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Abstract

Sediment inflows to the San Francisco Bay system have been significantly affected by man since the 1860's. Mining and agriculture caused large increases in sediment inflows during the late 1800's, and rapidly increasing fresh water diversions for irrigation are now causing depleted sediment inflows. In addition, maintenance dredging within the system alters sediment transport.

Sediments entering the system with land drainage consist largely of silts and clay minerals. These materials enter with high winter river flows and settle initially in the upper bays. Daily spring and summer onshore winds generate waves that suspend fine materials and hold them in suspension while tidal- and winddriven currents circulate the suspended material throughout the system and to the ocean.

The effectiveness of waves in suspending deposited material increases rapidly with decreasing water depth. As the upper bays fill with sediment to depths where wave action resuspends the annual load at the same rate as the supply, the water depths tend to remain constant there, and further accumulation of sediment in the system occurs seaward. Evaluation of historical bathymetric surveys, including the effects of rising sea level, shows progressive sedimentation in the system that is now approaching Central Bay. Future fresh water diversions will materially slow this trend and will cause reduced turbidity from sediment particles.

SEDIMENTATION IN THE SAN FRANCISCO BAY SYSTEM

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Sediment inflows to the San Francisco Bay system have been significantly affected by man since the 1860's. Mining and agriculture caused large increases in sediment inflows during the late 1800's, and rapidly increasing fresh water diversions for irrigation are now causing depleted sediment inflows. In addition, maintenance dredging within the system alters sediment transport.

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The processes of aggregation, deposition, suspension, erosion, and circulation of sediment materials in the San Francisco Bay system have been described by Einstein and Krone (1961), Peterson et al. (1975), Krone (1976), Conomos and Peterson (1977), and the U. S. Army Corps of Engineers (1977). These descriptions have time scales on the order of a year or less, and while they are largely qualitative, the descriptions illuminate the sediment movements in the system. Longer term descriptions of sedimentation were made by Gilbert (1917), who described the excessive accumulations in the Bay system that resulted from hydraulic mining activities during the period 1850 to 1884, and by Smith (1965) who extended Gilbert's calculations of changes in Bay water volumes using more recent bathymetric survey data.

Both the short and long term sediment studies and studies of hydrodynamics by McCulloch et al. (1970) and Imberger et al. (1977) show that the Bay system is dominated by effects of changing sediment and water discharges through the Sacramento-San Joaquin River system (Fig. 1) from Great Central Valley drainage. There has been for decades a continuing trend of increasing consumptive use of water in the Central Valley and of export of water – and sediments – that would otherwise flow through the San Francisco Bay system. The diversion of fresh water has accelerated during recent years, and during the past two years of drought the fresh water flow to the Bay system has been the lowest in history. In view of the decreases in fresh water flows that the system is experiencing and the possibility of further decreases, it is appropriate that the existing information on sedimentation be re-examined to identify areas that may concern those responsible for management of sediments and Bay system water quality. This chapter presents an overall description of sediment movements and identifies areas of concern.

