Preliminary Results from the Hydrodynamic Element of the 1994 Entrapment Zone Study

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This article discusses preliminary results from analyses of USGS hydrodynamic data collected as part of the 1994 Interagency Ecological Program entrapment zone study. The USGS took part in three 30-hour cruises and deployed instruments for measuring currents and salinity from April to June. This article primarily focuses on the analysis of data from five Acoustic Doppler Current Profilers (ADCPs) deployed in Carquinez Strait, Suisun Bay, and the Western Delta. From these analyses a revised conceptual model of the hydrodynamics of the entrapment/null zone has evolved. The ideas discussed in this newsletter article are essentially working hypotheses, which are presented here to stimulate discussion and further analyses. In this article we discuss the currently-held conceptual model of entrapment and present data that are inconsistent with this conceptual model. Finally, we suggest a revised conceptual model that is consistent with all of the hydrodynamic data collected to date and describe how the 1995 study incorporates our revised conceptual model into its design.

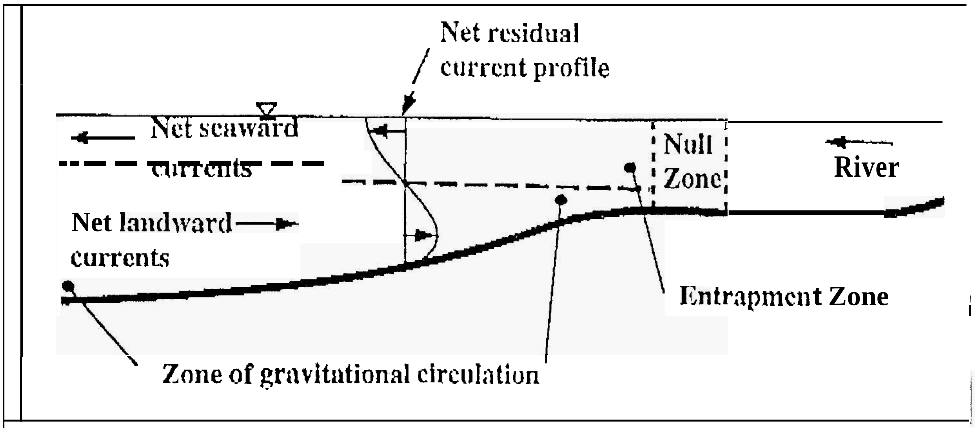

Figure 1
CONCEPTUAL MODEL OF THE ENTRAPMENT AND NULL ZONES

Existing Conceptual Model of Entrapment in the Northern Reach

The generally accepted conceptual model of the entrapment zone is that it is an area of the estuary where a flow convergence results in increased concentration of particulate matter; this usually occurs through the interaction of particle (or organism) sinking and net up-estuary flow at depth (Kimmerer 1992). For the purposes of this article, net, tidally-averaged, and residual all imply time scales whose periods are significantly longer than the diurnal tidal period of about 25 hours. The null zone, which is generally believed to coincide with the up-estuary limit of the entrapment zone, is a location in the estuary just down-estuary of where residual landward flow near the bottom ceases and where residual flow throughout the water column is seaward (Figure 1).

Both the entrapment and null zones have been associated with X2, the position of the near-bed 2 psu isohaline. This model of the entrapment zone assumes a landward flowing residual current along the bottom of the estuary known as gravitational circulation. Gravitational circulation is a residual two-layer flow in which low salinity water flows seaward in the surface layer, while denser, more saline water flows landward in the bottom layer; this two-layer flow results from the balance between the free surface slope acting in a down-estuary direction, and the longitudinal density (salinity) gradient acting in the up-estuary direction (Officer 1976). The commonly held conceptual model of entrapment is based on gravitational circulation, a tidally averaged or residual concept. Yet most (if not all) of the data previously used to substantiate this model are of short duration (transects), which are not suitable for studying residual or net processes.

