■ Interagency Ecological Program for the Sacramento-San Joaquin Estuary ■

IEP NEWSLETTER

VOLUME 13, NUMBER 2, SPRING 2000

CONTENTS

1999 Long-term Status and Trends

Contributed Papers

CONTRIBUTED PAPERS

RECENT RESEARCH ON THE HYDRODYNAMICS OF THE SACRAMENTO-SAN JOAQUIN RIVER DELTA AND NORTH SAN FRANCISCO BAY

Jon R. Burau[1], Stephen G. Monismith[2], Mark T. Stacey[3], Richard N. Oltmann[1], Jessica R. Lacy[2], and David H. Schoellhamer[1]

[1] USGS, jburau@usgs.gov
[2] Stanford University
[3] University of California, Berkeley

INTRODUCTION

This article presents an overview of recent findings from hydrodynamic research on circulation and mixing in the Sacramento-San Joaquin Delta (Delta) (Figure 1) and North San Francisco Bay (North Bay) (Figure 2). For the purposes of this article, North Bay includes San Pablo Bay, Carquinez Strait, and Suisun Bay. The findings presented are those gained from field studies carried out by the U.S. Geological Survey (USGS), as part of the Interagency Ecological Program (IEP), and Stanford University beginning about 1993. The premise behind these studies was that a basic understanding of circulation and mixing patterns in the Bay and Delta is an essential part of understanding how biota and water quality are affected by natural hydrologic variability, water appropriation, and development activities.

Data collected for the field studies described in this article have significantly improved our understanding of Bay and Delta hydrodynamics. Measured flows in the Delta have provided valuable information on how water moves through the Delta's network of channels and how export pumping affects flows. Studies of the shallows and shallow-channel exchange processes conducted in Honker Bay have shown that the water residence time in Honker Bay is much shorter than previously reported (on the order of hours to several tidal cycles instead of weeks). Suisun Bay studies have provided data on hydrodynamic transport and accumulation mechanisms that operate primarily in the channels. The Suisun Bay studies have caused us to revise our understanding of residual circulation in the channels of North Bay and of "entrapment" mechanisms in the low salinity zone. Finally, detailed tidal and residual (tidally averaged) time-scale studies of the mechanisms that control gravitational circulation in the estuary show that density-driven transport in the channels is governed by turbulence time-scale (seconds) interactions between the mean flow and stratification. The hydrodynamic research summarized in this article spans a range of estuarine environments (deep water channels to shallow water habitats and brackish water to freshwater) at time scales that range from seconds to years.

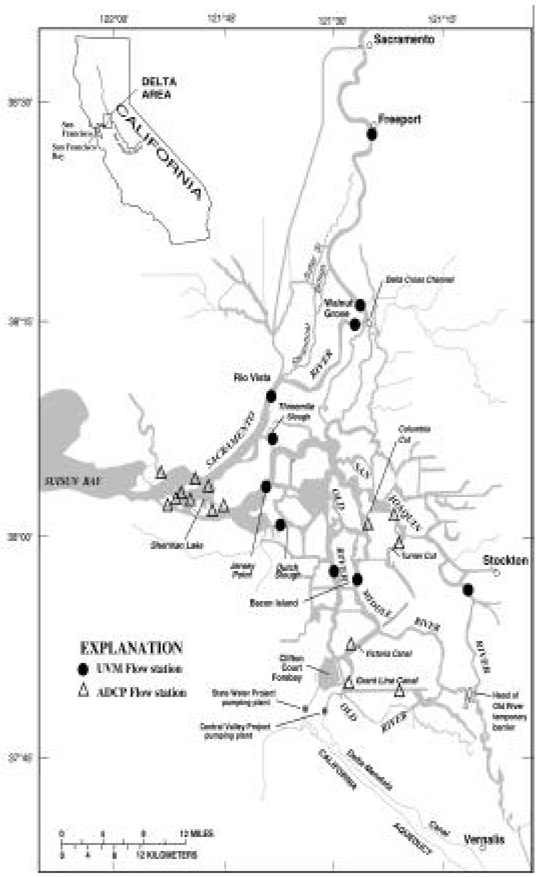

Figure 1 Map of the Delta showing the location of the current network of 10 UVM flow monitoring stations (solid circles). In situ acoustic Doppler current profilers (ADCP) have also been deployed for three month periods during the spring of 1996, 1997, and 1998 and the fall of 1998 (open triangles).

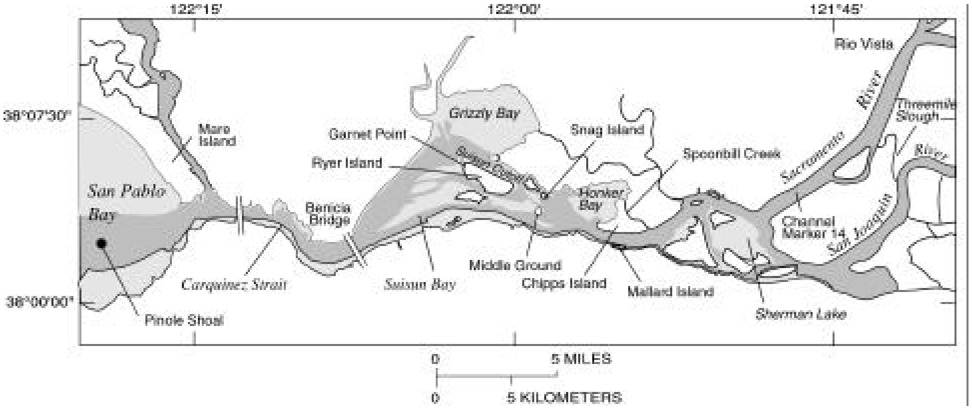

Figure 2 Map of North Bay, which, for the purposes of this article, includes San Pablo Bay, Carquinez Strait, and the western Delta

Funding for these studies was provided by the IEP, the USGS Federal-State Cooperative program, the U.S. Department of Interior Place-Based Program, the San Francisco Regional Water Quality Control Board, CALFED, the National Science Foundation, the Office of Naval Research, the city of Stockton, and the Contra Costa Water District.

