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Location of the Non-tidal Current Null Zone in Northern San Francisco Bay

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Variations in Sacramento–San Joaquin River discharge into northern San Francisco Bay causes shifts in location of the bottom density current null zone. At a river flow of 2000 m^3/s this null zone is approximately 20 km from the seaward end of the estuary, whereas at a river flow of 100 m^3/s it is 80 km from the seaward end; the corresponding distances of salinity penetration are approximately 40 and 90 km from the seaward end. Seaward of the null zone, during low (summer) river discharge conditions, the inward-flowing bottom density current appears typically strong (5–15 cm/s) relative to the outward-flowing river current (river discharge per unit cross-channel area) of <2 cm/s. Landward from this null zone the average river current increases with decreasing cross-channel area. This circulation implies that during the summer water within the null zone has the longest average advective replacement time relative to water seaward or landward of the null zone.

Introduction

When measurements of currents in estuaries are averaged over one or more tidal cycles, the mean or residual flow is considered non-tidal. This flow may consist of density-, river- and wind-induced components. Because of the density difference between river and sea water in estuaries, there is a constant tendency of landward flow of sea water beneath the net seaward flow of the less dense, lower salinity surface water [Figure 1(a)]. At the river end of the estuary, however, the mean river flow is seaward at all depths.

Therefore, at some area within the estuary–river system there exists a zone where the bottom density and the river currents have equal and opposite effects. This zone has been defined as the null zone where the mean near-bottom current speed is zero (e.g. Hansen, 1965).

Two significant effects can be attributed to the presence of a null zone in estuaries: (1) it is typically the area of most rapid sediment accumulation (Simmons, 1955; Inglis & Allen, 1957) and; (2) highest concentrations of suspended particulate matter occur there (Glangeaud, 1938; Postma, 1967; Schubel, 1968; Meade, 1972). In addition to these two well documented effects we wish to suggest that a water column in the null zone experiences the longest advective replacement time. The prolonged advective replacement time, which is defined later, may affect the distributions of time-dependent properties such as viable planktonic organisms and consequently water chemistry.

Few estuarine studies have investigated the position of the null zone relating to variations in river discharge. Landward movement of this zone with decreasing discharge has been noted in the Savannah River (Simmons, 1955), the Thames River (Inglis & Allen, 1957) and the Columbia River (Hansen, 1965) estuaries. In San Francisco Bay, the estuary of the Sacramento–San Joaquin Rivers (Figure 2), results of previous unpublished hydrographic investigations have emphasized tidal movements. Although the non-tidal and inward-flowing bottom density currents have been indicated as a major mechanism for the landward transport of salt in San Francisco Bay (Grimm, 1931), few estimates of these non-tidal currents are available (Conomos et al., 1971*a, b*).

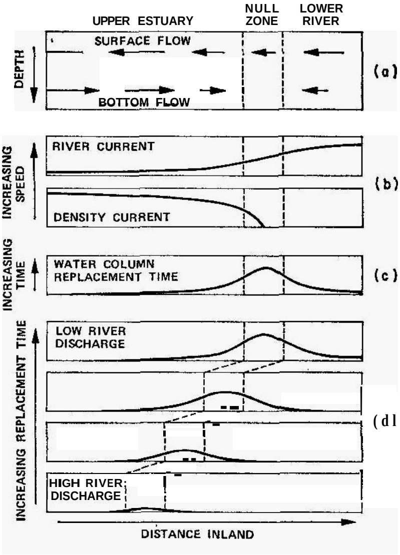

Figure 1. (a) Schematic representation of net drift in vertical section through a river-estuarine system; arrow lengths indicate relative current strength.
(b) Longitudinal variation of average river and density currents.
(c) Combined influence of river and density currents results in a longitudinal variation in the average advective water-column replacement time.
(d) Increasing river discharge diminishes water-column replacement time and shifts the null zone seaward.