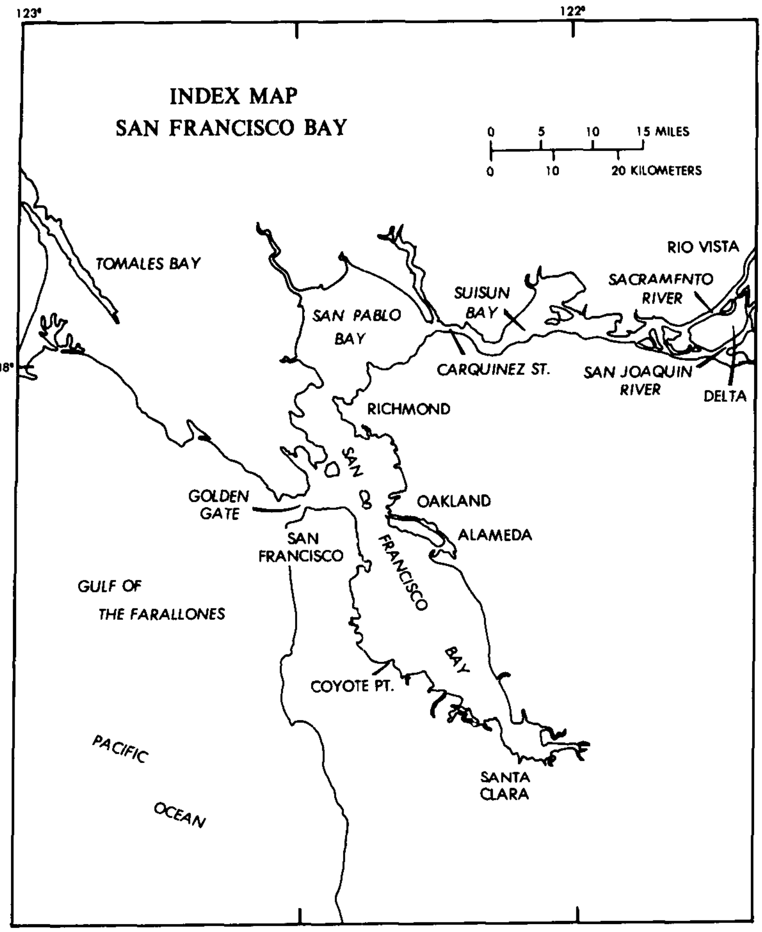

Fig. 1. San Francisco Bay system and environs.

SEDIMENT SUPPLY

Roughly 80 to 90% of the sediment entering the system is the product of soil erosion in the 163,000-km^2 inland drainage basin. The remainder comes from erosion of lands adjacent to the Bay system. The rate of sand transport by river flows of the Central Valley is diminished in the lower reaches of the rivers, so that the material entering San Pablo Bay is the remnant of the eroded soil and consists of clay and silt minerals carried in suspension as wash load, with only a small amount of fine sand. Most of the sediment enters with the higher winter and spring flows that result from rainfall and snowmelt.

Very large amounts of clay and silt were carried by Central Valley streams during the hydraulic-mining era in the Sierra Nevada, and this material remained in suspension in stream waters until the water velocity slowed in the broad shallow expanses of Suisun and San Pablo bays. Deposition in these upper bays was enhanced further by the increased salinities of these bays, which made suspended particles cohesive, and by the waves and gentle turbulence that caused suspended particles to collide repeatedly and form aggregates. Such aggregates have very greatly enhanced settling velocities. These "schlickens" created huge deposits in the upper bays and all but obliterated Vallejo Bay (now Carquinez Strait) at Martinez. Gilbert (1917) estimated the clay and silt deposit in the upper bays from mining debris by calculating the change in water volume. He believed that mining debris was still entering the Bay system at the time of his study, and he calculated that during the period 1849 to 1914 a total of 1.146×10^9 yd^3 was deposited. Undoubtedly additional amounts were lost to the ocean.

Hydraulic mining was stopped in 1884. Fresh water diversions for irrigation gradually increased until the early 1940's when the Central Valley Project and the federal dams in the San Joaquin Valley streams were built (see, for example, Gill et al. 1971). Very rapid decline in fresh water and sediment outflows occurred thereafter. A program for measuring suspended sediment outflows was initiated by the U.S. Geological Survey in 1957 (Porterfield et al. 1961), and estimates of sediment production are limited to calculations using subsequent suspended solids data and historic water outflows.

Estimates of sediment inflow to the Bay system were made by establishing a relation between annual water flow and annual sediment production during later years (Krone 1966). Annual production is useful because the long dry summers return the drainage system to virtually the same condition by 1 October, the start of the "water year," and each year's runoff can be considered independent of preceding years (Fig. 2). The data (Fig. 2) include those both for the San Joaquin