Each finding is presented briefly in a “highlight reel” format. Additional details can be obtained through the reference list, which include several websites, and from the principal investigators (e-mail addresses are provided). Where possible, each finding is presented as an observation followed by its implications. The article discusses the Delta then North Bay.

DELTA

Between 1987 and 1996 the USGS installed a network of ten tidal-flow monitoring stations in the Delta (Figure 1). Ultrasonic velocity meters (UVMs) are used to continuously monitor the tidal flows at these permanent installations. The net or tidally averaged flow at each station is calculated using a digital filter. Because the net flows are usually ten percent or less of the tidal flows (depending on proximity to the ocean) the tidal flows must be measured very accurately to keep the error in the estimated net flow reasonably small. For example, the net flows in very dry years could be on the order of the error in the tidal flow measurements. An error analysis using data from the Threemile Slough flow station suggests that the net flows at this station are accurate to within 0.5% of the peak tidal flows (Simpson and Bland 1999). Although error estimates have not been made at the other flow stations, the error estimate at Threemile Slough is likely lower than at stations that have longer acoustic path lengths and more complicated channel geometries, such as Rio Vista and Jersey Point. More information on the error analysis is available from Michael R. Simpson at the USGS (mrsimpson@usgs.gov).

In addition to the continuous flow monitoring stations, acoustic Doppler current profilers (ADCPs) also have been deployed in the Delta during spring 1996, 1997, and 1998 and fall 1998 to measure tidal flows over three-month periods at several additional locations. Both the UVM and ADCP measured flow data are being used to calibrate and validate several flow models being applied in the Delta. Some of what has been learned about the hydrodynamics of the Delta using these measured flow data is described here.

Delta Outflow

Daily indirect measurements of Delta outflow have been made by combining the data from four UVM stations; Sacramento River at Rio Vista, Threemile Slough, San Joaquin River at Jersey Point, and Dutch Slough (Figure 1). Data from this combination of stations are available, beginning February 13, 1996, to the present, from the USGS hydrodynamics data base and the IEP file server. The measured Delta outflow generally compares well with the mass-balance calculated Delta outflow (DAYFLOW, DWR 1986) during high-flow periods, except that the measured data are lagged by several days because DAYFLOW does not account for travel time through the Delta. During low-flow periods, however, Delta outflow calculated using the two methods can be different primarily because DAYFLOW does not account for the spring neap cycle filling and draining of the Delta (see below) and DAYFLOW uses imprecise estimates of consumptive use (Oltmann 1998a). The UVM computed outflow is generally greater than DAYFLOW during low-flow periods, although the opposite occurred in 1998.

Spring Neap Cycle Effects

The tidally averaged water-surface elevation in the Delta can vary by as much as one foot during the fortnightly (14-day) spring neap tidal cycle. A uniform one-foot change in the water-surface elevation in the Delta equates to a change in storage of about 50,000 acre-feet. Therefore, the spring neap cycle water level oscillation in the Delta can produce a significant oscillation in the net flows (filling and draining) and also in the position of the salt field. As a direct result of the Delta filling and draining, net flows can occur in a landward direction during late summer and fall in the lower reaches of the San Joaquin River at Jersey Point (Oltmann 1995; Oltmann and Simpson 1997). The ability of the “G” model (Denton 1993) to predict daily variations in salinity in the western Delta was significantly improved during the solstices of each year (a time when the difference between spring and neap tides is greatest) after the “G” model was modified to include spring neap cycle effects (computed by the Fischer Delta Model, Fischer 1982).

Effects of Barriers

Delta Cross-Channel Gates

Although the Delta cross-channel gates originally were installed in the 1950s to improve water quality in the central Delta, the gates now are used to keep fish in the Sacramento River from entering the central Delta. The flow data collected at the Sacramento River upstream and downstream of the gates near Walnut Grove show the effects of gate operation on local hydrodynamics. For example, net flow from the Sacramento River into Sutter and Steamboat Sloughs increases by about 1,800 cubic feet per second when the gates are closed, compared to periods when the gates are open (Oltmann 1995).

South Delta Hydrodynamics

Flow data (ADCP and UVM) from spring 1997 and 1998 document the combined effects on south Delta hydrodynamics of the barrier installed at the head of Old River, a 30-day pulse flow on the San Joaquin River, and high overall inflows from the San Joaquin River. The barrier at the head of Old River is installed to prevent emigrating salmon from being drawn into the export facilities through Old River. One purpose for the San Joaquin River pulse flow is to help salmon bypass the export facilities by moving them north through the Delta (Oltmann 1998b). The flow data showed that during low-flow periods, the hydrodynamics of the south Delta are influenced primarily by the tides, rather than by inflows and exports. Tracer-dye studies also were conducted in the south Delta during spring 1997 and 1998. The dye studies showed that the dynamic tidal flows in this area rapidly dispersed (mixed) the dye (Oltmann 1998b, 1999). See also the Honker Bay section that discusses the mixing that occurs in channel bends.

