EVALUATION OF TURBIDITY AND TURBIDITY-RELATED EFFECTS ON THE BIOTA OF THE SAN FRANCISCO BAY-DELTA ESTUARY

A Report Submitted to

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Disclosure Statement

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Executive Summary

This report evaluates the possible relationships that may exist among dredged material disposal at the Alcatraz disposal site, turbidity in Central San Francisco Bay, and potential impacts of turbidity on the biota of Central Bay. The specific objectives of the report were:

1. To assemble data on ambient turbidity levels in Central Bay;
2. To review the data on effects of turbidity and suspended solids on Bay organisms;
3. To identify any relationships between turbidity, suspended solids and the fisheries of the Bay, especially the striped bass sport fishery;
4. To evaluate the contribution of dredging and dredged material disposal to turbidity in the Bay and
5. To describe any predictive relationships between turbidity increases from dredged material disposal and sport and commercial species in the Bay.

San Francisco Bay is a broad, shallow estuary composed of distinct sub-embayments; the majority of freshwater and sediment input occurs in the Northern Reach. Suspended sediment concentrations and turbidity vary throughout the system depending upon freshwater inflow, tidal currents, wind velocity and other factors. In general turbidity is greatest in the Northern Reach, in the vicinity of the null zone. The location of the null zone may change depending upon freshwater discharge from the Sacramento-San Joaquin Delta. Turbidity generally declines downstream of the null zone; however, resuspension of deposited sediments by wind-driven wave action and currents may cause periodically high concentrations of suspended solids and increased turbidity in Suisun and San Pablo Bays. Suspended solids concentrations in Central Bay are generally least of all the sub-embayments, ranging from about 10 to 60 mg L^{-1}. Suspended solids in the null zone can reach values as high as 600 mg L^{-1}; however, concentrations of from 50 to 200 mg L^{-1} are more common.

Numerous studies have been carried out to measure turbidity or, alternatively, suspended sediments or secchi disk water transparency, in Central Bay. These studies show a wide range of variability associated with location, tidal currents, season, the presence or absence of dredged material disposal at the Alcatraz site, or the presence of sand-mining operations in Central Bay. Short-term, intensive sampling of suspended solids showed a range of values greater than 50% of the mean. Quarterly or annual sampling in Central Bay shows that suspended solids there remain lower than concentrations in South Bay, or in the Northern Reach. Monthly measurement of Secchi disk depth at Central Bay stations has shown an annual pattern of reduced transparency during winter months, followed by a gradual increase in transparency from summer into fall. The annual pattern of secchi disk transparency after 1985 was substantially different from that recorded between 1980 and 1985; overall transparency was reduced, and the seasonal progression of increasing transparency from summer through fall was apparently disrupted. There are insufficient data from other sources to relate secchi disk transparency patterns to changes in suspended solids concentration, or to engineering activities such as sand-mining, or dredged material disposal activity. Estimates of turbidity due to high-frequency dredged material disposal showed that increases (e.g. 6 to 7 mg L^{-1} TSS) could occur; whether such increases could result in a 25% decrease in surface water transparency cannot be determined. The calculated estimates of turbidity that might arise from frequent disposal are equivalent to the range of variation that might be expected due to ambient factors.

Particulate matter may affect estuarine biota in a number of different ways, including burial, covering in "turbidity flows," and particle-mediated effects on phytoplankton, zooplankton, benthos and fish. Other potential effects of suspended particulate matter on the biota include indirect effects such as the modification of substrate or changes in behavior, feeding, and reproduction. A substantial number of studies have been carried out to determine the direct and indirect impacts of increased suspended sediment concentrations on a variety of estuarine biota, including species that inhabit the San Francisco Estuary.

Phytoplankton and zooplankton were affected directly by particles suspended in the water. The effect of suspended particles on phytoplankton is directly related to light penetration into the water and the potential reduction of the photic zone in turbid conditions. Zooplankton, on the other hand, were affected by the concentrations of particles, presumably due to interference with normal processes of particle filtration and feeding. An estuarine copepod *Eurytemora affinis* responded to high suspended particle concentrations by reduced filtration; however, the critical factor for reduced filtration was concentration, since identical concentrations of mineral solids and natural food (phytoplankton) caused the same response.

Early life-history stages of fishes and invertebrates were, with one exception, tolerant of rather high concentrations of suspended solids. Only the American oyster (*Crassostrea virginica*) was affected (increased proportion of abnormal development in larvae) at concentrations similar to those that might occur in natural estuarine systems. Other species (*Ostrea edulis, Mercenaria mercenaria*) tolerated concentrations of mineral solids and natural silt much greater than those that might persist as the result of dredged material disposal activities.

Studies of fish eggs and larvae show that these forms are tolerant to rather high concentrations of suspended particles and mineral solids. Indeed, estuarine forms that have been tested, including white perch and striped bass normally spawn and develop in the zones of highest turbidity. Under such conditions it is not surprising that suspended solids concentrations generated by dredged material disposal operations have no effect.

Benthic organisms tolerated very high concentrations of suspended solids with little or no effect. A variety of mussels, clams and oysters survived suspended particle concentrations many times higher than those that occur in the vicinity of disposal operations. However, it has been shown that there is a critical interaction among suspended solids, temperature and dissolved oxygen concentrations.

Adult fishes generally tolerate exposure to high concentrations of suspended solids quite well. Studies of the effects of suspended solids on fishes show that mortality is related the shape, concentration, and hardness of the particles concerned, and that the primary cause of death is interruption of gas exchange across the surface of the gill. Studies of sublethal effects of suspended particles show that respiratory gas exchange impairment may begin to appear after long exposure to concentrations of mineral solids above about 500 mg L^{-1}, and that compensatory mechanism, such as increased red blood cell counts, could overcome the effects of reduced gas exchange at the gill. In general, fishes exposed to suspensions of natural silts and clays were less severely effected than those exposed to mineral solids such as kaolin, bentonite, montmorillonite or silicon dioxide.

Some species of estuarine fishes showed a preference for habitats with particular turbidity levels. However, studies of feeding success, prey recognition and food selectivity suggest that turbidity is a minor factor. Fish like striped bass larvae can detect and acquire prey in highly turbid conditions as well as in clear water. Such results demonstrate that fishes are well-adapted to survival and feeding in environments characterized by variable visibility and turbidity. This is particularly true for estuarine species, whose environment is affected by seasonal, daily, and tidal changes, all of which may cause changes in the concentration of suspended solids.

Disposal of dredged material at the Alcatraz site has not been studied in a manner that could allow conclusions to be drawn regarding whether the apparent decrease in surface water transparency in Central Bay is directly related to disposal, or if disposal is related in any way to the catchability of sport fish in the sub-embayment. Laboratory studies show that low-level increases in turbidity should have no effect on the presence, distribution or feeding abilities of estuarine and marine species that occupy central bay. Field studies at Alcatraz show that fishes may disperse in response to disposal events, but that they return within one hour or two; the implication is that fish schools move only a short distance in response to disposal events in Central Bay.

If dredge material disposal is to continue at the Alcatraz site, and if fisheries are to be protected, then there will exist the need to establish a comprehensive monitoring program at the disposal site, and throughout the Central Bay. The monitoring program will require the resources of government agencies and fishermen, and should be designed to collect data on turbidity and suspended particle concentrations throughout Central Bay, the long-term and long-range transport of suspended solids from disposal operations and other activities that resuspend sediments, including sand-mining, shipping, tides, winds, etc. Furthermore, the monitoring program must be designed such that all appropriate fish- and fisheries-related phenomena are measured, including distribution and movement of forage fishes and sport fish, short-term and long-term movements of fishes in response to disposal events, and the direct relationships of sport fish catch to turbidity and the presence or absence of dredged material disposal.

EVALUATION OF TURBIDITY AND TURBIDITY-RELATED EFFECTS ON THE BIOTA OF THE SAN FRANCISCO BAY-DELTA ESTUARY

I. Introduction

1. The environmental impacts of dredging and dredged material disposal on the San Francisco Estuary (the Estuary) have been a matter of discussion for more than a decade. Stating the problem simply, dredging and dredged material disposal are necessary to maintain navigation as a beneficial use of the Estuary (San Francisco Bay Regional Water Quality Control Board [SFBRWQCB], 1986). However, dredging-related activities may conflict with other beneficial uses of the Estuary such as preservation of rare and endangered species, fish spawning and migration, commercial or sport fishing, and shellfish harvesting (Table 1). A recent review of this subject has been published by Gunther *et al.* (1990). Of particular concern has been the question of whether disposal of dredged material at the Alcatraz disposal site has caused an increase in the turbidity of waters in Central San Francisco Bay, and whether this increased turbidity has had a negative impact on sport fishing success in Central Bay.

2. Sport fishing success in the San Francisco Estuary has declined over time, especially for striped bass (*Morone saxatilis*; McKechnie and Miller, 1971; Stevens, 1980; California Department of Fish and Game [DFG], 1989 and unpublished data). Sport fish catches, including striped bass, show a decline beginning in the 1960s (Chadwick, 1962; McKechnie and Miller, 1971) and continuing through the 1970s (DFG, 1989). Recent data (DFG, unpublished) show that the total sport fish and striped bass catch in Central Bay declined drastically between 1985 and 1986 (Brown, 1989; E. Fullerton, National Marine Fisheries Service, La Jolla, CA, personal communication; R. Tasto, DFG, personal communication). Some improvement of sport fish catch occurred in 1989 and 1990 (D. Lollock, DFG, personal communication), apparently coincident with a reduction of dredged material disposal activity at the Alcatraz site.

3. Measurements of water transparency (Secchi disk measurements) in Central San Francisco Bay have been collected in conjunction with trawl sampling since at least 1980 (DFG, unpublished data). These data show a substantial decrease in Secchi disk transparency of Central Bay waters. It has been suggested that this apparent decrease in transparency is related directly to dredged material disposal activities at the Alcatraz disposal site in Central Bay (see San Francisco Bay Regional Water Quality Control Board [SFBRWQCB], 1989; DFG, 1989; Gunther *et al.*, 1990).

4. The inference has been drawn that the decline in recreational fish catch in Central Bay is related to decreased water transparency (increased turbidity). It has been hypothesized that the effects of increased turbidity on the sport fishery is either direct (i.e., the fish are harmed by the turbidity, or are purposefully avoiding more turbid waters) or indirect (i.e., more turbid waters

Table 1. Beneficial uses of the San Francisco Bay-Delta Estuary designated by the State Water Resources Control Board (from SFBRWQCB, 1986)

Agricultural Water Supply[1]

Industrial Service Supply

Industrial Process Supply[2]

Groundwater Recharge[1]

Navigation

Water Contact Recreation

Non-water Contact Recreation

Ocean Commercial and Sport Fishing

Wildlife Habitat

Preservation of Rare and Endangered Species

Fish Migration

Fish Spawning[3]

Shellfish Harvesting[4]

Estuarine Habitat

Footnotes:
1. Delta only
2. Central Bay and Delta only
3. Potential beneficial use for South Bay and Lower Bay
4. Excluding Delta, Suisun Bay and Carquinez Strait

are avoided by forage fish and, in the absence of forage, desirable sport fishes are present in lower numbers). Neither of these hypotheses have been tested using data collected specifically for the purpose of determining whether dredged material disposal at Alcatraz is the cause of reduced sport fishery catch in Central Bay.

5. This report has been prepared in order to evaluate the relationship, if any, that may exist between dredged material disposal at the Alcatraz disposal site, decreased water transparency (increased turbidity) in Central San Francisco Bay, and possible impacts on the biota of the Central Bay. The specific objectives of this evaluation are to:
   - Assemble data on ambient turbidity at principal locations in the Bay under different seasonal and climactic conditions.
   - Prepare a review of information concerning the relationships between turbidity and organisms of San Francisco Bay.
   - Identify relationships between turbidity and important sport and commercial fisheries of the Bay, including feeding habits, catchability and health of striped bass.
   - Evaluate the contribution of dredging and dredged material disposal to overall turbidity in the various embayments of San Francisco Bay.
   - Identify, describe and evaluate known or predicted relationships between incremental increases in turbidity associated with dredging and dredged material disposal and sport and commercial species in the Bay.

II. Characteristics of the San Francisco Estuary

A. Physical Characteristics

6. The San Francisco Estuary (Figure 1a, 1b) was created by tectonic processes when crustal subsidence associated with the San Andreas and other faults formed the depression that is now the Estuary (Atwater, 1979). Wagner (1978) and Atwater (1979) suggest that the Estuary has gone through no fewer than three cycles of submergence and emergence over time. The existing San Francisco Estuary was formed about 10,000 years ago, at the end of the Wisconsin glaciation, when melting of the ice caps caused a rise in sea level and seawater entered the system.

7. The San Francisco Estuary ranks third among U.S. estuaries in terms of freshwater inflow (Table 2; Conomos *et al.*, 1985). Average inflow to the system (600 cubic meters per second; $m^3 s^{-1}$) is about one-thirtieth that of the Mississippi (Schubel and Hirschberg, 1982). Freshwater flow to the Estuary varies seasonally, with most of the freshwater entering the Bay during the winter and early spring months (Table 3; Peterson *et al.*, 1985).

8. The San Francisco Estuary comprises two distinct portions, the Northern reach and South Bay ((Figure 1a; Davis, 1982). The Northern reach and the South Bay are connected hydraulically; however they differ in that the Northern reach (Suisun Bay, San Pablo Bay and Central Bay; Figure 1a) receives the vast majority of freshwater input to the system (>90%), whereas the South Bay receives less than 10% of the freshwater inflow. Freshwater inflow to the South Bay is insufficient to drive the estuarine circulation that is essential to the functioning of a "typical" estuarine system (Davis, 1982). Pritchard (1967) would have classified South Bay as an "inverse estuary;" i.e., a system in which evaporation exceeds input from runoff plus precipitation. This simple classification is made difficult by seasonally variable patterns of flow and water circulation in the Estuary. During periods of high freshwater inflow from the Sacramento San Joaquin Delta low salinity water from the Northern reach penetrates South Bay causing stratification and gravitational circulation (Conomos *et al.*, 1985).

9. In its present configuration the San Francisco Bay is broad and very shallow. While the Estuary has the largest surface area of any coastal embayment on the West coast of North America (1240 km^2), the average depth of the Bay is 6.1 m, and median depth is only 2 m at mean lower low water (MLLW; Conomos *et al.*, 1985; Table 4). The broad shallows of the Bay are cut by narrow channels that are typically 10 to 20 m in depth. The major channels (e.g., Carquinez Strait and the Golden Gate) are scoured by tidal currents; the depth of many other deep channels (>10 m) in the Bay is maintained by occasional dredging (Conomos *et al.*, 1985). The Bay-wide tidal range is large compared to the average depth of the system. As a result, the amount of seawater entering the Bay with each tidal cycle (the tidal prism) is large, about 24% of the Bay volume (Conomos, 1979).

Figure 1a. The San Francisco Estuary, from the Sacramento-San Joaquin Delta to the Pacific Ocean. Broken lines divide the Estuary into "Blocks" designated by the Depaertment of Fish and Game for the evaluation of fisheries data.

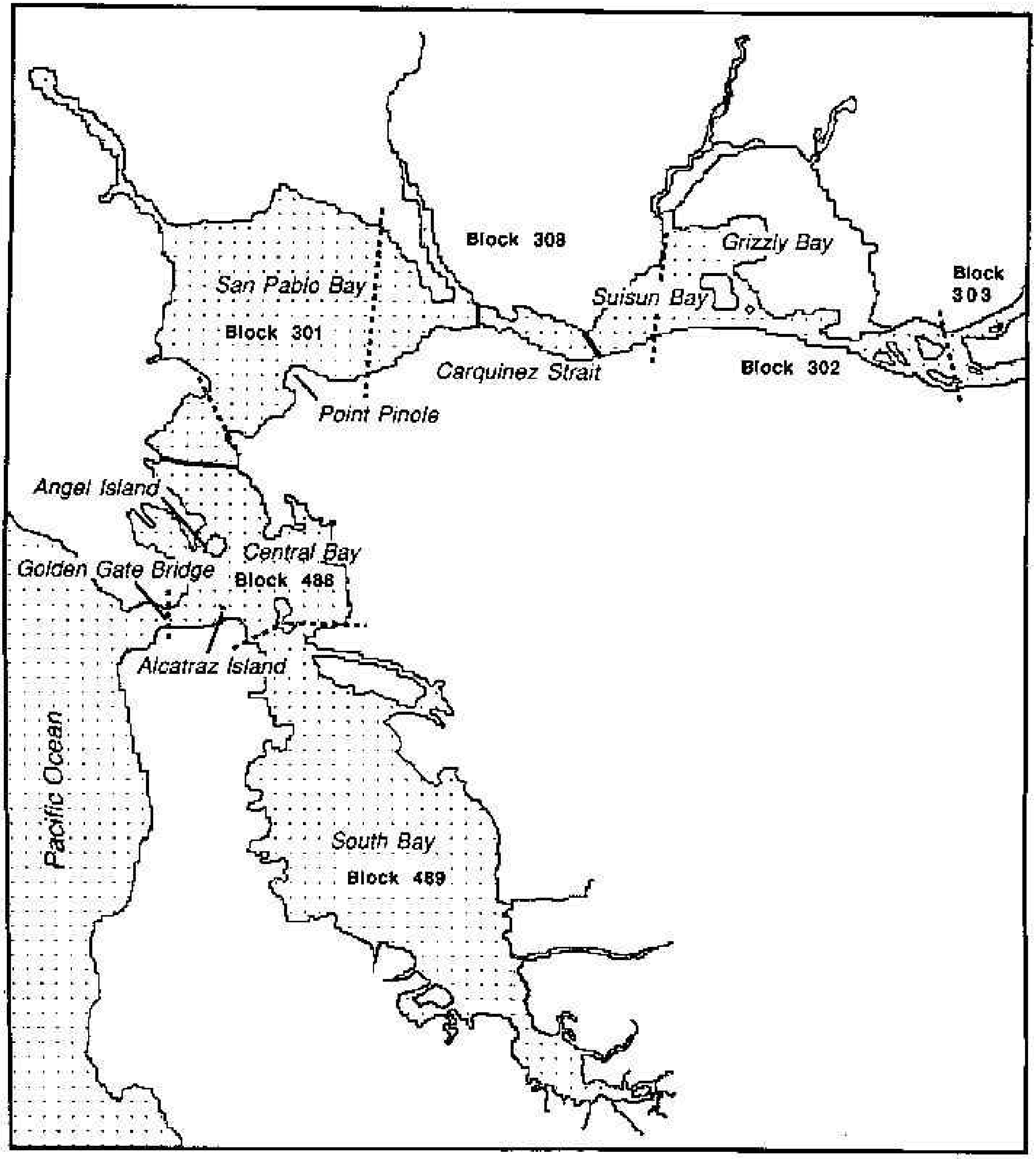


Figure 1b. Detailed map of the Central Bay (DFG Block 488) and portions of South Bay (DFG Block 489)

