San Pablo Bay, to the rest of San Francisco Bay, and to the Pacific Ocean. Tides are mixed diurnal and semidiurnal and the tidal range varies from about 0.6 m during the weakest neap tides to 1.8 m during the strongest spring tides. Freshwater inflow typically first encounters saltwater in northern San Francisco Bay, defined here as the lower rivers, Suisun Bay, and Carquinez Strait. The salinity range in northern San Francisco Bay is about 0-25 psu and depends on the season and freshwater inflow. Suspended and bed sediment in Suisun Bay is predominately fine and cohesive, except for sandy bed sediment in some of the deeper channels (Conomos and Peterson, 1977). The typical SSC range in northern San Francisco Bay is about 10-300 mg/L and sometimes up to about 1,000 mg/L at an ETM.

3. VERTICAL PROFILE AND TIME-SERIES DATA

Vertical profile and time-series data are used to analyze the influence of salinity, bottom topography, tides, and water column position on observation of ETMs in northern San Francisco Bay. Vertical profiles of SSC and salinity are measured during approximately monthly water-quality surveys of San Francisco Bay (Edmunds et al., 1997). Data are grouped into bins with a 1-m vertical resolution. Sampling sites in northern San Francisco Bay are shown in Figure 1. Cruises typically start near the time of slack before flood in Carquinez Strait and proceed landward (east), ending at Rio Vista a little more than 4 hours later, so the data are not truly synoptic. Data from 48 cruises from January 1993 to September 1997 for which the 2-psu surface isohaline was located in the study area are analyzed in this paper. Bottom salinity at Rio Vista, the most landward site, was less than or equal to 0.13 psu for all but two cruises. Thus, almost all cruises extend landward into virtually freshwater.

In addition to the monthly vertical profile data, time series of SSC at fixed stations have been measured in Suisun Bay. SSC and salinity were measured at 10-minute intervals at a height of 0.6 m above the bed in the Reserve Fleet Channel and Suisun Cutoff in September and October 1995 (J. Cuetara, U.S. Geological Survey, written communication, 1998). SSC is measured at 15-minute intervals at the Benicia Bridge at 1 m and 16 m below MLLW and at Mallard Island 1 m below the water surface and 6 m below MLLW (Buchanan and Schoellhamer, 1998, Figure 1). Data collected at the surface from May to August 1996 are presented in this paper because a large range of salinities was measured as salt returned to Suisun Bay during the period.

Time series of salinity are measured by the National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric Administration, 1998) at 6-minute intervals at the same elevations as SSC measurements at Benicia and by the California Department of Water Resources (DWR) (California Department of Water Resources, 1998) 1 m below the water surface at Mallard Island at 1-hour intervals. The salinity sensor at the bottom of the water column at Benicia failed in mid July 1996. NOAA also measures velocity profiles with an acoustic Doppler current profiler at 6-minute intervals at Benicia and DWR measures water surface elevation at hourly intervals at Mallard Island.

The time-series data were low-pass filtered to remove tidal frequencies and to provide a tidally averaged analysis of salinity and SSC. All low-pass filtering was performed with a Butterworth filter with a cutoff frequency of 0.0271 per hour. The strength of the spring/neap cycle at Benicia was quantified by calculating the low-pass root-mean-squared (RMS) water speed by squaring the measured water velocity 16 m below MLLW, low-pass filtering, and taking the square root. A RMS water-surface elevation at Mallard Island was calculated to quantify strength of the spring/neap cycle. For cruise data, NOAA tidal-current predictions for Carquinez Strait were used to delineate flood and ebb tides and to quantify the spring/neap cycle by taking the mean value of the four predicted maximum flood and ebb current speeds that were temporally centered on each cruise ($\overline{U_{max}}$).

4. RESULTS: CRUISE DATA

Salinity and maximum cruise SSC are related near the water surface but not near the bed in northern San Francisco Bay. Maximum surface SSC, 1 m below the water surface, was located between 0-6 psu at the bottom for 67 percent of the cruises (Figure 2). Maximum SSC 1 m above the bed, however, was located over a wide range of bottom salinity. Only 23 percent of maximum bottom SSC was located between 0-6 psu at the bottom. Similar results were found at both elevations when surface salinity was considered. Seventy-one percent of the cruise data were collected during a predicted flood tide in Carquinez Strait. The effect of this flood tide sample bias is discussed later in this article.