In contrast, time series data from deployments of ADCPs and Conductivity, Temperature, Depth (CTD) sensors can be low-pass filtered to remove the tidal signal so that residual processes can be directly estimated. The approximately 2 months of continuous hydrodynamic time series data collected in the spring of 1994 can be used to evaluate the conceptual model of the entrapment zone based on gravitational circulation. Specifically, is gravitational circulation the major contributor to the salt balance in Suisun Bay and is it the principal mechanism responsible for accumulation of particles and organisms in the low salinity zone (– 2 psu)?

Discussion of the Data

Figure 2 shows the approximate ADCP positions of the 1994 entrapment zone study. The ADCP data from the instruments located in the southern channel of Suisun Bay and the Western Delta show no evidence of upstream flow at the estuary bed even though the mean position of the 2 psu near-bed isohaline was near Mallard Island (Figure 3). Specifically, the ADCP data collected in Carquinez Strait near Martinez from April 22 to June 15 show strong residual near-bed currents of 15-20cm/s directed up-estuary (Figure 4). In contrast, ADCP data from Concord (Figure 5), Mallard Island, the Sacramento River near channel marker 10, and the San Joaquin River near Antioch show near-bed residual currents that were directed down-estuary, indicating a lack of gravitational circulation. ADCP data collected by NOAA in Carquinez Strait and at Concord from April 22 to May 22, 1992, are consistent with the data collected in 1994 in that near-bed, residual currents in Carquinez Strait were up-estuary, and near-bed residual currents were down-estuary at Concord. X2 was again landward of Mallard Island during the 1992 NOAA deployments as shown in Figure 3.

The observed magnitude of up-estuary near-bed residual currents in the Carquinez Strait ADCP data, coupled with the down-estuary near-bed residual currents in Suisun Bay, suggests the possibility of a topographic control of the gravitational circulation at the Benicia

