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SUSPENDED-PARTICLE TRANSPORT AND CIRCULATION IN SAN FRANCISCO BAY: AN OVERVIEW

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Circulation, Sediments, and Transfer of
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SUSPENDED-PARTICLE TRANSPORT AND CIRCULATION IN SAN FRANCISCO BAY: AN OVERVIEW

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ABSTRACT: Differences in the relative magnitude and timing of wind stress and river inflow in the northern and southern reaches of San Francisco Bay create different sedimentary conditions. The northern reach is a partially to well mixed estuary receiving most of the total annual fresh-water input (840 m^3 sec^{-1}) and suspended sediment input (4×10^6 metric tons) into the bay; more than 80% of the sediment is received during winter. Density-driven nontidal estuarine circulation (~5 cm sec^{-1}) maintains a turbidity maximum which changes seasonally in particle concentration (40 to 80 mg $litre^{-1}$). Strong tidal currents (≤225 cm sec^{-1}) and wind-generated waves resuspend sediment from the shallow bay floor: some of the riverborne sediment deposited during winter is resuspended during summer and transported landward to the turbidity maximum. Long-term sediment data (extrapolated from bathymetric charts) indicate that the northern reach is an effective sediment trap. In contrast, long-term sediment data suggest that the southern reach is experiencing net erosion. The southern reach receives little river inflow or riverborne suspended sediment, and the average nontidal circulation is weak (≤2 cm sec^{-1}). The principal source of suspended sediment (25 mg $litre^{-1}$) in the southern reach is the shallow bay floor (average depth 6 m).

INTRODUCTION

The impact of man's modification of San Francisco Bay has been extreme in its effects on the sedimentological aspects of the estuarine system. Large-scale modification began when placer mining (1848 to 1884) introduced huge quantities of sediment to the bay (11). These sediments caused extensive shoaling with as much as 1 m of sediment deposited in the northern reach. In addition to shoaling, the area of the bay has been reduced substantially by filling in and diking of the margins (22). The resulting volume decrease reduced the volume of

the tidal prism which in turn has decreased the tide-relate[illegible]ng of the bay waters.

The flushing problem is worsened by significant and continuing diversions of the Sacramento-San Joaquin River discharge, the major source of fresh-water inflow to the bay (12). This inflow adds large quantities of suspended sediment that are necessary for present ecological balance (14, 17), and generates an estuarine circulation cell which causes significant nontidal exchange with ocean water and which generates and maintains a turbidity maximum (4, 25).

Our purpose is to describe the suspended-sediment dispersal and the processes controlling this dispersal in order to provide an overview of the sedimentary environment. Particular emphasis is placed on summarizing previous studies and data from our own studies into a conceptual model that conforms with recent scientific advances in estuarine sedimentology (19).

In this paper we 1) describe the bay environment, emphasizing the agents that supply, resuspend, and transport sediment; 2) present a scenario that describes dispersal patterns within the bay and the nearby ocean, comparing and contrasting seasonal differences between the dissimilar northern and southern reaches of the bay; and 3) examine expected future changes in the sedimentary regime.

ENVIRONMENTAL SETTING

The San Francisco Bay system occupies a structural trough formed during the late Cenozoic. During the Pleistocene glaciation, the bay was part of a great drainage basin of the ancestral Sacramento, San Joaquin, and Coyote rivers (Fig. 1) in which sediment accumulated. The most recent sediments were deposited during the Wisconsin transgression which began 14,000 BP (31).

The bathymetry reflects the subaerial stream processes during the Pleistocene. The bay is relatively shallow, having an average depth of 6 m at mean lower low water (Table 1) or 2 m if the large expanses of mudflat are included (Fig. 2). The deepest point is Golden Gate where water depths exceed 100 m. The area has been reduced by 37% in the last 100 years from its natural state to its present 1.24×10^9 m^2 by shoaling caused by the inflow of hydraulic mining debris (11) and by land reclamation (22).

The prevailing wind flow, northwesterly and westerly maritime air, is strongest during summer, reaching average speeds greater than 4 m sec^{-1} (Fig. 3E, F). Although prevailing winter wind speeds are lower, biweekly storms cause southeasterly and southerly winds that can exceed 18 m sec^{-1} (Fig. 3F). Diurnal wind variations are greatest during summer, with typical afternoon speeds (9 m sec^{-1}) three times faster than morning speeds (20).

Prevailing summer winds generate waves with significant wave periods of 2 to 3 sec (29). During winter storms, 5-sec waves can be generated. Offshore, swell with periods 8 to 12 sec are common; during winter, 18-sec waves are moving landward (21). In addition to generating waves, the wind stress creates nontidal water mov[illegible] with speeds a few to several percent that of the wind speeds (cf. 30).

The tides are mixed and predominantly semidiurnal (6). The diurnal tidal range varies from 1.7 m at Golden Gate to 2.7 m at the south end of the southern reach. This creates a large tidal prism (Table 1) that is about 24% of the bay volume. The tides create currents that are strongest in the channels and that maintain the original Pleistocene stream valley topography. Maximum speeds of 225 cm sec^{-1} are present at Golden Gate and Carquinez strait and 100 cm sec^{-1} near station 32 (Fig. 1). There is tidal mixing between waters of the northern and southern reaches, with typical excursions of 10 to 12 km.