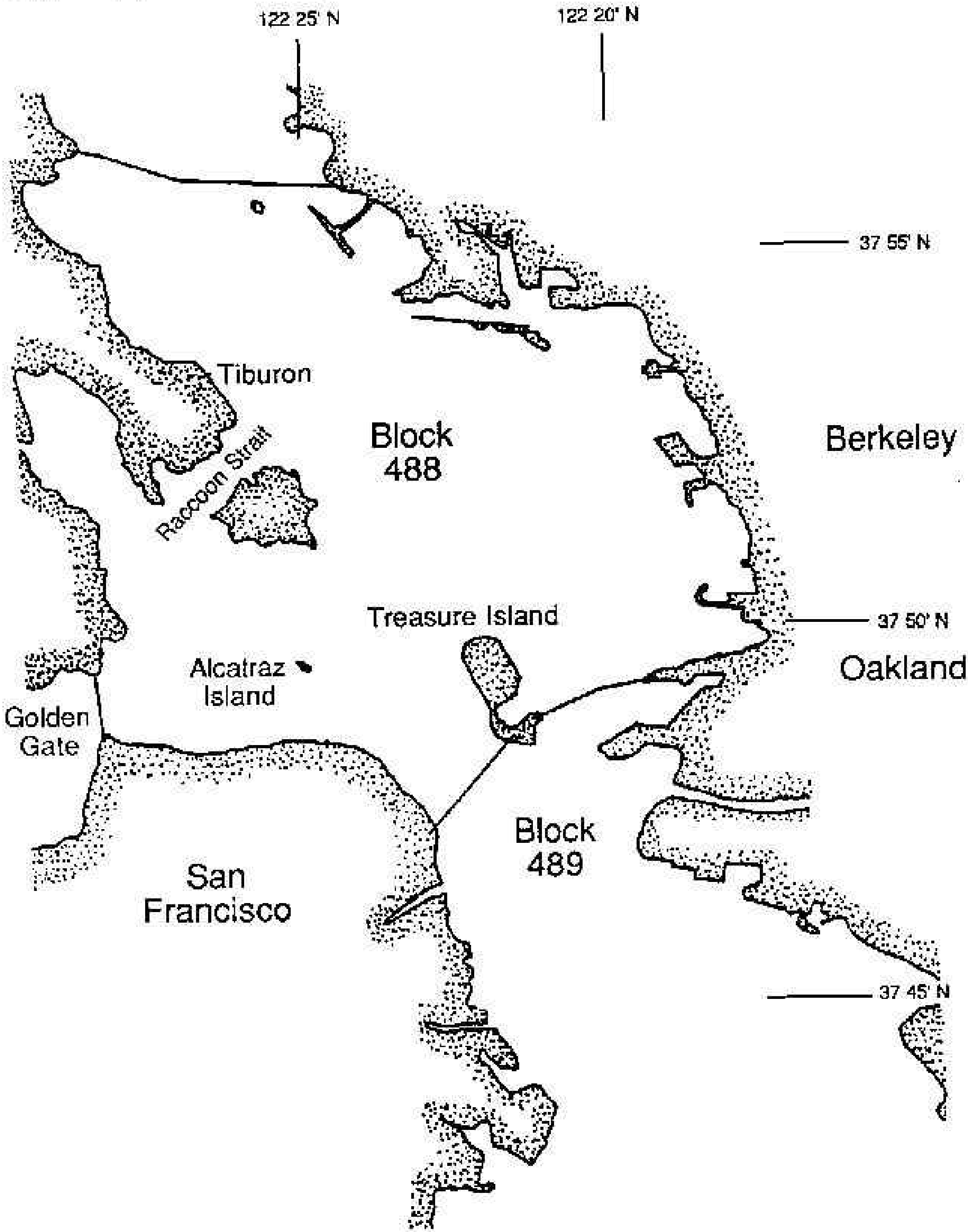


Table 2. Comparison of the San Francisco Bay drainage basin area, estuary surface area and freshwater inflow with other North American estuaries. From Conomos *et al.* (1985).

	Basin area 10^3 km^2	Surface area km^2	Inflow m^3 s^{-1}
San Francisco Bay	153	1,240	600
Columbia River	671	380	5,500
Fraser River	203	-	2,700
Delaware Bay	33	303	550
Chesapeake Bay	166	11,400	1,600

Table 3. Hydrological statistics for the Sacramento-San Joaquin River Basin. From Peterson *et al.* (1985)

Property	Value
Area	153,000 km^2
Historical mean-annual flow	1,070 m^3 s^{-1}
Present mean-annual flow	600 m^3 s^{-1}
Peak flows of Sacramento River floods	
January 1907	21,000 m^3 s^{-1}
March 1, 1940	12,000 m^3 s^{-1}

10. Krone (1979) estimated that 80% to 90% of the sediment entering San Francisco Bay comes from erosion in the drainage basins of the Sacramento and San Joaquin rivers. The suspended sediment load discharged to the Bay from the Delta was estimated by Conomos and Peterson (1977) at 4.0 X 10^6 metric tons per year; approximately 80% of that load is discharged during winter months. The total suspended sediment load to the Bay is not large compared to the major rivers of the world. It is about 50 times smaller than the sediment discharge of the Mississippi and 40 times less than the Red River (Schubel and Hirschberg, 1982).

11. The physical structure of San Francisco Estuary has been affected substantially by human activities. Gilbert (1917; cited in Krone, 1979) estimated that 1.2 X 10^9 cubic yards (yd^3) of sediment were deposited in the Estuary as the result of hydraulic mining for gold in the Sierra Nevada. The sediments from hydraulic mining created huge deposits in Suisun and San Pablo bays. According to Krone (1979), hydraulic mining debris decreased water depths throughout the Northern reach of the system, and all but obliterated Vallejo Bay at Martinez. Other human impacts on the physical structure of the Estuary include dredging and dredged material disposal, diking and drainage in the Delta for agricultural purposes, wetland drainage, diking to form salt evaporation ponds (primarily in the South Bay) and extensive shoreline development (Davis, 1982).

B. Biological Characteristics

12. The San Francisco Estuary supports a rich and diverse fauna comprising not only native species, but also more than 100 exotic species introduced during the past 140 years (Skinner, 1962; Carlton, 1979; Armor and Herrgesell, 1985). According to Smith and Kato (1979) the San Francisco Estuary supports over 100 species of fish, 70 bivalves and 30 decapod crustaceans. Major fisheries exist, or have existed, in the Bay region for chinook salmon (*Oncorhynchus tshawytscha*), white sturgeon (*Acipenser transmontanus*), striped bass, American shad (*Alosa sapidissima*), Pacific herring (*Clupea harengus pallasi*), Bay shrimp (*Crangon franciscorum*), oysters (*Crassostrea virginica* and *C. gigas*), soft-shell clams (*Mya arenaria*) and blue mussels (*Mytilus edulis*). There are active commercial fisheries in the Bay for Bay shrimp and Pacific herring; minor commercial fisheries exist for surfperches, sharks and rockfish.

13. The biota of the Estuary are distributed in a pattern typical of estuaries. That is, the numbers of species tends to decline as one moves away from the stable conditions of freshwater at the head and marine waters at the mouth (Remane and Schlieper, 1971). Biomass among estuarine populations tends to be distributed among a relatively few species that can tolerate the stressful, changing environment, but includes some predominantly oceanic species such as Dungeness crab (*Cancer magister*), English sole (*Parophrys vetulus*), and other species.

Table 4. Geostatistics of San Francisco Bay. From Conomos *et al.* (1985)

Statistic	Value
Area (MLLW)	1.04×10^9 m^2
including mudflats	1.24×10^9 m^2
Volume	6.66×10^9 m^3
Tidal prism	1.59×10^9 m^3
Average depth	6.1 m
Median depth	2 m
River discharge (annual)	20.9×10^9 m^3
Delta outflow	19.0×10^9 m^3
All other streams	1.9×10^9 m^3

14. Benthic species diversity in San Francisco Bay is greatest in the vicinity of the Golden Gate, where conditions of temperature and salinity remain most constant (Nichols, 1979). As one moves away from the marine influence, through Central Bay and into San Pablo and Suisun bays, species diversity decreases. This is due in part to the large interannual variations in salinity that occur in the Northern reach, as well as to rapid and large movements of surficial sediments that occur on a seasonal and interannual basis (Nichols, 1979; Nichols and Thompson, 1985). The numbers of species in South Bay is intermediate between that of the marine waters at the Golden Gate and the Northern reach. Nichols (1979) attributes this to the more stable salinity regime of South Bay waters.

15. Fishes undertake broad-scale movements in the Estuary. The major anadromous fish species (striped bass, white sturgeon, chinook salmon) occupy the entire Northern reach of the Estuary as they move from marine or Central Bay waters into riverine environments for spawning (Skinner, 1962). The young of anadromous species occupy freshwater and estuarine habitats for varying periods of time as they move from the spawning grounds through nurseries and back to marine waters.

16. Estuarine species are distributed throughout the system, and their movements correspond in large part to the seasonal and interannual patterns of salinity and density-driven flows in the Estuary (Herrgesell *et al.*, 1983; Armor and Herrgesell, 1985). Most of the estuarine species studied showed no response to freshwater outflow from the Delta. Those species that did show a response showed a "wet response," in that their abundance in catches increased during periods of high freshwater flow (Armor and Herrgesell, 1985). Armor and Herrgesell (1985) noted that several species of marine and estuarine fish showed a tendency to move upstream in the Estuary during periods of high Delta outflow. They speculated that this apparently anomalous response may have been due to upstream transport of organisms in bottom (landward-moving) currents when the Northern reach of the Estuary was highly stratified.

17. The only invertebrate fishery in the Bay, the Bay shrimp, shows a seasonal cycle of abundance (Skinner, 1962; DFG, 1987). The Bay is primarily a nursery area for young shrimp; ovigerous females and larvae in most years are located offshore. The seasonal cycle of shrimp abundance is related to the transport of juveniles into the system with intruding salt water from the ocean (Hatfield, 1985). Studies conducted between 1980 and 1982 suggest strongly that Bay shrimp distribution is controlled by the salinity regimes that accompany different levels of outflow from the Delta.

18. The distribution and abundance of the major benthic populations in the Estuary are controlled by such factors as salinity, freshwater discharge from the Delta, substrate changes and interspecies interactions (Nichols, 1979; Nichols and Thompson, 1985; Nichols *et al.*, 1986). Many of the more abundant benthic biota in the Estuary are introduced species (e.g., *Mya,*

Gemma, Corbicula, Potamocorbula, Ampelisca; Carlton, 1979; DWR, 1987), or may be newly introduced strains of species that are, or were, native to the Estuary (e.g., *Macoma balthica;* Carlton, 1979). In the Northern reach benthic species distributions are seasonally variable, controlled in large part by the length of time that low salinity water is present at a given location. In South Bay, benthic populations fluctuate in response to interspecies interactions, substrate modification (due to meteorological events) and predation (Nichols and Thompson, 1985). Existing populations of the newly-introduced clam, *Potamocorbula amurensis*, may be harvesting a large fraction of the phytoplankton biomass in the Northern reach (Nichols *et al.*, 1990; Carlton *et al.*, 1990). During periods of low Delta outflow, when the South Bay is well-mixed, benthic populations of *Gemma gemma* and *Macoma* may harvest the phytoplankton biomass and eliminate phytoplankton blooms.

C. The Striped Bass Fishery

19. Once the foremost fishing center of the West Coast, the San Francisco Estuary now supports commercial fisheries only for Pacific herring and Bay shrimp (Smith and Kato, 1979) and minor hook-and-line fisheries for surfperch, sharks and rockfish (DFG, unpublished). The major commercial fisheries of the past have succumbed to a number of negative influences including pollution, construction of dams, water diversion, and overfishing. Prohibitions on commercial fishing for striped bass and salmon were intended to protect the populations for the sport fisheries. Commercial fishing prohibitions were imposed on sturgeon in 1917; on striped bass in 1935; and on both chinook salmon and American shad in 1957 (Smith and Kato, 1979). Recreational fisheries for these species still exist in the Estuary.

20. The striped bass fishery in the San Francisco Estuary has been in decline since the 1960s (McKechnie and Miller, 1971; DFG, 1987,1989; DFG, unpublished data). Many reasons have been proposed to explain the decline of the striped bass in San Francisco Bay and the Sacramento-San Joaquin river system. Those reasons cited most often are entrainment of young by water projects, local agriculture and industry, reductions in food supply, water pollution (causing toxicity among larvae and juveniles, as well as the "annual die-off" in the Carquinez Straits; Kohlhorst, 1973, 1975), limited supply of eggs from a reduced population of adults, and overfishing (DFG, 1987). Stevens (1977, 1980; Stevens et al.,1989; see also DFG, 1989) has suggested that the primary factor causing decreased striped bass abundance in the Estuary is water diversion. Other authors (e.g., Brown, 1987) have offered an alternative hypothesis; i.e., that striped bass numbers are in decline because sensitive early life history stages are affected by toxic chemicals in the vicinity of nursery areas in the brackish waters of the Sacramento and the San Joaquin rivers, the Western Delta and the Northern reach of the Estuary.

21. Whatever the reason for the decline in the overall population of striped bass, the sport fishery has suffered. McKechnie and Miller (1971) noted that between 1960 and 1968 the biomass of striped bass caught per angler day in the partyboat fishery in Central Bay, San Pablo Bay and Suisun Bay remained relatively constant; however, the size of individual fish declined. Such data may suggest an alteration in the age-distribution of the striped bass population in the Estuary, and could be interpreted as a sign of a decline in the numbers of striped bass. Later evaluations of partyboat striped bass catch suggested that the numbers of fish were declining, a hypothesis supported by estimates of declining numbers of spawning adults in the population, and reductions in the "striped bass index."

22. Striped bass catch in the Estuary has declined precipitously in recent years. Historically the majority of striped bass taken in the sport fishery came from the San Pablo Bay-Carquinez Straits region (DFG Blocks "301" and "308," respectively; Chadwick, 1962; McKechnie and Miller, 1971; Figure 1a). Relatively few fish were taken in Central Bay (Block 488) or in the Delta (Block 303). Catches in Central Bay increased dramatically in the mid- to late-1950s (Chadwick, 1962; Figure 2). This increase in catch could have been due as much to new fishing techniques as to any increase in the abundance of striped bass. In the mid-1950s fishermen began to use deep-trolling techniques in search of striped bass in Central Bay and, in the 1960s fisherman began to attract stripers to bait by chumming. These changes in fishing techniques caused a remarkable increase in the numbers of fish caught from Central Bay; note in Figure 2 the very low numbers of striped bass taken in Blocks 301, 303, and 308 when landings were high in Central Bay.

23. Sport fish catch is often expressed as catch-per-unit-effort (CPUE), or the number of fish caught divided by the number of "angler-hours." Total CPUE from the 1970s and 1980s was relatively constant in San Pablo Bay (Block 301), but varied by about a factor of five in Block 488 (Central Bay; Figure 3). Total CPUE was least in Block 488 in 1978 (about 0.25 fish per angler hour) and 1986 (about 0.15 fish per angler hour). The highest total catch occurred in 1981, when CPUE was in excess of 0.6 fish per angler hour. During the same time period there was evidence of a continued decline in the catchable adult striped bass population (SFBRWQCB, 1989; Figure 3). CPUE for striped bass declined in San Pablo Bay (Block 301) from 1975 through 1987. In Central Bay (Block 488) CPUE was highest in 1975 - 1977 (Figure 3). After 1977, CPUE declined (0.1 fish per angler hour in 1978) and remained low thereafter(< 0.1 fish per angler hour), until 1987 when catch was slightly higher than in the previous six years, but still, well below the catch of 1975 through 1977 (Figure 3). Whereas total catch and striped bass catch (as CPUE) show some parallels in San Pablo Bay, total catch and striped bass catch in Central Bay varied independently; indeed, the best year for total catch in Central Bay (as CPUE; 1981) was among the lowest for striped bass (Figure 3). While CPUE data may not be a true

Figure 2. Total catch of striped bass in the San Francisco Estuary, 1938 through 1968. Statistics given for Central Bay, Carquinez Strait, San Pablo Bay and the Delta. Data from various sources cited in the text.