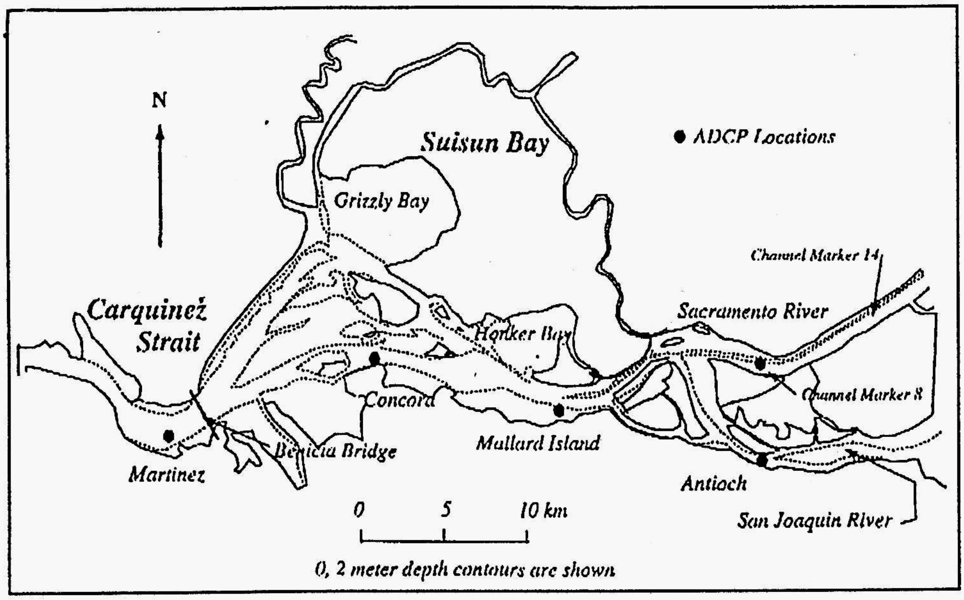

Figure 2
1994 ADCP POSITIONS

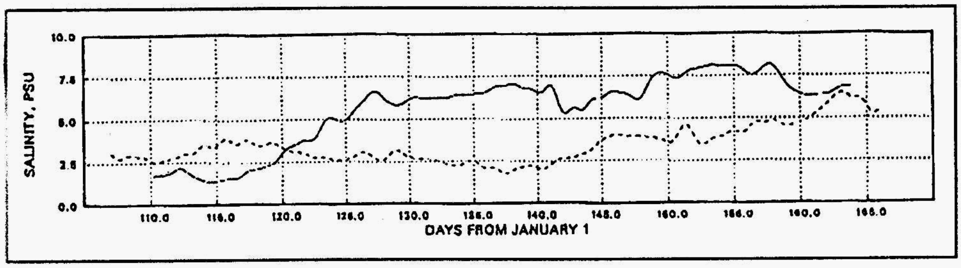

Figure 3
LOW-PASS FILTERED SALINITIES AT MALLARD ISLAND

Solid Line = 1992 near-surface sensor
Dashed Line = 1994 near-surface sensor
The near-bed sensor was not available in 1992

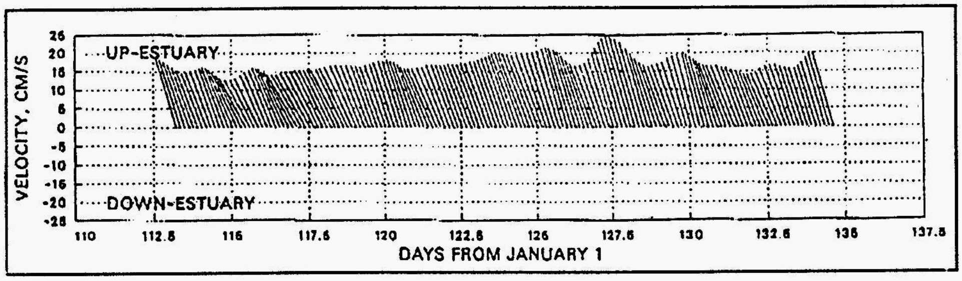

Figure 4
NEAR-BED RESIDUAL CURRENTS IN CARQUINEZ STRAIT NEAR MARTINEZ
In this stick diagram, currents are rotated into a local principal direction of 75 degrees determined by harmonic analysis.

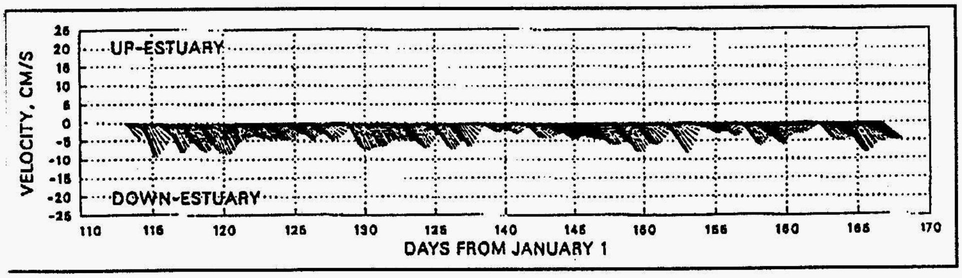

Figure 5
NEAR-BED EULERIAN RESIDUAL CURRENTS IN SUISUN BAY NEAR CONCORD
In this stick diagram, currents are rotated into a local principal direction of 82 degrees determined by harmonic analysis.

Bridge, where the depths change from about 19 meters in Carquinez Strait to about 11 meters in Suisun Bay. The concept of topographic control is well known (Armi 1986; Farmer and Armi 1986), and we believe the rapid decrease in depth just landward of the Benicia Bridge may be responsible for the change in near-bed residual currents from 15-20 cm/s up-estuary in Carquinez Strait to 5-10 cm/s down-estuary at Concord in both the 1992 and 1994 data sets. It is, therefore, likely that a null zone (location where the near-bed residual current changes from up-estuary to down-estuary) was geographically fixed to an area near the Benicia Bridge in the spring of 1992 and 1994 even though the mean position of the 2 psu near-bed isohaline was near or up-estuary of Mallard Island during these periods.