Maximum SSC 1 m above the bed of northern San Francisco Bay, while not related to bottom salinity, is related to longitudinal position in the estuary. Maximum bottom SSC was located in Carquinez Strait during 67 percent of the cruises (Figure 3). Maximum surface SSC, however, was distributed throughout northern San Francisco Bay. Only 27 percent of maximum surface SSC were located in Carquinez Strait. Empirical-orthogonal-function analysis of the cruise data (not shown) produced similar results.

5. RESULTS: TIDALLY AVERAGED TIME-SERIES DATA

During the dry season of spring and summer, when freshwater flows to the estuary decrease, salinity returns to northern San Francisco Bay. Tidally averaged surface salinity at Benicia, the seaward boundary of Suisun Bay, increased from 0 psu in late May to 10 psu in June 1996 (Figure 4). At Mallard Island, the landward boundary of Suisun Bay, tidally averaged surface salinity increased from 0-2 psu in late June 1996.

Tidally averaged surface SSC did not show any maxima associated with a particular tidally averaged salinity as salinity increased in Suisun Bay in 1996

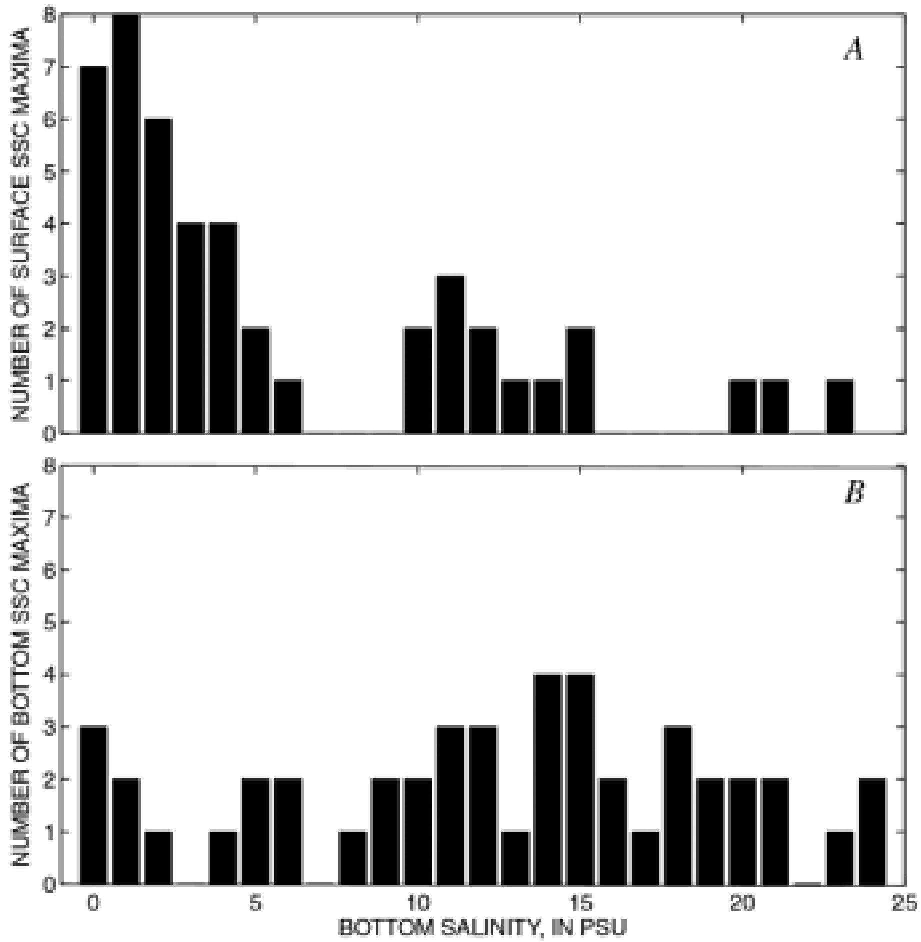

Figure 2. Positions of maximum cruise suspended-solids concentrations (SSC) at the surface *A* and bottom *B*, relative to salinity, northern San Francisco Bay.