In this paper we briefly describe variations in the location of the density and river current null zone in the main channel of Northern San Francisco Bay relative to variations in river discharge, but we do not attempt to explain its geographic position. Particular emphasis is given to low-river-discharge conditions (summer) when the average speed of the river current (river discharge per unit cross-channel area) is small relative to the speed of the bottom density current. For this discussion we have used unpublished current velocity data from the U.S. Army Corps of Engineers. These measurements lack temporal and spatial detail, but they are the only data available suitable to define the change in location of the null zone with seasonal changes in river discharge.

Methods

Water velocity measurements were made at half-hourly intervals with Price type AA current meters (Carter & Anderson, 1963) at five depths and eight stations throughout the estuary (Figure 2) during a wide range of river discharges from 1956 to 1969 (Table 1). The record lengths varied from 24 to 31 h. Because of a lack of more detailed and longer term current measurements, mean monthly Sacramento–San Joaquin River discharge measurements were used to represent the river inflow conditions to San Francisco Bay during the current surveys. Salinity was determined at hourly intervals concurrent with the velocity measurements; mean profiles were constructed from these data.

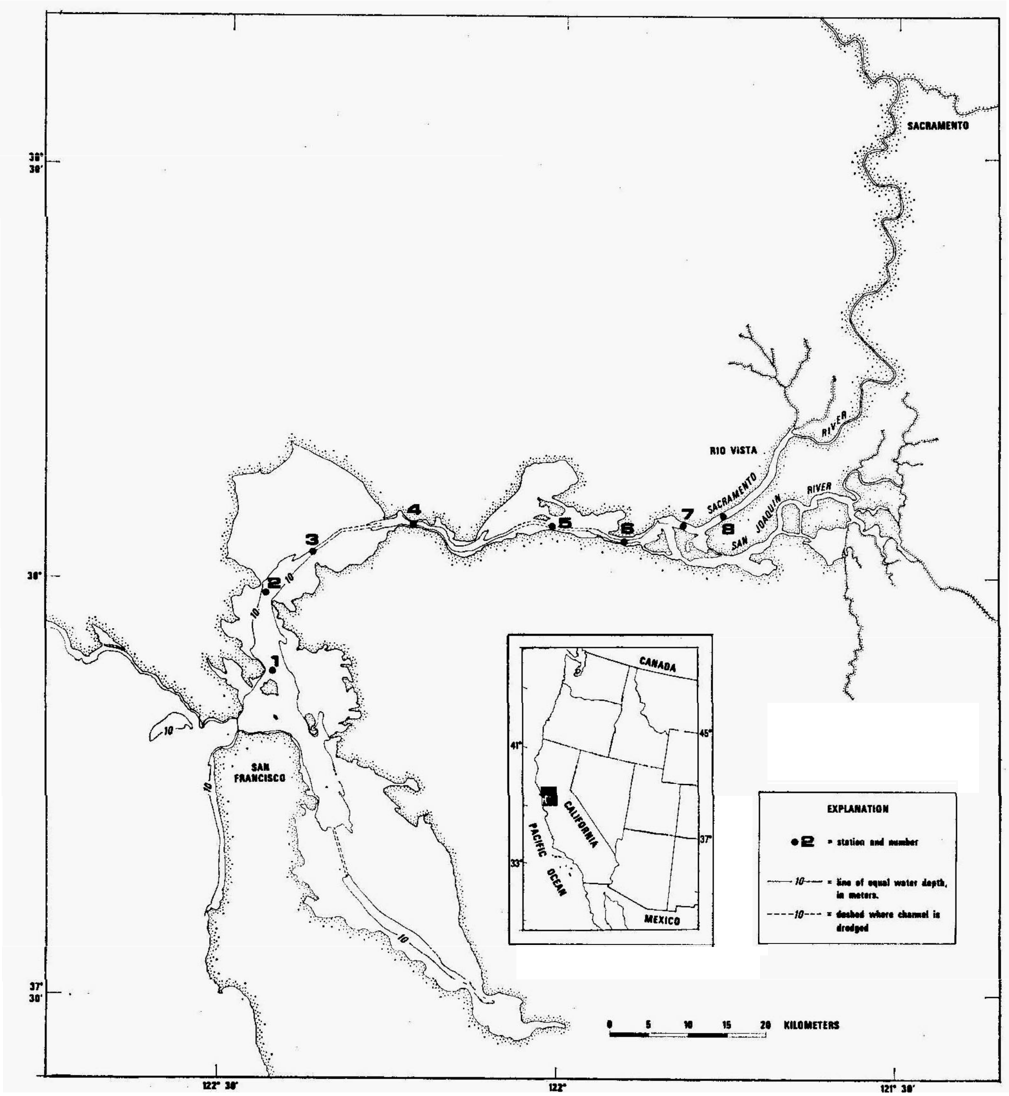

Figure 2. The San Francisco Bay system and environs showing locations of stations (1–8) where water velocity and salinity were measured.

Estimates of the non-tidal velocities, which may contain wind-, river- and density-induced components, were obtained by harmonic analysis of velocities using the method of least-squares. Because the tides are of a mixed nature, a Fourier function containing diurnal (24·8-h period) and semi-diurnal (12·4-h period) harmonics was used. Only the constant, i.e. non-tidal, current component extracted by the harmonic analysis is discussed below.

Results

Non-tidal current speeds and mean salinities for all available data are shown in Figure 3. The only possible estimate of the reproducibility of non-tidal currents for these records was made using the first 248 h and the last 24·8 h of velocity measurements taken over a 31-h period (i.e. a comparison with one-fifth non-overlapping measurements). The mean difference between non-tidal currents estimated from these data (the 300 m^3/s data in Figure 3) for five depths at six locations was 0·5 cm/s with a range of 1·8 cm/s. Assuming a fivefold (linear) extrapolation