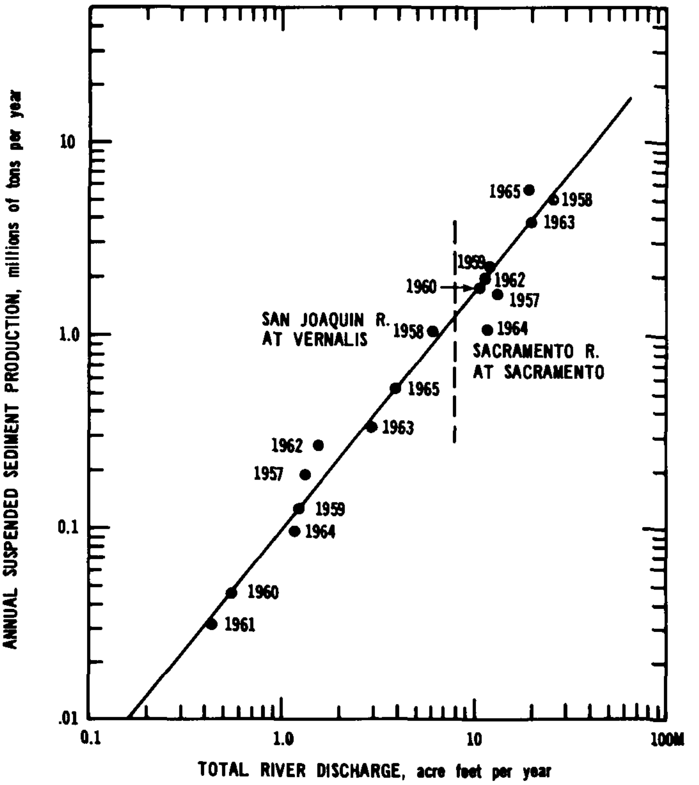

Fig. 2. Relation of annual suspended sediment production to river discharge. Reproduced from Krone (1966).

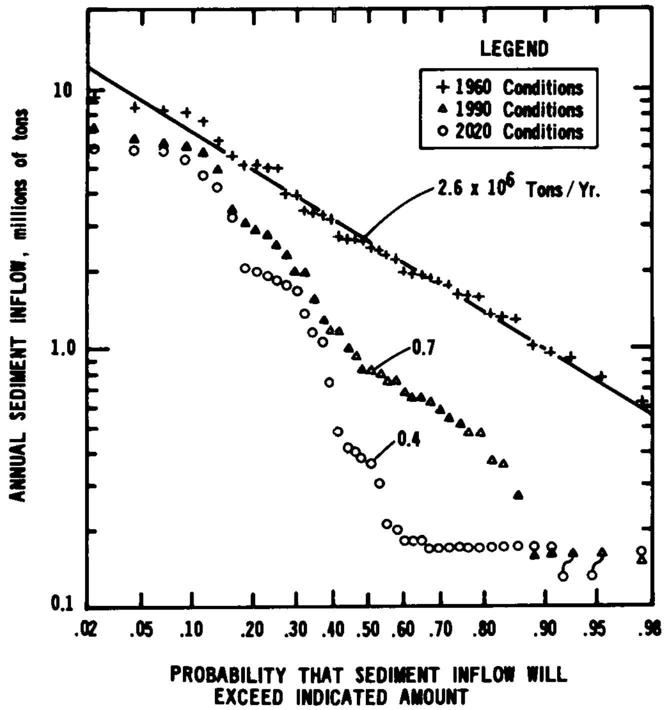

Fig. 3. Annual suspended sediment inflow from the Delta to the Bay system. Reproduced from Krone (1966).

and Sacramento rivers; the plots show that the relation indicated by the line represents both rivers reasonably well.

This relation was applied to the historic fresh water flows, modified by the U.S. Bureau of Reclamation (USBR) to the fresh water flows to the Bay system that would have occurred if the facilities and demands of 1960 existed throughout the period of record. The resulting sediment production for the wide range of flows that occurred between 1921 and 1971 is plotted on logarithmic-probability ordinates (Fig. 3). This plot, shown by the crosses, shows a 20-fold range, with a median annual production of 2.6 million *t*. The USBR projected water development and water demands for the years 1990 and 2020 and appropriate water management operations are applied to the same historic data, leading to the other two plots. These plots show that if such plans are realized the Bay system will experience "droughts" of sediment inflow a larger and larger fraction of the time.