More than 90% of the mean annual river discharge (840 m^3 sec^{-1}) entering the bay is contributed to the northern reach by the combined flows of the Sacramento and San Joaquin rivers (Table 1); the remaining 10% is contributed

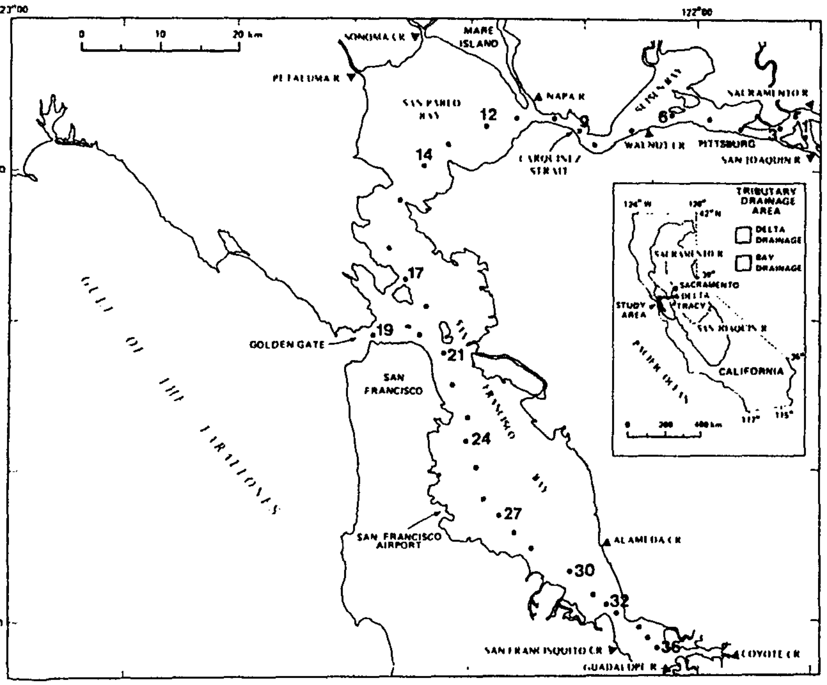

Figure 1. The San Francisco Bay system comprises Suisun Bay, San Pablo Bay, and San Francisco Bay, but is termed San Francisco Bay herein. The northern reach is Suisun Bay, San Pablo Bay and the northern portion of San Francisco Bay (to Golden Gate). The southern reach is San Francisco Bay south of Golden Gate. Station numbers are established hydrographic stations occupied near-monthly from 1969 to 1975. The drainage basins of the Sacramento-San Joaquin River system and of the peripheral streams are in inset.

by small tributary streams and sewage inflow. River ru[illegible] greatest during winter (Fig. 3A).

Dilution of Pacific Ocean water entering Golden Gate by seasonally varying river discharge controls the salinity distribution (Fig. 3B). Water density is controlled by salinity, as bay-wide synoptic water temperature variations rarely exceed 3°C. The geographic distribution of river discharge and vertical salinity field (Fig. 4A, C) shows that the northern reach varies as a partially mixed estuary with vertical salinity differences often 10‰ during winter and as a well mixed estuary with a vertical salinity difference less than 5‰ during summer. The southern reach is an embayment with seasonally varying water properties that are largely controlled by water exchanges from the northern reach and the Pacific Ocean. Intrusion of low salinity water into the southern reach is particularly evident during winter periods of wet years (Fig. 4A; 18). Some salinity stratification is present during winter, whereas during summer the water is nearly isohaline with depth because of vertical mixing caused by tidal currents and wind.

Analyses of current meter data (unpublished) indicate dissimilar long-period (several days) fluctuations in water movement in the northern and southern reaches. The waters of the southern reach have little net motions throughout the

Table 1. Geostatistics of San Francisco Bay

Statistic	Value
Area (MLLW)[1]	1.04×10^9 m^2
Including mudflats	1.24×10^9 m^2
Volume[1]	6.66×10^9 m^3
Tidal prism[2]	1.59×10^9 m^3
Average depth[3]	6.1 m
From hypsometric curve[4]	2 m
River discharge (annual)	20.9×10^9 m^3
Delta outflow[5]	19.0×10^9 m^3
All other streams	1.9×10^9 m^3
Suspended sediment inflow (annual)[6]	
Into delta	4.7×10^6 metric tons
From delta into bay	3.3×10^6 metric tons
All other streams	0.9×10^6 metric tons
Total into bay	4.2×10^6 metric tons
Sediment accumulation rate[7]	350 mg cm^{-2} yr^{-1}

1 Planimetered from Fig. 2; at mean lower low water
2 From (7).
3 Volume divided by area; at mean lower low water
4 Obtained graphically from hypsometric curve and includes mudflats (Fig. 2).
5 From (9).
6 From (27); measured from 1957-1959
7 Assuming uniform deposition throughout bay, no dredging, and no sediment loss to ocean; obtained from annual suspended sediment inflow divided by area of bay (including mudflats).

10*10^6 yd^3 * 765 l/yd^3 * 1-2 kg/l * 1 metric ton/1000 kg
= 7.6-15*10^6 metric tons

column (herein termed nontidal), whereas in the northern reach and at Golden Gate, estuarine circulation is clearly defined (25).

Our 3-year study using bimonthly releases of surface and seabed drifters (3, 5) has verified these observations (Fig. 5). The northern reach-ocean section has a permanent estuarine circulation cell maintained by the density difference between Sacramento-San Joaquin River water and seawater. This density difference produces a constant net landward bottom flow of dense seawater in opposition to net seaward flow of less dense river water. These currents have equal and opposite effect on the nontidal flow in the null zone (25). The null zone can be portrayed graphically by the convergence of seabed drifters (Fig. 5B). In contrast, the southern reach, because of the small supply of river inflow and therefore the weaker salinity stratification, does not exhibit two-layer estuarine circulation, but has seasonally reversing near-bottom and surface currents. The strong prevailing winds of summer alter any weak density-induced circulation and control the nontidal drift (Fig. 5, inset). The effect of winter storms causing strong episodic water movements in the southern reach is major but has not been evaluated.