Effects of the Confluence (Including Sherman Lake)

Tidal flows were measured using ADCPs at nine sites in the confluence area for a three-month period during fall 1998. These data showed that the net flow through Sherman Lake was from the Sacramento River to the San Joaquin River. The net flows through Threemile Slough, which were measured by a UVM during the same time period, also were from the Sacramento River to the San Joaquin River. Surprisingly, the magnitude of the net flow through Sherman Lake, a shallow water habitat that also provides an important hydraulic connection between the Sacramento and San Joaquin rivers, was about 1.5 times that of Threemile Slough (R. N. Oltmann unpublished data).

Effects of Meteorology

Variations in atmospheric pressure and wind can significantly affect water-surface elevations and flows in the Delta (Oltmann 1998a). An increase in atmospheric pressure results in a lowering of water levels and a “draining” of the Delta; a decrease in atmospheric pressure results in raising water levels and a “filling” of the Delta. Changes in atmospheric pressure are often accompanied by increased wind speeds that also can alter water levels and flows in Delta channels. For example, a drop in atmospheric pressure and sustained westerly winds on December 12, 1995, resulted in the elimination of the daily low-high tide and the associated ebb flow throughout the Delta.

More information is available from Richard N. Oltmann at the USGS (rnoltmann@usgs.gov).

NORTH BAY

Although the Bay and Delta are often considered separately, they are intimately connected by the tides. Tidal forcing varies spatially throughout North Bay and the Delta in direct proportion to proximity with the Pacific Ocean. The tides and tidal discharges reach their peak at the Golden Gate Bridge and gradually diminish until, on the eastern fringes of the Delta, tidal flows completely give way to riverine influences (Walters and Gartner 1985). Computer-model-generated residual current plots often show a deceptively simple one-way exchange from the Delta to the Bay even though the daily tidal flows in the western Delta are often 50 to 60 times the net flows (Oltmann 1998b). The large tidal exchanges can introduce large net landward directed fluxes of water, salt, and suspended particulate matter by lateral mixing, or dispersive processes, that can far exceed the fluxes of these quantities from the net flows (Fischer and Dudley 1975). Therefore, the net exchange of salt, suspended particulate matter, biota, etc., past a given location, which includes advective (net flow) and dispersive components (tidal correlations), can be (during low flow periods, in particular) from the Bay to the Delta. Salinity intrusion into the Delta from the Bay during late fall is a good example of up-estuary dispersive transport in opposition to Delta outflow.

The flows in the Delta and in the Bay, where saltwater is present, are fundamentally different. The flows in the Delta, for example, are simply driven by water-surface slopes (gradients). Tidal flows are caused by water-surface slopes that result from the propagation of the tide wave and net flows are driven by tidally averaged water surface slopes that are created by riverine inputs, exports, and by tidal nonlinearities (for example, spring neap cycle “filling and draining”) and changes in the local meteorology.

All of the water-surface-slope-derived flow patterns described above in the context of the Delta also operate in the Bay. However, the physics of the flows in the Bay are relatively more complicated than the flows in the Delta because of the presence of higher concentrations of salt, and, as a consequence, the underlying physics of the flows in the Bay are relatively less well understood. Salinity affects the density of the water and, therefore, spatial differences (gradients) in salinity can drive density-driven (baroclinic) flows such as gravitational circulation; a circulation pattern wholly absent throughout most of the Delta because water is fresh in the Delta. The location where flows change from being fundamentally riverine (barotropic) to flows that include both barotropic and baroclinic components is based on the presence or absence of salinity, not geography (for example, Bay versus Delta). For practical purposes, this change occurs at X2; only water surface slope-driven flows exist landward of X2, whereas, seaward of X2, a combination of water surface slope and density driven flows prevail. X2 is the distance, in kilometers from the Golden Gate Bridge, of the near-bed tidally averaged salinity of 2.

The remainder of this article focuses on physical insights we have gained over the last few years in North Bay, the area of the estuary where saltwater and freshwater mix.

HONKER BAY

Since most of the hydrodynamic research before 1995 focused on channel dynamics, little was known about the transport and mixing within shallow areas until this time, despite the fact that as early as 1975 Hugo Fischer (Fischer and Dudley 1975) suggested that approximately 70% of the upstream migration of salt is due to lateral shear and shallow-channel exchange processes. Lateral shear is the change in current speed that occurs between the side of the channel where the current speeds are slower and the center of the channel where the current speeds are greatest. The primary reason for the lack of field studies aimed at quantifying the shallows-channel exchange contribution to transport, in general, and to salinity intrusion specifically, is that these processes evolve from the storage and release of waters from the shallows into the channels that occurs over a large area. The amount of equipment needed to cover the spatial scale of these exchanges was simply not available to researchers in this estuary before 1995.

CALFED’s general interest in shallow water habitats and the unknown, although suspected, important role the shallows of Suisun Bay play in the Bay-Delta ecosystem prompted the USGS and Stanford University to carry out two experiments in Honker Bay (December 1996 through March 1997 and April through August 1997). Although previous work suggested that the water residence times in Honker Bay were on the order of weeks, these studies found that the exchange between Honker Bay and its bounding channel was relatively rapid (hours to several tidal cycles) (Lacy 2000). In contrast, sediment transport measurements conducted as part of the hydrodynamic studies suggest that sediment residence times are on the order of months (Ruhl and Schoellhamer 1999). The marked difference between the water versus sediment residence times could have important implications to the exposure pathways of organisms to contaminants. For example, direct exposures of organisms to pulses of contaminants in solution (for example, dissolved forms of pesticides) will be limited in Honker Bay because of the relatively short water residence times (Lacy 2000). However, exposure to contaminants via ingestion of particulate materials may be enhanced by the longer residence times of the suspended particulate matter. Brown and Luoma (1995) reported higher concentrations of metals (cadmium, chromium, vanadium, and nickel) in bivalves in Honker Bay than anywhere else in Suisun Bay. Moreover, disruption of the reproductive capabilities in the Asian clam, *Potamocorbula amurensis*, also was found in Honker Bay (Brown and Luoma 1998). At the same time, this highly opportunistic clam, which is found in large numbers throughout North Bay (Figure 2) and serves as a primary food source for bottom-feeding ducks and sturgeon, has virtually disappeared from Honker Bay (J. Thompson, personal communication, see “Notes”). The longer residence time of suspended particulate matter is a possible explanation for the higher metals concentrations in bivalves in Honker Bay and one feasible explanation (among others) for their subsequent population decline in this area.