The estimated annual *average* sediment inflows are presented in Table 1. If the bed load is taken to be 0.065 of the total and the dry unit weight of the sediment deposit is 33 lbs·ft^{-3} (Schultz 1965), the average annual volume of sediment "deposit" under 1960 conditions would be 10.5 million yd^3 which is close to Schultz' (1965) estimated of 11.1 million yd^3.

Decisions on future water diversions are lacking, and the projections shown for 1990 and 2020 are subject to decisions between competing political pressures for fresh water diversion and Bay system water quality. Figure 3 does show, however, the drastic reductions in sediment inflow to the Bay system that would result from future diversions planned by USBR in 1966.

TABLE 1. ESTIMATED ANNUAL AVERAGE SUSPENDED SEDIMENT PRODUCTIONS ($10^6 t \cdot yr^{-1}$)[a]

Sediment Source	Stream Conditions 1960	1990	2020
Sediment supplied to the Delta	3.75	3.42	3.34
Sediment from the Delta to San Francisco Bay system	3.35	1.79	1.22
Sediment from local streams to:[b]			
Suisun Bay	0.23	0.23	0.23
San Pablo Bay	0.29	0.29	0.29
San Francisco Bay	0.51	0.51	0.51
Total sediment to Bay system	4.38	2.82	2.25

[a] 1.0*t* (common short ton) = 0.907*t* (metric tonnes)

[b] From Smith (1965, Table 5). 1957 to 1959 values, measured and estimated, are data of Porterfield et al. (1961).

SEDIMENT CIRCULATIONS

The fine cohesive particles that comprise most of the material are transported in suspension. Their transport throughout the system is determined by the water movements, and by the local hydraulic conditions that facilitate deposition, erosion, and aggregation. The water movements in the Bay system are exceedingly complex and are very strongly affected by fresh water flows, the distribution of salinity, and wind stresses. A description of the general character of water movements will serve to explain sediment movements, however.

The Bay system consists of a number of broad shallow bays interconnected by narrow openings (Fig. 1). The western part of North San Francisco Bay and the narrow opening to the Pacific Ocean (Golden Gate) are quite deep, however, and water depths are maintained by the strong tidal currents. The large surface areas of the bays, combined with the restricted connections, cause progressive delays in the tides with distance from the ocean and relatively deeper channels at the narrow openings. The system is resonant to the tides, with the result that the mean range of the tide at the southern tip of South Bay is 2.2 m, 1.0 m greater than the mean ocean tide range of 1.2 m at the Golden Gate (U. S. Army Corps of Engineers 1961). This resonance causes north-south tidal currents in the central portion of the Bay system that is out of phase with flows through the Golden Gate, with the result that there is circulation between San Pablo Bay and South San Francisco Bay.

Fresh water outflows from Central Valley drainage superimpose another circulation system on the oscillatory tidal flows. More dense ocean waters tend to move upstream under the seaward flowing fresh waters (see also Conomos 1979). The oscillatory flows that result from tidal motion, combined with irregularities of the bed, cause vertical mixing with the result that there is an oscillatory but net landward movement of saline water near the bed, and this water dilutes fresh seaward flowing water above. The location and length of this mixing zone depend strongly on the fresh water flow and the flow history (McCulloch et al. 1970; Peterson et al. 1975; Imberger et al. 1977; Conomos 1979). During extremely large discharges the mixing zone extends out into the

Pacific Ocean. More commonly during winter flows the mixing zone extends from the Golden Gate to Carquinez Strait. As winter fresh water flows decrease the mixing zone moves landward, and during typical summer flows during the period 1943 to 1970, the mixing zone extended from mid San Pablo Bay to Antioch.

South San Francisco Bay is also strongly affected by high fresh water flows, with fresh water "lenses" developing during high flows (McCulloch et al. 1970; Imberger et al. 1977; Conomos 1979).

Winds affect water circulations, particularly in the broad bays where the fetch is appreciable. The winds of greatest importance appear to be the daily onshore breezes that blow from the ocean to the hot Central Valley during spring and summer. These winds also generate waves in the shallow bays every day during these months (see also Conomos 1979).