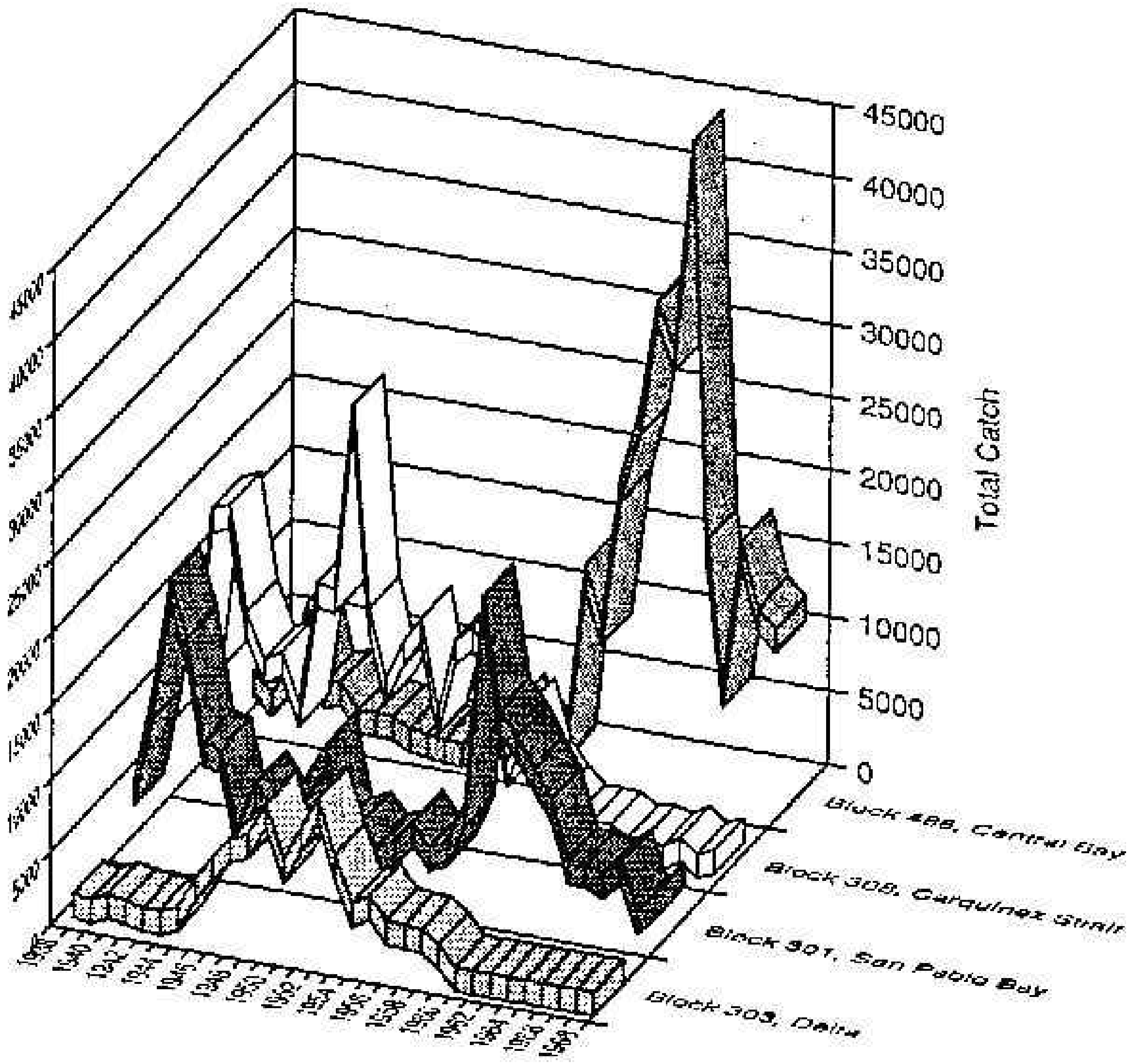
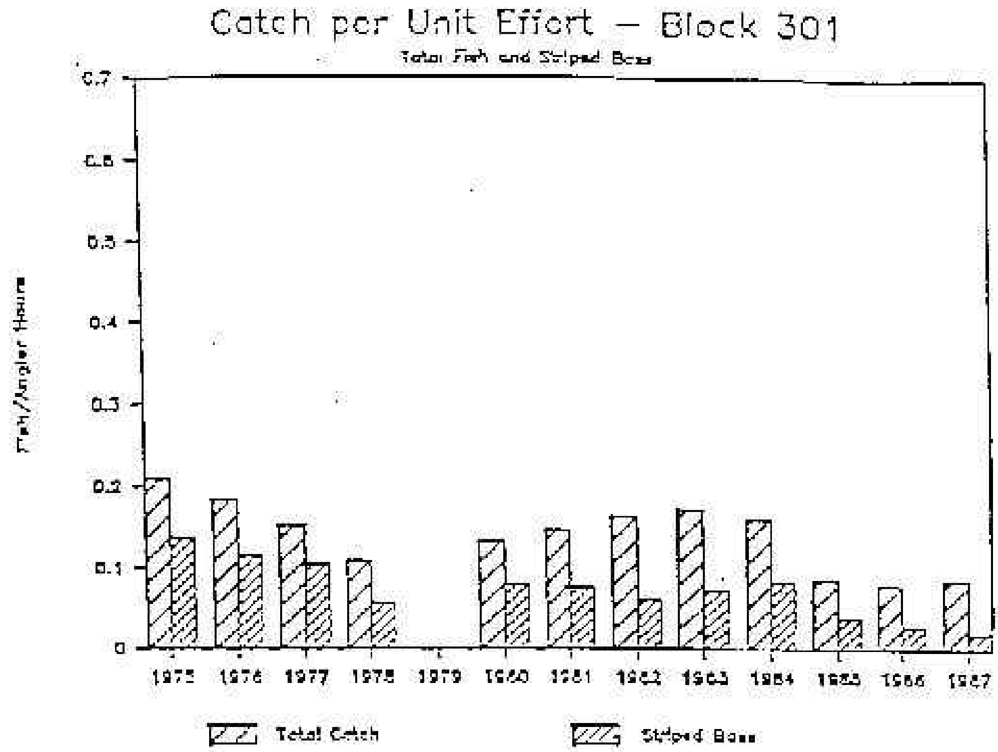
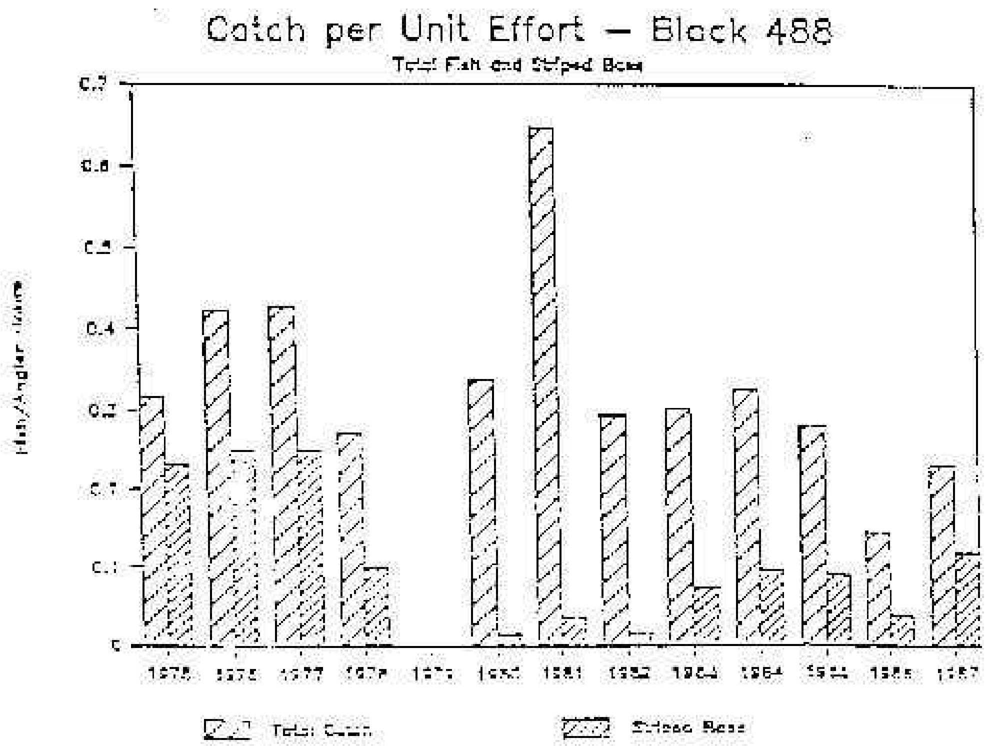


Figure 3. Catch per unit effort for striped bass and all other sport fishes in two sectors of San Francisco Bay, Block 301 (San Pablo Bay) and Block 488 (Central Bay). Data from SFBRWQCB (1988).





indicator of population trends (e.g., low CPUE may prompt fewer fishermen to partake in fishing, and may thus result in higher CPUE), the constant, low yield of bass in the 1970s and 1980s is strong evidence that a low - and possibly declining - stock was available to fishermen.

24. The argument has been made that the reduced catch of sportfish, including striped bass, in the Central Bay (Block 488) is related to dredged material disposal at the designated Alcatraz disposal site (Figure 1b). More specifically, it has been hypothesized that either the increased frequency and volume of dredged material disposal or disposal in a slurried state has caused an increase in turbidity throughout Central Bay. This increase in turbidity may be the cause for the reduced catch of sportfish in Central Bay, due either to the direct impact of turbidity on fish or due to some change in the Central Bay environment that leads to sport fish being present in reduced numbers and/or inaccessible to the fishery. As an example, the alleged increased turbidity in Central Bay might lead to avoidance of Central Bay waters by forage fish. In the absence of forage, sport fish may move to other portions of the Bay to feed, and may not be available to partyboat anglers.

25. The alternative to this argument is that the reduced catch of striped bass and other species in Central Bay waters is not a matter of fish being present and not catchable; rather, the reduced catch in Central Bay may be a reflection of reduced numbers of fish, especially striped bass, in Central Bay. More likely, it is a reflection of reduced numbers of adult striped bass throughout the San Francisco Estuary (CDF&G, 1989; Stevens et al., 1989). Under circumstances where adult fish are present in limited - perhaps critical - numbers, CPUE would be expected to decline to very low levels in all portions of the Estuary.

26. The remainder of this report will evaluate the question of the potential effects of turbidity on the catchability of sport fish in general, and striped bass in particular, in Central San Francisco Bay. The report will present data on the ambient concentrations of suspended particulate matter throughout the Estuary, the sources of particulate material in the system (particularly dredging and dredged material disposal), the relationships of key aquatic biota in the San Francisco Estuary to turbidity in the environment, and the possible relationship between catchability of fish in the Estuary and measured increases in turbidity.

III. Turbidity in San Francisco Estuary

A. Turbidity Defined

27. "Turbidity" is an inexact term that Pickering (1976) described as "...qualitative and relative, to be used in much the same manner as warmth." Perhaps the most widespread misuse of the term turbidity is as a measure of the concentration in water of suspended sediment (Pickering, 1976). Stern and Stickle (1978) noted the proliferation of definitions of turbidity and recommended use of the definition proposed by the American Public Health Association (APHA, 1976):

    "[turbidity is]...an expression of the optical property of a sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample."

    APHA (1976) qualifies the definition with the statement that:

    "...attempts to correlate turbidity with weight concentrations of suspended matter are impractical because the size, shape, and refractive index of the particulate materials are important optically but bear little direct relationship to the concentration and specific gravity of the suspended matter."

28. Duchrow and Everhart (1971) attempted to establish a relationship between turbidity and particle concentration for trout streams. They concluded that there were too many variable factors to allow a turbidity measurement to be converted to a corresponding suspended sediment concentration. However, disagreement exists; for example, in their text *Ecology of Inland Waters and Estuaries*, Reid and Wood (1976) provided a definition of turbidity that relates light penetration directly to suspended solids: "...[turbidity] is the term used to describe the degree of opaqueness produced in the water by suspended particulate matter."

29. Attempts to quantify turbidity have led to a proliferation of methods, instruments, standards and units of measure (Pickering, 1976). The different instruments used to measure turbidity measure various optical properties of water; e.g., percent light scattering at a particular angle, percent transmission over a specific path length and extinction length. Units of measure used in studies of turbidity in San Francisco Bay include:
    - Secchi Disk transparency depth: the point at which a black and white disk of specified diameter disappears from sight in the water column;
    - Formazin Turbidity Units (FTU): the amount of light passing through a suspension calibrated using a suspension of formazin;
    - Nephelometric Turbidity Units (NTU): the amount of light scattered at 90^{0} when the turbidimeter is calibrated with formazin. (We caution the reader that nephelometry in the Estuary has used vastly different measurement systems, and not all "NTUs" representing turbidity in Bay samples are the same).

30. It is common practice to calibrate any instrument to be used for turbidity measurement with a uniform particle suspension such as formazin, titanium

dioxide or polystyrene spheres. The data are expressed as NTU or FTU; formazin is the preferred calibration standard. Austin *et al.* (1974) noted that calibrations of turbidity as a concentration (mg L^{-1} or other mass-volume relationships) are not derived from direct optical measurements; calibration of turbidimeter readout to concentration units must come from calibration techniques that generate a transfer function for the instrument. The transfer function cannot be attained with a single-point calibration.

31. In this report we shall attempt, wherever possible, to express turbidity data from San Francisco Bay as a concentration of suspended particulate matter (mg suspended particulate matter or total suspended solids [TSS] per liter of water; mg L^{-1}). However, in many instances concentration data are not available, and the data are limited to "turbidity" expressed as NTU or FTU. In such instances we must follow Pickering's (1976) caution that it is almost impossible to convert from one measure (e.g., turbidity as FTU or NTU) to the other (suspended particulate matter or suspended sediment).

32. Some data sets from the Estuary provide large quantities of high-quality data that tempt one to make the extrapolation from turbidity to TSS. Some studies have measured both turbidity and TSS, or TSS and Secchi disk depth. For example, in their studies of the entrapment zone Arthur and Ball (1979) measured TSS gravimetrically and turbidity as NTU. Their data showed close agreement between turbidity and suspended particulate data in the same sample. The State of California Department of Water Resources Water Quality Surveillance data from 1983, 1984 and 1985 (DWR, 1984, 1985, 1986) provide turbidity, suspended solids and Secchi disk data from the same samples. Regression of turbidity on suspended solids data for three of the DWR stations (stations D4 in the Sacramento River, D9 in Honker Bay and D41 at Point Pinole in San Pablo Bay) gave excellent coefficients of determination (from 64.0 to 90.2% of the variation explained at a given station (Figures 4 to 6). However, inspection of the equations shows that the regression for turbidity on TSS from station D41 had a slope (0.87) nearly twice that for samples from the Sacramento River and from Honker Bay (slopes = 0.47 and 0.50, respectively). These differences in slope could easily be due to the factors noted by APHA (1976) as uncontrollable in establishing turbidity-TSS relationships; i.e., particle size, particle shape, mineral composition of the particles, etc.

B. Sources of Turbidity in the San Francisco Bay-Delta Estuary

33. The major source of suspended sediments to San Francisco Bay waters is discharge from the Sacramento and San Joaquin rivers. As described by Arthur and Ball (1978, 1979), interactions between density flows, riverine discharge, particle flocculation, wind, tidal currents and other factors combine to create an entrapment zone and cause a "turbidity maximum" in the northern reach of the Estuary, usually coinciding with salinities of from 1 to 6 parts per thousand. The entrapment zone is also a zone of particle

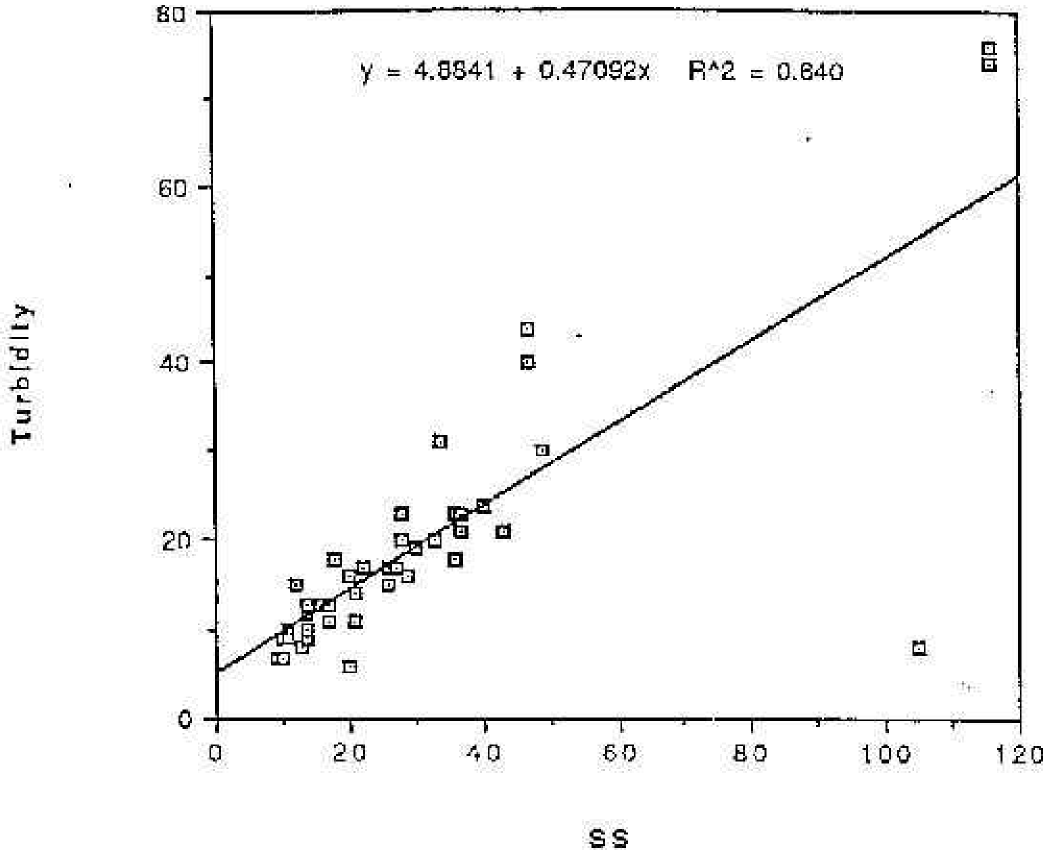


Figure 4. Relationship of turbidity (as NTU) to suspended particulate matter (as mg L^{-1}) in DWR water quality data collected at station D4 (Sacramento River) from 1983 through 1985. Data from California Department of Water Resources, 1984, 1985, 1986.

