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Summary of Findings About Circulation and the Estuarine Turbidity Maximum in Suisun Bay, California

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Suisun Bay, California, is the most landward subembayment of San Francisco Bay (fig. 1) and is an important ecological habitat (Cloern and others, 1983; Jassby and others, 1995). During the 1960s and 1970s, data collected in Suisun Bay were analyzed to develop a conceptual model of how water, salt, and sediment move within and through the Bay. This conceptual model has been used to manage freshwater flows from the Sacramento-San Joaquin Delta to Suisun Bay to improve habitat for several threatened and endangered fish species. Instrumentation used to measure water velocity, salinity, and suspended-solids concentration (SSC) greatly improved during the 1980s and 1990s. The U.S. Geological Survey (USGS) has utilized these new instruments to collect one of the largest, high-quality hydrodynamic and sediment data sets available for any estuary. Analysis of these new data has led to the revision of the conceptual model of circulation and sediment transport in Suisun Bay.

A primer on estuarine physics

Estuarine scientists use many terms to describe the complicated physical processes in estuaries, where freshwater from the rivers mixes with saltwater from the sea. The salinity of freshwater is 0 practical salinity units (psu) and the salinity of seawater is 35 psu. The gravitational pull of the sun and moon generates tides with *flood* (*landward*) and *ebb* (*seaward*) currents. Tidal currents are strongest during full and new moons, called *spring tides*, and weakest during half moons, called *neap tides*. This sloshing back and forth is usually much greater than the *tidally-averaged* (*residual*) movement of water caused by river inflow or wind. Tidal and residual currents carry and mix (*transport*) salt, sediment, plankton, and other constituents. Saltwater is heavier than