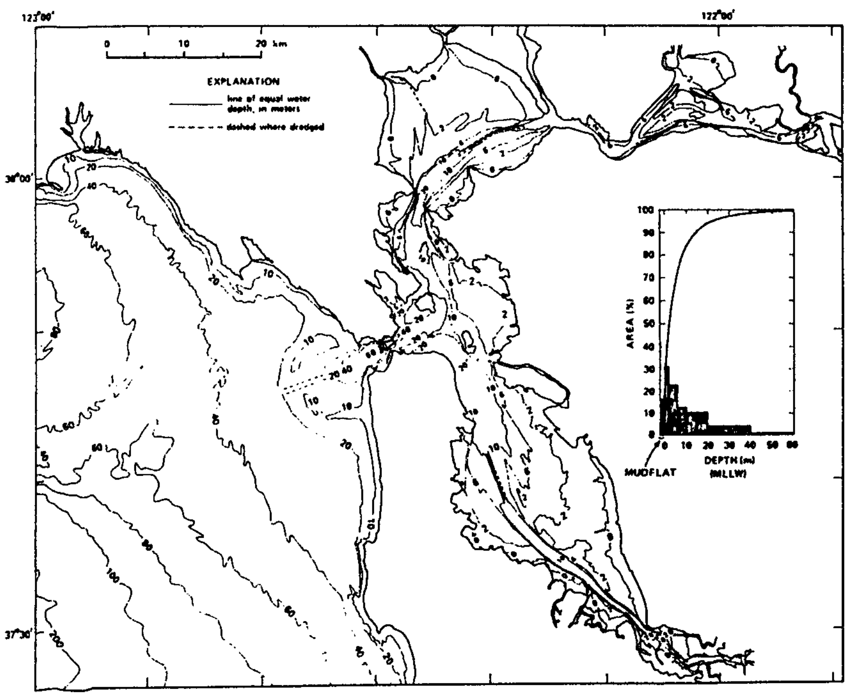

Figure 2. Bathymetric chart of San Francisco Bay. Compiled from CGS charts 5531, 5532, 5533, 5534, and 5072. Datum is mean lower low water. Hypsometric curve (inset) constructed from bathymetric contours, and includes mudflats.

Nontidal current speeds in the northern reach, estimated by drifter data, average 4 and 5 cm sec^{-1} for the near-bottom landward drift and surface seaward drift, respectively. Speeds determined by vector addition of current-meter data are approximately double these values (25, unpublished data). In the southern reach, the sluggish movements, regardless of direction, are between 1 and 2 cm sec^{-1} (3).

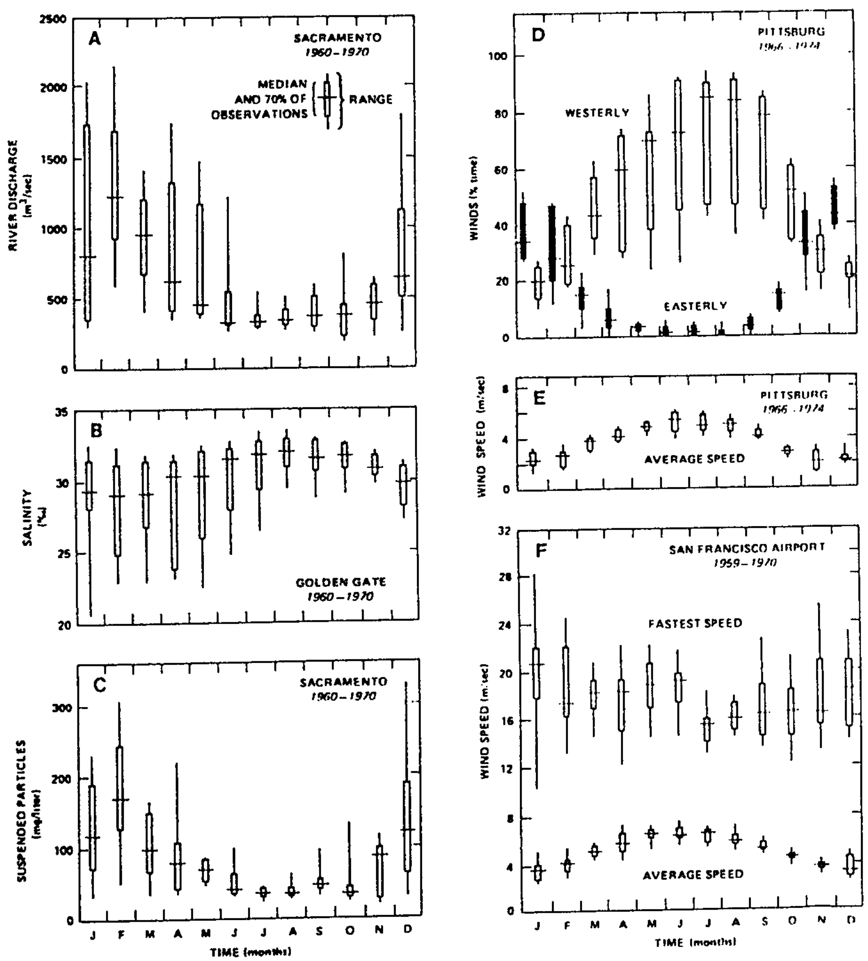

Figure 3. Monthly means of selected environmental variables. (A) Sacramento River discharge at Sacramento. (B) Surface salinity at Golden Gate. (C) Suspended particulate matter at Sacramento. Wind direction (D) and prevailing wind speeds (E) at Dow Chemical Facility, Pittsburg. (F) Prevailing and fastest wind speed at San Francisco International Airport.