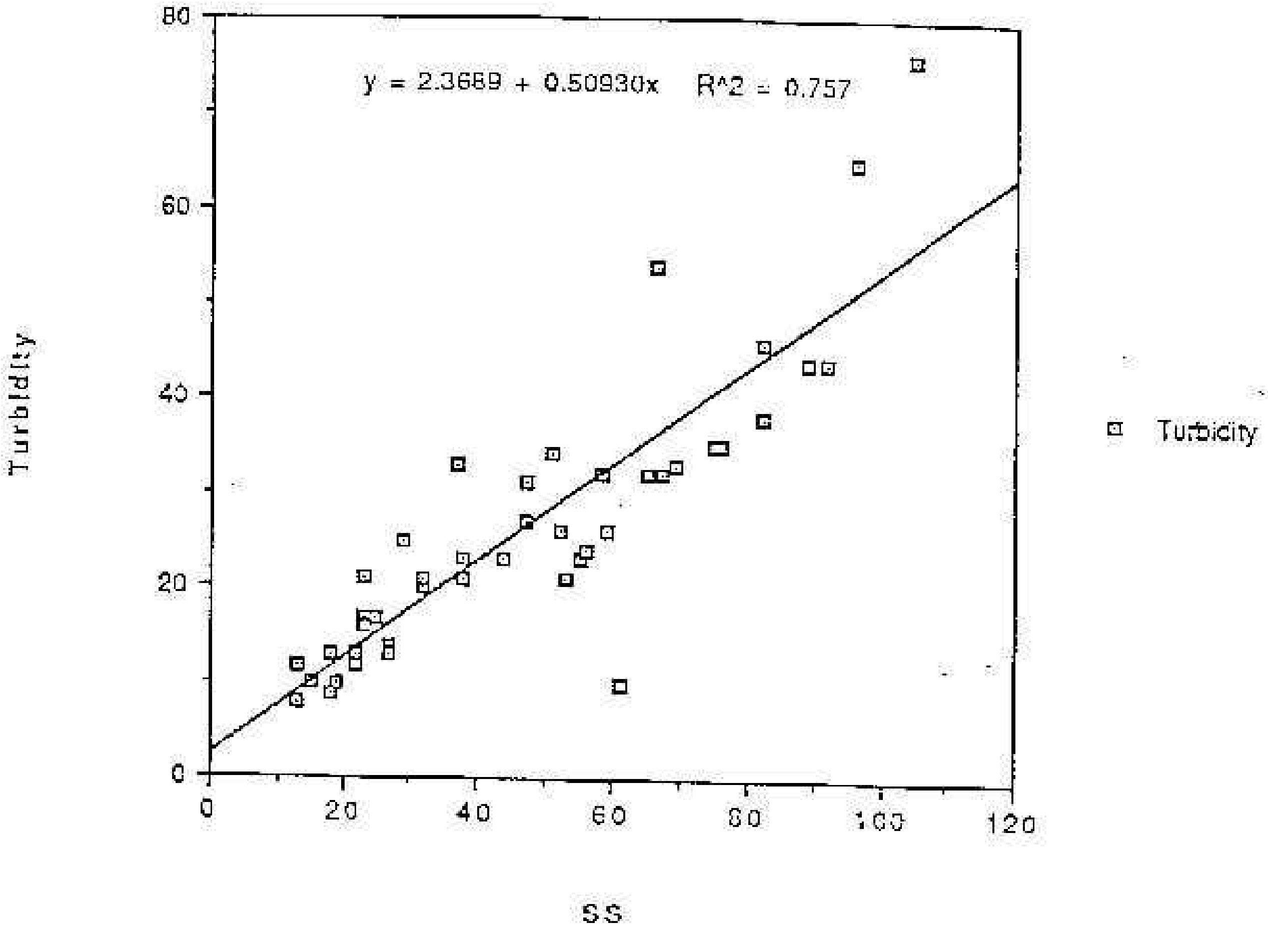


Figure 5. Relationship of turbidity (as NTU) to suspended particulate matter (as mg L^{-1}) in DWR water quality data collected at station D9 (Honker Bay) from 1983 through 1985. Data from California Department of Water Resources, 1984, 1985, 1986.

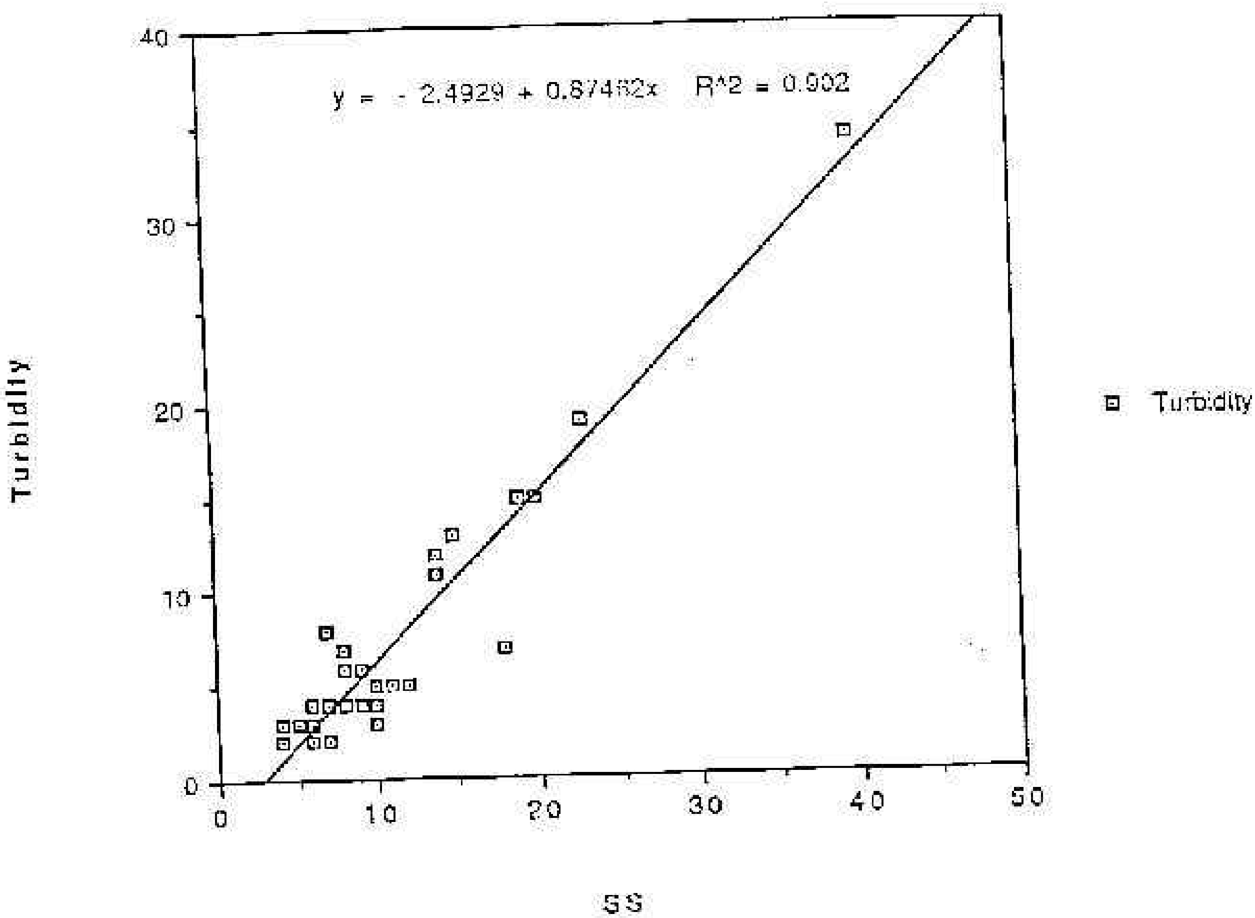


Figure 6. Relationship of turbidity (as NTU) to suspended particulate matter (as mg L^{-1}) in DWR water quality data collected at station D41 (Point Pinole) from 1983 through 1985. Data from California Department of Water Resources, 1984, 1985, 1986.

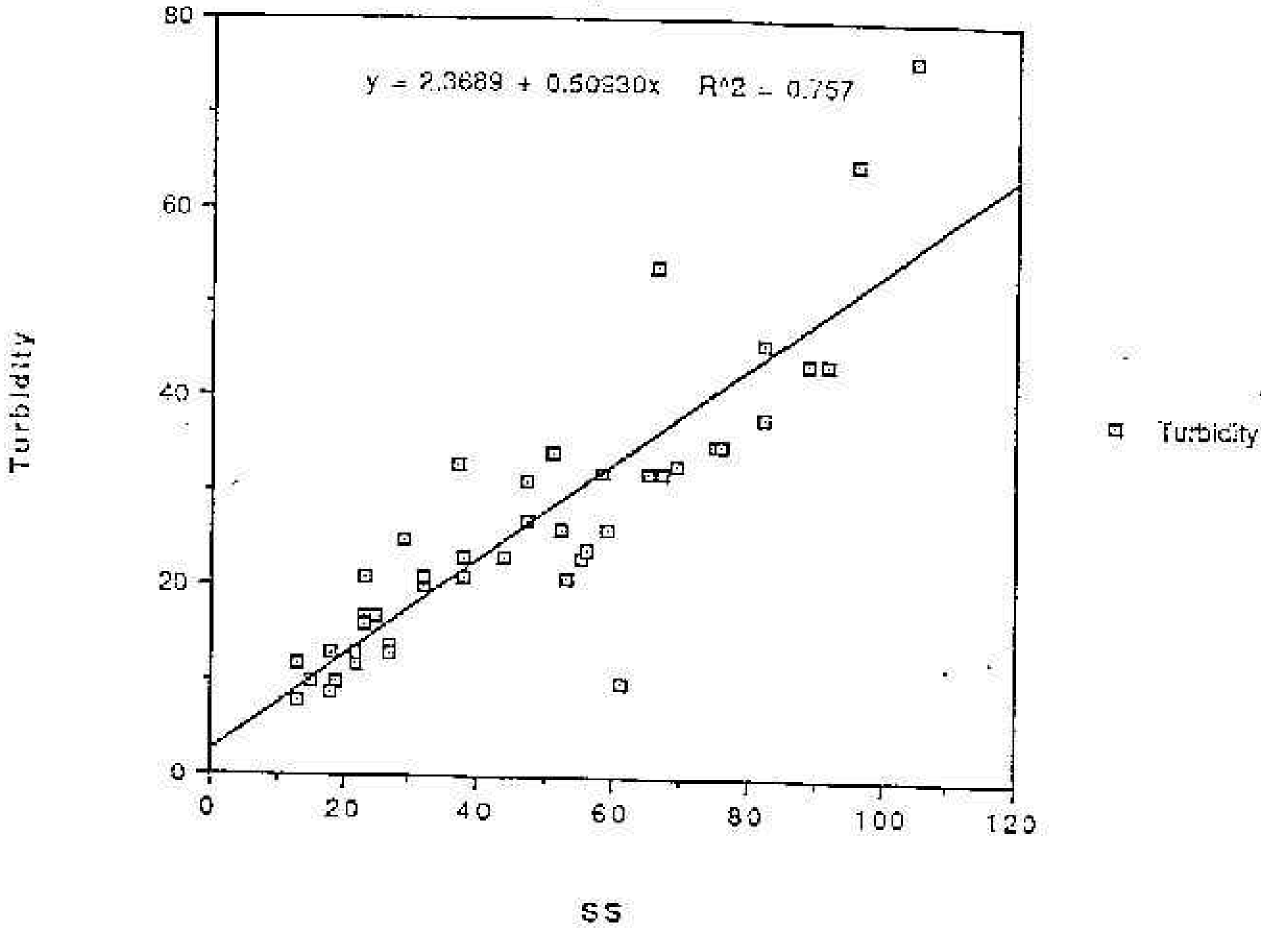


Figure 5. Relationship of turbidity (as NTU) to suspended particulate matter (as mg L^{-1}) in DWR water quality data collected at station D9 (Honker Bay) from 1983 through 1985. Data from California Department of Water Resources, 1984, 1985, 1986.

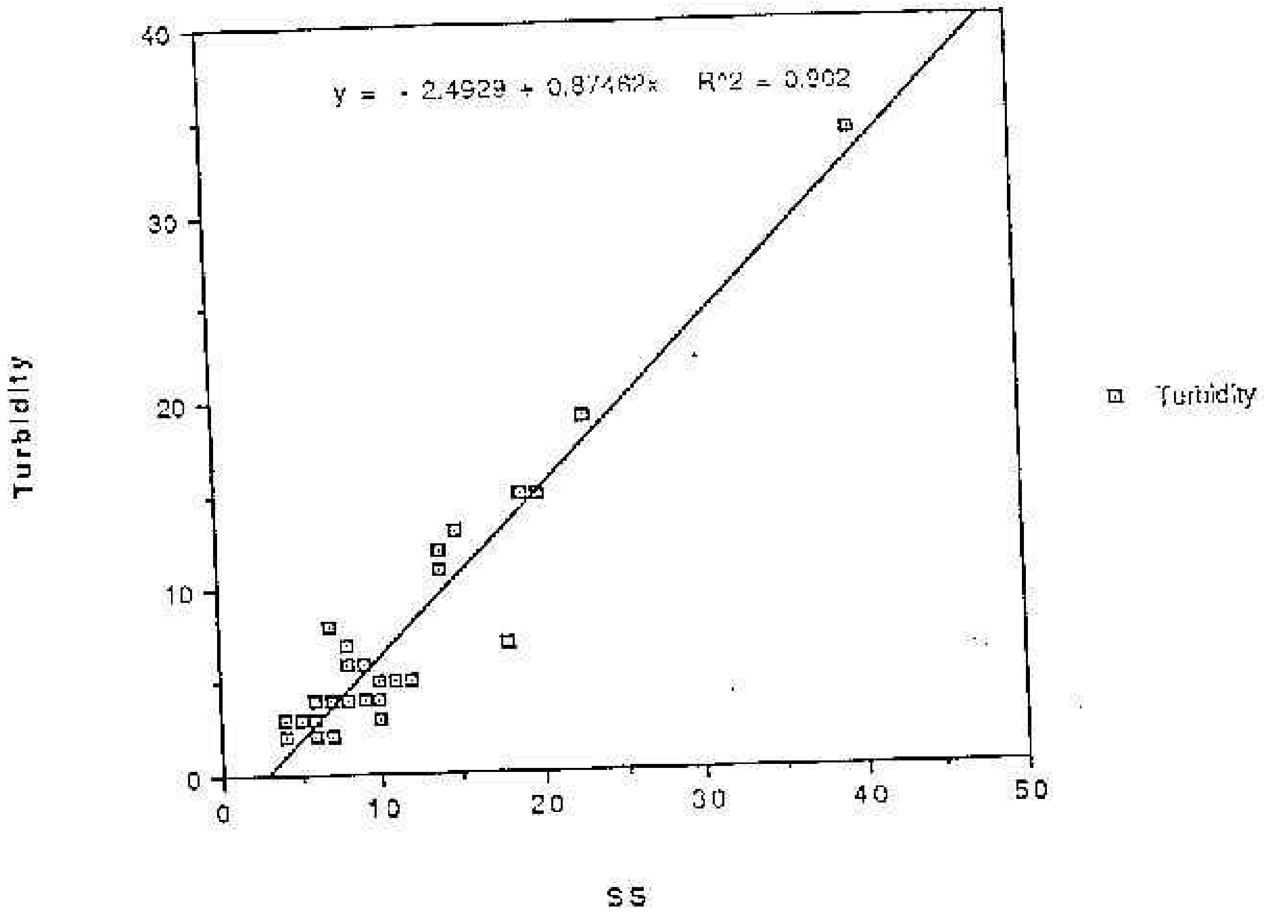


Figure 6. Relationship of turbidity (as NTU) to suspended particulate matter (as mg L^{-1}) in DWR water quality data collected at station D41 (Point Pinole) from 1983 through 1985. Data from California Department of Water Resources, 1984, 1985, 1986.

flocculation and rapid sedimentation, usually leading to reduced suspended sediment loads downstream. The suspended solids in the entrapment zone include mineral solids, detritus, phytoplankton and zooplankton (Arthur and Ball, 1978, 1979).

34. Deposited sediments are also a source of suspended sediments in the Bay-Delta system. Sediments deposited on the broad, shallow reaches of the Bay can easily be resuspended during the periodic strong winds of summer and during winter storms (Arthur and Ball, 1979; Krone, 1979). Various studies of sediments, sedimentation and the benthic community have shown that the sedimentary deposits in the Bay are highly dynamic, often undergoing rapid and large changes of sediment scouring and redeposition (Krone, 1979; Thomson-Becker and Luoma, 1985; Nichols and Thomson, 1985; F. Andersen, Romberg Center, Tiburon, CA,unpublished data, 1990).

35. Other sources of suspended matter in Bay waters include wastewater discharges, urban runoff, and a variety of engineering activities (shoreline-based construction, sand-mining, dredging, dredged material disposal, etc.; USCOE-SFD, 1976; Krone, 1979; Conomos, 1979). Suspended particulate matter contributions from wastewater discharges, urban/nonurban runoff, and shoreline-based construction are not known at this time. The contribution of dredging and dredged material disposal to TSS concentrations in the Estuary will be discussed below.

C. Ambient Concentrations of Suspended Solids in the Estuary

36. Suspended particulate matter in the San Francisco Estuary is much more than just "suspended sediment." It comes from a variety of sources, including "undifferentiated material from the rivers, ocean, sewage effluents, [material] resuspended from the bottom and [that] produced *in situ* by biological processes" (Conomos *et al.*, 1985). Suspended particulates may comprise mineral solids from erosion and surface runoff, detritus from the death and decay of organic matter in the Estuary and its watershed, and minute living organisms such as the phytoplankton and zooplankton. In this section of the report we shall provide an overview of suspended particulate matter concentration, turbidity measurements, and estimates of transparency made using Secchi disk measurements. These data come primarily from reports and papers prepared by participants in the Interagency Ecological Studies Group, especially the California Department of Fish and Game, the California Department of Water Resources, the U.S Bureau of Reclamation and the U.S. Geological Survey.