There is strong evidence that large amounts of sediment are deposited in Suisun and San Pablo bays during winter runoff (U. S. Army Corps of Engineers 1977). Waves that appear daily on the bays suspend this material and hold it in suspension while slow tidal currents transport the material to channels (Einstein and Krone 1961). During flood tides this material moves upstream through Carquinez Strait, and because the particles aggregate rapidly at the high suspended sediment concentrations that prevail, the aggregates tend to settle and there is a higher concentration near the bed (Arthur and Ball 1979). These particles move upstream with the net upstream flow near the bed, mixing vertically upward with the more saline waters. Aggregates whose settling velocities approximate or exceed the upward velocity of the more saline waters accumulate in the mixing zone and cause the well-known "turbidity maximum" there (Conomos and Peterson 1977).

Little deposition occurs in this mixing zone now because the large tidal prisms of Suisun, Grizzly, and San Pablo bays, combined with the narrow channels, cause high velocity currents that keep the channels scoured to their self-maintained depths. An attempt to cut an 11-m deep approach basin for a wharf at Benicia, however, resulted in the formation of a 5-m deep deposit in three months. Large amounts of sediment are in motion there.

Material suspended by waves in San Pablo Bay continually feeds this net upstream flow. The vertical density gradient in the mixing zone causes the velocity profile there to have exceptional velocity gradients. These gradients promote the collision of suspended particles and thereby promotes their aggregation (Krone 1972). Particles and aggregates from San Pablo Bay mix upward with riverborne dispersed particles and "scavenge" them. Algae are also scavenged this way. Aggregates carried seaward in the upper portions of the flow settle as the tidal current slows in San Pablo Bay, to either be carried back upstream for another cycle or to circulate further in San Pablo Bay.

Suspension of deposited material by waves is a process that has several important aspects. For a given wave, the maximum bed shear stress is very sensitive to water depth and is proportional to the square of the maximum near-bed orbital velocity, u^2_{max},

$$u^2_{max} = [\pi H/(T \cdot \sinh \cdot 2\pi h/L)]^2 \text{, approximately}$$

where H is the wave height, T is the wave period, L is the wave length, and h is the water depth (Komar and Miller 1973). Since $1/(\sinh \cdot 2\pi h/L)$ falls off very rapidly with depth, and its square falls even faster, it is evident that the applied stress is sensitive to depth. The suspending force is periodic, and upward diffusion is weak. The result is that fine particles are winnowed from coarser particles, so that over a period of time when suspended material is transported away by tidal currents, the remaining material is coarser than the original deposit. The applied shear stress must exceed the shear strength of the deposit before there is any suspension (Alishahi and Krone 1964).

Winnowing of sediments in San Pablo Bay is shown by the data of Storrs et al. (1963) (Fig. 4). The surface of the bed was coarser during the summer and fall than it was after the high fresh water flows. An armor having a high content of fine sand and silt is found in wind-swept shallow parts of San Pablo Bay. Below this armor, which can support a person, reside large depths of the mud from hydraulic mining.