(Figure 4). This result differs from the cruise data for which surface ETMs usually were observed between 0-6 psu bottom salinity. This discrepancy is discussed later in this article. Tidally averaged surface SSC almost always was greater at Benicia than at Mallard Island. SSC at Benicia varied with the spring/neap cycle, with minima during neap tides and maxima during spring tides. Tidally averaged SSC was slightly greater at Mallard Island only during weaker neap tides in late May and late June.

Similar results were found near the bed at two sites that are closer together as salinity returned to Suisun Bay after a wet rainy season in 1995. Tidally averaged salinity increased in the Reserve Fleet Channel (seaward site) and Suisun Cutoff (landward site) in October 1995, ranging from about 1-10 psu (Figure 5). Tidally averaged SSC always was greater in the Reserve Fleet Channel than in Suisun Cutoff, varied with the spring/neap cycle at both sites, and did not show any maxima associated with a particular salinity.

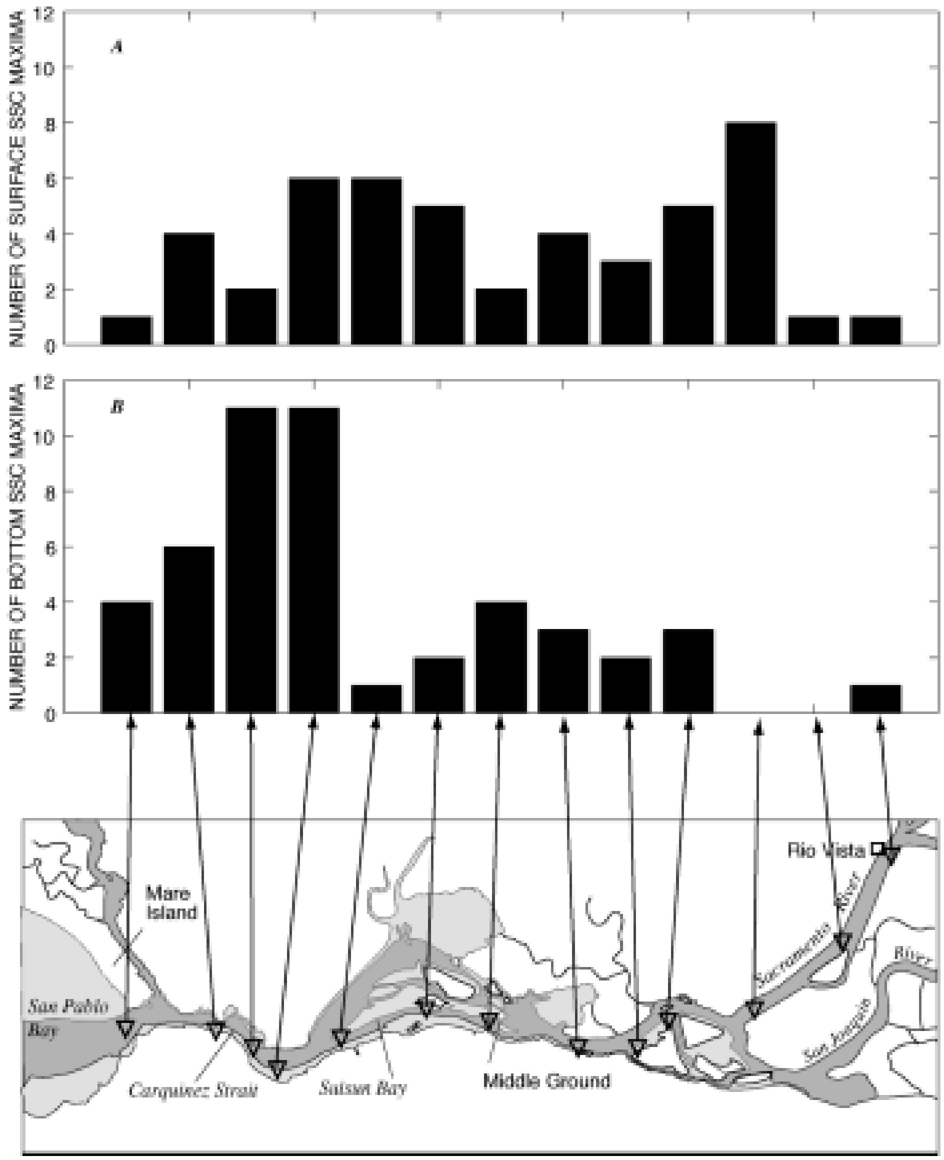

Figure 3. Position of maximum cruise suspended-solids concentration (SSC) at the surface *A* and bottom *B*, relative to sampling site, northern San Francisco Bay.