37. Turbidity in San Francisco Bay and the Estuary shows interannual, annual, seasonal and daily variations that are superimposed upon turbidity gradients caused by riverine inputs. TSS are generally high in the vicinity of the Delta and in Grizzly Bay (Figure 7; Conomos *et al.*, 1985), but increase to a maximum in the null zone. The null zone, or area of no-net motion (Pritchard, 1967), is that portion of the Estuary where landward and

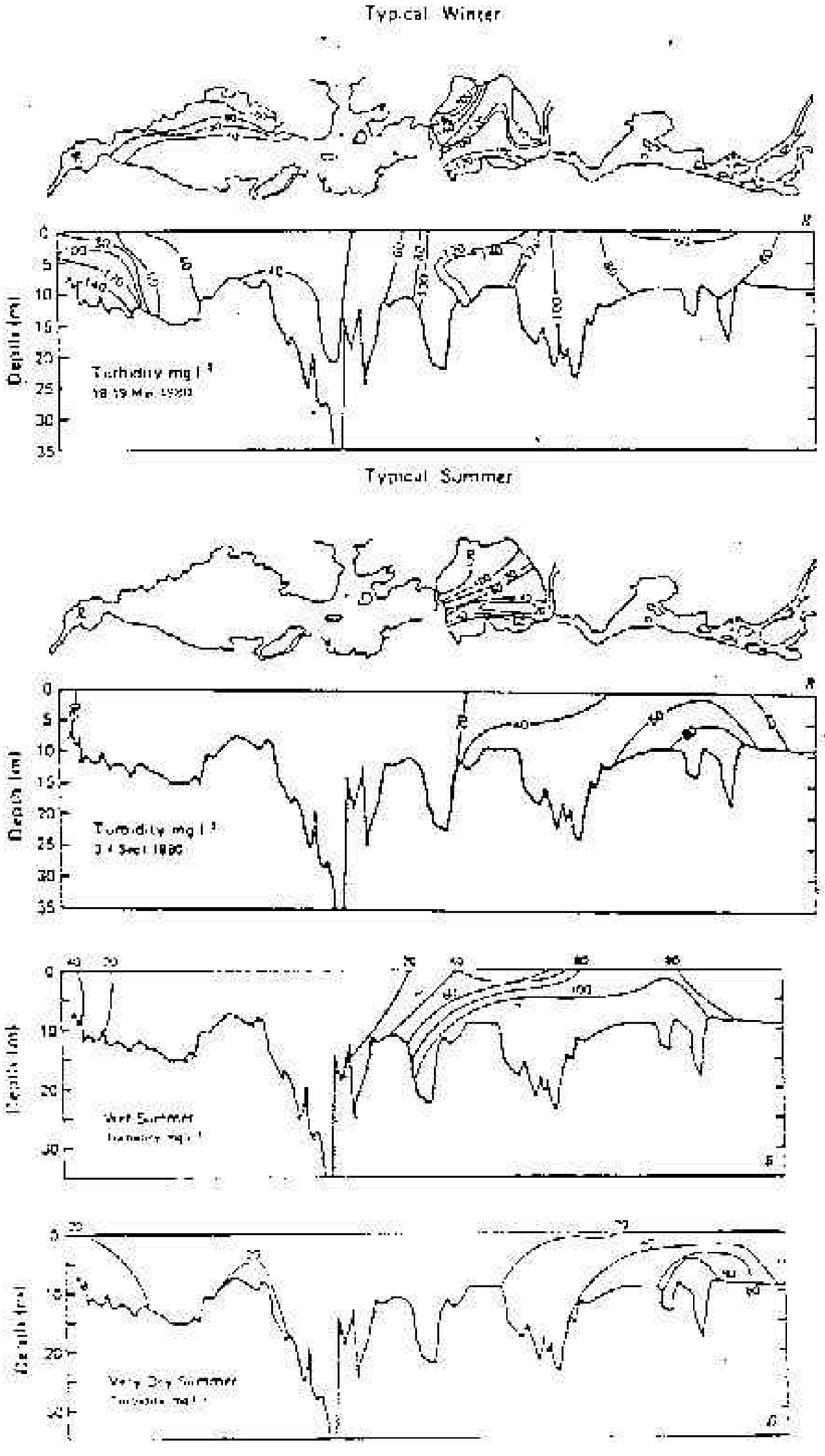


Figure 7. Distribution of turbidity (as mg L^{-1} suspended particulate matter) in the San Francisco Estuary. Top; turbidity during high flow in March, 1980. Second from top; turbidity during low flow of September, 1980. Bottom two panels; turbidity for "wet" summer and "dry" summer, respectively. From Conomos et al. (1985)

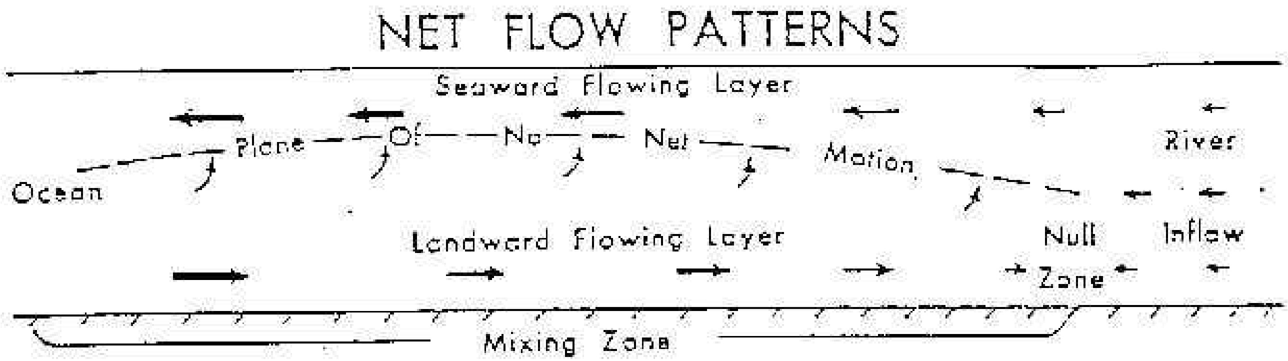
seaward density-driven currents have an equal and opposite effect. The mixing that occurs between deeper waters and surface waters in the null zone results in a cycling and concentration of particulate matter that may include suspended mineral solids, detritus, phytoplankton, and zooplankton (the "turbidity maximum," or the "entrapment zone"; Figure 8; Arthur and Ball, 1978, 1979).

38. A high degree of variability is perhaps the most notable feature of suspended solids and turbidity data in the Estuary. Ambient suspended particle concentrations in the northern part of the Estuary may reach concentrations greater than 600 mg L^{-1} in the entrapment zone (Figure 9; Arthur and Ball, 1978). Much lower values are more common, however. Mean TSS values for Suisun and San Pablo bays for the period 1960 through 1966 were 45 and 65 mg L^{-1}, respectively (US Army Corps of Engineers, San Francisco District [USCOE-SFD], 1976). For the period 1970 through 1975 TSS values averaged 82 mg L^{-1} in Suisun Bay and 77 mg L^{-1} in San Pablo Bay (USCOE-SFD, 1976). Data were also available for water transparency (i.e., Secchi disk depths). For the period 1960 through 1964, mean Secchi disk readings for Suisun and San Pablo bays were 27 and 49 centimeters (cm), respectively. For 1970 through 1975, the mean Secchi disk depth for Suisun Bay was 23 cm (USCOE-SFD, 1976).

39. The U.S. Bureau of Reclamation (USBR) measured TSS as well as turbidity and Secchi disk depth at sites in the Sacramento and San Joaquin rivers, the Western Delta and Suisun and San Pablo bays for nearly twenty years. Mean TSS concentrations in Suisun Bay during periods of higher river flow (November through May) were 58 mg L^{-1}. The same data for San Pablo Bay showed mean TSS values of 30 mg L^{-1}. For the dry portion of the year (May to October) the average TSS in was 74 mg L^{-1} in Suisun Bay and 39 mg L^{-1} in San Pablo Bay (USBR, 1987).

40. DWR water quality surveillance data showed substantial within-year and between-year variation for TSS data taken in 1983, 1984 and 1985. TSS concentrations were highest during high Delta outflow in 1983 (March and April) between the Sacramento River and Suisun Bay. TSS concentrations in the Sacramento River in March and April, 1983, were 116 mg L^{-1}. Downstream, in San Pablo Bay (station D41 at Point Pinole), TSS concentrations in March and April, 1983, were 40 and 23 mg L^{-1}, respectively. During the period of low Delta outflow in 1983 TSS concentrations in the Sacramento River and at Point Pinole declined to less than 15 mg L^{-1}.

41. Suspended particulate matter concentrations generally decrease downstream of the entrapment zone, toward the Central Bay (that portion of San Francisco Bay between the Richmond-San Rafael Bridge and the Oakland Bay Bridge; see Figure 1). Figures 7a through 7d show the general pattern of turbidity in the Estuary for measurements made in 1980



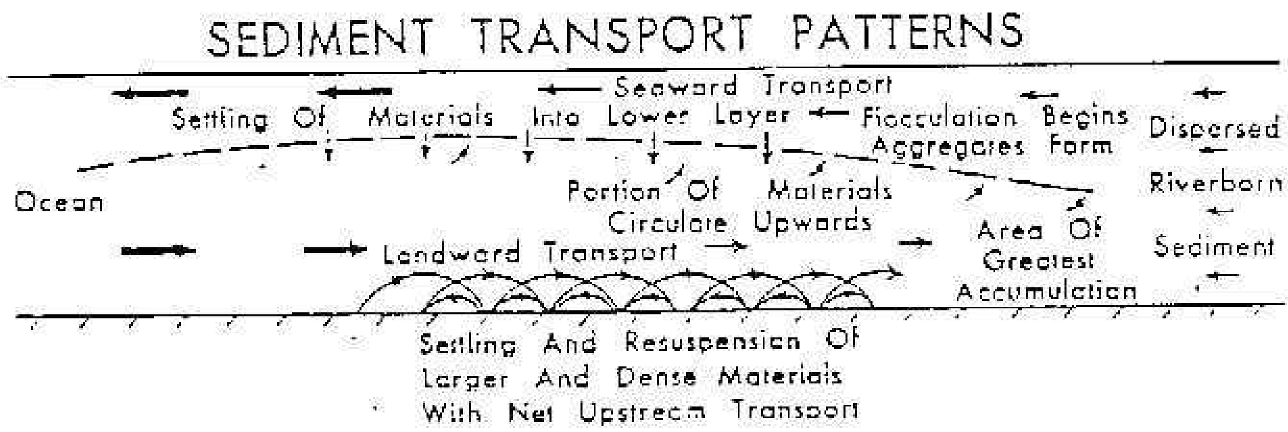


Figure 8. Schematic representation of the location of the entrapment zone based upon net flow patterns (top) and sediment transport patterns (bottom) in an estuary with two-layered flow and vertical mixing. From Arthur and Ball (1978)

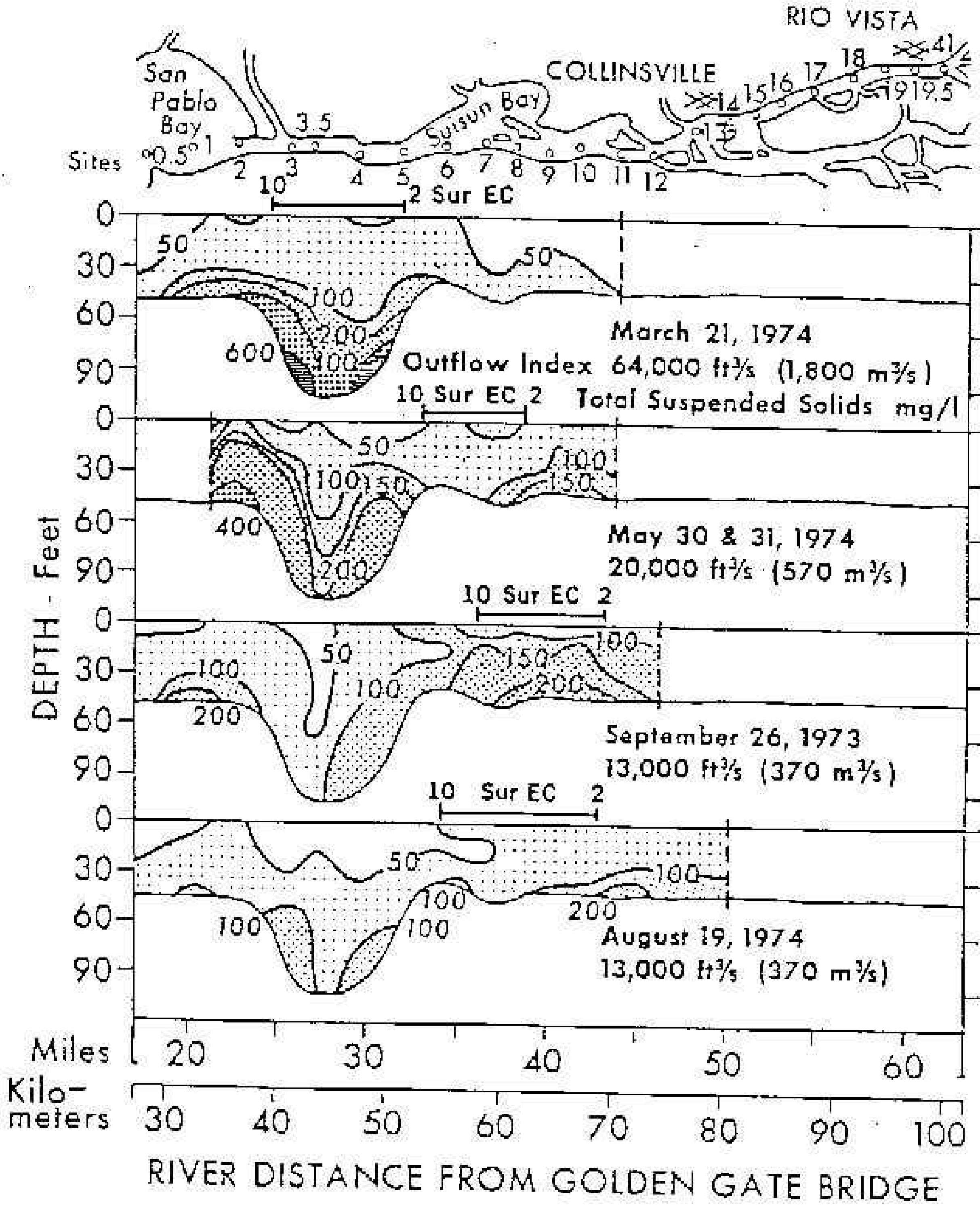


Figure 9. Distribution patterns of suspended solids relative to salinity on high slack tides at various rates of outflow from the Sacramento-San Joaquin Delta. From Arthur and Ball (1978).

(Conomos *et al.*, 1985). In a "typical" winter high flow period (March, 1980) TSS was greatest in San Pablo Bay (120 to 140 mg L^{-1}) and declined to less than 60 mg L^{-1} in Central Bay. Typical summer TSS was greatest in Suisun Bay (maximum above 80 mg L^{-1}) and declined to less than 20 mg L^{-1} in Central Bay (Conomos *et al.* 1985).

42. Data included in the USCOE-SFD report on dredge disposal in San Francisco Bay showed that TSS in Central Bay averaged 18 mg L^{-1} from 1960 through 1964, and 36 mg L^{-1} from 1970 through 1975 (USCOE-SFD, 1976). Of the four sites evaluated, seasonal variation in turbidity was least in Central Bay. We hasten to point out that these data were averaged over five-to-six years, and do not give an adequate representation of the variability of TSS concentrations that might occur within shorter sampling periods at a single location.

43. The US Geological Survey (USGS) has maintained monitoring programs to measure physical and chemical characteristics of San Francisco Bay waters for more than 20 years. The USGS data include measurements of turbidity as well as occasional measurements of TSS. USGS turbidity data are reported as NTU, as measured on a Turner Model 10 nephelometer. Typical turbidity in Central Bay (USGS stations 16, 17, 18, 19, 20, 21) may range from 0.13 to about 0.44 NTU in Central Bay, compared to values of greater than 2.0 in San Pablo and Suisun Bays (USGS, 1979, 1986, 1989). For reference purposes, Turner model 10 turbidity measurements of 0.29 off Tiburon (September, 1984) corresponded to gravimetric TSS data from the same sample of 11.5 mg L^{-1}; turbidity of 1.96 NTU in Suisun Bay corresponded to TSS of 96.4 mg L^{-1}. By comparison, USBR turbidity measurements in Suisun Bay showed that mean FTUs of 39 and 38 corresponded to suspended solid concentrations of 58 and 74 mg L^{-1}, respectively (USBR, 1987).

44. USGS (1989) reported turbidity and TSS data for the whole of the San Francisco Estuary for the year 1980. TSS concentrations at the Golden Gate in January 1980 were low, ranging from slightly over 2 mg L^{-1} to 5.5 mg L^{-1}. Concentrations increased to between 15 and 20 mg L^{-1} in March, 1980, with a high value of 39.7 mg L^{-1}. Throughout the remainder of 1980, TSS at the Golden Gate varied from sampling date to sampling date, but never exceeded the highest value recorded (39.7 mg L^{-1}) on 19 March. The peak in TSS concentrations in Central Bay occurred in March, 1980, when concentrations measured at all stations were in excess of 20 mg L^{-1}. TSS at USGS station 15 (near the Richmond-San Rafael Bridge; see Figure 1) was 132.5 mg L^{-1} on 19 March, 1980.

45. USGS (1989) also measured TSS in water samples from South Bay in 1980. With the exception of samples taken in June, 1980, TSS in South Bay samples were no greater than in Central Bay samples, and significantly less than in samples from San Pablo Bay. June samples from several stations in the South Bay had a range of TSS of from 4.2 mg L^{-1} to 79.5 mg L^{-1}.

D. Turbidity at the Alcatraz Disposal Site

46. Winzler and Kelly (1985) measured TSS in Central San Francisco Bay at the Alcatraz disposal site during July of 1985. Their samples were taken at depths of 4, 7, and 11 m below the surface, and were analyzed for TSS by gravimetry. During the 12 hours of the study TSS at the Alcatraz site ranged from a high of 56 mg L^{-1} to a low of 9 mg L^{-1}. With few exceptions, TSS concentrations were greatest in the samples taken from 11 m, and least in the samples taken at 4 m. Mean TSS for samples taken at Alcatraz during the study was 19.3 mg L^{-1}. Depth-integrated TSS concentrations were calculated from the Winzler and Kelly data in order to compare them with Hauck *et al.* (1990; below). Average TSS concentrations from the three depths ranged from 10 mg L^{-1} to 37 mg L^{-1}. The overall site average for the 12-hr period was 19.5 mg L^{-1}.

47. The TSS concentrations measured at Alcatraz by Winzler and Kelly (1985) were similar to those measured by SAIC (1987a, 1987b) in 1986, and to those measured by Hauck *et al.* (1990) in 1988. SAIC measured TSS at Alcatraz in conjunction with studies of dredged material disposal. Their background TSS concentrations ranged from 9 mg L^{-1} to 17 mg L^{-1} in samples taken during the latter part of the summer of 1986.

48. Some of the most comprehensive measurements of turbidity in Central Bay were made by the US Army Engineers, Waterways Experiment Station (Hauck *et al.*, 1990). These measurements were made in the summer of 1988, and included TSS averaged over depth and tide, as well as replicate samples at individual points. None of the samples were taken during disposal operations, or in a manner that would allow one to evaluate the effects of disposal on Central Bay turbidity. Transect data averaged over depth and time showed that TSS in Central Bay ranged from 28 mg L^{-1} off Berkeley to about 15 to 17 mg L^{-1} near the Golden Gate (Figure 10; Hauck *et al.*, 1990). Single point samples showed TSS concentrations in Central Bay ranging from 26 mg L^{-1} in mid-channel off Tiburon and 24 mg L^{-1} just west of Treasure Island, to 10 mg L^{-1} in mid-channel east of Angel Island (Figure 11). The time-averaged data from Winzler and Kelly (1985; see above) gave a TSS concentration at Alcatraz of 19.5 mg L^{-1}. TSS concentrations measured by Hauck *et al.* (1990) varied widely; standard deviations were, in most cases, equal to more than 50% of the mean. The variability in the data is reflective of the strong influence that tide, wind, and depth of water may have on turbidity in the Bay system (Krone, 1979; Conomos *et al.*, 1985; MEC, 1990a, 1990b).

