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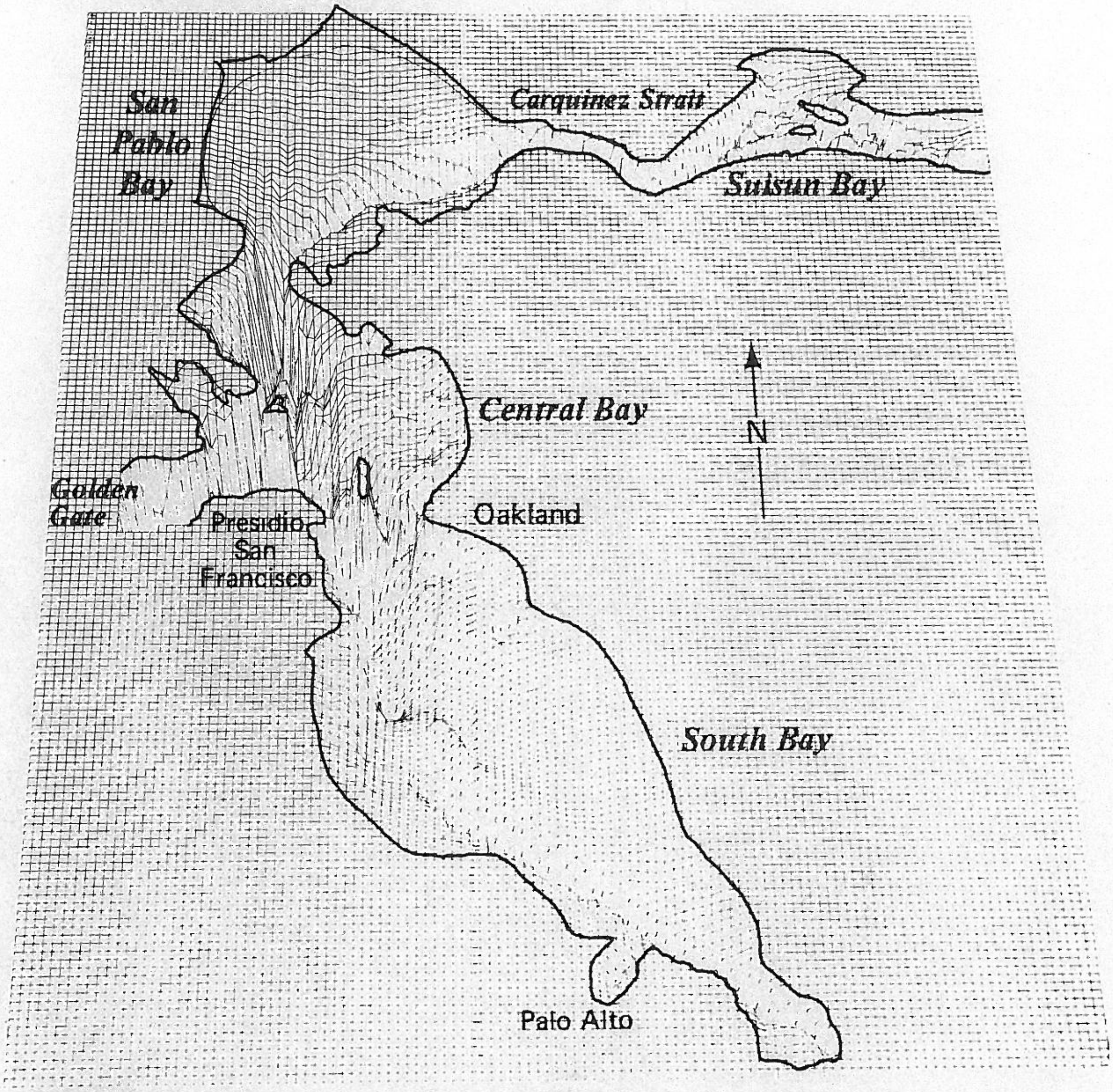
A REVIEW OF CIRCULATION AND MIXING STUDIES OF SAN FRANCISCO BAY, CALIFORNIA



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The flood and drought extremes illustrate the variability of the seasonal pattern. Although ocean water usually represents a significant fraction of the water in the bay, fresh water on the surface flowed out the Golden Gate continuously for nearly 2 weeks during the collosal flood of 1862 (Young, 1929), and freshwater fish were present in the bay for months afterward (Thomas, 1978). Peterson and others (1985) estimated that river inflows to the bay of at least 120,000 m^3/s (4 million ft^3/s) would have been necessary to overcome the tides at the Golden Gate during this period.