6. DISCUSSION

SSC maxima in northern San Francisco Bay are not associated with a singular salinity. Cruise data from northern San Francisco Bay indicate that there is an ETM at low salinity (0-6 psu) 1 m below the water surface. This is a larger salinity range for ETM location, however, than is observed in estuaries with a salinity-dependent ETM (Le Bris and Glemarec, 1996; Grabemann et al., 1997). The processes that account for a salinity-dependent ETM, gravitational circulation, salinity stratification, and bed storage, occur in northern San Francisco Bay and are modified by bottom topography and tides.

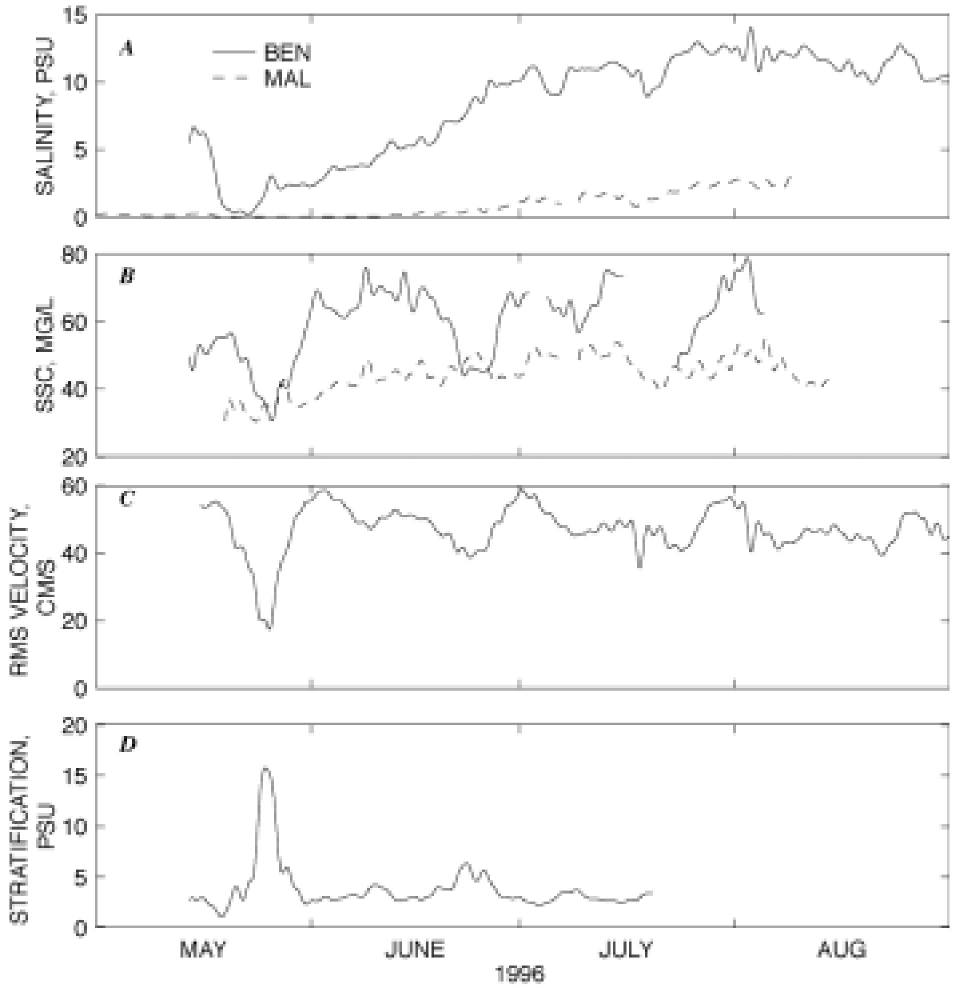

Figure 4. Tidally averaged surface salinity *A* and suspended-solids concentration (SSC) *B* at Benicia and Mallard Island, root-mean-squared (RMS) bottom velocity at Benicia *C*, and tidally averaged salinity stratification at Benicia *D*, northern San Francisco Bay.