of the mean difference obtained using these one-fifth non-overlapping measurements, we consider the reproducibility of non-tidal current speeds to be about 3 cm/s. This estimate of reproducibility cannot account for variations with periods longer than fractions of a day. Such variations caused by changes in river discharges or wind may be large (Bowden & Gilligan, 1967). In this paper, non-tidal currents less than 3 cm/s are considered weak and variable.

Table 1. **Dates of water velocity and salinity measurement and corresponding monthly mean Sacramento–San Joaquin River discharge to San Francisco Bay estuary.**

Stations[a]	Date	Discharge[b] (m^3/s)
1, 2, 3, 4, 5, 6	21–22 September 1956	300
1, 2, 3, 4, 5	13–14 February 1958	2300
4, 5, 6, 7, 8	13–14 September 1967	400
4, 6, 7, 8	28–29 March, 1968	1000
6, 7, 8	27–28 August 1968	100
6, 8	12–14 May 1969	1700

[a] Station locations indicated in Figure 2.
[b] Data from U.S. Bureau of Reclamation, Sacramento, California.

Non-tidal velocity profiles (Figure 3) show the expected seaward flow of low salinity water and landward flow of deeper high salinity water. During low river discharge conditions (100 m^3/s), the non-tidal flow weakens to values approaching the 3 cm/s limit of uncertainty. The approximate position of the null zone varies from stations 1 and 2 for a river discharge of 2000 m^3/s to stations 5 and 6 for discharges of 300 and 400 m^3/s, a longitudinal shift of more than 40 km.

The river current, which is defined as the river discharge divided by cross-channel area, typically exhibits large seasonal variation (Figure 4). During the high-river discharge (2300 m^3/s) the estimated river current of about 1 to 3 cm/s at the seaward end of the estuary is similar to that 80 km landward during low-river discharge (100 m^3/s). As an extreme example, during the 1862 flood, when the river discharge was estimated to exceed 100 000 m^3/s (Young, 1929) the river current at the Golden Gate would have exceeded 100 cm/s.

In contrast to the expected large variations in river current (as much as two orders of magnitude), the variations in bottom density current have been observed to be much smaller. Maximum near-bottom non-tidal current speeds obtained here vary from 5 to 15 cm/s for river discharges varying from 300 to 1000 m^3/s (Figure 3). These speeds are comparable to maximum bottom drifter speeds in San Francisco Bay of 6 cm/s (Conomos *et al.*, 1971*a*, *b*) and to maximum non-tidal currents determined by current meter of 10 to 20 cm/s in the Mersey estuary (Bowden & Gilligan, 1971) and of about 10 cm/s in the James River estuary (Pritchard, 1967).