In contrast, although ocean salt usually penetrates landward no farther than Suisun Bay, it intruded inland as far as Courtland on the Sacramento River and Stockton on the San Joaquin River during the extreme drought of 1929-31. During the summer of 1931 river inflows to the delta were persistently less than 15 m^3/s (500 ft^3/s) and were effectively zero during a two-week period (State of California, 1932). It is likely that delta discharge was effectively zero for significant periods during this drought.

Since then addition of a number of reservoirs and diversion structures have changed the freshwater discharge of the delta. Although no reasonable amount of storage can overcome extreme floods and droughts, the additions of upstream storage have had a significant influence on delta discharges (Williams and Fishbain, 1987). A principal effect has been to delay discharge from winter and spring until summer and fall, permitting consumption of 40 percent and export of an additional 24 percent of the historical annual freshwater discharge of 34 km^3 (27.6 million acre-feet) (Nichols and others, 1986). Summer flows are maintained now by reservoir releases whose purposes are to supply users and to suppress salinity intrusion into the delta (Conomos and others, 1985). Upstream storage has also reduced the discharge peaks of winter storms (Williams and Vorster, 1987).

Despite the attention that responsible agencies have focused on estimating delta discharges, questions remain about discharge quantities during the irrigation season. The present method for estimating daily delta discharges (State of California, 1986) involves uncertain assumptions about consumptive use in the delta and traveltime of water through the delta. Measurement of discharges into Suisun Bay is an alternative, but a practical method has yet to be found that is accurate enough to determine net discharges during low-discharge conditions (Smith, 1969).

Evaporation

Evaporation has a relatively minor effect on the water balance of San Francisco Bay as a whole. On an annual basis net evaporation (actual evaporation minus precipitation) accounts for less than 7 percent of an average annual delta discharge of 12 km^3 (10 million acre-feet), assuming an annual evaporation of 0.73 m (2.4 feet) (Selleck and others, 1966) over a surface area of 1.1×10^9 m^2 (270,000 acres) (Conomos, 1979). Seasonal variations, however, are significant, and net evaporation can nearly equal delta discharges during summers of dry years. Net evaporation during July accounts for a loss of about 90 m^3/s (3,200 ft^3/s), assuming 0.19 m (0.6 feet) evaporation (Selleck and others, 1966) over the same surface area. The effects of evaporation will be ignored in the remainder of this report, and the delta discharge effects described can be assumed to be for delta discharges in excess of evaporation.

MAJOR CIRCULATION AND MIXING CHARACTERISTICS OF SAN FRANCISCO BAY

	Low Delta Discharge (less than 400 m^3/s)	High Delta Discharge (greater than 1000 m^3/s)
NORTHERN REACH		
Circulation:	gravitational circulation in channels (Peterson and others, 1975; Walters and Gartner, 1985; Walters and others, 1985) tide- and wind-induced net horizontal circulation (Walters and others, 1985; Smith and Cheng, 1987)	intense gravitational circulation seaward of null zone, and river-like flow landward of null zone (Peterson and others, 1975; Walters and others, 1985)
Null zone:	Suisun Bay and landward (Peterson and others, 1975) approximate salt balance in late summer (Winkler, 1985)	Carquinez Strait and seaward (Peterson and others,1975) rapid seaward movement in channel during runoff events, slow landward movement afterward (Imberger and others, 1977)
Mixing:	mean residence times of two to three months affected by a combination of delta discharge and mixing(Glenne, 1966; Walters and others, 1985; Denton and Hunt, 1986)	mean residence times less than two weeks controlled by delta discharge (Glenne, 1966; Walters and others, 1985; Denton and Hunt, 1986)
SOUTH BAY		
Circulation:	tide- and wind-induced net horizontal circulation (Walters, 1982; Cheng and Casulli, 1982; Walters and others, 1985; Cheng and Gartner, 1985)	gravitational circulation in channel, initially southward at surface and northward at bottom, and *vice-versa* later (McCulloch and others, 1970; Conomos, 1979; Walters and others, 1985)
Mixing:	three mixing zones separated by San Bruno Shoal and constriction at the San Mateo Bridge (Powell and others, 1986) mean residence times of a few months affected by mixing and exchanges with Central Bay (Walters and others, 1985; Denton and Hunt, 1986)	intrusion of fresh water southward dependent upon magnitude of runoff event (Imberger and others, 1977; Conomos, 1979) and vertical mixing (Cloern, 1984) mean residence times of a few weeks affected by exchanges with Central Bay and mixing (Walters and others, 1985; Denton and Hunt, 1986)