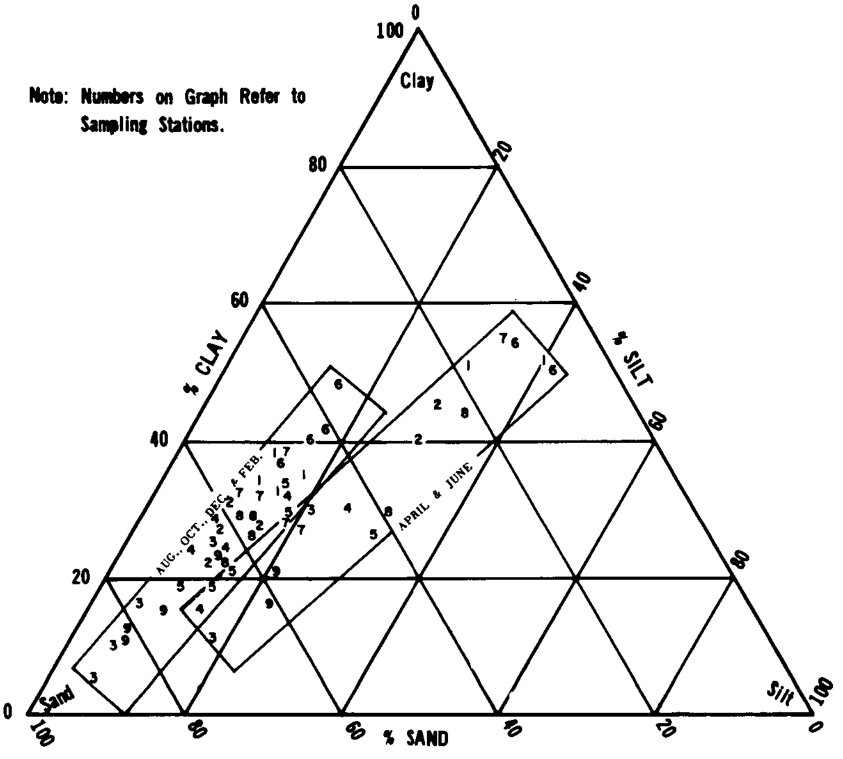

Fig. 4. Surface sediment particle-size distribution, San Pablo Bay, August 1961-June 1962. Data from Storrs et al. 1963. Numbers refer to Sanitary Engineering Research Laboratory (SERL) sampling stations.

Material suspended in San Pablo Bay and carried southward with tidal currents contains less fine sand and is easily carried with tidal currents as they circulate throughout the system. Suspended material settles wherever the water is quiet, such as in shallow areas at night when the wind dies, or in navigation facilities. Where subsequent wave action or tidal currents are insufficient to resuspend deposited material, it accumulates. Material from San Pablo Bay may deposit and be resuspended many times as it circulates and finds its way to a resting place or is carried to sea, progressively becoming finer-grained and more easily transported. Marsh areas now diked off once accumulated this fine material and probably reduced the loss to the ocean.

The scenario is repeated in miniature for each of the streams tributary to the bays, and areas of sandy material can be found near their mouths and near eroding banks. Bay waters are muddy during periods of high runoff and progressively become clearer during each year as the quantity remaining in suspension diminishes.

LONGER-TERM SEDIMENT DEPOSITION

The surface of the oceans is rising at an approximate rate of 0.2 m·century^{-1} (Fig. 5). If there were no deposition of sediment, the bays would continually deepen. Alternately, if deposition is so rapid that the water depths become shallow, wave action erodes the new deposit down

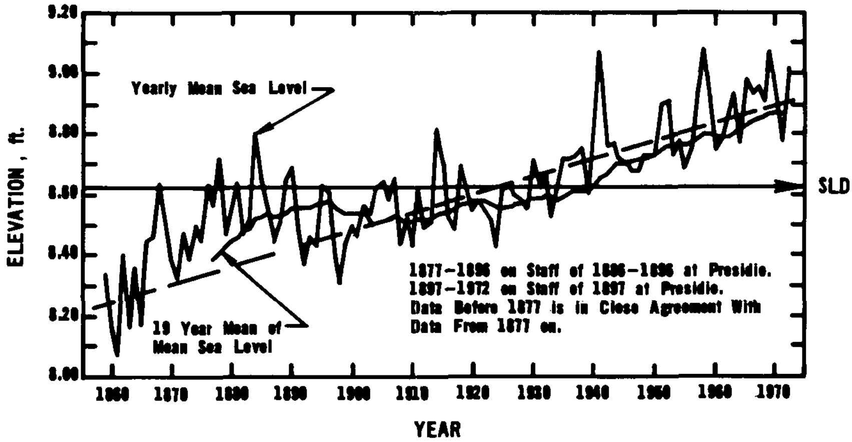

Fig. 5. Yearly mean sea level changes at San Francisco, California, 1860-1970. Data from National Ocean Survey.

to a depth where wave erosion compensates deposition, assuming no armoring by coarse material. When the supply of sediment inflow is adequate, therefore, water depths would tend to remain constant, and the rate of deposition would follow sea level rise. When the sediment supply is inadequate, the water depths would increase.