Discussion

Location of the null zone

The null zone migrates longitudinally in response to changes in river discharge (Figure 3). An explanation for this is that the null zone can be considered to be the area where the bottom density and river currents are equal and opposite. However, when the river current increases, the density current does not increase proportionally.

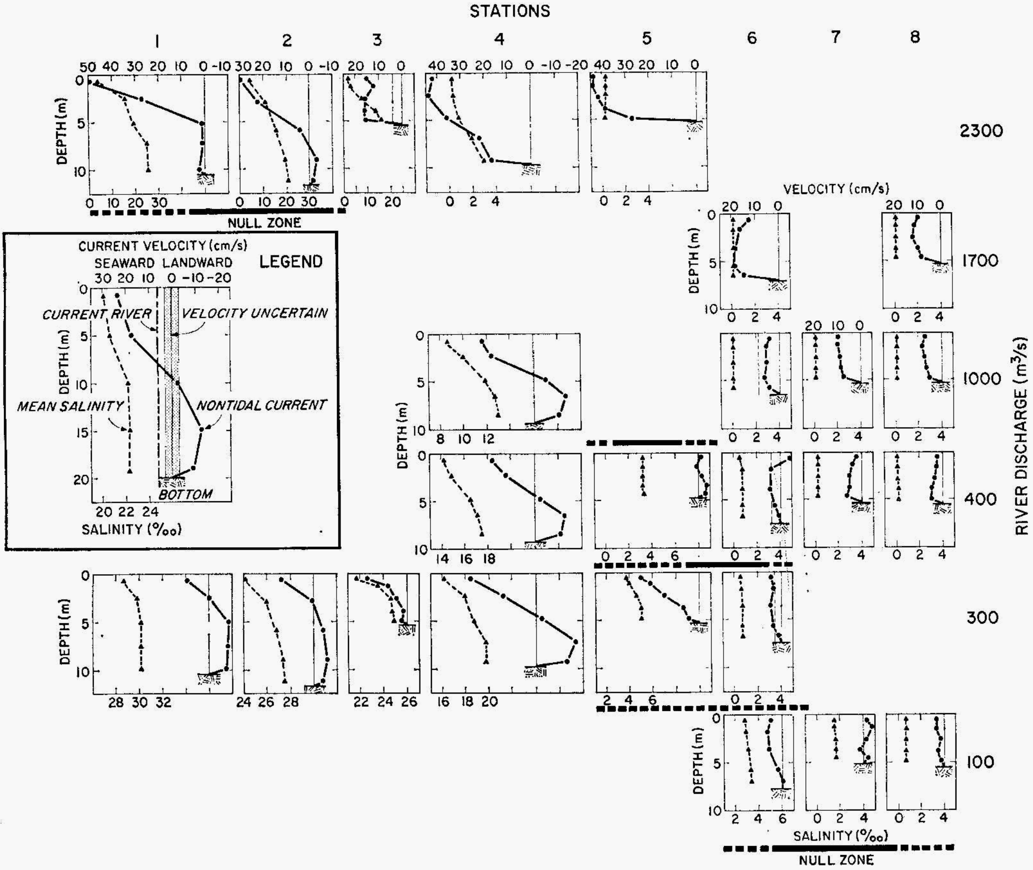

Figure 3. Non-tidal currents and mean salinity at Stations 1 through 8 (Figure 2) in San Francisco Bay estuary during different river discharge conditions. Profiles are from half-hourly velocity and hourly salinity measurements over a 24·8-h tidal cycle. The location of null zone is indicated by a solid line beneath the velocity profiles where the position is defined by the data and by a dashed line where it is inferred. Blank spaces indicate no measurements were taken.