TABLE 2.--Characteristics of circulation and mixing in San Francisco Bay for low and high Delta discharges. In parentheses are key references which are listed in references section

MIXING OF RIVER AND OCEAN WATER DURING LOW AND HIGH DELTA DISCHARGES

Knowledge of circulation characteristics provides a necessary foundation for understanding mixing in San Francisco Bay. Mixing is determined by the path that a water mass takes and by its comingling with other water masses along that path. Direct measurements of mixing in the bay are rare because they require following specific parcels of water, and thus involve technically difficult and labor-intensive tasks. Instead, most mixing characteristics of the bay have been inferred from observations of salinity distributions. In general, much less is known about mixing than about circulation in San Francisco Bay (Walters and others, 1985).

Perhaps the simplest mixing characteristic of an embayment is its mean residence time. Estimates of mean residence times for delta discharges near 100, 1,000, and 10,000 m^3/s (3,500, 35,000, and 350,000 ft^3/s) of Denton and Hunt (1986), Walters and others (1985), and Glenne (1966) are illustrated in figure 14 for individual embayments. The results of other studies suggest limitations to the utility of these mean residence time estimates of whole embayments.

Northern Reach

Low Delta Discharges

The large salinity differences between Suisun, San Pablo, and Central Bays during low-discharge conditions permit estimation of exchange ratios, freshwater fractions, and diffusive transport fractions, so that Denton and Hunt (1986), Walters and others (1985), and Glenne (1966) calculate similar residence times within the degree of approximation expected (fig. 14a). For delta discharges near 100 m^3/s (3,500 ft^3/s) the estimates are 28 to 35 days in Suisun Bay and 20 to 25 days in San Pablo Bay. Glenne's slightly different estimates can be attributed partly to a different, more sparse data set.

Delta discharge (advection) and diffusive processes (gravitational circulation and net horizontal circulation) both appear to be important determinants of mean residence times (fig. 15). Glenne estimated that the mean residence time that results from delta discharge only, about 60 and 170 days in Suisun and San Pablo Bays, respectively, is reduced in both embayments significantly by all other mixing processes, to about 30 and 20 days (fig. 15). Walters and others estimated slightly different reductions, 45 to 35 days in Suisun Bay, and 84 to 25 days in San Pablo Bay, but the trends are similar.