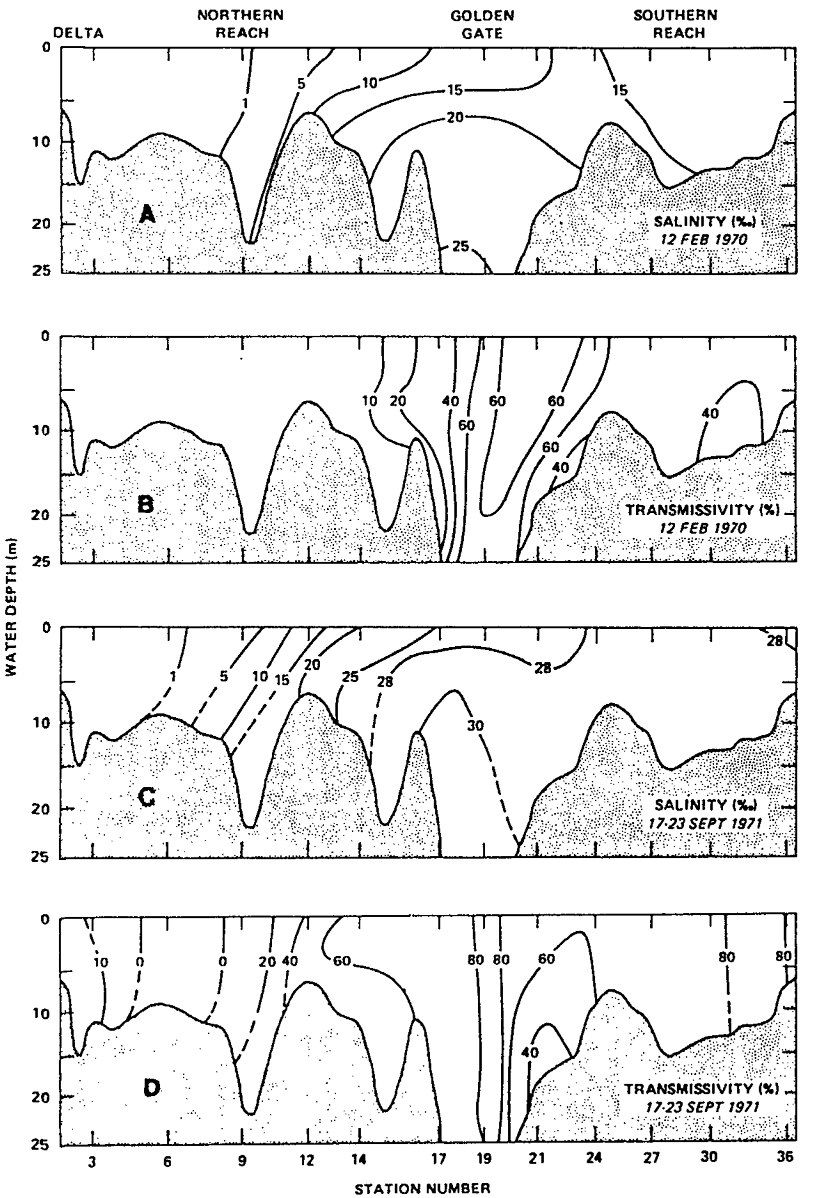

Figure 4. Vertical distribution of salinity (A, C) and transmissivity (B, D), during high and low river discharge periods of Sacramento-San Joaquin (S-SJ) and southern reach streams (SRS). Data obtained at hydrographic stations (Fig. 1) with methods described by Peterson and others (26). February (mean monthly) river discharges: S-SJ = 2170 $m^3\ sec^{-1}$; SRS = 16 $m^3\ sec^{-1}$. September river discharges: S-SJ = 460 $m^3\ sec^{-1}$; SRS = 2 $m^3\ sec^{-1}$.