Finally, the hydrodynamic and suspended-sediment transport studies also highlight the importance of seemingly innocuous (small) hydraulic pathways. Significant tidally driven [not residual (net) current driven] transport of water mass, salinity, suspended sediment, and by extension biota, can occur in small channels, such as Spoonbill Creek, which connects Honker Bay with the Sacramento River (Warner and others 1997), or Threemile Slough, which connects the Sacramento River with the San Joaquin River.

Water Residence Times

To examine large-scale circulation patterns in Honker Bay, a series of drifter experiments was conducted as part of the hydrodynamic studies. In regions with complex shape and variable depth, techniques such as drifters, which track masses of water over the tidal cycle, can provide a better estimate of the tidal excursion than can measurements of velocities at a single point. The tidal excursion is the distance a parcel of water (a drifter) travels over a tidal cycle (ebb + flood). The drifter studies demonstrated that tidal excursions in Honker Bay are the same order of magnitude as the length of Honker Bay, and that water residence times in Honker Bay range from several hours to several tidal cycles. The relatively short water residence time in Honker Bay may limit its importance as a distinct shallow water habitat (Lacy 2000).

In summer, tidally averaged (residual) currents throughout Honker Bay are directed landward (into Honker Bay toward the Delta), producing upstream transport of salt and neutrally buoyant particles (Lacy 2000). This is in contrast to conventional wisdom regarding the circulation in the shallows where the residual currents, in the absence of gravitational circulation, are assumed to flow seaward in concert with net Delta outflow. The flood-directed residual currents in Honker Bay are due to the mixing of waters that flow into Honker Bay from Suisun Cutoff (where the phase of tidal currents is later than in the main channel) with waters that flow into the Honker Bay from the main channel. The flood tide starts in Honker Bay when the main channel starts to flood, but the beginning of the ebb is tied to the ebb in Suisun Cutoff. As a result, salt and particulate matter in Honker Bay is more likely to leave Honker Bay by Chipps Island to the east or through Spoonbill Creek, than to the west. Thus, the shallows of Honker Bay serve to lengthen the residence time of Suisun Bay as a whole (Lacy 2000).

Suspended Solids Concentrations

The highest suspended solids concentrations in Honker Bay occur from late April through early May (Ruhl and Schoellhamer 1999)—when the shallows of Suisun Bay are a host to the critical life stages of several species of concern—not during large runoff events. If toxic substances are associated with suspended particulate matter, then higher suspended-solids concentrations during this period could lead to increased organism exposure during this time. Elevated suspended solids during this period are caused by wind-wave resuspension of fluvial inputs deposited during large runoff events. The cycle of deposition and wind-wave resuspension of bed sediments suggests that the sediment residence times in Honker Bay are on the order of months (Ruhl and Schoellhamer 1999).

The general observation that residence times for negatively buoyant particles (sediment) are higher in the shallows has important implications for the residence times of other suspended particles, such as phytoplankton cells, which also can be negatively buoyant. Therefore, the buoyancy of phytoplankton cells is important in determining their residence time in the shallows (Arthur and Ball 1979; Ball and Arthur 1981). The shallow waters of Grizzly and Honker bays are zones of net phytoplankton production, while the adjacent deep channels are net sinks for phytoplankton biomass (Cloern and others 1985). Therefore, residence time of phytoplankton in the shallows is an important factor in determining the rate at which shoal-derived organic matter (food) is transported to consumers living in the deep regions of Suisun Bay.

Effects of Geography

Geography can have a dramatic effect on transport of salt, sediment, and biota. Geographic effects are intrinsically site specific, depending on both structural and hydrodynamic influences, and the interaction between them (although armored levees, by design, significantly constrain this interaction). For example, the interaction between the physical configuration of an individual channel—its capacity in terms of its cross-sectional area and roughness, its length and sinuosity—with the local tidal and riverine forcing determine its tidal and residual transport characteristics. Yet, characterizing the tidal and residual transport characteristics of each channel individually, in isolation, provides an incomplete picture. It is the interactions among the flows in the channels and between the channels and the shoals in the Bay and Delta that controls where things (salt, sediment, biota, etc.) ultimately go and how they get there. Not only must the physical configuration of the shoal (aerial extent, volume, tidal prism, fetch, etc.) be considered when trying to understand the role it plays in transport, but also its connection with the main channel(s), as well as the characteristics of the channel itself also must be considered. This section describes several specific examples of the effects of geography on transport. In each case, the connections between channels and between channels and shoals (at least within a tidal excursion) are emphasized.

Channel Length—Spoonbill Creek

Drifter studies indicate that during neap tides, exchange between Honker Bay and the Sacramento River through Spoonbill Creek is limited to the easternmost part of Honker Bay. During spring tides, exchange through Spoonbill Creek can influence most of Honker Bay, due to greater tidal excursions. In summer, there is a persistent tidally averaged salinity gradient across Honker Bay with the fresher water in the eastern part of the Bay towards Spoonbill Creek. This suggests Spoonbill creek provides a direct connection between Honker Bay and the Sacramento River (Lacy 2000).