Because variations in river current are much greater than variations in density currents, the location of the null zone will be modulated predominantly by varying river discharge. The few data available show that the null zone will be located generally in areas of the estuary where the river current is in the order of a few cm/s (as opposed to tens of cm/s). For example, in Northern San Francisco Bay, during typical low discharge conditions (300 m^3/s), the null zone was located more than 50 km landward from Golden Gate where the river current was about 2 cm/s (Figures 3 and 4). Throughout the season the river current just landward of the null zone was between 1 and 9 cm/s (dashed lines, Figure **3)**. The null zone may have been seaward of Golden Gate during the flood of 1862 when the surface current at Golden Gate was not reversed by the rides for 10 days, and the surface water was entirely fresh (Young, 1929).

These observations in San Francisco Bay agree with the few other such data that are available. In the Thames River estuary, the estimated river current near the null zone during 130 m^3/s discharge (when the estuary could be characterized as mixed) was less than 3 cm/s (Inglis & Allen, 1957). Similarly in the Columbia River estuary during 4900 m^3/s discharge (when the estuary could be characterized as stratified), the river current near the null zone was about 10 cm/s (Hansen, 1965).

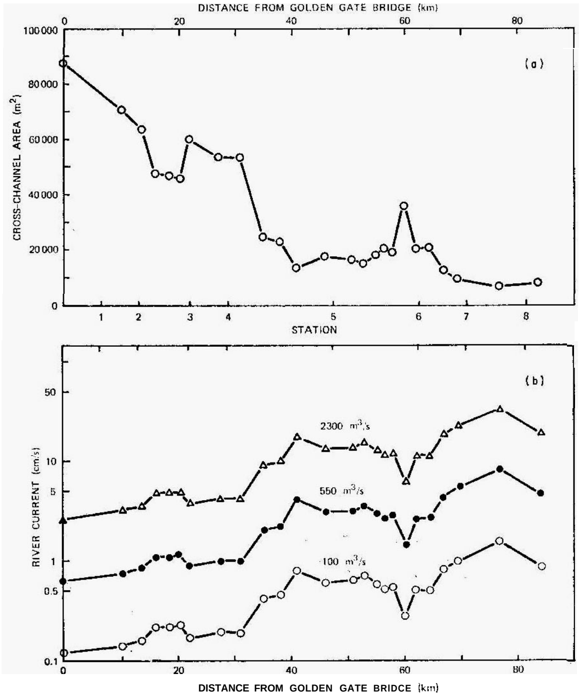

Figure 4. Distribution of cross-channel area and estimated river flow per unit cross-channel area with increasing distance from the seaward end of the estuary. Data for cross-channel area from Glenne & Selleck (1969).

Thus the location of the null zone changes markedly, mainly in response to seasonal variations in river discharge. In the following we will discuss an important consequence of estuarine circulation, the relatively long advective replacement time of water parcels in the null zone.

Water-column replacement time

Methods of estimating the water replacement, residence, or flushing time of estuaries have been reviewed by Bowden (1967). Water-column replacement time is defined as the average time required for water to enter and leave the estuary. It is controlled by river discharge, density current, tidal mixing and wind-induced currents. Advective water-column replacement time, τ, as used in this paper, is the average time required for the water to flow through a unit length of the estuarine system,

$$\tau = \left\{ \frac{1}{s} \int_{b}^{0} w|v|\,\mathrm{d}z \right\}^{-1},$$

where $|v|$ is the absolute value of the landward or seaward current speed, s the cross-channel area, w the depth-variable channel width, z the water depth, and the integration is performed from the bottom, b, to the surface, 0. This definition is not to be confused with the general definition of advective residence time for an estuarine system. It is used to illustrate variations in the average, longitudinal, advective water flow within an estuarine system regardless of the direction of flow.

The water-column replacement time in an idealized estuary can be considered to result from the combination of river and density current variations (Figure 1). In this simple case, wind effects are absent (or can be considered to contribute primarily to turbulent processes); cross-channel variations in current speeds are removed by averaging; and cross-channel areas decrease in a landward direction. The river current (river discharge per unit cross-channel area) decreases in a seaward direction as the cross-channel area increases [Figure 1(b)], while density currents decrease landward and ultimately vanish [Figure 1(c)]. These opposing flows produce an area of longest advective replacement time in the null zone [Figure 1(d)].