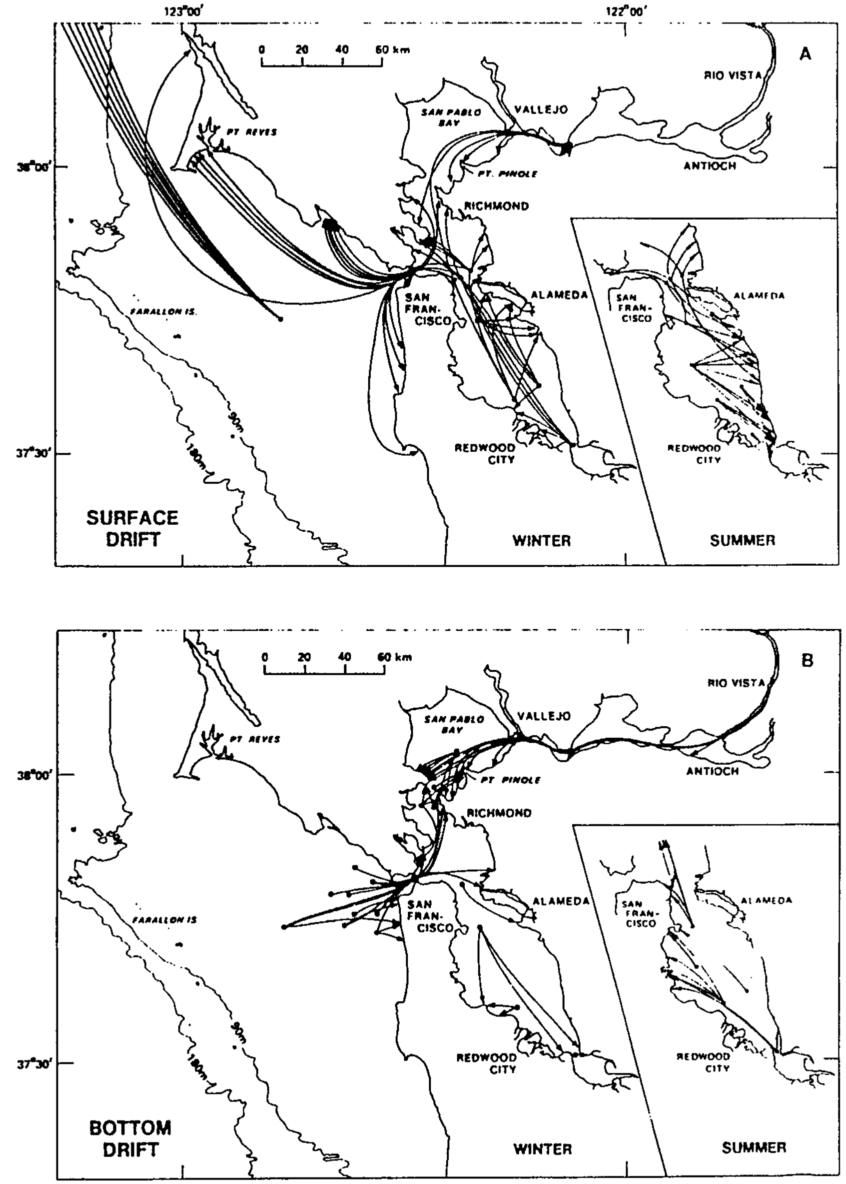

Figure 5. Release and recovery points for surface (A) and seabed (B) drifters in the bay and adjacent ocean. Drifter movements are shown as arrows drawn from release points to recovery locations and portray simplified paths of movement occurring within 2 months of release. Winter release: December 1970 (modified from 3). Summer release (southern reach only shown as inset): September 1971. Data are typical of 18 releases over a 3-year period (1970-1973).

SEDIMENTS

Source

The rivers are the major source of sediments to the bay and delta, contribut-
ıg 5.6×10^6 metric tons annually (27). Of the 4.2×10^6 metric tons that flow ıto bay waters, 81% originate from the Sacramento-San Joaquin River drainage Table 1), while the remainder is contributed by the local streams (Fig. 1). ighty-five percent of all sediment enters the bay as suspended load (27). This ıspended fraction is classified as silty clay (34), typically having a sand-silt-clay ıtio of 15:30:55 (27). Sediment input varies greatly during the year, being roportional in concentration to the river discharge (Fig. 3A, C). Over 80% of ıe suspended riverborne sediment from the Sacramento River is contributed uring winter.

Surficial Sediments

Near-equal amounts of silt and clay with various amounts of sand comprise ıe upper 5 cm of modern sediment (data sources: U.S. Geological Survey and eferences in 10). Poorly sorted silty clay, clayey silt and sand-silt-clay (Shepard lassification; 34) are present in the southern reach and the shallow part of the orthern reach, while sand and silty sand cover the deeper areas of the central ortion of the bay and of the northern reaches. Gravelly sands are found at olden Gate, and grade seaward to a well sorted sand that covers most of the ontinental shelf.

Suspended Sediment

Most (70 to 97%) of the suspended particulate matter in the turbidity maxi-ıum is lithogenous sediment. The remaining fraction, which changes seasonally nd spatially in concentration and composition, includes both living and detrital iogenous matter (4,25,26).

The turbidity maximum is the dominant feature of the suspended sediment istribution in the northern reach (4,25,26). The turbidity (Fig. 4D) and sus-ended sediment concentrations (Fig. 6B) are higher in the null zone than in ther the upper or lower part of the reach, a situation not unlike other partially ıixed estuaries (13,15,19,24,28,32,35). This maximum is a consequence of the ypical response of the longitudinal distribution of suspended sediment to estu-ine circulation: some riverborne suspended sediment settles by gravity from ıe seaward-flowing surface layer to the landward-flowing bottom layer where it entrained, transported to and trapped in the null zone (19).

Particle concentrations of near-surface waters are greatest in the northern each, having typical concentrations of 15 to 20 mg litre^{-1} in the river (0°/₀₀ ılinity) and 90 mg litre^{-1} in the turbidity maximum (Fig. 6B). The lowest oncentration, 10 mg litre^{-1}, is at Golden Gate (station 19). The southern reach as water of intermediate (25 mg litre^{-1}) concentrations. The median concentra-ons are highest during winter at Golden Gate and the southern reach reflecting

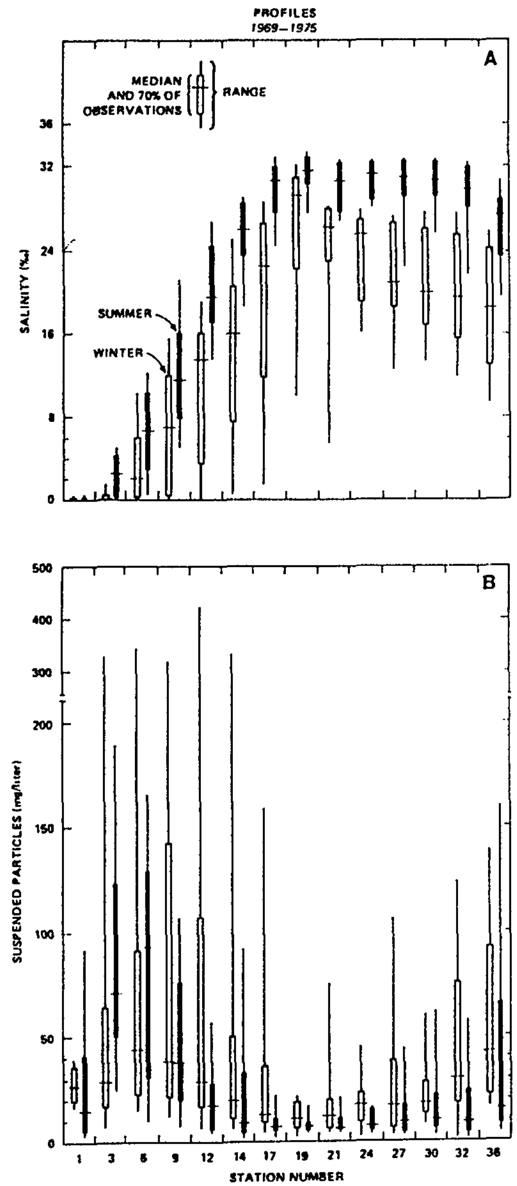

Figure 6. Longitudinal distribution of salinity (A) and suspended particles (B) at 2 m during winter (December through April) and summer (July through October) at near-monthly intervals (1969 to 1975) at hydrographic stations (Fig. 1). Water collection methods and salinity determinations described by Peterson and others (26). Suspended particle concentrations determined from air-dried suspensate retained on a 0.45-μm pore diameter silver filter.