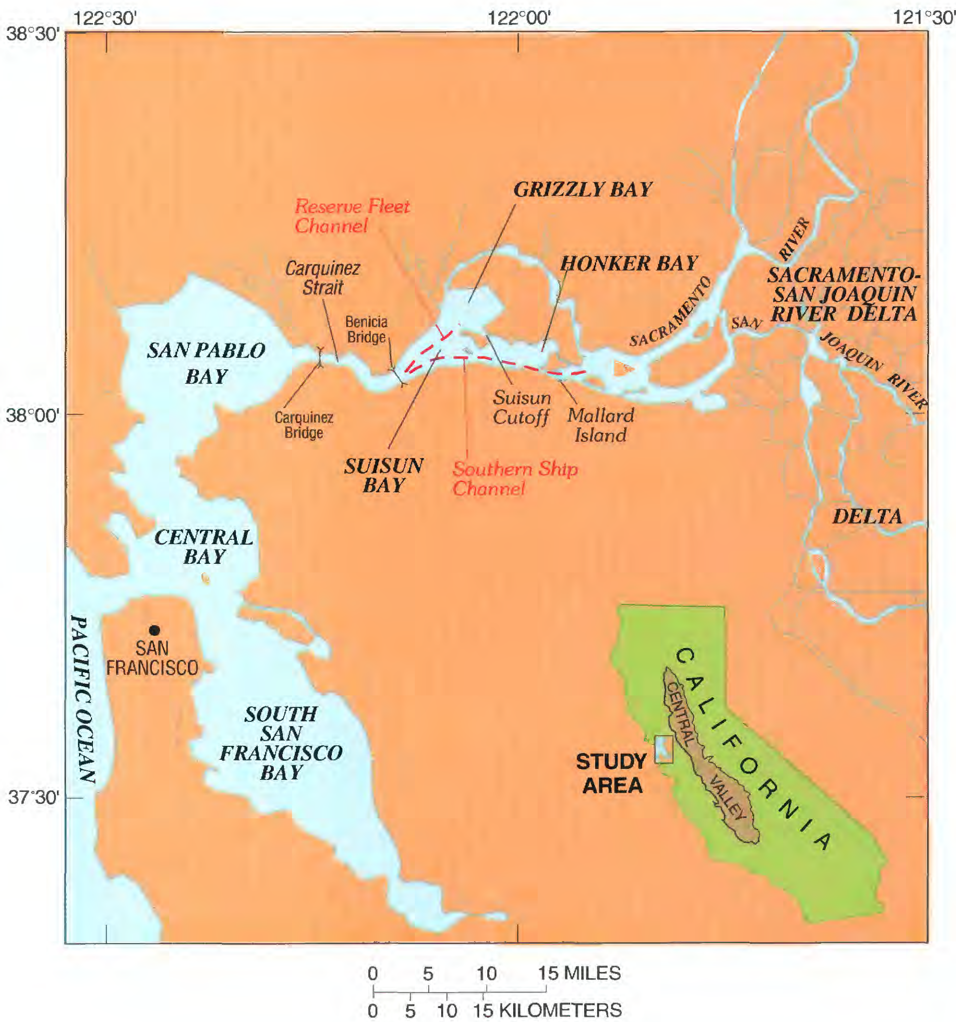

Figure 1. Location of study area, Suisun Bay, California.

freshwater; therefore, saltier water tends to be near the bottom of estuaries. The difference in the amount of salinity between the top and bottom of the water column (*stratification*) can be great enough to prevent the top and bottom waters from mixing. Salinity is greatest near the ocean and smallest near the rivers. This difference in longitudinal salinity (*gradient*) from the river to the ocean can cause the tidally averaged currents to flow landward along the bottom and seaward along the surface (*gravitational circulation*) (fig. 2). The *null zone* is the region in the estuary where the residual, near-bottom, landward current reverses and flows in the seaward direction as a result of river inflow. In many estuaries, the null zone contains an *estuarine turbidity maximum* (ETM) where SSC and turbidity are greatest.

Existing conceptual model of gravitational circulation in Suisun Bay

The existing conceptual model of circulation and entrapment in Suisun Bay is based on the aforementioned general characteristics of estuaries, laboratory studies, water-velocity data from meters deployed during a few tidal cycles, and water samples collected during research cruises. River flow transports suspended sediment and other suspended material, such as plankton, seaward near the water surface. Laboratory studies suggest that when fine sediment particles from the rivers encounter small amounts of salt, they adhere to other particles (*flocculate*) and sink more rapidly (Arthur and Ball, 1978). These particles (*flocs*) descend to near the bottom of the water column, where the residual current is landward; thus, the flocs become "entrapped" in Suisun Bay and form an ETM in the null zone. Certain species of plankton and larval fish also accumulate near the ETM in Suisun Bay and the western Delta (Arthur and Ball, 1979). In this estuary, the ETM and the region of increased abundances of certain aquatic organisms is known as the *entrapment zone*. Increasing river flows push the entrapment zone seaward and decreasing river flows allow the entrapment zone to move landward. Results of water-sampling programs in the 1970s suggested that the entrapment zone is associated with surface salinities that range from 1 to 6 psu and provided indirect evidence that gravitational circulation is responsible for the entrapment zone (Arthur and Ball, 1978, 1979). The position of the 2-psu bottom salinity has significant statistical relation with many estuarine communities (Jassby and others, 1995) and is used as a basis for regulation of freshwater flow into Suisun Bay.

New technology

Technological advances during the 1980s and 1990s have improved our ability to measure water velocity, salinity, and suspended sediment. Acoustic Doppler current profilers (ADCP) can measure vertical profiles of water velocity at 1-meter (or less) intervals every 10 minutes for as long as 3 months (fig. 3). The resulting time series of vertical velocity profiles can be analyzed to determine how gravitational circulation changes as salinity and the spring-neap tidal cycle change. Conductivity-temperature-depth (CTD) sensors can automatically and continuously measure salinity at any location and depth in Suisun Bay for several months. Optical backscattering (OBS) sensors measure the amount of suspended material in the water. Output from these sensors is converted to SSC with calibration curves developed from analyses of water samples (Buchanan and Schoellhamer, 1996). The OBS sensors can be deployed with other