If a purely advective model (Figure 1) is to illustrate meaningful properties of the estuary, then obviously the advective replacement rates must be large compared with diffusive rates. Estimates of the relative importance of these two processes require considerably more detail than given here (Bowden & Gilligan, 1971; Hansen & Rattray, 1966; Hansen, 1965). In lieu of this detail, a number of observations are available which suggest that advection is important to the null zone and to water replacement time.

Longitudinal distribution of properties

In the upper region of partly-mixed estuaries high concentrations of suspended particulate matter and rapid sediment accumulation rates are common (Glangeaud, 1938; Postma, 1967; Schubel, 1968; Meade, 1972). This area is typically one of rapid sediment accumulation (Simmons, 1955; Inglis & Allen, 1957). The position of such concentrations of suspended particles (the turbidity maximum) in San Francisco Bay (Figures 5(a), 6; Figure 8 in Meade, 1972; Conomos & Peterson, in press) correlates well with the null zone location.

This maximum is composed of not only inorganic riverborne and resuspended sediments but also a biogeneous fraction which increases in relative abundance during the low discharge summer months [Figure 5(c) and (d)]. The biogeneous component is made up of phytoplankton (McCarty *et al.*, 1962; Storrs *et al.*, 1963, 1964; Bain & McCarty, 1965; Peterson *et al.*, in press) and zooplankton (Painter, 1966; Turner, 1966; Turner & Heubach, 1966; Heubach, 1969). Highest phytoplankton productivity is found in the turbidity maximum (Conomos & Peterson, in press; Peterson *et al.*, in press).

Sedimentologists have explained the presence of turbidity maxima by the advective transport which maintains particulate matter at the convergence of the landward flowing density current and the seaward-flowing near-bottom river current (Figure 1; Glangeaud, 1938; Postma, 1967; Schubel, 1968; Meade, 1972). Also, this estuarine circulation cell has been cited as an important zooplankton transport mechanism and the null zone defines the landward extent of advective zooplankton penetration (Alexander *et al.*, 1931, 1935; Rogers, 1940; Pritchard, 1953; Bousfield, 1955; Barlow, 1955; Hulbert, 1957; Pearcy & Richards, 1962; Cronin *et* al., 1962; Bayly, 1965; Cronin & Mansueti, 1971; Massmann, 1971; Graham, 1972). Neither the increased concentration of inorganic suspended particulate matter or of plankton in the upper estuary can be explained by horizontal diffusive processes because such diffusion would tend to destroy a maximum.