ıe seasonality of the river input (Fig. 6), and are often highest in shallower 'ater. Although the extreme concentrations are highest in the turbidity maxi-ıum during winter, the median concentration there is highest during summer.

Typical particle modal diameters of suspended sediment (preliminary mea-ırements by particle counter) are 4 μm in river water (0°/oo salinity), 8 μm in ıe turbidity maximum, Golden Gate and the southern reach. These measure-ıents agree with data gathered by the U.S. Corps of Engineers (38) which show ıedian diameters of particles suspended in bay waters ranging between 1 and 6 m.

SEDIMENT TRANSPORT PATTERNS

The bay is a dynamic system: the large tidal prism causes strong tidal motion, he strong wind field creates large waves and substantial nontidal currents, and he high annual river inflow (three times that of the bay volume) causes estu-rine circulation in the northern reach and contributes density-induced advec-ion in the southern reach. This high energy environment, coupled with the large ediment inflow and the shallowness of the bay, causes the suspended and surfi-ial sediment to be quite mobile. This mobility is evidenced by the fact that ıore sediment is dredged annually from channels than is contributed to the bay y rivers (33).

The dispersal of these sediments through the interaction of transport, deposi-ion and resuspension is on a seasonal cycle, with riverborne sediment supply nd deposition dominant during winter and sediment resuspension and redeposi-ion dominant during summer (8). These seasonal differences, combined with he differences in hydrologic, hydrographic and sedimentologic processes and ates between the northern and southern reaches make the bay a complicated ystem to evaluate. Enough is known from previous data and from our ongoing tudies, however, to present a simple conceptual model of the basic sediment ransport patterns. As the processes are seasonally modulated, we begin with inter in the northern reach.

Winter Conditions

Sediment enters the northern reach in great quantities (Table 1) during winter Fig. 3C). The bedload material, the coarser-grained fraction, and some of the ggregated finer-grained fraction of the suspended load deposit soon after enter-ıg the estuary (8, 11). Some of the deposited material is periodically resus-ended by the tidal currents. Our seabed drifter data indicate that virtually no ediment entrained in the near-bottom river currents is transported seaward of ıe null zone: the sediment motion is arrested by the landward flowing density urrent. Of the seabed drifters released landward of the null zone, none of the undreds recovered have been found seaward of the zone (Fig. 5B; 3,5). The eposited particles cause shoaling in the null zone, which, at this time of the ear, is located in San Pablo Bay (25), while the suspended portion is maintained in the null zone and constitutes the turbidity maximum. The suspended particles with lower settling velocities are maintained in the seaward flowing surface layer (Fig. 5A). The concentrations in this layer are determined by relative rates of 1) resuspension caused by tidal currents and by wind waves (8); 2) settling of particles, partly enhanced by particle aggregation (16, 19), and 3) dilution of turbid low salinity water by progressive mixing with less turbid high salinity ocean water (Figs. 4, 6). Some of the deposited portion is later suspended and entrained in the landward flowing density current and transported landward to the turbidity maximum (Fig. 5B). Most of the seaward flowing near-surface sediment is transported through Golden Gate as a lobe-shaped effluent plume and dispersed seaward, while another portion, visible as a turbid water mass, drifts into the southern reach of the bay (2).

The southern reach is also accumulating riverborne sediment from the local streams during winter. Sediment not deposited is transported with the near surface waters through Golden Gate, or is dispersed into the northern reach (Fig. 5). The high winds accompanying periodic winter storms generate waves that resuspend the sediment and allow it to be transported by currents.

Summer Conditions

Summer is marked by a much decreased sediment influx and a concomitant increase in wind speed. This creates a relative increase of wind-wave induced resuspension over deposition (8). Sediment in the northern reach and the northern portion of the southern reach that had been deposited during winter is resuspended by waves and tidal currents (Fig. 8 in 19) and transported to the null zone and the turbidity maximum. As the null zone has migrated landward into the Suisun Bay region because of the diminished river discharge (25), the Mare Island area, which was largely bypassed during high discharge conditions, receives landward moving sediments (8) and shoals dramatically (35).

We do not know much about the disposition of sediments in the southern reach during summer. It appears that the southern reach does not accumulate much new sediment and, in the last several decades, is probably losing sediment to the northern reach. Long-term sediment budgets based on comparisons of bathymetric charts (1856-1957) (37) and our field observations suggest that large expanses of the northern, subtidal part of the southern reach appear to be kept scoured of erodable sediment. Shell debris covers the bottom, and benthic faunal communities consist in large part of species represented by mature, well-established specimens and appear stable with time (F. H. Nichols, oral communication). Net accumulation of fine-grained sediment, however, occurs in the margins and southern portion of the southern reach. This accumulation is apparently controlled by the tidal-current generated particle settling and scour lag effects similar to those described in the Wadden Sea by van Straaten and Kuenen (39) and Postma (28). But there is seasonal erosion in the margin areas as well: at a mudflat at the southern end of the bay, up to 9 cm of sediment has been eroded away within one summer month (23).

Transport to Ocean

Our drifter data, at variance with hydraulic model studies (33), suggest that e bay maintains a pronounced estuarine circulation cell and is an effective diment trap during normal (i.e., Fig. 3A) river discharge conditions. Of the abed drifters released at Golden Gate (regardless of tidal stage) and landward, ily a few of the thousands recovered were found seaward of Golden Gate. onversely, of the surface drifters released at Golden Gate (regardless of tidal ige) and seaward, none of the thousands recovered were found landward of olden Gate. It follows then, assuming that bottom sediment transport direcons are similar to those of the seabed drifters, that little if any sediment is ansported seaward along the bottom. Virtually all the sediment lost to the ean is clay or fine-grained silt and is suspended in the seaward-flowing surface rrent (Fig. 5A), with concentrations similar to those at Golden Gate (Fig. 6B). ie concentrations are somewhat proportional to the river discharge levels.