6.1. Gravitational circulation

A natural sill is located at the boundary of Carquinez Strait and Suisun Bay slightly landward (east) of the Benicia sampling site. There is a decrease in MLLW depth from 18-11 m in the landward direction at the sill. This topographic control places an upstream limit on gravitational circulation (Jay and Musiak, 1994; Burau et al., 1998) that traps particles and creates an ETM in eastern Carquinez Strait. At the sill, the channel also bifurcates and the width of the southern channel is constricted, which also may limit gravitational circulation (Armi and Farmer, 1986). Sites in Carquinez Strait had the greatest occurrence of SSC maxima at the bottom of the water column for the cruise data (Figure 3). Tidally averaged SSC almost always was greater at Benicia than at Mallard Island as salinity increased in Suisun Bay (Figure 4).

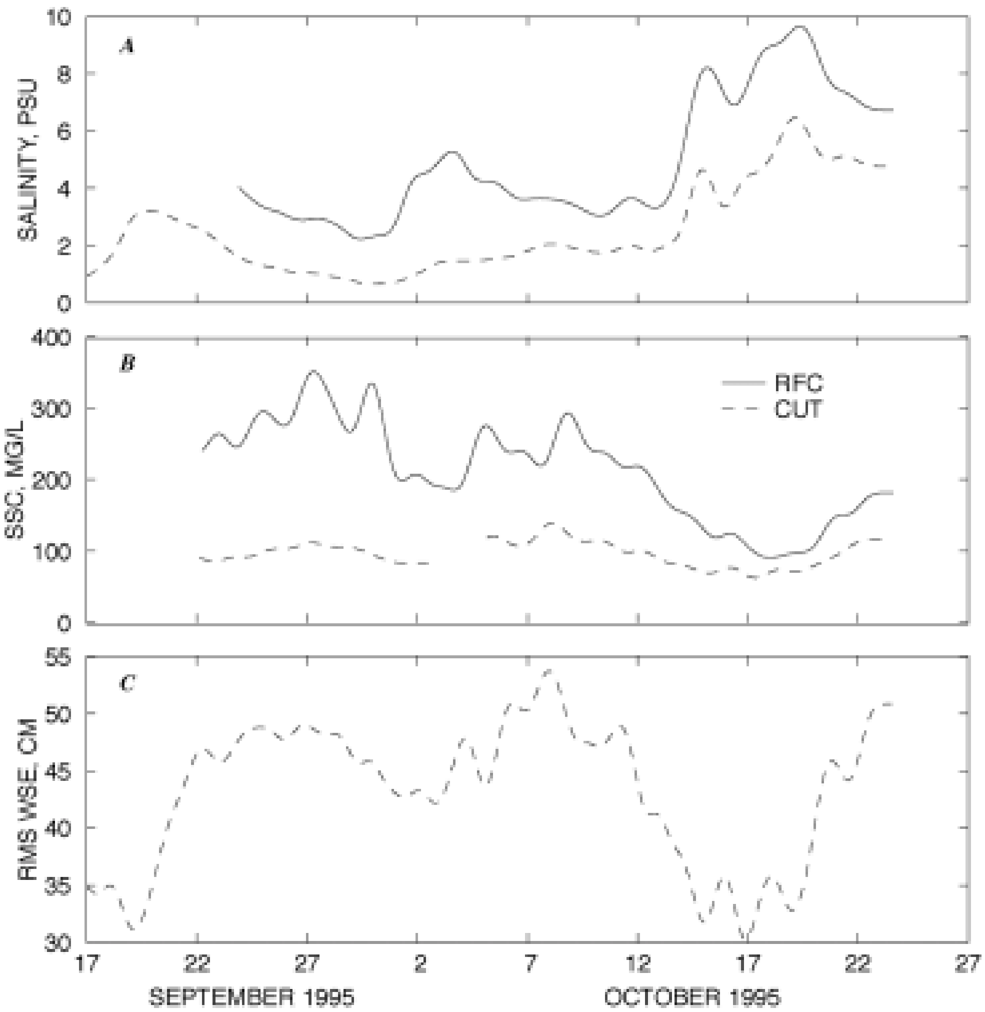

Figure 5. Tidally averaged bottom salinity *A* and suspended-solids concentration (SSC) *B* at the Reserve Fleet Channel and Suisun Cutoff, and root-mean-squared water-surface elevation (RMS WSE) at Suisun Cutoff *C*, northern San Francisco Bay.