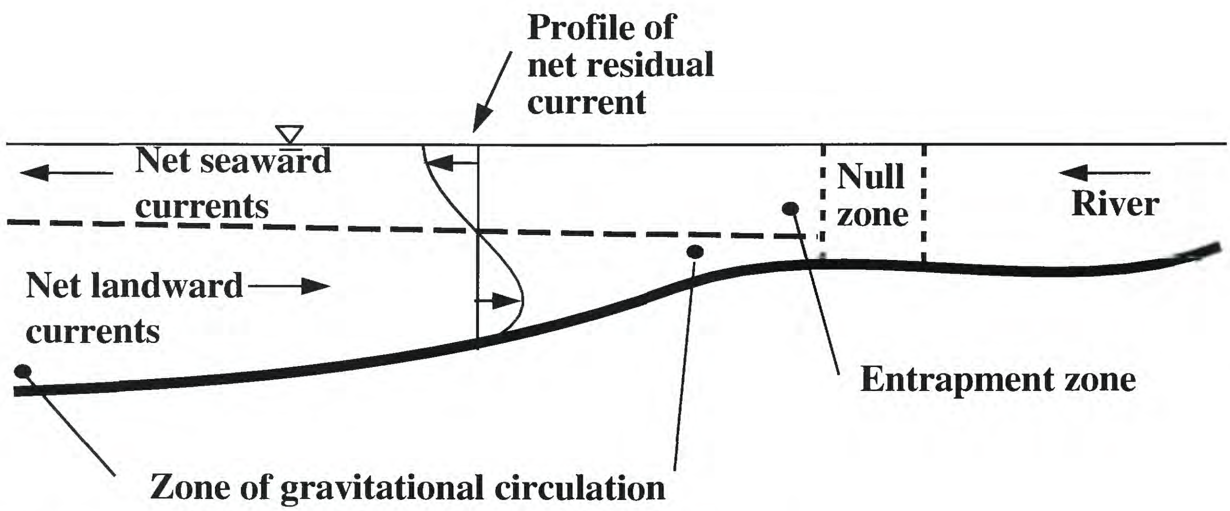

Figure 2. Existing conceptual model of the entrapment and null zones, Suisun Bay, California.

Figure 3. Acoustic Doppler current profiler (ADCP).

instruments to continuously measure time series of SSC. These time series can be analyzed to determine how SSC varies with salinity, freshwater flow, wind, and the spring-neap tidal cycle (Schoellhamer, 1996). High-quality, long-term data sets from ADCPs, CTDs, and OBS sensors provide the necessary information to better understand the tidal and seasonal variability of salinity intrusion, gravitational circulation, SSC, and entrapment in Suisun Bay. Some results of the analyses of these data are summarized below.

Revised conceptual model of gravitational circulation

Velocity data collected during the 1990s and a complete review of all historical current-meter data collected in Suisun Bay and the Sacramento River have been used to develop a revised conceptual model of gravitational circulation in Suisun Bay. The data suggest that gravitational circulation has the following characteristics:

- It dominates residual transport in Carquinez Strait unless freshwater inflows are so high that the waters in the strait are completely fresh (Burau and others, 1993; Monismith and others, 1996);
- It is rare in the southern ship channel during the spring, but consistently has been measured during the autumn in the northern part of Suisun Bay (Burau and others, in press);
- It has been measured in the lower Sacramento River when local, near-bottom salinities have exceeded about 2 psu (Nichol, 1996);
- It is weakest during spring tides and strongest during neap tides (Burau and others, 1993); and
- It can occur as landward pulses of water that develop along the bottom at the beginning of flood tides during weak neap tides, when the water column is stratified (Monismith and others, 1996).

These observations differ from the existing conceptual model of gravitational circulation. For example, gravitational circulation is not dependent on a particular salinity, it varies in strength in Suisun Bay, and it is altered by the spring-neap tidal cycle. A revised conceptual model (table 1) was developed using results from other studies and quantitative scaling of stratification and mixing to explain these observations (Burau and others, in press). The revised conceptual model includes the following changes:

- Gravitational circulation increases with water depth (Walters and others, 1985);
- A semipermanent null zone is located near the Benicia Bridge during spring (Burau and others, in press), and other geographically fixed null zones may be located elsewhere in Suisun Bay, where deep channels become shallower in the landward direction (see bathymetry in fig. 4);
- Gravitational circulation is suppressed by increased vertical mixing during spring tides (Walters and others, 1985); and
- The horizontal salinity gradient (rate of change of salinity along the estuary), not salinity, drives gravitational circulation (Hansen and Rattray, 1965).