A complete review of all of the historical near-bed current meter data collected in Suisun Bay (Cheng and Gartner 1984; Mortenson 1987) and in the Sacramento River (George Nichol, 1990, personal communication) suggests the following spatial and temporal characteristics of gravitational circulation in the northern reach:

(1) Gravitational circulation dominates residual transport in Carquinez Strait unless freshwater inflows are so high that no salt water is present.
(2) Gravitational circulation has not been measured in Suisun Bay in the spring but has been consistently measured in the fall (Figure 6).
(3) Gravitational circulation has been measured in the Sacramento River at channel marker 14 when the near-bed salinities have locally exceeded about 2 psu.

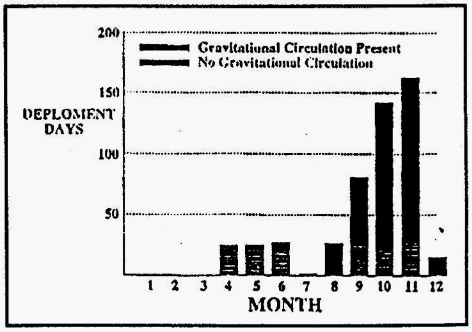

Figure 6
OCCURRENCE OF NET UP-ESTUARY NEAR-BED CURRENTS
Data collected by Cheng and Gartner, NOAA, and Mortenson.

(4) When gravitational circulation is present in the northern reach, its magnitude is modulated by the fortnightly (14-day period) spring/neap cycle: gravitational circulation is weakest during spring tides and strongest during neap tides.

In *summary,* the available data suggest a seasonal variability in the strength of the gravitational circulation in Suisun Bay which is tied, through the salt field (horizontal density gradient), to winter fresh water flows. In the spring, gravitational circulation appears to be weak or absent in the southernmost channel of Suisun Bay. However, **as** salinities increase in Suisun Bay **as** the summer progresses, the strength of the gravitational circulation increases until winter runoff flushes salinity out of the northern reach. In the following sections we suggest a revised conceptual model of how gravitational circulation works in **Suisun** Bay that at least qualitatively explains the depth, fortnightly and seasonal variability observed in the gravitational circulation.

Revised Conceptual Model of Entrapment in the Northern Reach

Officer (1976) developed a simplified model of gravitational circulation for a uniform channel that assumes a balance between the tidally averaged horizontal pressure gradient (which can be split into a density gradient component $\frac{\partial\rho}{\partial x}$ that drives the gravitational circulation and a water surface gradient component, essentially the tides, $\frac{\partial\zeta}{\partial x}$ and shear induced vertical mixing from the density current profile itself. On the basis of this balance he presented the following equation for the residual current profile.

$$u_z = \frac{g}{N_z}\cdot[\frac{1}{2}(H^2 - z^2)\frac{\partial\zeta}{\partial x} - \frac{1}{6\rho_o}(H^3 - z^3)\frac{\partial\rho}{\partial x}] \quad (1)$$

where u_z is the longitudinal residual velocity as **a** function of z, g is gravity, N_z is a vertical eddy viscosity (a vertical **mixing** parameterization), H is the mean depth, z is distance in the vertical direction measured positive from the bed, ζ is sea level, ρ is density, ρ_o is a reference density (usually taken to be that of fresh water), and x is distance in the horizontal (or along channel) direction. Officer's relation (Equation 1) describes the three principal factors we now believe control the strength of the gravitational circulation: the horizontal density gradient ($\frac{\partial\rho}{\partial x}$), depth ($H$), and vertical mixing ($N_z - \frac{U^2}{H}$). Although Officer's relation has the correct essential ingredients, it is based on a balance that is limited to the vertical **mixing** created by the density current profile itself and ignores vertical **mixing** by the tides.