Another sill that supports the formation of an ETM in Suisun Bay is between the Reserve Fleet Channel and Suisun Cutoff sites. Two topographic features that place an upstream limit on gravitational circulation at the sill are a decrease in MLLW depth from 9-5 m in the landward direction at the sill and constriction of the channel in Suisun Cutoff (Burau et al., 1998). This topographic control traps particles in the Reserve Fleet Channel. Tidally averaged SSC always was greater in the Reserve Fleet Channel than in Suisun Cutoff as salinity returned to Suisun Bay in 1995 (Figure 5). Gravitational circulation is driven by the longitudinal salinity gradient (Hansen and Rattray, 1965), so these ETMs are dependent on the presence of a nonzero salinity gradient, not a particular salinity.

6.2. Salinity stratification

Turbulence suppression by salinity stratification is most likely to occur in Carquinez Strait, where water depths in the study area are greatest (Burau et al., 1998). Stratification is greatest during neap tides, which reduces vertical mixing, increases deposition, and decreases SSC

(Figure 4). Neap tides are the only times when tidally averaged surface SSC is less at Benicia than at Mallard Island. For example, during a neap tide in late May 1996, tidally averaged stratification of almost 16 psu between surface and bottom measurements (15 m apart) account for the smallest tidally averaged SSC measured at Benicia during the study period. In addition, bottom velocities were negligible during ebb tides during this period (not shown), increasing the duration of slack tide to hours and enhancing deposition. Deposition during neap tides creates a supply of easily erodible sediment on the bed in Carquinez Strait. When tidal energy increases as the subsequent spring tide is approached, this sediment is resuspended and gravitational circulation keeps a portion of the sediment in Carquinez Strait, creating an ETM. Thus, deposition associated with salinity stratification and subsequent resuspension is a contributor to the ETM observed in Carquinez Strait.

6.3. Bed storage

Increased sediment deposition associated with stratification is a source of suspended solids for bed storage in Carquinez Strait, especially at the subtidal time scale during neap tides. On the tidal time scale, slack tide in northern San Francisco Bay typically is only a few minutes in duration, which permits few of the suspended solids to deposit during a slack tide. In addition, the duration of high and low water slack tides in northern San Francisco Bay is symetric. In contrast, high water slack in the Tamar Estuary lasts 2-3 hours, during which time suspended solids deposit on the bed (Uncles and Stephens, 1993). Assymetry of slack tide duration in the Tamar Estuary also helps create an ETM at or landward of the freshwater/saltwater interface, which is not observed in northern San Francisco Bay.

Deposition and erosion cycles are more aligned with the spring-neap cycle than the tidal cycle. About one-half of the variance of SSC is caused by the spring- neap cycle, and SSC lags the spring-neap cycle by about 2 days (Schoellhamer, 1996). The relatively short duration of slack water limits the duration of deposition of suspended solids and consolidation of newly deposited bed sediment during the tidal cycle, so suspended solids accumulate in the water column as a spring tide is approached and slowly deposit as a neap tide is approached. Tidally averaged SSC in northern San Francisco Bay is similar to the spring/neap cycle (Figures 4 and 5). This observation is especially true at Benicia and the Reserve Fleet Channel where stratification and deposition are greatest at neap tide.

Wind-wave resuspension of bed sediment in shallow water subembayments is another topographically controlled source of suspended solids in northern San Francisco Bay. Major subembayments that are less than 2-m deep at MLLW are Grizzly and Honker Bays within Suisun Bay and San Pablo Bay, to the west of Carquinez Strait (Figure 1). An annual cycle of deposition and resuspension begins with a large influx of sediment during winter, primarily from the Central Valley, and much of this material deposits in San Pablo and Suisun Bays (Krone, 1979). Stronger winds during spring and summer cause wind-wave resuspension of bed sediment in these shallow waters and increase SSC (Krone, 1979; Schoellhamer, 1996, 1997). Gravitational circulation in Carquinez Strait transports suspended solids from San Pablo Bay to Suisun Bay (Conomos and Peterson, 1977).