49. Ogden Beeman and Associates (1989) measured turbidity at the Alcatraz disposal site at various times from April, 1988 through August, 1989. Their measurements were made in order to evaluate dredged material disposal activity. Transects taken across the designated disposal area at Alcatraz prior to dumping operations showed substantial variation in turbidity (as

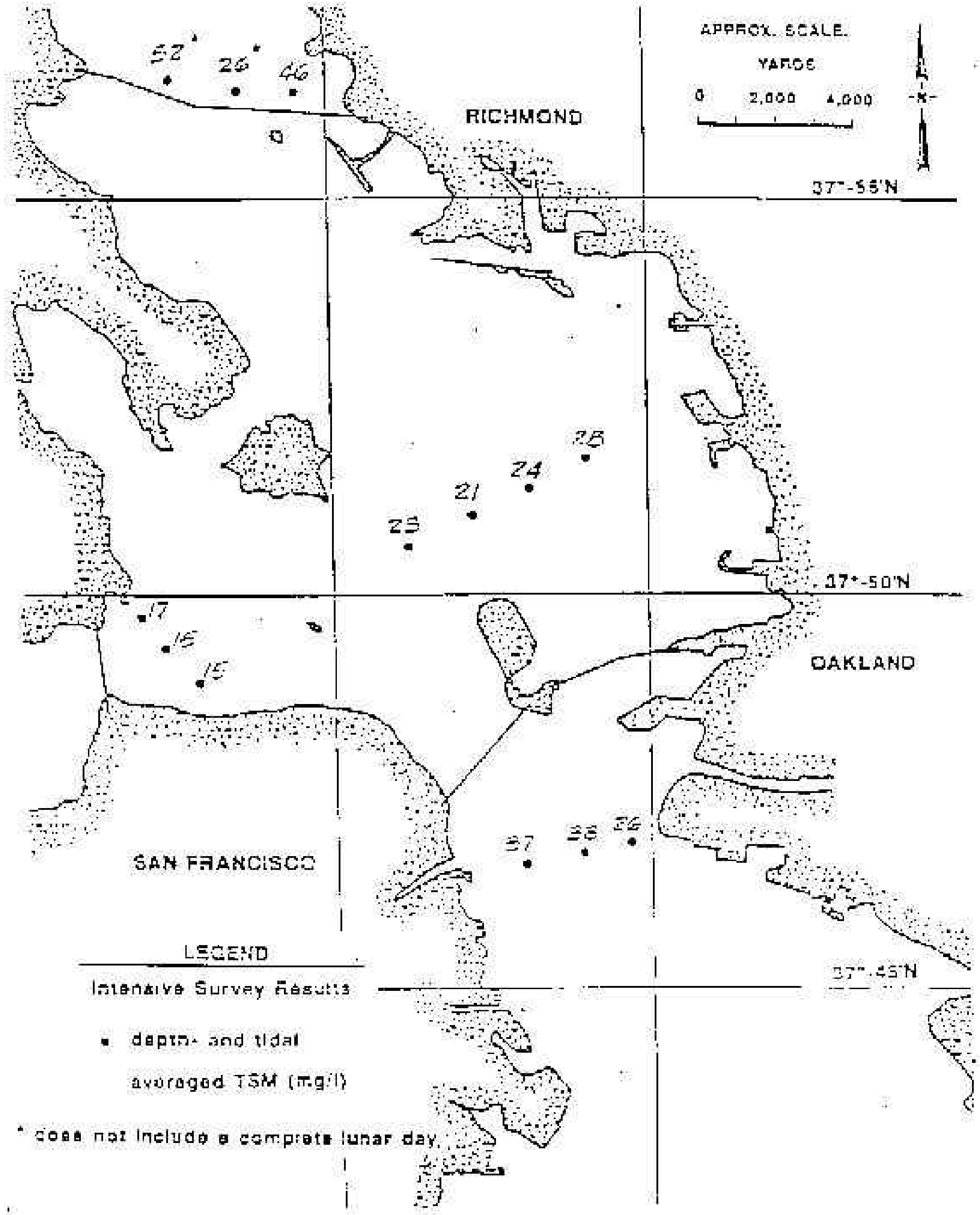


Figure 10. Depth- and tidal-averaged total suspended particulate matter data for the intensive survey of Central Bay carried out by Hauck et al. (1990). TSM data are given as mg L^{-1}.

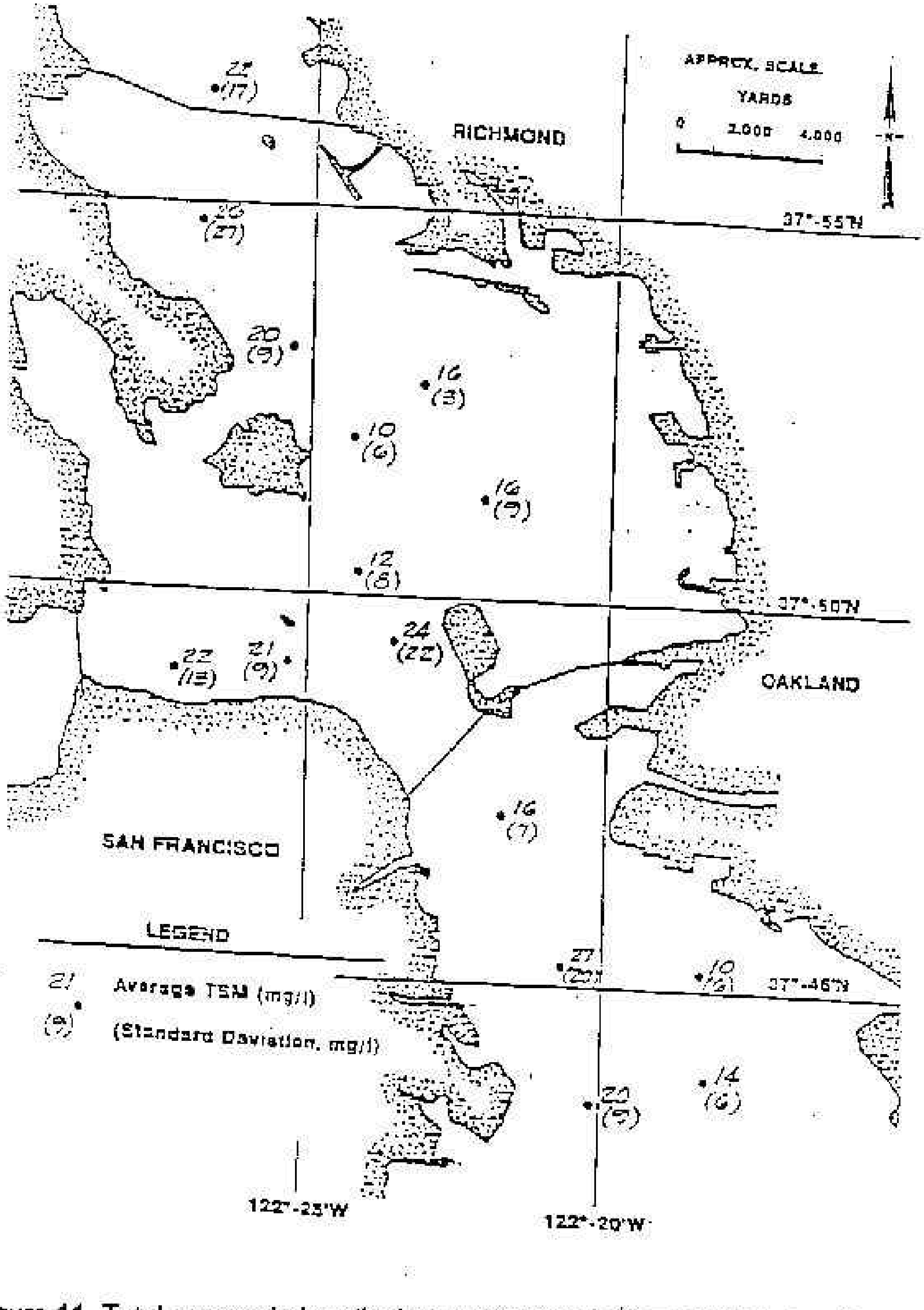


Figure 11. Total suspended particulate matter (mg L^{-1}) measured at point stations throughout Central Bay. From Hauck et al. (1990).

NTU; Ogden Beeman and Associates, 1989), ranging from low values of 2.5 to 3.0 NTU (September, 1988) to a high of 16. The lowest overall background turbidity at Alcatraz was recorded in September, 1988 (mean = 2.8 NTU), while the highest was measured on 16 August, 1988 (11.3 NTU).

50. Turbidity was measured at the Alcatraz site in September, 1988 by Johnson Offshore Services (1989). While the numerical values of the turbidity measurements from that study are still subject to clarification (our analysis suggests a systematic bias. We have concluded that the TSS values in the report should be multiplied by a factor of 0.1), the trends in turbidity measured at Alcatraz are of interest. Corrected suspended solids concentrations from Johnson Offshore Services (1989; corrected by a factor of 0.1) showed that turbidity patterns at Alcatraz vary substantially with tidal phase and tidal current flow. In general, corrected TSS were low (about 10 to 20 mg L^{-1}) at slack water on the higher high tide (Figure 12). TSS increased on the ebb tide and attained corrected TSS concentrations between 30 and 45 mg L^{-1}. Occasional peaks of TSS were recorded by the in-place nephelometers and, in all cases, coincided with a flooding tide; TSS concentrations in these instances reached corrected values as high as 78 mg L^{-1} (Figure 12).

51. Background TSS concentrations from the vicinity of Alcatraz in Central Bay were measured in May, 1990 (MEC, 1990a.). TSS measured at a depth of 3 m were 6 mg L^{-1}, and increased to 14 mg L^{-1} at 6.1 m, and 22 mg L^{-1} at 9.15 m. TSS concentrations in bottom waters at Alcatraz were 14 mg L^{-1}.

52. In a separate study of turbidity and suspended particulate matter at Angel Island and in Raccoon Strait (Figure 1), MEC (1990b) measured background TSS concentrations at depths of from 1.5 m to 15 m. During ebb tides in May, 1990, TSS concentrations were 40.6 and 69.7 mg L^{-1}. However, when samples were taken on ebb tides during June, 1990, TSS concentrations averaged 13.6 and 9.7 mg L^{-1}. Interestingly, the TSS maxima measured during ebb tides was not at the bottom; rather, concentrations were either uniform (as on 17 May), or the highest TSS occurred at or near the surface (TSS at 1.5 m on 22 May = 121 mg L^{-1}). Mean TSS concentrations during flooding tides were between 13.6 and 17.6 mg L^{-1}. MEC (1990b) also measured Secchi disk depth in the vicinity of Angel Island in May and June, 1990. Background Secchi disk depths ranged from 106 cm to 152 cm.

53. As noted previously, Secchi disk data are not a measure of turbidity or suspended solids concentration, *per se*. Rather, they are a measure of the transparency of water. Therefore, Secchi disk depth measurements may be influenced by a number of factors that do not influence direct measurements of suspended particulate load or turbidity (e.g., dissolved pigments in the water, surface conditions, quality of the observer; Reid and Wood, 1976; MEC, 1990b)

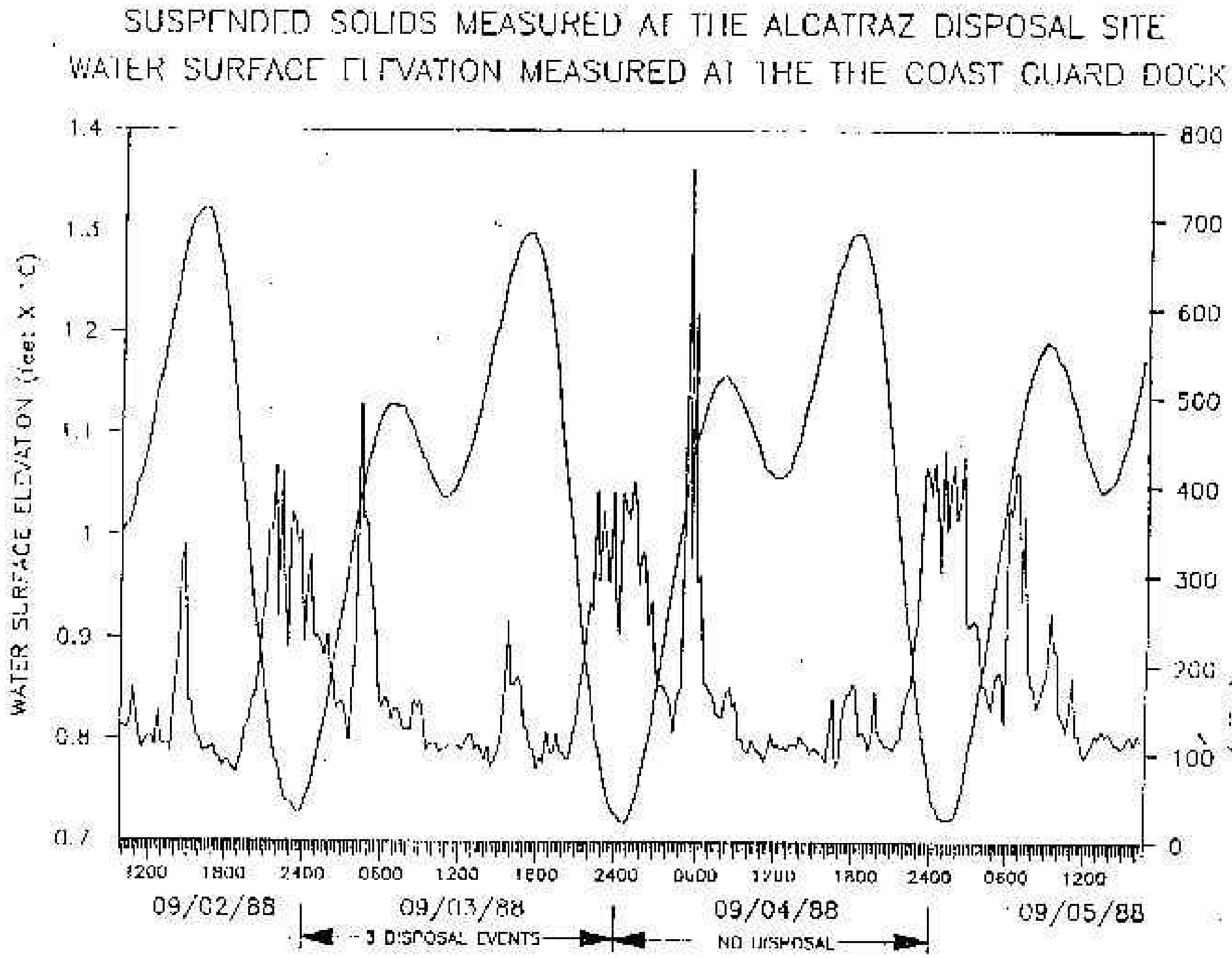


Figure 12: Suspended solids measured at the Alcatraz disposal site compared to water surface elevations measured at the Coast Guard Dock. (From Johnson Offshore Services, 1988). Note that the TSS concentrations (right scale) should be multiplied by 0.1.

54. Secchi disk data for Suisun Bay (USBR, 1987) varied widely, with individual measurements ranging from less than 10 cm to more than 140 cm, depending upon season, Delta outflow, water year, time of day, weather, wind, and other factors (Figure 13; see also Arthur and Ball, 1978, 1979). In the Northern reach, Secchi disk depths were generally least in the entrapment zone (Arthur and Ball, 1979), and were considerably higher both upstream and downstream of that point. Average Secchi disk depth measured in Suisun Bay (1968 through 1987) was 34 cm from November to April, and 38 cm from May to October (USBR, 1987). Average Secchi disk depth in San Pablo Bay was 53 cm between November and April (1971 to 1987), and 75 cm from May through October (USBR, 1987).

55. The California Department of Water Resources (DWR) measured water quality at a number of Stations throughout the northern reach of the Estuary. Secchi disk data from those studies shows the wide variation expected between and among stations, depending upon time of day, weather conditions, water flow, etc. (DWR, 1984, 1985,1986). At DWR station D4 (at the mouth of the Sacramento River), Secchi disk depths ranged from 19 cm to 82 cm in 1983. The lowest readings (least light penetration) were measured between January and April (19 to 28 cm), whereas the highest readings (44 to 82 cm) occurred between May and November.

56. Secchi disk depths measured at the same station in 1984 showed higher overall transparency (range of monthly readings from 28 to 76 cm), but less of a difference in transparency between the periods of high and low Delta outflow. Transparency between January and April ranged from 38 to 76 cm, while the range from May through December was from 36 to 51 cm.

57. Average Secchi disk depth in 1985 was greater than that measured in 1983 and 1984 (DWR, 1985). Secchi disk depths varied from a low of 34 cm (May, 1985) to a high of 70 cm (December, 1985). Transparency during the period of high runoff (40 to 64 cm; January through April) had a range that was similar to the range of measurements taken over the remainder of the year (34 to 70 cm; May through December).

58. Similar patterns were seen for Secchi disk depths measured at DWR station D7, located at a shallow-water station subject to sediment resuspension from wind-driven wave action in Grizzly Bay. Transparency was limited. In 1983, Secchi disk depths ranged from 18 to 43 cm. In 1984 and 1985 measured transparency in Grizzly Bay was similar (DWR, 1984,1985,1986), ranging between 20 and 50 cm in 1984, and 24 and 72 cm in 1985.