Smith (1965) reported calculations made by the U. S. Army Corps of Engineers that used averages of water depths over 1/8-min quadrangles. Averages for successive bathymetric surveys were compared to obtain changes in water depths with no allowance made for sea level rise. Tables 2 and 3 were constructed from Smith's data using linear interpolation where necessary to determine the changes over comparable time periods. The tables are arranged with areas in their geographical sequence from the Delta southwestward through the system. A pattern of deposition becomes apparent from the data in Table 2 when the accumulation or loss during successive periods is compared for successive bays. Suisun and Grizzly bays filled during the first periods and lost relatively small amounts during the second and third periods. San Pablo Bay accumulated a large amount during the first period when hydraulic mining provided a supply and successively smaller amounts during the next two periods. North San Francisco Bay showed negligible accumulation during the first period and markedly increasing amounts during the later periods. South San Francisco Bay showed deepening water during all three periods.

The rise in sea level was evidently sufficiently rapid prior to 1870 so that the sediment accumulation rate in most of the system was not sufficient to compensate the increase in water volume due to sea level rise. The very large amount of finer-grained material produced by hydraulic mining and by poor agricultural practices caused very rapid deposition in Grizzly, Suisun, and San Pablo bays. The erosion in Suisun and Grizzly bays shown to occur during the subsequent two periods indicates that the rate of supply during the first period exceeded the transport capacity of waves and currents. In fact, erosion during the second and third periods indicates that some of the

TABLE 2. APPARENT SEDIMENT ACCUMULATION ($10^6 yds^3$)[a,b]

Area	1870-1896 (27 years)	1897-1922 (26 years)	1923-1950 (28 years)
Suisun & Grizzly Bays & Carquinez Strait	64.3	-17.2	-4.7
San Pablo Bay	181.3	60.2	17.4
North San Francisco Bay	0.66	67.4	106.4
South San Francisco Bay	-36.1	-51.1	-55.0

[a] Data from Smith (1965)
[b] $1.0 yd^3 = 0.76 m^3$

material deposited during the first period was transported toward San Pablo Bay in addition to the river-borne material that entered during these later periods. As this material eroded under wave action, the finer-grained fraction was washed out, and the bed became progressively more resistant to erosion. The water depths in Grizzly and Suisun bays probably now are approaching values that can be expected to remain constant unless the supply of sediment is stopped.

San Pablo Bay continued to accumulate sediment during the second and third periods, but at decreasing rates.

North San Francisco Bay did not receive much material during the period of hydraulic mining discharge, which suggests that the upper bays trapped most of the sediment that remained in the system. The losses of water volumes during the second and third periods show that the capacities of the upper bays to store material were decreasing, and the material worked its way through the upper bays until it found a permanent resting place in North San Francisco Bay. This interpretation is strengthened by the presentation of average annual apparent deposition rates presented in Table 3.

The average annual loss in water volume (the apparent sediment accumulation rate) for the total of Suisun, Grizzly, San Pablo, and North San Francisco bays is 4.2 million $yd^3 \cdot yr^{-1}$ for both second and third periods.

The figures for South San Francisco Bay in Tables 2 and 3 are strikingly different: the water volume increased during all three periods. The average annual rate of sea level rise was used to calculate the annual change in water volume. As shown in Table 3, the observed increase in water volume exceeded that due to sea level rise during all three periods. Considering the uncertainties in the determination of sea level in the earliest bathymetric surveys it can be concluded that there were comparable rates of slow erosion in South San Francisco Bay during all three periods. Hydraulic mining debris did not cause accumulations in the open water areas of South San Francisco Bay, nor did material from Central Valley appear to be accumulating there even in 1950.