Spoonbill Creek also provides a steady flux (mostly dispersive, involving tidal correlations) of suspended solids from Honker Bay to the Sacramento River (Warner and others 1997). This dispersive transport occurs because the length of Spoonbill Creek is significantly less than the tidal excursion through the creek. Sediment-laden water, that originates in Honker Bay, leaves Spoonbill Creek with each ebb and is almost completely mixed with Sacramento River water, which contains less sediment. The concentration of suspended sediments in the water returning through Spoonbill Creek on the flood is much lower than was present on the ebb. This process of “ebb-mixing-flood” results in a net transport of sediment from Honker Bay to the Sacramento River. The dispersive transport in Spoonbill Creek is an example of tidal pumping (Fischer and Dudley 1975); an often overlooked, yet extremely efficient transport mechanism that has nothing to do with the local residual currents (net flows).

That channels with tidal excursions greater than their lengths can produce significant net dispersive transports is a general finding that has important implications in the Delta. For example, the tidal excursions in Threemile Slough and Sherman Lake are often greater than their respective lengths. Therefore, dispersive transport in Threemile Slough and in Sherman Lake probably far exceeds the transports computed based on the fixed site net flows alone. Drifter studies conducted in Sherman Lake in fall 1998 confirm this conclusion because the tidal excursion from the Sacramento River through Sherman Lake to the San Joaquin River is 3.6 miles longer than the tidal excursion in the opposite direction (J. Cuetara, personal communication, see “Notes”). This implies that during low-flow periods, the measured net flows underestimate the actual exchange between the Sacramento and San Joaquin rivers through Sherman Lake and through Threemile Slough because most of the water originally from the Sacramento River that exits both Sherman Lake and Threemile Slough into the San Joaquin does not return when the tidal current reverses. This is a classic case of tidal pumping (Fischer and Dudley 1975)

Channel Curvature—Snag Island Channel

In the channel flowing west from Honker Bay behind Snag Island, episodic cross-channel circulation is strong enough to mix the entire cross section in less than one hour. The cross-channel circulation is caused by centrifugal acceleration around the bend in Snag Island Channel and, at times, by lateral gradients in salinity. These observations suggest that channel curvature can be a very important mixing mechanism. Many channels in the estuary and Delta are curved, and the mixing caused by transverse currents is poorly understood and likely not well represented in most numerical models of the estuary (Lacy 2000).

For more information on the hydrodynamics of Honker Bay, contact Jessica Lacy (jlacy@leland.stanford.edu), Stephen G. Monismith (monismith@cive.stanford.edu), or Jon R. Burau (jrburau@usgs.gov). For information on sediment transport contact, John C. Warner (jcwarner@ucdavis.edu), Catherine A. Ruhl (caruhl@usgs.gov), or David H. Schoellhamer (dschoell@usgs.gov). For information regarding drifter studies in Suisun Bay and the Delta, contact Jay I. Cuetara (jcuetara@usgs.gov).

Suisun Bay and Carquinez Strait

Over the years there has been considerable interest in the effect of gravitational circulation on transport and on the accumulation of particles and biota in North Bay. Therefore, a considerable amount of research has been directed towards a better understanding of the basic physics in this area. Primarily through IEP support, the USGS has deployed large numbers of acoustic Doppler velocity profilers (ADCPs) and salinity-measuring equipment since 1993. Although much research needs to be done, particularly at the shorter (tidal and turbulence) timescales, our increased knowledge of the basic physics has allowed a better understanding of the observed temporal and spatial variability in gravitational circulation. For more information, contact Jon R. Burau (jrburau@usgs.gov), Stephen G. Monismith (monismith@cive.stanford.edu), or Mark T. Stacey (mstacey@socrates.berkeley.edu).

Gravitational Circulation

The horizontal salinity gradient (saltwater near the ocean to freshwater in the Delta), not salinity itself, drives gravitational circulation (Hansen and Rattray 1965). Gravitational circulation increases with water depth and is suppressed by increased vertical mixing that occurs during spring tides when the tidal currents are stronger (Walters and Gartner 1985; Burau and others 1998). Therefore, a combination of factors controls gravitational circulation strength—the horizontal salinity gradient, current speed, and depth (Smith and others 1991; Monismith and others 1996; Burau and others 1998; and Stacey and others 1999). These three factors have geographic consequences, which are described below.

Geographic Consequences

Rapid reductions in depth along the axis of the estuary can act as internal hydraulic controls (Armi 1986). This means, in effect, that significant reductions in depth (shoals or sills) can severely reduce or completely eliminate gravitational circulation. Because North Bay has several shallow areas that occur in the channels (such as Pinole Shoal and the reduction in depth near the Benicia Bridge), this depth dependence suggests that gravitation circulation in the North Bay and the western Delta operates as a series of independent cells bounded by sills (or shoals) at either end.

Gravitational circulation dominates residual transport in Carquinez Strait unless the waters in the strait are completely fresh (Burau and others 1993; Smith and others 1995; Monismith and others 1996). Gravitational circulation is likely stronger and a more persistent feature in Carquinez Strait than anywhere else in the Bay (Burau and others 1998) because a persistent horizontal salinity gradient exists along the axis of the strait for most of the year, and it is deep (approximately 50 ft, mean lower low water [MLLW]).