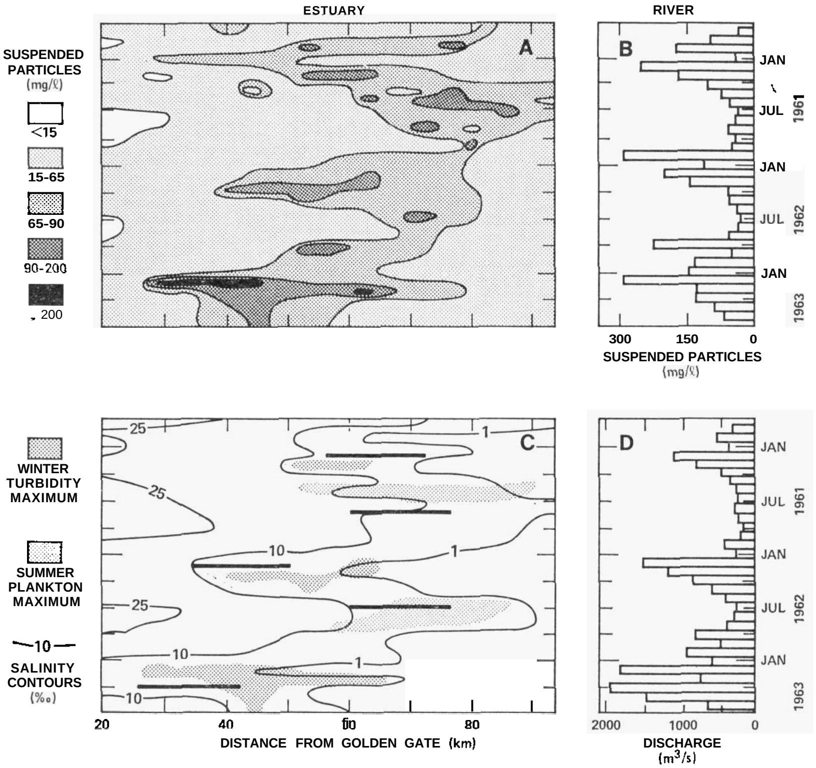

Figure 5. Seasonal distribution of properties in the northern reach of San Francisco Bay, **1961-63.**
(a) Suspended particle abundance.
(b) Suspended particle abundance in Sacramento River.
(c) Salinity and turbidity maximum as determined by particle concentrations of a 2-m depth; winter maxima composed predominantly of river-borne lithogenous particles; summer plankton maximum is the area of phytoplankton numbers greater than 1000 per ml. Approximate locations of null zone are indicated by solid black lines. Suspended particle and salinity data in estuary from Storrs *et al.*, **1963, 1964.**
(d) Combined monthly-mean discharges of Sacramento and San Joaquin Rivers.

This transport mechanism may not adequately explain why phytoplankton productivity is higher in the turbidity maximum than elsewhere in the estuary. The occurrence of longest water-column replacement times in the null zone permits the plankton population to increase its numbers by growth; and conversely, when the residence time of a water parcel is short relative to the time-scale of phytoplankton growth rates, the phytoplankton do not have sufficient time to increase their population size through reproduction. Hence, the longer water-column residence time, and possibly the particle convergence, would favour the development of large standing stocks of plankton in the upper estuary. It has been observed, for example, that both the highest productivity and phytoplankton standing stocks are associated with the null zone in San Francisco Bay (Peterson *et* al., in press).

While many factors, both physical and biological, may be important to the development and maintenance of plankton distributions in estuaries, it must be emphasized that before variations in a plankton population can be attributed solely to physiological differences (i.e. growth rate effects controlled by salinity and temperature), the distributional effects due to variations in physical processes must be clarified (Ketchum, 1954; Barlow, 1955). To our knowledge, only the studies of the Tees estuary by Alexander *et al.* (1931, 1935) describe both the non-tidal circulation and plankton distribution in a river-null zone-estuary system.

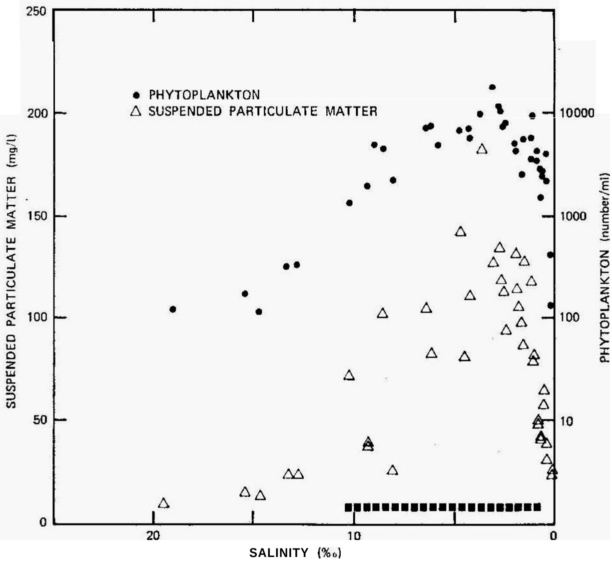

Figure 6. Distribution of suspended particulate matter and phytoplankton relative to salinity, 19 June 1961 (Data from McCarty *et al.*, 1962); monthly-mean Sacramento–San Joaquin River discharge is 120 m³/s. Dashed lines indicate approximate salinities of null zone in Figure 3 during similar river discharge on 27–28 August 1968.

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