Based on one-dimensional modeling of stratified water columns, we can construct (see Monismith ***et al*** 1995) an alternate parameterization of gravitational circulation strength based on a horizontal Richardson Number, Ri_x, whose formulation relies on a balance between the **mixing** energy of the tides $(- \frac{U^2}{T}$, which, when using a **straining** time scale, $[T - \frac{H}{U})$, gives $- \frac{U^3}{H}]$ and the potential energy from the gravitational circulation induced stratification $[- (\frac{\Delta\rho}{\rho_o}\frac{gH}{T})$ where **Ap** can be scaled assuming an advective balance **as** $(UT\frac{\partial\rho}{\partial x})$, which gives $(\frac{g}{\rho_o})UH\frac{\partial\rho}{\partial x}$, where $U, H,$ Tare appropriate velocity, depth, and time scales. This balance becomes:

$$\frac{U^3}{H} - \frac{g}{\rho_0}UH\frac{\partial\rho}{\partial x}, \quad (2)$$

which can be rewritten **as** a nondimensional'ratio:

$$Ri_x = \frac{g}{\rho_o}\frac{H^2}{U^2}\frac{\partial\rho}{\partial x} \quad (3)$$

The horizontal Richardson number, Ri_x, involves the same dependent variables **as** does Officer's relation [proportional to the horizontal density gradient, depth (squared), and inversely proportional to the tidal energy (U^2)] yet includes tidal **mixing** directly in its formulation and is, therefore, at least theoretically, more appropriately applied to macrotidal systems like Suisun Bay. A more intuitive form of Equation **3** is:

$$Ri_x = \frac{(\frac{g}{\rho_o})\frac{\partial\rho}{\partial x}}{(\frac{U}{H})^2} \quad (4)$$

where U is the near-surface velocity. In this form, Ri_x can be thought of **as** representing a ratio between the horizontal density gradient ($\frac{\partial\rho}{\partial x}$) that ***drives*** the gravitational circulation (which also stratifies and thereby stabilizes the water column) ***balanced against*** the (water column average) vertical shear $((\frac{U}{H}))$ squared, which tends to ***reduce*** the strength of the gravitational circulation through vertical mixing.

When the numerator in Equation 4 is large relative to the denominator, we Expect a strong gravitational circulation cell. Conversely, if the numerator is small and the denominator is large, we expect no gravitational circulation to develop. In between these extremes, a critical condition exists where the destratifying influence of the vertical shear is perfectly balanced by the density gradient induced stratification. Above this critical value, gravitational circulation exists; below it, vertical mixing by the tides inhibits its development. We refer to this condition **as** the critical horizontal Richardson number, $Ri_{x(crit)}$.

If we assume the horizontal Richardson number is a good predictor of the occurrence of gravitational circulation and that its critical value, $Ri_{x(crit)}$, is independent of position, then we can estimate, from data, the difference in the relative magnitude of the horizontal density gradient required for gravitational circulation to exist in Carquinez Strait and in Suisun Bay. For gravitational circulation to occur in Carquinez Strait we have,

$$\frac{g}{\rho_o}\frac{H^2_{car}}{U^2_{car}}\frac{\partial\rho}{\partial x}\Big|_{car} \geq Ri_{x(crit)} \quad (5)$$

and for gravitational circulation to occur in Suisun Bay,

$$\frac{g}{\rho_o}\frac{H^2_{sus}}{U^2_{sus}}\frac{\partial\rho}{\partial x}\Big|_{sus} \geq Ri_{x(crit)} \quad (6)$$

Equating the two Richardson numbers at criticality and rearranging,

$$(\frac{\partial\rho}{\partial x})_{sus} \approx (\frac{H_{car}}{H_{sus}})^2(\frac{U_{sus}}{U_{car}})^2(\frac{\partial\rho}{\partial x})_{car} \quad (7)$$

From the ADCP data collected last spring, we know that $H_{car} = 15m$, $U_{car} = 85cm/s$, and $H_{sus} = 8m$, $U_{sus} = 78cm/s$ (data collected near the naval weapons station, the velocity scale in both cases is the near-surface RMS current) so that Equation 7 becomes

$$(\frac{\partial\rho}{\partial x})_{sus} = 3(\frac{\partial\rho}{\partial x})_{car} \quad (8)$$

which suggests that for gravitational circulation to exist in **Suisun** Bay, it requires three times the horizontal density gradient required in Carquinez Strait.