Gravitational circulation is rare in Suisun Bay's southern (ship) channel during the spring because the tidal currents are relatively strong [M2 tidal amplitude of approximately 90 cm/s] at this location and the ship channel is relatively shallow (approximately 30 ft MLLW) (Burau and others 1998). The M2 tidal amplitude is a single number that is often used to characterize the strength of the tides and tidal currents. The M2 tidal amplitude is the largest "partial tide" in San Francisco Bay (by approximately a factor of two) and is computed by harmonic analysis) (Burau and others 1998). Harmonic analysis decomposes the tides and tidal currents into a series of sinusoidal components of astronomically known frequencies. The M2 partial tide has a period of 12.42 hours.

Gravitational circulation has been measured during the fall in Suisun Cutoff because the tidal currents there are relatively weak (M2 tidal amplitude of approximately 60 cm/s) (Mortenson 1987; Stacey 1996; Burau and others 1998). Sills at either end of Suisun Cutoff reduce its tidal currents, and most likely define the end points of an independent gravitational circulation cell within the Cutoff.

Gravitational circulation has been measured in the lower Sacramento River (Nichol 1996) because the tidal currents in the river also are relatively weak (M2 amplitude of approximately 50 cm/s). This observation has implications for salt transport in the western Delta in dry years. Because the amplitude of the tide wave is greatly reduced as it passes through Suisun Bay on its way to the Delta, vertical mixing generally is significantly weaker in the Delta compared to the Bay. The reduction in vertical mixing, coupled with the relatively deep channels of the western Delta (> 30 ft), suggests that gravitational circulation could contribute significantly to the upstream migration of salt in the western Delta in dry years (this needs to be confirmed with additional data) (Burau and others 1998).

Relation to X2

The linkage between gravitational circulation and salt flux may have important consequences for the relation between flow and X2. The more than 20-year salinity data set of the U.S. Bureau of Reclamation, used by Jassby and others (1995) to develop X2-organism abundance relations, shows that the dependence of X2 and, hence, salinity intrusion in the Bay-Delta system on flow is much weaker than would be expected. One explanation for this is that there is a feedback mechanism—increased flow pushes the salt field down estuary—thus, intensifying the salinity gradient (Monismith and others 1996). However, when the salt gradient is stronger (compressed), strong gravitational circulation is more likely, as is strong upstream salt flux, which resists the downstream progression of X2. Thus, the seasonal-scale response of the salinity field to flow variations may be attributed to physical processes, such as gravitational circulation, which take place at the tidal time scale. For more information, contact Stephen G. Monismith (monismith@cive.stanford.edu).

Estuarine Turbidity Maxima

Because gravitational circulation ceases or becomes weaker over sills that separate deeper sections of the channels, this suggests the sills create geographically fixed null zones (Burau and others 1998). A null zone is a region in the estuary where the net current flowing landward along the bottom reverses direction. In most estuaries, a null zone also is associated with a region of high turbidity known as estuarine turbidity maxima (ETM) (Burau and others 1998). An ETM and null zone often are found immediately seaward of a sill. Suspended-solids data have confirmed the existence of a strong and persistent ETM seaward of the sill near the Benicia Bridge and west of the sill near Garnet Point on Ryer Island in Suisun Bay (Figure 2) (Schoellhamer and Burau 1998). An ETM also may exist at Pinole Shoal and at the sill north of Middle Ground (Figure 2).

Analysis of data collected in Suisun Cutoff during summer 1995 suggests that sediment and salt are transported differently (Schoellhamer and Burau 1998). This contrasts with the conceptual model offered by Arthur and Ball (1979) who suggest that entrapment of suspended material evolves directly from gravitational circulation (salt transport). Specifically, analyses of these data found that the salt flux through Suisun Cutoff was greater during neap tides than during spring tides. Suspended-solids fluxes, on the other hand, had the opposite temporal trend; lower fluxes occurred during neap tides and greater fluxes occurred during spring tides (Schoellhamer and Burau 1998). For more information, contact David H. Schoellhamer (dschoell@usgs.gov) or Jon R. Burau (jrburau@usgs.gov).

Turbulence

During November 1994, Stanford University and the USGS made a series of turbulence measurements (Stacey 1996; and Stacey and others 1999). The results from these studies that link the high frequency (seconds) turbulent motions to the tidal and residual time-scale transports of interest to the biologists are described here.

Residual circulation is created in an unsteady fashion as a time average of a series of density-driven current pulses at the tidal timescale. The interaction between stratification, shear, and turbulent mixing is fundamental in establishing the magnitude and timing of these pulses. The timing of these pulses, relative to other processes such as the resuspension of sediment, is critical in determining the net transport in the system. For example, if suspended-sediment concentration is low during the density-current pulses, the net transport will be low. On the other hand, if the pulses occur simultaneously with higher suspended-sediment concentrations, the net transport will be greater than predicted by computations based on a simple time average (Stacey 1996). Tobin and others (1995) observed density-current pulses concurrent with high suspended-sediment concentrations at Mallard Island that resulted in a net landward suspended-sediment flux, despite seaward net flow. It is possible that the tidal-timescale correlation between the density-current pulses and elevated suspended-solids concentration could provide the mechanism for ETM formation near X2 in the absence of residual gravitational circulation because the necessary gradient in salinity that drives the pulses ends near X2.

Turbulence in the Bay, which sets the level of shear and strongly influences the timing and magnitude of the residual flows, is largely produced at the bed by the interaction of the tidal flows with the bottom. There is, therefore, a high-energy region of active turbulent production near the bed. The upward transport of turbulence from the bed is limited from above by the presence of stratification. The degree to which this turbulence is able to "erode" the stratification (mix the near-bed waters with the overlying water) is critical to setting the net circulation and transport (Stacey 1996).