Schultz (33) estimated the annual sediment loss to the ocean, based on a i-year (1924-1960) average discharge and a suspended sediment concentration Golden Gate of 50 mg litre^{-1}, to be about 30% of the annual riverborne load 'able 1). His estimate is inspired by his hydraulic model studies: sediment retenon curves based on the dispersal of gilsonite (simulating surficial sediment), owed that at least 35% of the sediment immediately landward of Golden Gate tidally dispersed seaward, and the percentage retained increases landward. We ggest, in light of our suspended sediment data (10 mg litre^{-1} at station -Golden Gate, Fig. 6B) and our conceptual model that emphasizes the iportance of the estuarine circulation cell and null zone, that his 30% loss timate be revised downward to 6% during normal discharge conditions. This timate is closer to Gilbert's (11) original estimates and predictions of 4% loss.

Large-scale loss of sediment throughout the water column to the ocean ould occur only if river discharge is sufficient to force the null zone seaward rough Golden Gate. Such discharge levels would be at least 4 times normal ormal indicated in Fig. 3A); such discharges occur statistically at 5- to 10-year equencies (40).

Seaward flowing suspended sediments apparently bypass the Gulf of the irallones and are dispersed at sea or are returned to the bay in the bottom flowing currents, as no clays or fine silts are found on the continental shelf. though the sediment on the shelf bottom is demonstrably Sacramento-San aquin River debris (41), it apparently represents relict sand stranded during e Holocene transgression or contributed from the bay during exceptionally gh but infrequent river discharges. The fine-grained fraction is winnowed away the strong sea, swell, and currents.

FUTURE OUTLOOK

It is difficult to predict the sediment dispersal patterns that will prevail in ture decades because of the difficulty in predicting the course of future water-

supply development in the area tributary to the bay (12, 14) and of potential ship channel deepening. Large freshwater diversion projects that would seriously deplete the annual flow of the Sacramento-San Joaquin River system would reduce the riverborne suspended sediment mass (17).

In addition to reducing the suspended sediment supply, river diversion would damp the density-induced estuarine circulation cell in the northern reach (3) and, hence, would affect the position of the turbidity maximum. River-generated two-layered nontidal flow through Golden Gate would diminish and tidal movements would become relatively more dominant. The mode and degree of sediment exchange with the ocean would thus be altered in a yet unknown manner.

Complex and as yet undefined interrelations must also be evaluated when predicting the importance of reduced river flow on the locations and rates of shoaling and on the suspended sediment concentrations and composition. For example, the implications of suspended sediment on availability of incident light (water transparency) and in turn on the phytoplankton growth rates and plant nutrient cycles are not clear (14, 17). Similarly, deepening the ship channel in the northern reach may alter the water circulation patterns and rates by enhancing the density induced circulation (1), and, as in the Savannah Harbor case, may result in an increase in shoaling (36). This deepening may also reduce the near-surface suspended sediment concentration by increasing the water column depth.

REFERENCES

1. Burgh, Ir. P. van der. 1968. Prediction of the extent of saltwater intrusion into estuaries and seas. J. Hydraulic Res. 6(4):267-288.
2. Carlson, P.R., and D.S. McCulloch. 1974. Aerial observations of suspended sediment plumes in San Francisco Bay and the adjacent Pacific Ocean. J. Res. U.S. Geol. Surv. 2(5):519-526.
3. Conomos, T.J. 1975. Movement of spilled oil as predicted by estuarine nontidal drift. Limnol. Oceanogr. 20(2):159-173.
4. Conomos, T.J., and D.H. Peterson. 1974. Biological and chemical aspects of the San Francisco Bay turbidity maximum. Mémoires de l'Institut de Géologie du Bassin d'Aquitaine 7:45-52.
5. Conomos, T.J., D.S. McCulloch, D.H. Peterson, and P.R. Carlson. 1971. Drift of surface and near-bottom waters of the San Francisco Bay system: March 1970 through April 1971. U.S. Geol. Surv. Open-file Map.
6. Disney, L.P., and W.H. Overshiner. 1925. Tides and currents in San Francisco Bay. U.S. Dep. Com., U.S. Coast Geod. Surv., Spec. Pub. 115. 125 p.
7. Edmonston, A.D., and Raymond Matthew. 1931. Variation and control of salinity in Sacramento-San Joaquin delta and upper San Francisco Bay. California Dep. Public Works Bull. 27. 440 p.
8. Einstein, H.A., and R.B. Krone. 1961. Estuarial sediment transport patterns. Amer. Soc. Civil Eng. Proc., J. Hydraulics Div. 87(HY2):51-59.
9. Federal Water Pollution Control Administration. 1967. Effects of the San Joaquin Master Drain on water quality of the San Francisco Bay and Delta. Centr. Pacific Basins Comprehensive Water Pollution Control Proj. Rep. 101 p.