6.4. Tides and surface ETM observation

There commonly is an ETM at low salinities (0–6 psu) near the surface, according to the cruise data (Figure 2), but not according to the tidally averaged data (Figures 4 and 5). Cruise data can be described as the sum of a tidally averaged component and a component representing the instantaneous deviation from the tidally averaged value. Thus, the instantaneous deviation component represents a tidal time-scale process that accounts for this discrepancy.

The cruise data are susceptible to biasing by tidal time-scale processes because 71 percent of the measurements during the cruises were made during a predicted flood tide in Carquinez

Strait. Because of this sampling bias, the difference between the tidally averaged and cruise observations of the surface ETM location could be caused by a slack tide process that reduces SSC in Carquinez Strait or a flood tide process that increases SSC at low salinities.

Salinity-dependence and longitudinal position of the surface ETM observed during cruises is modulated by the spring/neap cycle. During neap tides ($\overline{U_{max}} < 0.98\ m/s$), the surface ETM was located at salinities from 0-2 psu landward of Middle Ground in Suisun Bay (Figure 6). During spring tides ($\overline{U_{max}} > 1.15\ m/s$), the surface ETM was seaward of Middle Ground (toward Mare Island) at salinities from 0.3–20.4 psu. Thus, the process that accounts for the difference in the surface ETM observations between the tidally averaged and cruise data is more pronounced during neap tides than during spring tides. Whether or not the spring/neap modulation is present during ebb tides cannot be determined from Figure 6 because no cruises were conducted during neap ebb tides.

One process that could account for the difference between the tidally averaged and cruise observations of the surface ETM location is baroclinically driven pulses at the beginning of flood tide where the longitudinal baroclinic forcing is greatest (Burau et al., 1998; Schoellhamer and Burau, 1998). This location is where the longitudinal salinity gradient is greatest, which usually is where salinity is 0-2 psu. Pulses increase bed shear stress and vertical mixing and, thus, surface SSC. These pulses are strongest during neap tides and have been observed to cause tidally averaged landward transport of suspended solids, despite seaward water transport at mid-depth at Mallard Island during neap tides (Tobin et al., 1995). The water-quality cruise data usually are collected during flood tide and, therefore, soon after a pulse.