Common turbulence models, especially the simple models, poorly predict the extent of mixing away from the bed. Thus, the predictive ability of a three-dimensional model, which is needed to simulate the density-driven current pulses described above, will depend upon the turbulence model (Stacey 1996; Stacey and others 1999).

There is a strong asymmetry between ebb and flood tides in the structure of the turbulence—with more intense turbulence occurring on flood tides. This asymmetry may have implications for sediment transport (more sediment is suspended on flood tides than on ebb tides) and for biological migration (organisms may be able to distinguish flood tides from ebb tides by the energy in the turbulence), as well as for the creation of residual flows (Stacey 1996; Burau and others 1998; Stacey and others 1999).

For more information contact Mark T. Stacey (mstacey@socrates.berkeley.edu) or Stephen G. Monismith (monismith@cive.stanford.edu).

ACKNOWLEDGMENTS

Funding for a majority of the oceanographic equipment used in the Suisun and Honker Bay studies was obtained through the U.S. Department of the Interior Place Based Program (formerly the Ecosystem Initiative and INATURES programs). The UVM network in the Delta is primarily supported by the IEP, although the contributions from the City of Stockton and Contra Costa Water District also are acknowledged. Deployment costs and the analysis of these data by the USGS hydrodynamics group (Burau, Oltmann, and others) was funded by the IEP and the USGS Federal-State Cooperative Program. The USGS sediment transport group (Schoellhamer and others) is supported by the IEP, San Francisco Bay Regional Water-Quality Control Board, and the USGS Federal-State Cooperative Program. The Stanford group (Monismith and others) has been supported by the Physical Oceanography Program of the National Science Foundation, by CALFED, the IEP, and by the Office of Naval Research. Jay Cuetara, James DeRose, Paul Buchanan, Jeffrey Gartner, Brad Sullivan, Robert Sheipline, Rick Adorador, Jon Yokomizo, Jim George, and Jim Burau, of the USGS spent many hours in the field to collect the data used in these analyses.

REFERENCES

Armi L. 1986. The hydraulics of two flowing layers with different densities: Journal of Fluid Mechanics 163:27–58.

Arthur JF, Ball MD. 1979. Factors influencing the entrapment of suspended material in the San Francisco Bay-Delta Estuary. In: Conomos TJ, editor. San Francisco Bay: the urbanized estuary. San Francisco (CA): American Association of the Advancement of Science, Pacific Division. p 143–74.

Ball MD, Arthur JF. 1981. Phytoplankton settling rates—a major factor in determining estuarine dominance [abstract]. Estuaries 4:246

Brown CL, Luoma SN. 1995. Use of the euryhaline bivalve *Potamocorbula amurensis* as a biosentinal species to assess trace metal contamination in San Francisco Bay. Marine Ecology Progress Series 124(1–3):129–42.

Brown CL, Luoma SN. 1998. Metal trends and effects in *Potamocorbula amurensis* in North San Francisco Bay. IEP Newsletter 11(2):33–5.

Burau JR, Gartner JW, Stacey M. 1998. Results from the hydrodynamic element of the 1994 entrapment zone study in Suisun Bay. In Kimmerer WJ, editor. Report of the 1994 entrapment zone study: Interagency Ecological Program for the San Francisco Bay/Delta Estuary Technical Report 56. Sacramento (CA): California Department of Water Resources. p 13–62.

Burau JR, Simpson MR, Cheng RT. 1993. Tidal and residual currents measured by an acoustic Doppler current profiler at the west end of Carquinez Strait, San Francisco Bay, California, March to November 1988. U.S. Geological Survey Water-Resources Investigations Report 92–4064. 79 p.

Cloern JE, Cole BE, Wong RLJ, Alpine AE. 1985. Temporal dynamics of estuarine phytoplankton—a case study of San Francisco Bay. Hydrobiologia 129:153–76.

Denton RA. 1993. Accounting for antecedent conditions in seawater instrusion modeling-application for the San Francisco Bay-Delta. San Francisco (CA): 1993 American Society of Civil Engineers National Conference on Hydraulic Engineering.

[DWR] California Department of Water Resources. 1986. DAYFLOW Program documentation and DAYFLOW data summary user's guide.

Fischer HB. 1982. DELFO and DELSAL-Flow and transport models for the Sacramento-San Joaquin Delta: description and steady-state verification. Report HBF–82/01. Hugo B. Fischer, Inc.

Fischer HB, Dudley E. 1975. Salinity intrusion mechanisms in San Francisco Bay, California. Proceedings of the Sixteenth Congress of the International Association for Hydraulic Research 1:124–33.

Hansen DV, Rattray M. 1965. Gravitational circulation in straits and estuaries. Journal of Marine Research 23:104–22.

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecological Applications 5:272–98.

Lacy JR. 2000. Circulation and transport in a semi-enclosed subembayment [Ph.D. thesis]. Stanford (CA): Stanford University. Available from Stanford University.

Monismith SG, Burau JR, Stacey M. 1996. Hydrodynamic transport and mixing processes in Suisun Bay. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): American Association for the Advancement of Science, Pacific Division. p 123–53.

Mortenson WE. 1987. Investigation of estuarine circulation in Suisun Bay. The Bay Institute of San Francisco Exhibit 49. California Water Resources Control Board Hearing 13. 70 p.

Nichol GD. 1996. Estuarine circulation cell of the lower Sacramento River [Ph.D. thesis]. Reno (NV): University of Nevada. 197 p.

Oltmann RN. 1995. Continuous flow measurements using ultrasonic velocity meters: an update. IEP Newsletter Autumn 1995:22–5.