Even though very little data have been collected that can be used to compute horizontal salinity (density) gradients (spring 1995 entrapment zone data will change this), the filtered ADCP data collected last spring are qualitatively consistent with the above discussion and suggest that in the relatively shallow channels (≈11m) of Suisun Bay, the magnitude of the horizontal salinity gradient is generally too weak in the spring to overcome the energy available from the tidal currents for vertical mixing. Conversely, deep waters like Carquinez Strait (≥18m) can sustain a gravitational circulation cell in the spring because:

1) Deeper waters require a smaller horizontal density gradient to exceed a critical horizontal Richardson number, and
2) Salinities "pile up" (topographically controlled) behind the change in depth that occurs near the Benicia Bridge, which locally confines and increases the horizontal salinity gradient in Carquinez Strait during the spring.

On the basis of the historical current neter data (Figure 6), it appears that gravitational circulation begins in the outhern channel in Suisun Bay in late ummer or early fall depending on fresh water inputs to the bay. Because the depths and the tidal energy generally vailable for vertical mixing in Suisun Bay are not markedly different between pring and fall (both of these time periods re during the equinoxes when the tidal nergy is weak, Figure 7), we hypothe- ze, based on Equation **3**, that the lack f gravitational circulation in Suisun Bay n the spring and its occurrence in the fall re due to an increase in the horizontal alinity gradient in the fall over that in he spring.

Long-Term Variations in Tidal Energy

The dynamics that control the magnitude of the net near-bed currents are among the most complicated in surface water physics since they involve shear-buoyancy interaction at turbulence time and space scales. The study of vertical mixing through turbulent interactions in a stratified water column is not only fundamental to understanding long-term transport processes in the estuary, but is essential to produce realistic long-term 3D model results (*eg*, the problem of turbulence closure). In this article, however, we skip over the complexities that occur at the turbulence and intertidal time scales (primarily because they are poorly understood) and provide instead a heuristic discussion of how the tidal currents affect density-driven residual transport. Moreover, an important goal of this research is to develop a relatively simple, easily measurable parameterization, like Ri_x, that predicts the occurrence of gravitational circulation, which could be related to ecosystem parameters and could easily be applied as a management tool.

The previous sections have discussed the dependence of the gravitational circulation on the depth, H, and on the horizontal density gradient, $\frac{\partial\rho}{\partial x}$. From Equation 3, we see that the magnitude of the tidal currents, U, also play a role (*eg*, inversely proportional to the tidal current squared). In fact, variations in the current, U, change Ri_x substantially more than do the horizontal density gradient, $\frac{\partial\rho}{\partial x}$, variations. When the overall magnitude of the currents are higher, during spring tides, we see reductions in the strength of the gravitational circulation. Conversely, during periods of generally weak tidal currents (neap tides), when vertical mixing is less, increased gravitational circulation is observed. Figure 7 shows the variation in tidal energy (proportional to $<u^2>$ where the $< >$ represent a tidal filter) throughout the year for 1991, 1992, and 1993. Although this plot looks deceptively like a tidal record, each local maximum on this plot represents a spring tide and each local minimum a neap tide. From Figure 7, one can see that the tidal energy available for vertical mixing changes significantly within the year and between years. The solstices are periods of maximum tidal range and weakest neaps. Conversely, the vernal and autumnal equinoxes are periods of minimal tidal range and energetic neap tides. The 1992 and 1994 ADCP data were collected near the vernal equinox during a period of energetic neap tides. The energetic neap tides in combination with what we believe were relatively weak horizontal density gradients (the density gradients were not actually measured) likely account for the observed lack of net upstream bottom currents in Suisun Bay during the spring of 1992 and 1994.