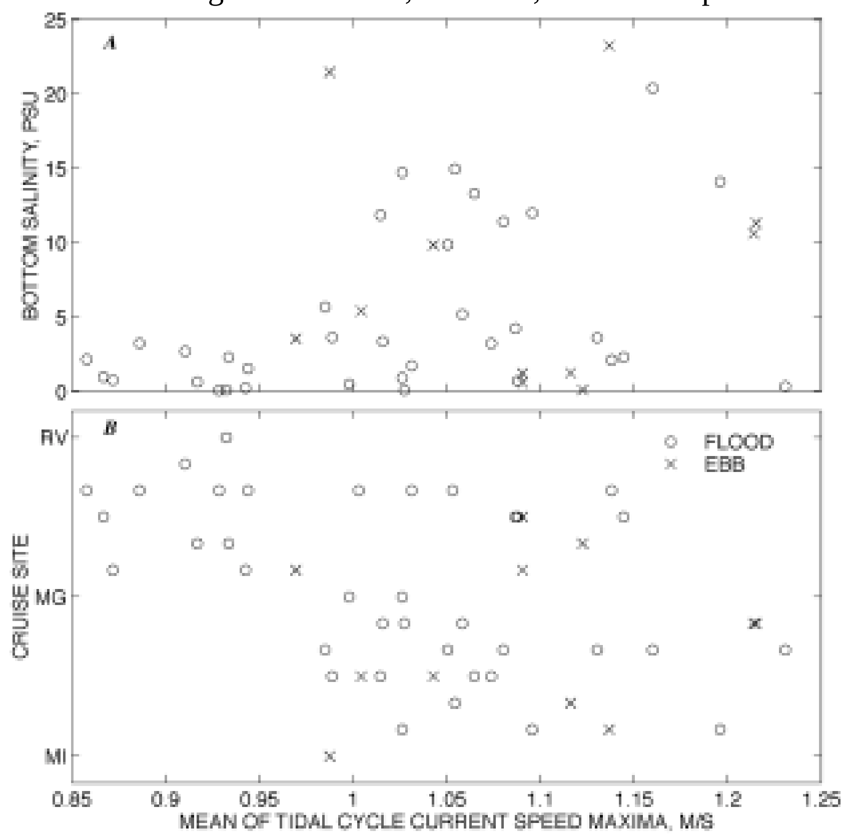

Figure 6. Bottom salinity *A* and sampling site *B* of the maximum cruise surface suspended-solids concentrations relative to the mean of the predicted tidal cycle current speed maxima ($\overline{U_{max}}$) in Carquinez Strait, northern San Francisco Bay. Predicted tidal

currents in Carquinez Strait, at the time the maximum SSC for a cruise was sampled, were used to determine tidal phase. RV, Rio Vista; MG, Middle Ground; MI, Mare Island.

Another process that could account for the difference between the tidally averaged and cruise observations of the surface ETM location is particle settling during slack tide in Carquinez Strait, which reduces surface SSC. Stratification in Carquinez Strait is greatest during neap tides, which reduces vertical mixing, enhances settling, and decreases tidally averaged surface SSC (Figure 4). During spring tides, stratification is reduced, so vertical mixing, bed-shear stress, and surface SSC are greater. During cruises, the surface ETM always was located in or near Carquinez Strait during spring tides, independent of the salinity (Figure 6).

Observed surface ETM location, relative to longitudinal position and salinity, is affected by semidiurnal and diurnal tides and the spring/neap tidal cycle. Flood- tide sampling bias during cruises, baroclinically driven pulses during flood tide, and spring/neap modulation of particle settling at slack tide in Carquinez Strait probably account for the discrepancy between the surface ETM location derived from tidally averaged data and cruise data.

7. CONCLUSIONS

Salinity, bottom topography, and tides affect the locations of estuarine turbidity maxima (ETM) in northern San Francisco Bay. ETMs are not associated with a singular salinity. Bottom suspended-solids concentration (SSC) during cruises and tidally averaged SSC did not show any maxima associated with a particular salinity. Observation of a surface ETM at 0-6 psu bottom salinity during 67 percent of the water-quality cruises probably is a result of (1) 71 percent of the cruise data being collected on flood tide, (2) baroclinically driven pulses during flood tide, and (3) spring/neap modulation of salinity stratification and particle settling at slack tide in Carquinez Strait. The longitudinal salinity gradient, not salinity, creates gravitational circulation and ETMs.

Bottom topography, especially sills in the channels, is another factor controlling the location of ETMs in northern San Francisco Bay. Locations of ETMs are related to bottom topography because salinity stratification and gravitational circulation are enhanced seaward of sills. Maximum bottom SSC was located in Carquinez Strait during 67 percent of the cruises, and tidally averaged SSC was greater in Carquinez Strait and the Reserve Fleet Channel, which are both seaward of sills, compared with more landward sites. Vertical mixing and SSC are greatest in Carquinez Strait during spring tides. Therefore, surface ETMs were always located in or near the Strait (seaward of Middle Ground) during spring tide cruises, regardless of salinity. Wind-wave resuspension of bed sediment in shallow water subembayments is another topographically controlled source of suspended solids.

The spring/neap tidal cycle affects the locations of ETMs. Bottom shear stress and SSC are greatest during spring tides and smallest during neap tides. Salinity stratification in Carquinez Strait is greatest during neap tides, which is the only time when tidally averaged SSC in Carquinez Strait was less than at a landward site at Mallard Island. Baroclinically driven pulses also are strongest during neap tides, when a surface ETM always was observed in the eastern half of the study area (landward of Middle Ground) and between 0-2 psu during cruises.

Observations of an ETM can be affected by sample timing, relative to the tidal cycle. The design of estuarine water-quality sampling programs should consider variability caused by diurnal and semidiurnal tides and the spring/neap cycle, whenever practical.

8. ACKNOWLEDGMENT

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