Effect of gravitational circulation on salt and suspended sediment transport

According to the existing conceptual model, gravitational circulation transports salt and suspended sediment similarly, with residual landward transport near the bottom and residual seaward transport near the surface (fig. 2). Data from concurrent deployments of ADCPs, CTDs, and OBS sensors for several months, however, demonstrate that salt and suspended-sediment transport are different. Landward pulses that develop along the bottom at the beginning of flood tides during weaker neap tides greatly increase the residual landward salt flux (mid-August and mid-October, fig. 5). SSC, however, is smallest during these neap tides and greatest during spring tides. During neap tides, when the landward pulses occur, relatively little suspended sediment is available to be transported by the pulses. During spring tides,

Table 1. Revisions to the conceptual model of gravitational circulation and the estuarine turbidity maximum in Suisun Bay, California
[psu, practical salinity units]

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

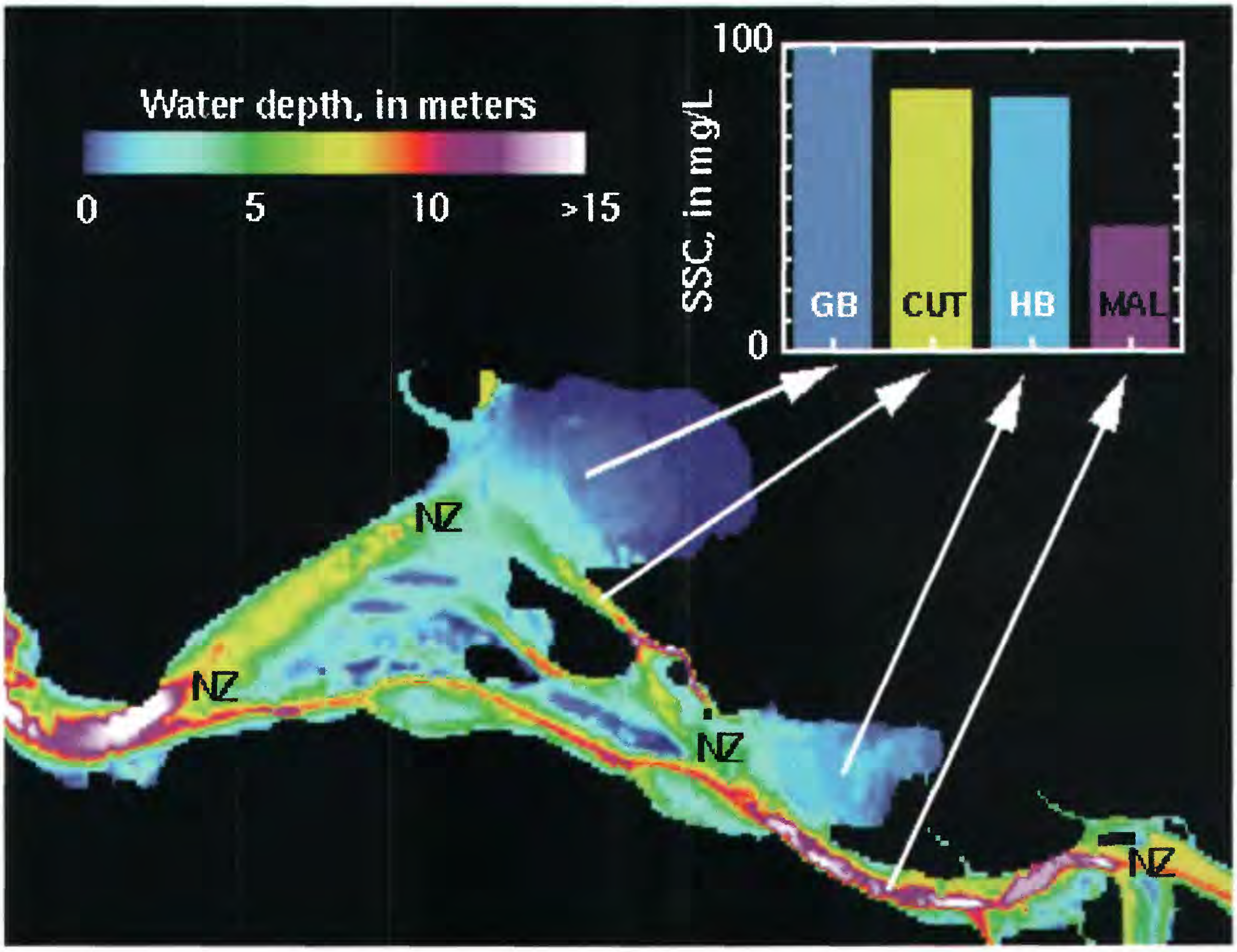

Figure 4. Suisun Bay bathymetry, geographically fixed null zones (NZ), and mean suspended-solids concentration (SSC) measured during summer 1995 in Grizzly Bay (GB), Suisun Cutoff (CUT), Honker Bay (HB), and Mallard Island (MAL). The western null zone near the Benicia Bridge has been confirmed with measurements, and the other null zones are likely, on the basis of a revised conceptual model of gravitational circulation. The null zones are present when a seaward longitudinal salinity gradient is present. Schematic is not to scale.

SSC is greater during floodtide than ebbtide, possibly because of greater resuspension and transport of sediment from geographically fixed null zones, so the tidally averaged flux of sediment is landward (early August and early October, fig. 5). Landward transport of sediment occurs during spring tides when gravitational circulation is weakest; thus, gravitational circulation does not necessarily cause "entrapment" in Suisun Bay.

Wind-wave sediment resuspension in shallow water

Much of the water in Suisun Bay is less than 2 meters deep, especially in the large subembayments of Grizzly and Honker Bays (fig. 4). Winds, which are typically strongest during summer, generate waves that resuspend sediments in shallow water and can make the SSC much greater in shallow water than in deeper water (fig. 4). Tidal and residual currents transport these resuspended sediments from shallow water to the adjacent deeper channels of Suisun Bay, such as Suisun Cutoff. A smaller SSC is typically found in the channels that are farther from the large, shallow subembayments, such as the southern ship channel near Mallard Island (fig. 4); thus, shallow water can be a source of sediment to the channels, contributing to the observations of an ETM in Suisun Bay.