Oltmann RN. 1998a. Indirect measurement of Delta outflow using ultrasonic velocity meters and comparison with mass-balance calculated outflow. IEP Newsletter Winter 1998:5–8.

Oltmann RN. 1998b. Measured flow and tracer-dye data showing anthropogenic effects on the hydrodynamics of south Sacramento-San Joaquin Delta, California, Spring 1996 and 1997. U.S. Geological Survey Open–File Report 98–285. 16 p.

Oltmann RN. 1999. Measured flow and tracer-dye data for spring 1997 and 1998 for south Sacramento-San Joaquin Delta, California. IEP Newsletter 12(3):37–44.

Oltmann RN, Simpson MR. 1997. Measurement of tidal flows in the Sacramento-San Joaquin Delta, California. U.S. Geological Survey poster. Available via the Internet at http://sfBay.wr.usgs.gov/access/flow/flow.html.

Ruhl CA, Schoellhamer DH. 1999. Time series of suspended-solids concentration in Honker Bay during water year 1997: 1997 Annual Report. San Francisco Estuary Regional Monitoring Program for Trace Substances. Available via the Internet at http://www.sfei.org/rmp/1997/c0304.htm

Schoellhamer DH, Burau JR. 1998. Summary of findings about circulation and the estuarine turbidity maximum in Suisun Bay, California. U.S. Geological Survey Fact Sheet FS–047–98. 6 p.

Simpson MR, Bland R. 1999. Techniques for accurate estimation of net discharge in a tidal channel. In: Proceedings of the IEEE Sixth Working Conference on Current Measurement; 1999 Mar 11–13, San Diego, California. p 125–130.

Smith PE, Cheng RT, Burau JR, Simpson MR. 1991. Gravitational circulation in a tidal strait. In: Proceedings of the American Society of Civil Engineers 1991 National Conference on Hydraulic Engineering; 1991 Jul 29–Aug 2, Nashville, Tennessee. p 429–34.

Smith PE, Oltmann RN, Smith LH. 1995. Summary report on the interagency hydrodynamics study of the San Francisco Bay-Delta Estuary, California. Interagency Ecological Program for the Sacramento-San Joaquin Estuary. Technical Report 45. Sacramento (CA): California Department of Water Resources. 72 p.

Stacey MT. 1996. Turbulent mixing and residual circulation in a partially stratified estuary [Ph.D. thesis]. Stanford (CA): Stanford University. Available from Stanford University.

Stacey MT, Monismith SG, Burau JR. 1999. Measurements of Reynolds stress profiles in unstratified tidal flow. Journal of Geophysical Research 104(C5):10933–49.

Tobin A, Schoellhamer DH, Burau JR. 1995. Suspended-solids flux in Suisun Bay, California. In: Espey WH, Combs PG, editors. Water Resources, American Society of Civil Engineers First International Conference on Water Resources Engineering; 1995 Aug 14–18, San Antonio, Texas. p 1511–5.

Walters RA, Gartner JW. 1985. Subtidal sea level and current variations in the northern reach of San Francisco Bay. Estuarine, Coastal and Shelf Science 21:17–32.

Warner JC, Schoellhamer DH, Burau JR. 1997. A sediment transport pathway in the back of a nearly semi-enclosed subembayment of San Francisco Bay, California. In: Wang SY, Carstens T, editors. Environmental and coastal hydraulics—protecting the aquatic habitat. Proceedings of the 27th Congress of the International Association of Hydraulic Research; 1997 Aug 10–15, San Francisco, California. p 1096–1101.

NOTES

Janet Thompson, U.S. Geological Survey. Conversation with author in 1999.

Jay Cuetara, U.S. Geological Survey. 1999 unpublished report.

ENVIRONMENTAL FACTORS INFLUENCING THE DISTRIBUTION AND SALVAGE OF YOUNG DELTA SMELT: A COMPARISON OF FACTORS OCCURRING IN 1996 AND 1999

Matt Nobriga[1], Zach Hymanson[1], and Rick Oltmann[2]

[1] *DWR, mnobriga@water.ca.gov, (916) 227-2726*
[2] *USGS*

INTRODUCTION

The delta smelt (*Hypomesus transpacificus*) is listed as a threatened species under both the Federal Endangered Species Act (FESA) and the California Endangered Species Act. Through formal consultation under Section 7 of the FESA, USBR and DWR received a Biological Opinion from the USFWS, which allows for the incidental take of delta smelt arising through operation of the Central Valley Project and the State Water Project. The incidental take of delta smelt is estimated as part of the ongoing CVP and SWP fish salvage operations. Salvage levels of young delta smelt have exceeded incidental take levels every spring and summer since 1994, except in the high spring outflow years of 1995 and 1998 (Nobriga and others 1999). These high salvage levels have resulted in changes to project operations, often leading to the curtailment of water exports. An extended period of high salvage and export curtailment in 1999 raised substantial concerns and numerous questions that remain unanswered.

Previously, Nobriga and others (1999) described the high numbers of delta smelt salvaged at the State and federal Delta fish facilities in spring 1999 as “surprising since [the 1999 Delta inflow] hydrograph showed a similar pattern to 1996,” a year of lower delta smelt salvage. However, additional work presented here shows this characterization was too general. In this article we provide a more thorough analysis of differences between 1996 and 1999 to help explain the differences in delta smelt salvage between these moderately high outflow years. We examined information from a variety of sources (Table 1) to assist with the interpretation of observed patterns. Overall, we found the differences in delta smelt salvage between spring 1996 and 1999 were due to differences in