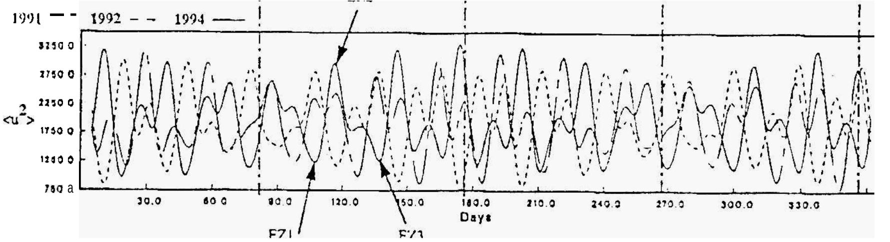

Figure 7
FILTERED PREDICTED CURRENT SPEED SQUARED AT MALLARD ISLAND FOR CALENDARYEARS 1991,1992, AND 1994
The labels **EZ1, EZ2**, and EZ3 represent the times when the biological synoptic sampling occurred.

In summary, our revised conceptual model of the northern reach based on Eulerian measurements is **as** follows:

(1) The depth dependence in Equation 3 explains, in part, why we see strong gravitational circulation in Carquinez Strait (H≥19m) and none in Suisun Bay (H≈11m) in the spring.
(2) The inverse relation to velocity squared, U^2, in Equation 3, accounts for the spring/neap modulations in gravitational circulation strength. The velocity squared is an index of the tidal energy available for vertical mixing. Increased vertical mixing from the increased tidal energy available during spring tides breaks down stratification, which effectively short circuits the gravitational circulation induced two-layer flow.
(3) The horizontal density gradient, $\frac{\partial\rho}{\partial x}$, drives the gravitational circulation; without it, gravitational circulation does not exist. The strength of the horizontal density gradient in proportion to the depth squared and in inverse proportion to the velocity

squared (eg, the horizontal Richardson number) provides a possible explanation for the absence of gravitational circulation in the spring in Suisun Bay and its occurrence in the fall. Although there have been very few data collected in Suisun Bay from which horizontal salinity (density) gradients can be calculated, we hypothesize that the density gradient in the spring may be too weak to drive the gravitational circulation (eg, the horizontal Richardson number is less than its critical value in the spring). During the summer, salinities and the horizontal salinity gradient increase until the horizontal Richardson number exceeds its critical value, and gravitational circulation occurs.

(4) A semi-permanent null zone (and possibly a turbidity maximum) is probably located near the Benicia Bridge in the spring. At the very least, net near-bed currents are significantly reduced in the channels of western Suisun Bay from what they are in Carquinez Strait. A null zone probably moves from near the Benicia Bridge into Suisun Bay and possibly as far as the Western Delta sometime during the late summer when the horizontal density gradients become strong enough to overcome tidal mixing.

Management Implications

This revised conceptual model has signif cant implications to proposed dredgin in Suisun Bay and to the generally accepte hydrodynamic explanation for the tu bidity maximum and the entrapmen zone.

If the depths near the Benicia Bridge ar significantly lowered (dredged from 11r deep and 92m wide to 14m deep an 183m wide) as part of the John F. Balc win and Stockton ship channel dredgin projects (USACOE 1989), the bath metric control that reduces the strengt of the gravitational circulation in Suisu Bay from what it is in Carquinez Strai will be moved from the vicinity of th Bridge into the interior of Suisun Ba (Point Edith). This change in bath metry could result in elevated salinitie in Suisun Bay and the Western Delta. detailed hydrodynamic study in the are adjacent to the Benicia Bridge is needec however, to verify the importance an extent of this topographic control.