The data in Tables 2 and 3 are temporal and spatial averages. While they are valuable for the analysis given above, they are not suitable for descriptions of local areas. Sediment can move around within each of the areas used in Tables 2 and 3 without affecting the average. Smith's report shows the local changes in 1/8 min quadrangles between bathymetric surveys. Further, the data do not preclude the movement of fine material into and back out of South San Francisco Bay each year. All present evidence indicates that annual supplies of Central Valley sediments do in fact enter South San Francisco Bay under present conditions. Only the finest material, clay and silt, remains in the suspended load, however, and deposits are stable only in areas protected from

TABLE 3. AVERAGE ANNUAL SEDIMENT ACCUMULATION RATES ($10^6 yds^3 \cdot yr^{-1}$)[a]

Area	1897-1922 (26 years)	1923-1950 (28 years)
Suisun & Grizzly Bays & Carquinez Straits	-0.66	-0.17
San Pablo Bay	2.31	0.62
North San Francisco Bay	2.59	3.80
Loss of Water Volume	4.24	4.25
Volume of Sealevel Rise	1.29	1.29
TOTAL	5.5	5.5
South San Francisco Bay		
Loss of Water Volume	-1.96	-1.96
Volume of Sealevel Rise	1.07	1.07
TOTAL	-0.91	-0.91

[a] Calculated from data in Table 2.

waves and currents. I believe that a much smaller portion of the fine-grained sediments were transported into South San Francisco Bay during the hydraulic-mining era because the trap efficiency of the upper bays was much greater then.

If the 1960 condition data (Fig. 3) can be compared with the data for 1923 to 1950 in Table 3, it is possible to calculate a sediment balance that shows the average budget (Fig. 6). The 5.5 million yd^3 deposited in the upper bays is assumed to have come entirely from inflow. The increase in water depths in South San Francisco Bay, which would result largely from erosion of very fine-grained material that would be carried to the ocean or to marsh areas, is assumed not to have contributed to deposition in the northern bays.

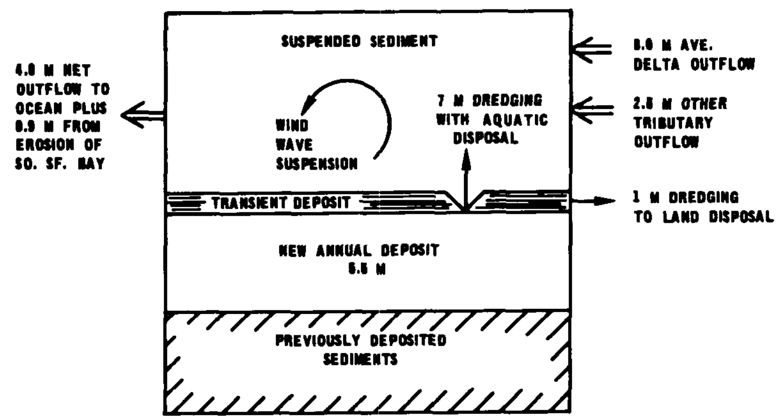

Fig. 6. Average annual San Francisco Bay sediment deposition budget. Values in millions of cubic yards of deposit.

FUTURE CHANGES

Projected fresh water diversions indicate that future supplies of suspended sediment to the Bay system will be less than historic supplies and will vary over a much wider range. At present, the Bay system steadily removes fine suspended material during each year following the winter and spring runoffs. If less sediment is supplied as the result of increased water diversion, Bay system waters will clear. Several successive years of very low flows will surely result in greatly reduced suspended sediment concentrations in Bay waters and reduced turbidity. The ample nutrient levels in Bay waters, particularly with low fresh water flows, will promote growth of algae to objectionable levels.

The clay minerals sorb toxic materials from waste discharges and thereby remove such materials from the water column. The sorbed materials are removed from the water column when the sediments are removed from suspension and thereby provide an assimilative capacity for such undesirable substances. If significant reductions of sediment inflows are to be made, either waste discharges into the Bay system will have to be greatly modified or water quality will deteriorate.

We have not acquired the necessary field data nor made quantitative calculations that show the effects of changing fresh water and sediment flows to the Bay system on the quality of Bay waters. Decisions on water diversions are being made without such information. Detailed descriptions of the water and sediment transport are needed in order to predict the effects of various fresh water and sediment outflows on the Bay system.

New bathymetric surveys will be made in a few years. These data, combined with continuing measurements of suspended sediments, should enable more precise descriptions of trends in sediment accumulation in the Bay system.

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