59. DWR Secchi disk depths for station D41 (Point Pinole) showed a high degree of transparency. In 1983 Secchi disk readings at D41 ranged from 28 cm to a high of 136 cm (August; DWR, 1984). During the period of low Delta outflow (May through October, 1983), had Secchi disk depths of from 50 cm to 136 cm (mean=98 cm). Secchi disk depths for 1984 and 1985 were greater than in 1983 (DWR, 1985, 1986). In 1984 values ranged from

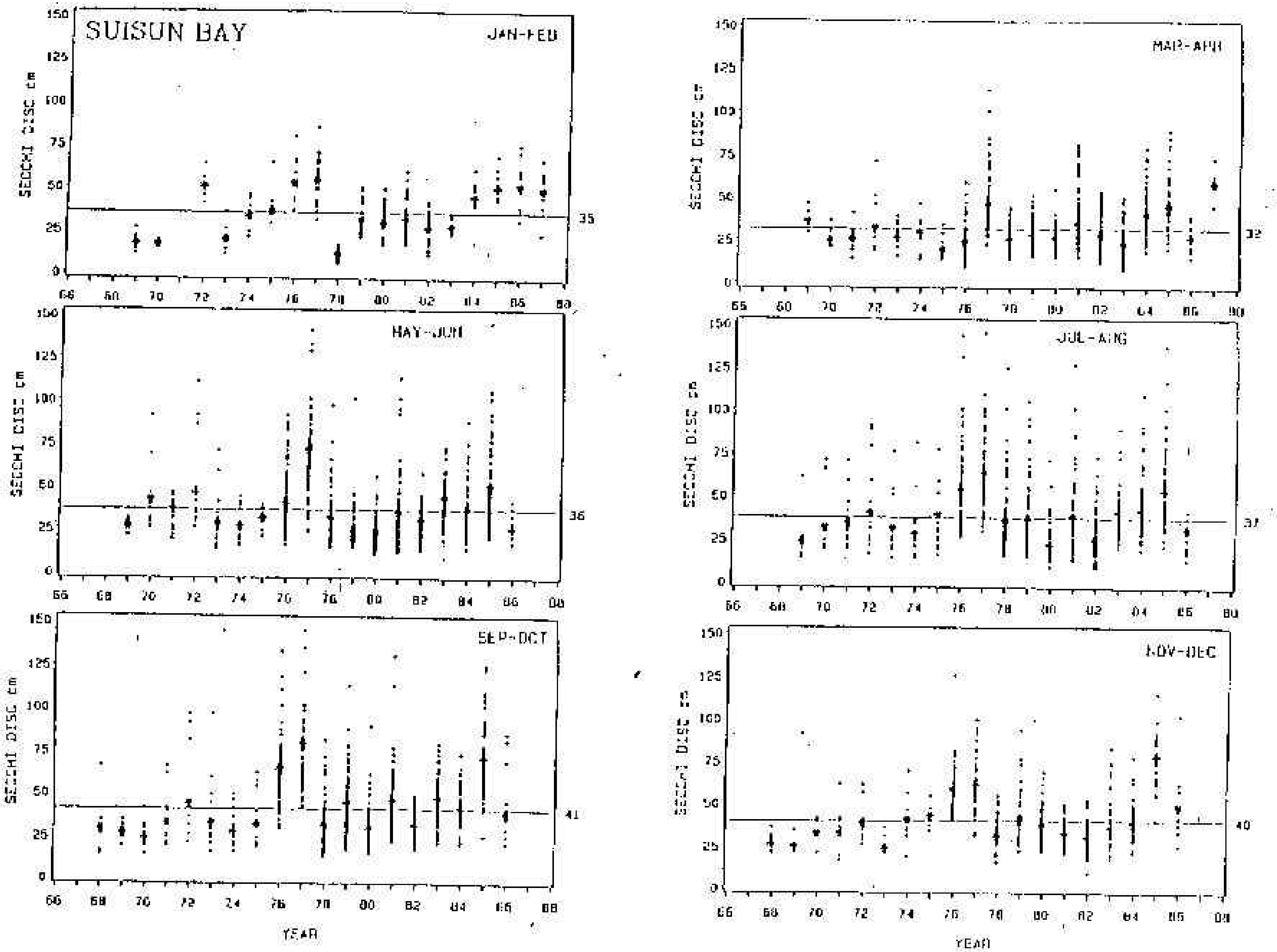


Figure 13. Water transparency (Secchi disc) in the Suisun Bay area, by months, 1968-87. The dots are individual measurements and each asterisk equals a bimonthly mean. The reference line equals the mean of means for each plot.

60 cm (December) to a high of 144 cm. During 1985, values ranged from a low of 72 cm (January) to 168 cm in April (DWR, 1986).

60. Secchi disk depths for Central Bay averaged 48 cm from 1960 through 1964, and 130 cm from 1970 through 1975 (USCOE-SFD, 1976). Recent samples (MEC, 1990b) showed that Secchi disk depths at several stations near Angel Island ranged from 120 to 150 cm.

61. California Dept. of Fish and Game (DFG) measured Secchi disk depths on a monthly basis from 1980 through 1988 in conjunction with fisheries sampling in Central Bay. DFG data show some interesting patterns (Figure 14). First, the month-to-month and year-to-year Secchi disk transparency data were highly variable; they are probably determined, at least in part, by the tide stage and meteorological conditions prevailing at the sample site at the time of sampling (Figure 14).

62. Second, the Secchi disk depths from DFG sampling shows a general annual trend; that is, lower Secchi disk depths typically occur in the early months of the year (January to March), followed by increasing depths through the summer and into the fall. This pattern is particularly noticeable for the years 1980 and 1981 (Figure 14).

63. Third, the plot of DFG Secchi disk depths for the years following 1985 show an apparent decline in water transparency, as well as a change in the annual pattern of water transparency. During the months of January through June, overall water transparency in 1986, 1987 and 1988 appears to be lower than in previous years . For 1986, 1987 and 1988, transparency during August and September was substantially lower than in all previous years. During the fall (October through December) transparency was, again, somewhat reduced from most previous years, and substantially lower than in 1980 and 1981.

64. The most noticeable trend in the DFG Secchi disk data is that the values from 1986, 1987 and 1988 remained low throughout the year, only once exceeding 100 cm. This is contrary to almost all the previous years, in which there occurred a seasonal pattern in which water transparency increased from the lows of January to March, to high values (mostly above 100 cm) in the fall and early winter months.

E. Turbidity Due to Sand Mining Operations

65. As part of the study of sand-mining operations at Angel Island, MEC (1990b) measured TSS concentrations in the plume adjacent to the sand barge. TSS concentrations inside and outside the barge plume differed substantially. Samples taken at a fixed, 4 m depth showed that TSS was increased inside the plume in nearly all cases. Most TSS concentrations inside the barge plume were greater than those outside the plume by a factor of 1.5 to 2.0. When samples were taken while drifting with the barge plume, it was noted that TSS concentrations increased measurably above

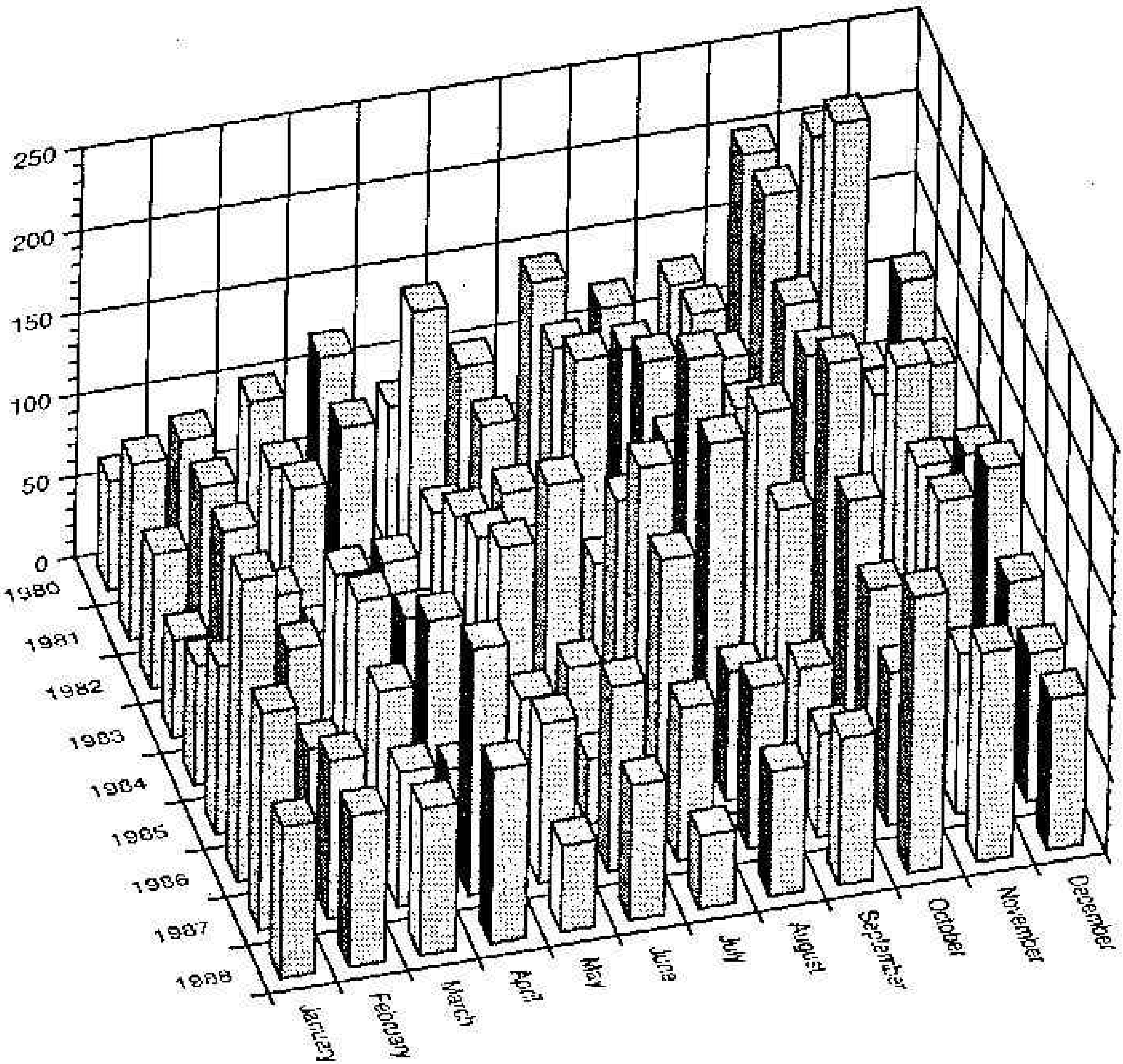


Figure 14. Secchi disk transparency in Central Bay waters measured monthly from 1980 through 1988. The vertical axis is in centimeters. Data from California Department of Fish and Game.

background values, but decreased to background concentrations within a relatively short distance (500 to 800 m).

F. Turbidity Due to Dredging Activity

66. Contributions of TSS from dredging activities differs with the nature of the material being dredged and the dredging equipment (Barnard, 1978). Vellinga (1989) summarized TSS generated by different types of dredging activities (Figure 15). The greatest TSS concentrations were generated by suction dredges (hopper dredges) with overflow, whereas the lowest TSS occurred when a "grab crane" (clamshell) dredge was used. Herbich *et al.* (1989) performed similar evaluations (Figure 16). Concentrations of TSS in the lower water column near open clamshell dredging operations ranged from 100 mg L^{-1} 245 m downcurrent from the dredge to almost 300 mg L^{-1} 60 m downstream. Herbich *et al.* (1989) showed that the use of a closed clamshell reduced resuspension dramatically (Figure 16); the highest TSS measured 60 m from the dredge site was less than 100 mg L^{-1}.

67. Studies conducted in San Francisco Bay showed that hopper dredge activity generated TSS concentrations as high as 2500 mg L^{-1} in the lower water column, at the draghead. Lower water column TSS concentrations were less than 500 mg L^{-1} 100 m down current from the dredge site (USCOE-SFD, 1976). Clamshell dredging in Oakland Harbor was also monitored (USCOE-SFD, 1976). When no overflow was allowed from the barge, TSS in the lower water column 50 m away from the dredge site was less than 300 mg L^{-1} (9 m depth). Surface and mid-depth TSS concentrations increased to between 50 and 80 mg L^{-1} at 50 m, and declined to about 20 mg L^{-1} 400 m away from the dredging operation (USCOE-SFD, 1976). These data are similar to that seen in other studies (Barnard, 1978; Tramontano and Bohlen, 1984).

68. When dredged material is disposed at unconfined aquatic sites some loss of finely divided material at the point of release in inevitable. Losses occur during passage through the water column, upon impact with the bottom, and as a result of scouring of the bottom by currents (Gordon, 1974). Typically, only a small amount of disposed dredged material - usually fine fractions - remains in the water column for any period of time, and the plume usually disperses rapidly (Gordon, 1974, Tavolaro, 1984). Dredged material disposal in the San Francisco Estuary differs in at least one important respect from disposal in other areas; that is that the existing disposal sites in the San Francisco Bay are dispersive sites. That is, it is assumed that dredged material disposed at these sites will become resuspended in the water column, will be transported away, and eventually removed from the Bay through the Golden Gate.

69. Gunther *et al.* (1990) provided a review of dredged material disposal in the Estuary up to 1986. Their review is summarized here. USCOE-SFD (1976) monitored turbidity plumes during dredged material disposal at the Alcatraz

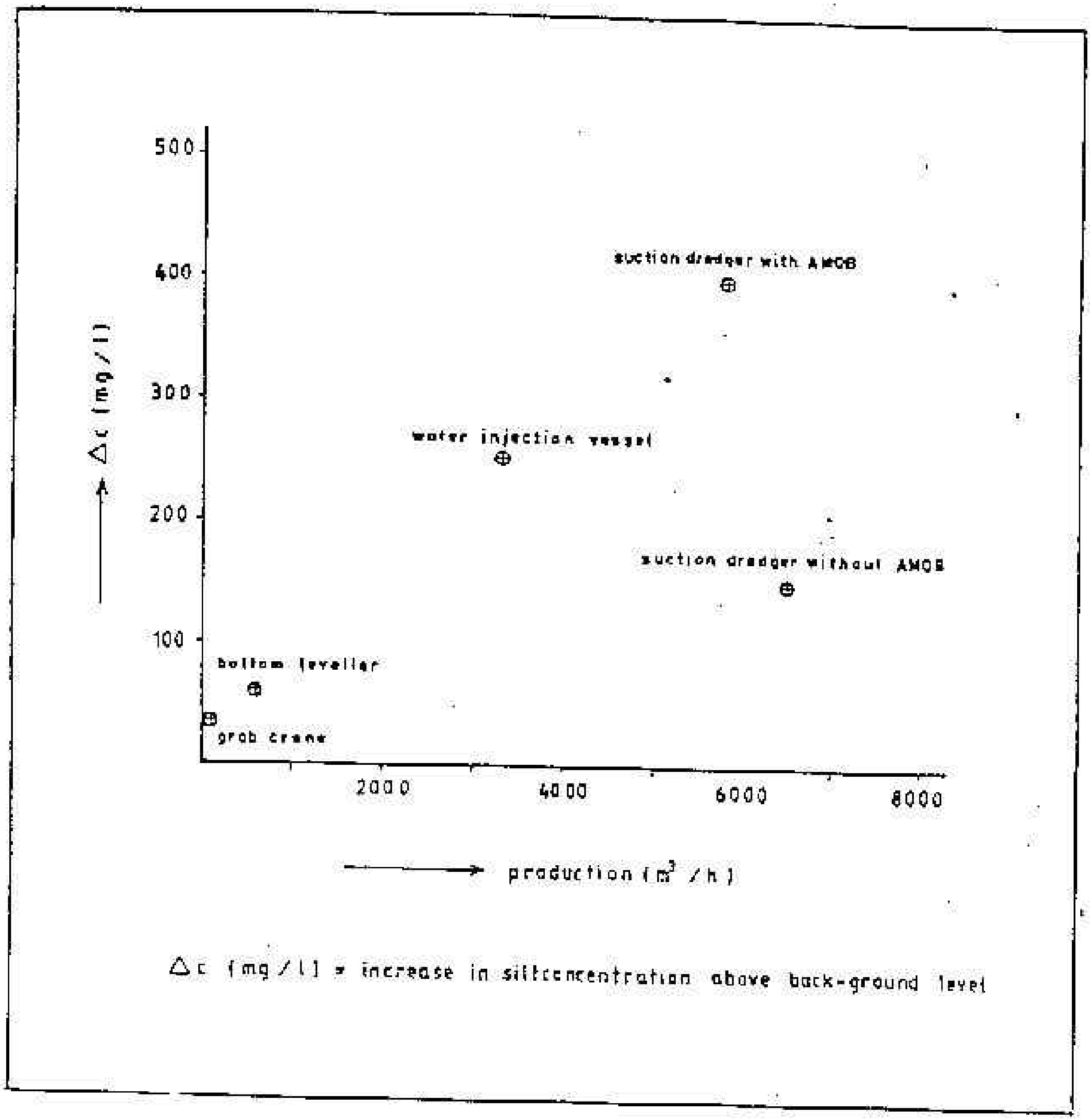


Figure 15. The depth-averaged turbidity increase observed in relation to estimated dredging production by various mechanisms. From Vellinga (1989).