C-099623

10. Folger, D.W. 1972. Characteristics of estuarine sediments of the United States. U.S. Geol. Surv. Prof. Paper 742. 94 p.
11. Gilbert, G.K. 1917. Hydraulic-mining debris in the Sierra Nevada. U.S. Geol. Surv. Prof. Paper 105. 154 p.
12. Gill, G.S., E.C. Gray, and David Sechler. 1971. The California water plan and its critics: A brief review, p. 3-27. *In* D. Sechler (ed.), California water; A study in resource management. Univ. Calif.
13. Glangeaud, L. 1938. Transport et sédimentation dans l'estuarie et a l'embouchure de la Gironde. Caractères pétrographiques des formations fluviatiles, saumatres, littorales, et néritiques. Bulletin de la Société Géologique de France 8:599-630.
14. Goldman, C.R. 1971. Biological implications of reduced freshwater flows on the San Francisco Bay-Delta system, p. 109-124. *In* D. Sechler (ed.), California water; A study in resource management. Univ. Calif.
15. Inglis, Clyde, and F.H. Allen. 1957. The regimen of the Thames estuary as affected by currents, salinities and river flow. Min. Proc. Inst. Civil Eng. (London) 7:827-878.
16. Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes—final report. Univ. California (Berkeley) Hydraulic Eng. Lab. and Sanitary Eng. Res. Lab. 110 p.
17. Krone, R.B. 1966. Predicted suspended sediment inflows to the San Francisco Bay system. Report to Central Pacific River Basins Comprehensive Water Pollution Control Proj., Federal Water Pollution Control Proj., Federal Water Pollution Control Admin. (Southwest Region). 33 p.
18. McCulloch, D.S., D.H. Peterson, P.R. Carlson, and T.J. Conomos. 1970. Some effects of fresh-water inflow on the flushing of south San Francisco Bay: A preliminary report. U.S. Geol. Surv. Circ. 637A. 27 p.
19. Meade, R.H. 1972. Transport and deposition of sediments in estuaries, p. 91-120. *In* B.W. Nelson (ed.), Environmental framework of coastal plain estuaries. Geol. Soc. Amer. Mem. 133.
20. Miller, Albert. 1967. Smog and weather—The effect of the San Francisco Bay on the bay area climate. San Francisco Bay Conserv. Development Comm. 40 p.
21. National Marine Consultants. 1960. Wave statistics for seven deep water stations along the California coast. Prepared for U.S. Army Corps Eng. District, Los Angeles. 20 p.
22. Nichols, D.R., and N.A. Wright. 1971. Preliminary map of historic margins of marshland, San Francisco Bay, California. Open-file rep. U.S. Geol. Surv. 10 p.
23. Nichols, F.H. In press. Infaunal biomass and production on a San Francisco Bay mudflat. *In* B.C. Coull (ed.), Ecology of Marine Benthos, Belle W. Baruch Library in Marine Sci., v. 6, Univ. South Carolina Press.
24. Nichols, M.M. 1972. Sediments of the James River estuary, Virginia, p. 169-212. *In* B.W. Nelson (ed.), Environmental framework of coastal plain estuaries. Geol. Soc. Amer. Mem. 133.
25. Peterson, D.H., T.J. Conomos, W.W. Broenkow, and P.C. Doherty. 1975a. Location of the nontidal current null zone in northern San Francisco Bay. Estuarine Coastal Marine Sci. 3(1):1-11.
26. Peterson, D.H., T.J. Conomos, W.W. Broenkow, and E.P. Scrivani. 1975b. Processes controlling the dissolved silica distribution in San Francisco Bay, p. 153-187. *In* L.E. Cronin (ed.), Estuarine Research. Chemistry and Biology, v. 1. Academic Press, New York.
27. Porterfield, George, N.L. Hawley, and C.A. Dunnam. 1961. Fluvial sediments transported by streams tributary to the San Francisco Bay area. Open-file rep. U.S. Geol. Surv. 70 p.
28. Postma, H. 1967. Sediment transport and sedimentation in the estuarine environment, p. 158-179. *In* G.H. Lauff (ed.), Estuaries. Amer. Ass. Advance. Sci. Pub. 83.
29. Putnam, J.A. 1947. Estimating storm-wave conditions in San Francisco Bay. Trans. Amer. Geophys. Union 28(2):271-278.
30. Rattray, Maurice, Jr. 1967. Some aspects of the dynamics of circulation in fjords, p. 52-62. *In* G.H. Lauff (ed.), Estuaries. Amer. Ass. Advance. Sci. Pub. 83.
31. Schlocker, Julius. 1974. Geology of the San Francisco North Quadrangle, California. U.S. Geol. Surv. Prof. Paper 782. 109 p.
32. Schubel, J.R. 1968. Turbidity maximum of northern Chesapeake Bay. Sci. 161:1013-1015.
33. Schultz, E.A. 1965. San Francisco Bay dredge spoil disposal. Prepared for presentation to the Committee on Tidal Hydraulics, 53rd meeting San Francisco, May, 1965. 48 p.
34. Shepard, F.P. 1954. Nomenclature based on sand-silt-clay ratios. J. Sedimentary Petrology 24(3):151-158.
35. Simmons, H.B. 1955. Some effects of upland discharge on estuarine hydraulics. Amer. Soc. Civil Eng. Proc. 81 (Separate 792). 20 p.
36. Simmons, H.B. 1965. Channel depth as a factor in estuarine sedimentation, p. 722-730. *In* Proc. Federal Interagency Sedimentation Conf. 1963. U.S. Dep. Agr. Misc. Pub. 970. 933 p.
37. Smith, B.J. 1965. Sedimentation in the San Francisco Bay system, p. 675-708. *In* Proc. Federal Interagency Sedimentation Conf. 1963. U.S. Dep. Agr. Misc. Pub. 970. 933 p.
38. South Pacific Division Laboratory. 1957. Report of soil tests, Bay Model sediment samples. U.S. Army Corps Eng., South Pacific Div. Lab. 17 p.
39. Straaten, L.M.J.U. van, and Ph. H. Kuenen. 1958. Tidal action as a cause of clay accumulation. J. Sedimentary Petrology 28(4):406-413.
40. U.S. Army Corps of Engineers. 1963. Flood control. Append. B. Tech. Rep. on San Francisco Bay barriers. U.S. Army Eng. District, San Francisco. 80 p.
41. Yancey, T.E., and J.W. Lee. 1972. Major heavy mineral assemblages and heavy mineral provinces of the central California coast region. Geol. Soc. Amer. Bull. 83:2099-2104.

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