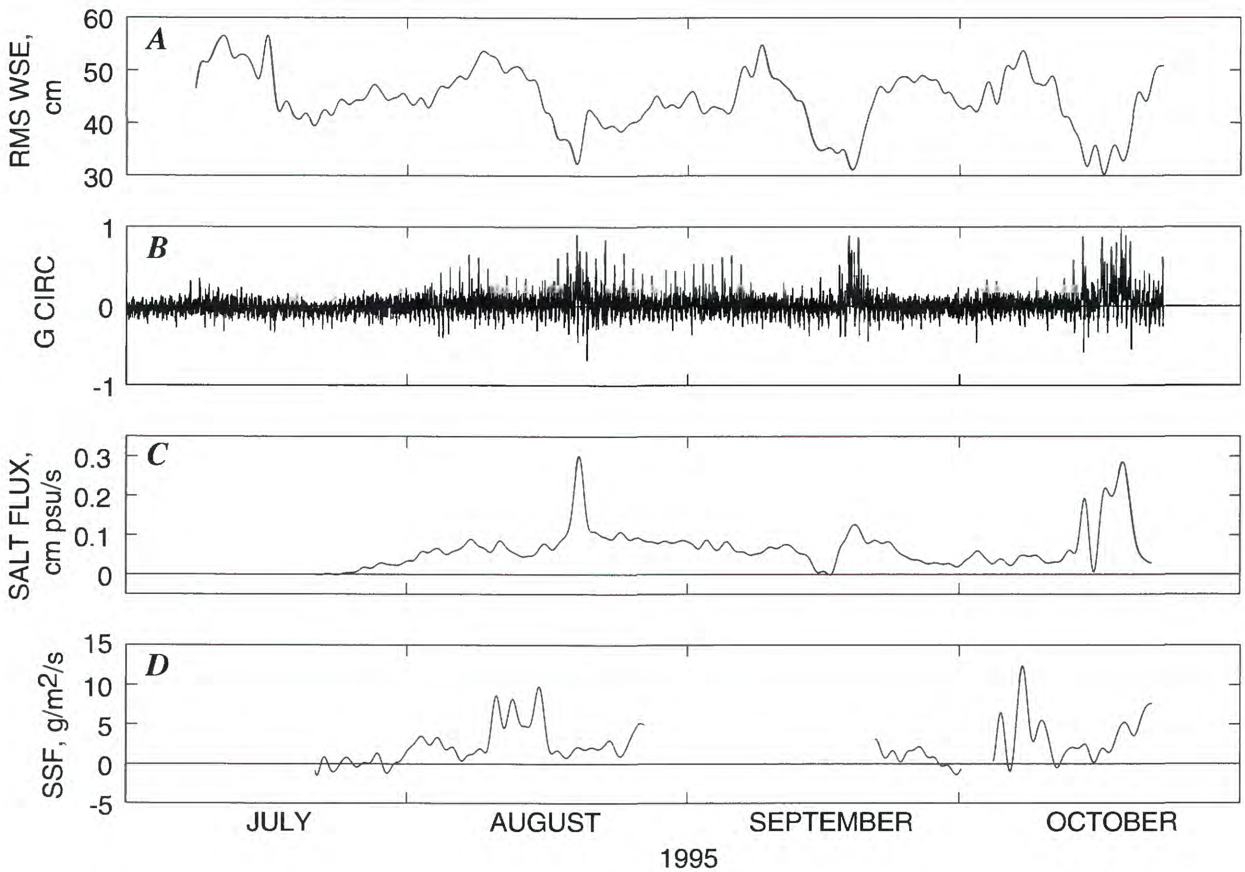

Figure 5. Gravitational circulation (G CIRC), salt flux, in centimeters practical salinity units per second, and suspended-solids flux (SSF), in grams per square meter per second, Suisun Cutoff, 1995. (A) The root-mean-square water-surface elevation (RMS WSE), in centimeters (Schoellhamer, 1996) shows the spring-neap tidal cycle. (B) Principal components analysis of acoustic Doppler current profiler data was used to determine the nondimensional time series of gravitational circulation (G CIRC; Stacey, 1996). (C) Landward, near-bottom residual salt flux. (D) Landward near-bottom residual SSF. Positive values in B, C, and D are landward. During spring tides (large values in A), vertical mixing reduces stratification and gravitational circulation (B), landward salt flux is relatively small (C), but landward SSF is relatively large (D). During neap tides (smaller values in A), gravitational circulation in the form of landward pulses (larger values in B) increase the landward salt flux, but SSC (not shown) is relatively small, and the SSF is less affected.

Conclusions

A conceptual model of gravitational circulation and entrapment was developed in the 1970s to help explain the ecological significance of Suisun Bay, a subembayment of San Francisco Bay. New technology developed during the 1980s and 1990s has greatly improved our ability to measure water velocity, salinity, and SSC. Analyses of these data have led to revisions in the conceptual model of gravitational circulation and the estuarine turbidity maximum in Suisun Bay (table 1). Gravitational circulation increases with water depth, null zones are geographically fixed, gravitational circulation is suppressed by increased vertical mixing during spring tides, and the longitudinal salinity gradient, not salinity, drives gravitational circulation. Gravitational circulation occurs as near-bottom pulses of landward flow that transport salt, but often little sediment. Wind-wave resuspension of bottom sediment in shallow water can affect SSC observed in the deeper channels. The conceptual model will continue to be improved as we continue to measure and analyze data from Suisun Bay.

Acknowledgments

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