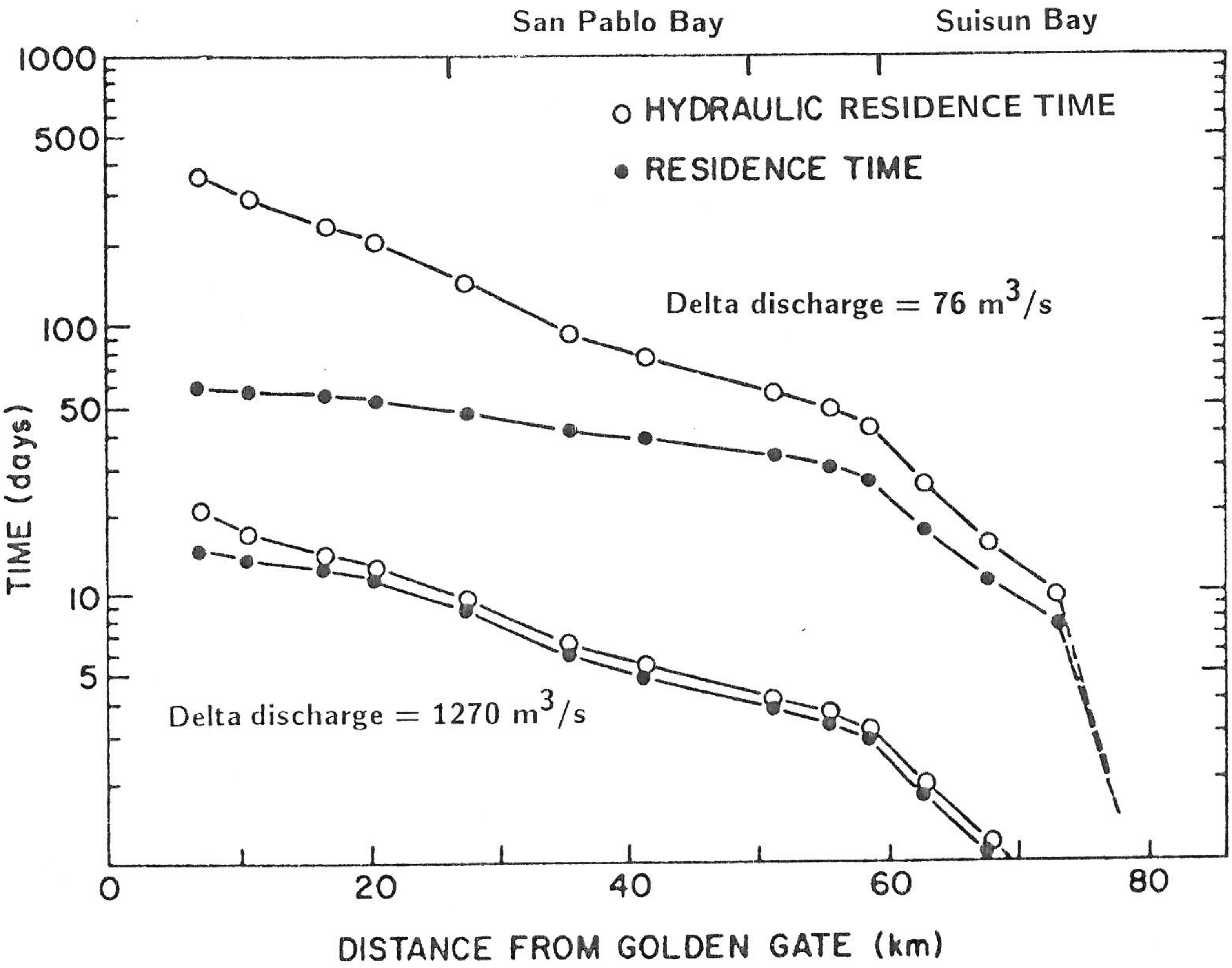

FIGURE 15.--Estimates of mean residence times for segments of the northern reach divided into an advective portion (induced by delta discharge and called hydraulic residence time) and a diffusive portion (induced by gravitational circulation and the net horizontal circulation) (figure 16 of Glenne, 1966 as modified by Conomos, 1979). Delta discharge controls residence times for high delta discharges (lower two curves are close), but the diffusive reduction of residence time is large for low delta discharges (upper two curves are separated). The delta discharge quantities, added to Glenne's figure by Conomos (1979), have been changed to reflect those appropriate for the hydraulic residence time curves.

Gravitational circulation and the shallow-channel exchange enhance mixing of fresh water seaward. They also are the principal factors that mix ocean water landward. The landward transport of salt by gravitational circulation and net horizontal circulation and the flushing effect of the delta discharge adjust toward an approximate balance of salt in the northern reach during the low delta-discharge period. Harder (1977) estimated that salinities in Carquinez Strait near Benicia are affected by the pattern of delta discharge for the previous 90 days. Similarly, Winkler (1985) concluded that prediction of monthly mean salinities in Suisun Bay could be made with monthly discharges for the same month and one previous month. Because the low-discharge period usually exceeds three months, a balance is probably achieved during most years.

Conomos (1979) concluded from theoretical arguments that 60 to 70 percent of the overall upstream salt intrusion results from processes other than the gravitational circulation during low freshwater inflows. Walters and Gartner (1985) concluded for one location in Suisun Bay that gravitational circulation was the dominant factor in the net salt flux during neap tides, but that its contribution was highly variable over the spring-neap cycle. Walters and others (1985) concluded that insufficient data exist for the northern reach to be conclusive about the relative contributions of these processes to net salt fluxes.

High Delta Discharges

For delta discharges of about 1300 m^3/s (46,000 ft^3/s) mean residence times appear to be about a week each for Suisun and San Pablo Bays (fig. 14a). Glenne (1966) showed that delta discharge dominates mean residence times at or above this value, which means that mean residence times and hydraulic residence times are nearly equal (fig. 15). The high-discharge estimates of Denton and Hunt (1985) are probably too large because they exceed hydraulic residence times. For delta discharges of 10,000 m^3/s (350,000 ft^3/s) Walters and others (1985) and Denton and Hunt (1986) estimate that mean residence times for the whole northern reach decrease to less than 5 days (fig. 14a).