Given that gravitational circulation wa not measured in Suisun Bay in the sprin of 1992 and 1994, what does this impl about the existence of a turbidity max mum or entrapment zone based o existing conceptual models? Numerou publications (Arthur and Ball 1979 Peterson *et al* 1975; and others) hav explained the turbidity maximum and entrapment zone as resulting from a hydrodynamic null zone. The lack of measured net up-estuary bottom currents in Suisun Bay in the spring suggests that if a turbidity maximum or entrapment zone does exist in the spring, a mechanism other than gravitational circulation must be responsible for it.

Conclusions and Ongoing Research

It is not surprising that a gravitational circulation/null zone based model of entrapment persisted, because much of the hydrodynamic data were collected in the fall when gravitational circulation has been observed in Suisun Bay (Figure 6). The horizontal Richardson number accounts, at least qualitatively, for the observed spatial and temporal variations in the gravitational circulation. However, before the revised conceptual model presented in this article can be accepted, a long-term (spring through fall) study is needed in which all of the parameters in the horizontal Richardson number are directly measured. This study is now under way. Seven ADCP-CTDs were deployed in Suisun Bay in late May 1995. The location of other *in situ* hydrodynamic instrumentation (Figure 8) was carefully chosen to measure all of the relevant parameters in the horizontal Richardson number along the axis of the northern reach. Moreover, because gravitational circulation does not appear to dominate spring-summer residual transport in the southern reach of Suisun Bay, shallows/channel exchange is likely to play a significant role. Therefore, six current meters with CTDs were deployed in the shallows of both Grizzly and Honker Bays in early July 1995 to address shallows residence times and shallows/channel exchange processes. Most of the instruments in this study were recovered in mid-September; the rest were recovered in mid-October 1995.

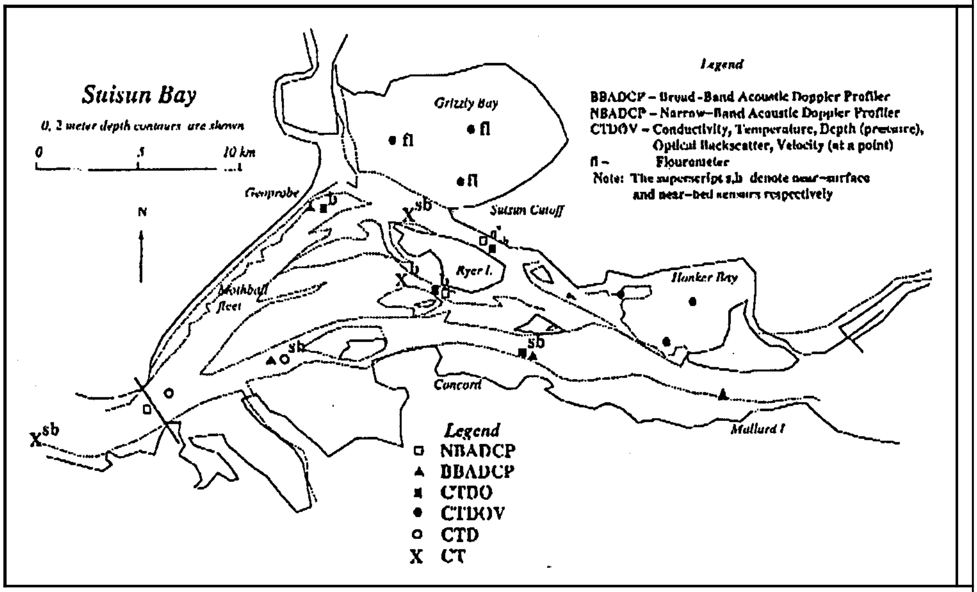

Figure 8
POSITIONS OF *IN SITU* INSTRUMENTS IN 1995
Channel stations were deployed the first week of June; shallows stations were deployed the first week in July.

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