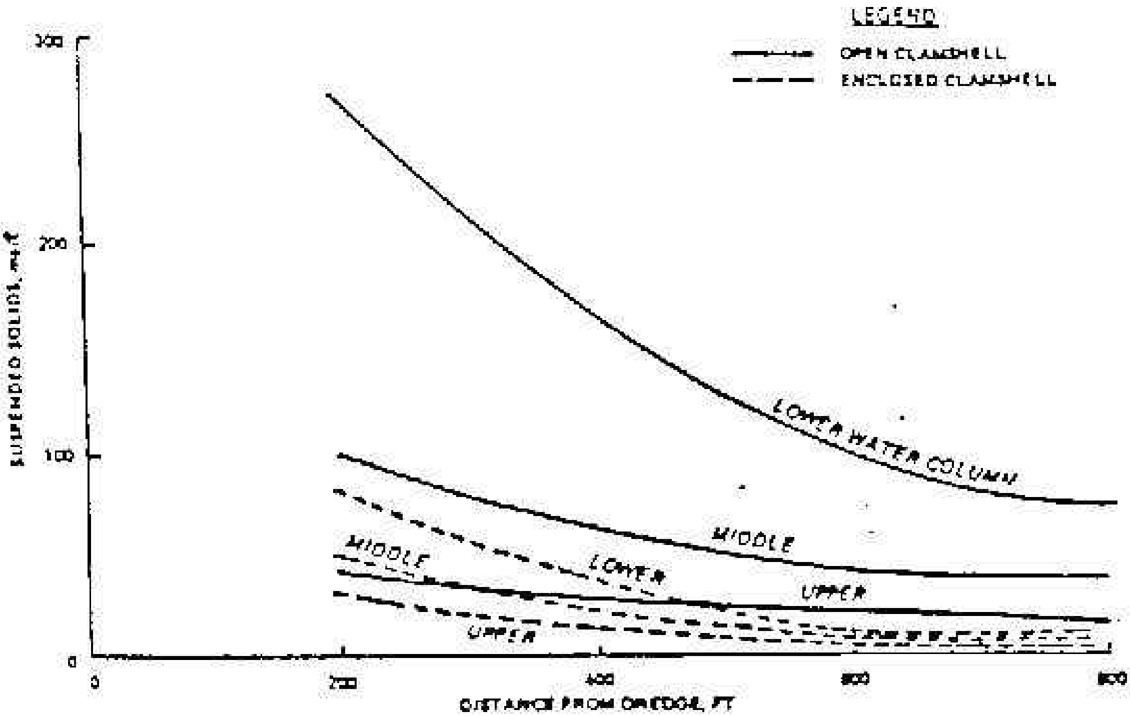


Figure 16. Resuspended sediment levels generated by open- and closed-clamshell dredging operations in the St. John's River, FL. Figure from Herbich *et al.* (1989).

and Carquinez disposal sites. Vertical profiles of TSS were taken at stations 50, 100 and 400 m down-current from the sites of disposal. Maximum turbidity occurred in bottom waters close to both disposal sites (Figure 17). Surface waters were less turbid than bottom waters, and TSS usually returned to background concentrations throughout the water column 10 to 15 minutes after disposal (USCOE-SFD, 1976). Special studies at the Carquinez Strait disposal site showed that TSS at the mud-water interface 100 m downcurrent of the disposal barge reached 9,000 mg L^{-1}; these concentrations decreased to background levels after 25 minutes. The special study at the Carquinez site also showed that very high TSS concentrations could be attained (20,000 mg L^{-1}; "turbidity currents") at the mud-water interface, and that elevated TSS could occur as far as 1400 m down-current from the barge. The existence of these very high concentrations rarely lasted longer than 10 minutes (USCOE-SFD, 1976).

70. Science Applications International Corporation (SAIC) monitored disposal of dredged material at the Alcatraz disposal site. SAIC (1987a, 1987b) tracked the TSS plume from 11 disposal events on six different days. TSS data were estimated from acoustic backscattering data. The plume of disposed material moved with tidal currents; disposal of dredged material at slack water resulted in plumes that showed little lateral movement. Disposal at ebb and flood resulted in plumes that migrated in the direction of the tide at rates up to 140 cm sec^{-1}. Background TSS values during the study were from 9 to 17 mg L^{-1}. Plumes of disposed material were tracked until they dissipated, which was usually in about 10 to 15 minutes. In that time, TSS in the lower water column ranged from about 44 mg L^{-1} to 165 mg L^{-1}. In one instance TSS of 80 mg L^{1} persisted for as long as 20 minutes after disposal.

71. Gunther *et al.* (1990) analyzed the SAIC (1987) to determine whether the frequency of disposal activity at the Alcatraz site had an effect upon residual turbidity in the waters of Central Bay and . They found that, in most instances, the interval between disposal events at the Alcatraz site was great enough to allow turbidity to decrease to background concentrations. However, under circumstances of high disposal frequencies (up to 40 disposal events per day; Figure 18) it is possible that turbidities in Central Bay could increase slightly. Gunther *et al.* (1990) recommended that special studies be carried out to determine the persistence and patterns of suspended sediment increases in Central Bay during periods of high disposal frequency.

72. Ogden Beeman Associates (1988, 1989) measured turbidity at the Alcatraz site before, during, and after dredged material disposal. The study was carried out from spring, 1988 through August, 1989. The samples taken were depth composites, taken from 0.3 m below the surface, at mid-depth (approximately 6.m) and 0.3 m from the bottom. Four sites were sampled; one at the center of the disposal site and at one site, each, to the NW, SW and SE, on the perimeter of the site. The highest turbidity measured was 94

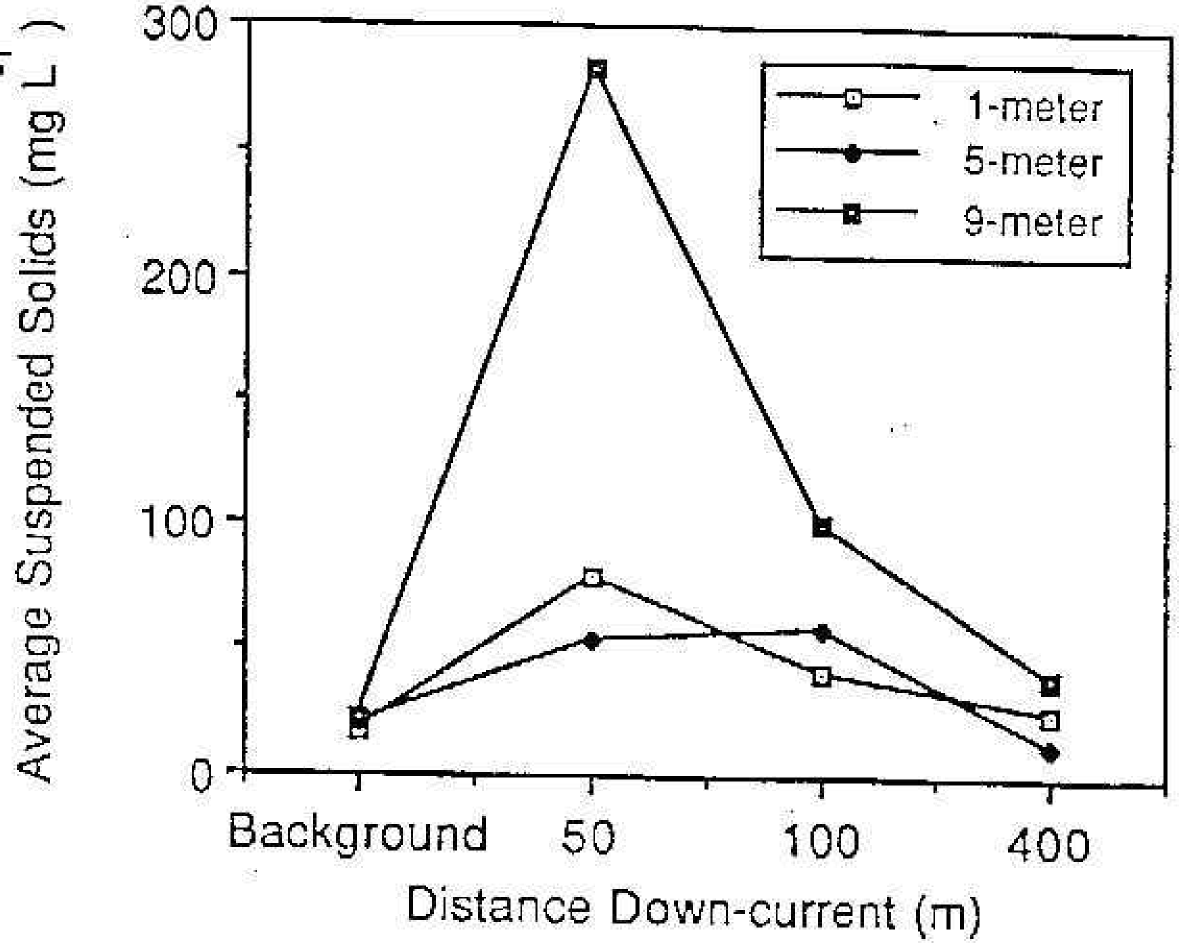


Figure 17. Suspended solids measured at three depths in the water column downstream from a dredged material disposal operation in San Francisco Bay, at the Alcatraz disposal site. From Gunther et al. (1990).

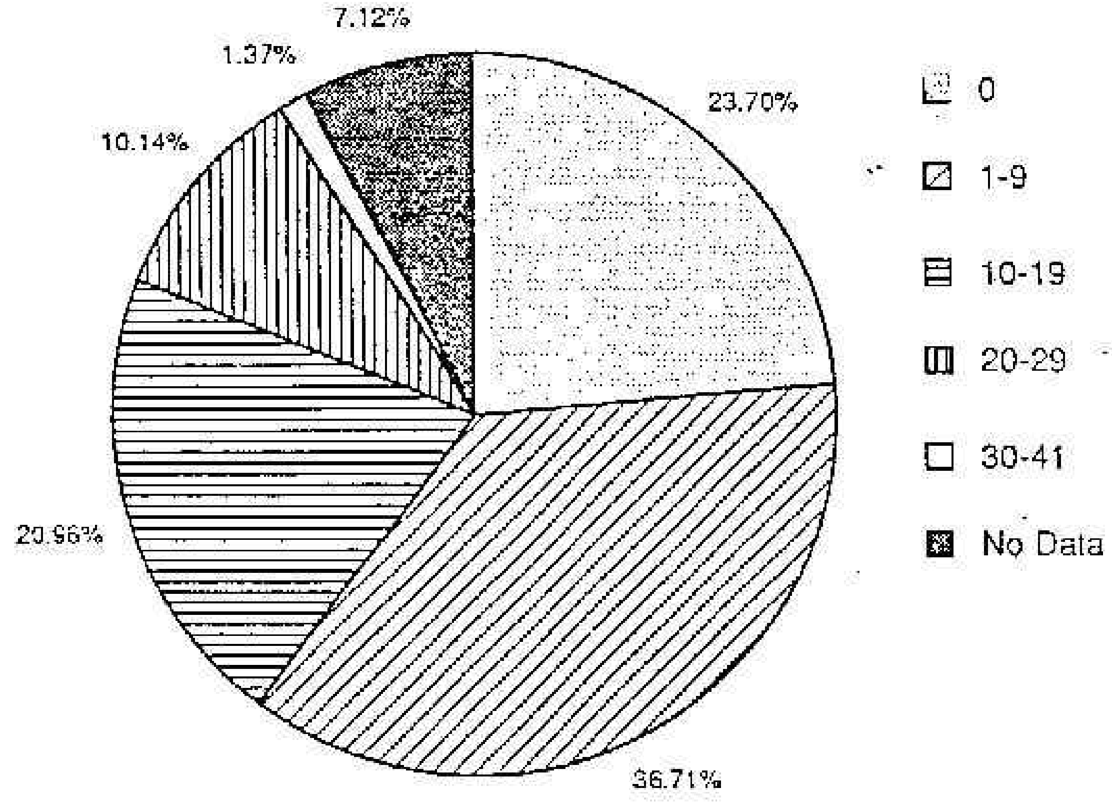


Figure 18. Frequency distribution of counts of dumps per day at the Alcatraz disposal site, January 1986 to December 1987. From Gunther et al. (1990)

(NTU) on 15 June, 1989, during disposal of maintenance dredged material from the Port of Richmond. Turbidities on the perimeter of the disposal site on that date ranged from 7.6 to 9.8 NTU. Ogden Beeman (1988,1989) measured turbidity at Alcatraz during another disposal event on 3 August. Turbidity at the center of the site during disposal was 9.3 NTU, while values on the perimeter ranged from 8.4 to 12.0. With the exception of the value of 94 NTU measured on 15 June, 1989, turbidities at the Alcatraz site were low-to-intermediate, ranging from very low values (2.5 to 3.0 NTU) on 22 September 1988, to a uniform value of 15 at all stations sampled on 20 July, 1989. As with other studies of turbidity in the Central Bay, these data point out the variable nature of turbidity in the area.

73. Johnson Offshore Services Group (1988) monitored turbidity at and near the Alcatraz disposal site in September, 1988. Turbidity was monitored using nephelometers fixed in place on a transect across the disposal site at a depth of about 5 m. The nephelometers were in place between 1 September and 17 September 1988. The monitoring period covered a time period that included numerous disposal events at the Alcatraz site.

74. Johnson Offshore Services (1988) reported that the nephelometers were calibrated with formazin, and that water samples were taken for gravimetric analysis of TSS. However, the TSS concentrations reported, whether as nephelometric turbidity units (NTU) or TSS, disagree with all other data reported from Central Bay, in general, and the Alcatraz disposal site, in particular. It was not possible to verify the Johnson Offshore data, since documentation of calibrations was not included in the report, and the raw nephelometry data were not made available for analysis (F. Johnson, personal communication). It would appear that the Johnson Offshore (1988) data suffer from a systematic error. TSS concentrations are reported as ranging from about 100 mg L^{-1} to almost 800 mg L^{-1} (Johnson Offshore, 1988; Figure 12), while data from all other sources available to us report TSS concentrations of from slightly less than 10 mg L^{-1} to a maximum of 198 mg L^{-1} in Central Bay (see sections above and below). Ogden Beeman Associates (1989) sampled turbidity at the Alcatraz site the month before and just after the end of the Johnson Offshore study. Their turbidity data, reported as from 2.5 to 16.0 NTU, would correspond to TSS concentrations of 12.5 to 80 mg L^{-1}. Such results are consistent with data from SAIC (1987), Hauck *et al.* (1990), MEC (1990a, 1990b.) and others who have determined TSS directly in Central Bay waters.

75. MEC (1990a) monitored turbidity in the water column during several disposal events at Alcatraz during May, 1990. Some samples were taken outside the influence of the disposal event and were compared to data from samples taken in the disposal plume. On 1 May 1990, ambient TSS near the Alcatraz site was from 6 to 22 mg L^{-1}. At the time of disposal, TSS at the 6.5 m depth increased to 86 mg L^{-1}, and the influence of the descending material could be seen to a depth of about 13 m (TSS at 9 m = 38 mg L^{-1}, at 12 m = 44 mg L^{-1}). Samples taken further from the site of disposal (in both

time and space) showed that TSS were greatest in the bottom waters (38 mg L^{-1}), whereas TSS at the surface and mid-depth had returned to pre-disposal concentrations (TSS at 3.1 m = 12 mg L^{-1}; at 9 m = 18 mg L^{-1}).

76. Monitoring of TSS during other disposal events gave essentially the same result; TSS increased at depths of from 6 to 15 m and decreased, thereafter, eventually returning to ambient concentrations. In one study turbidity was measured at the 6 m depth while drifting with the plume; concentrations at the 6 m depth reached 66 mg L^{-1} immediately after disposal, but decreased shortly thereafter as the disposed material settled out of the water column. While individual studies of suspended material distribution after disposal show a rapid decrease in concentration, there have been no systematic studies of turbidity or suspended solids concentrations during consecutive disposal events.

IV. Effects of Suspended Particulate Matter and Turbidity on the Biota

77. The first part of this section reviews the literature on the effects of turbidity and suspended particulate material on aquatic organisms. The second part provides an analysis and evaluation of turbidity and suspended particulate matter in relation to the question of fish catchability in Central San Francisco Bay. The literature on suspended solids effects on biota is massive, and a large part of it deals with impacts on freshwater biota. This review concentrates primarily on the effects of suspended material on estuarine biota. The studies reviewed here are discussed in relation to the turbidities and suspended particulate concentrations measured in the San Francisco Estuary, in general, and in Central San Francisco Bay, in particular.

A. Literature Summary

78. The European Inland Fisheries and Advisory Commission (EIFAC; 1964) listed four ways in which turbidity or excessive suspended solids might affect aquatic organisms. These were:
    - Action directly on the organisms which would either kill or reduce growth rate and resistance to disease;
    - Prevention of the successful development of eggs and/or larvae
    - Modification of natural movements or migrations; and
    - Reduction in the abundance of available food.

    More up-to-date understanding of the role played by suspended particulate matter in the transport and distribution of pollutants in estuarine systems leads us to add to the EIFAC (1964) list at least one other way in which suspended solids may affect aquatic organisms: that is the transport in or release to the water column of toxic chemicals that may have a direct or indirect impact on the biota (Cairns, 1968; McLaren and Little, 1987; Segar, 1989; see reviews in Morton, 1976; Stern and Stickle, 1978).

79. The discussion that follows is related only to the effects of solids and turbidity on the biota. The relationships between particles, toxic chemicals and dredging, while of concern, cannot be addressed here. For further information on this subject the reader is referred to Gunther *et al.* (1990) and Davis *et al.* (1990), wherein the partitioning of chemical contaminants to suspended particulate matter are discussed in greater detail. It should be sufficient, at this juncture, to point out that the dredged material disposed at the Alcatraz site represents material shown to cause no significant toxicity or bioaccumulation of chemical pollutants in standardized laboratory tests (EPA-COE, 1977, 1990). While differences of opinion exist on this topic (for example, O'Connor *et al.* (1982) and Gunther *et al.*, 1990 have concluded that disposed dredged material poses less of a threat to biota in the water column than that calculated by Segar, 1989), the present discussion will focus only on particle- and turbidity-related effects.

1. Burial and Turbidity Flows

80. The most clear-cut impact of suspended particulate matter on the biota may occur through the process of gross settling and deposition of sediments. When particulate matter in the water column settles it forms a new layer of sediment atop existing layers, covering organisms that live on, or in, the sediments. When such deposition occurs rapidly (as in the settling of disposed dredged material) and when newly deposited sediments accumulate to substantial depths, members of the benthic community that cannot burrow up through the new sediment may be eliminated (Ellis, 1936; Masch and Espey, 1967). Burial of benthic communities occurs at the designated disposal sites in San Francisco Bay. This is unlikely to lead to a significant loss of benthic resources in the Bay for several reasons. First, the disposal areas in the Bay have been in use for many years, and any loss of benthic resources due to disposal have been a part of Bay ecology for decades. Second, the disposal areas in the Bay are an exceedingly small fraction of the Bay bottom, and the small fraction of benthic resources at those sites were not critical to Bay ecology when disposal began, and are not critical at present. Third, the designated disposal sites in the Bay are in Central Bay and San Pablo Bay, regions where benthic productivity is not high, compared to that in South Bay (Nichols, 1979). Fourth, disposal at the various designated sites in the Bay is quite frequent; disposal at Alcatraz may average of 10 to 20 events per day (Gunther *et al.*, 1990). The benthic communities at these sites, therefore, are in a continual state of disruption and recolonization, and have been since in-Bay disposal was first allowed at these sites.

81. Very high concentrations of suspended particulate matter in the water may affect the biota in a manner that is similar to gross burial. Under certain conditions, such as in areas of salt flocculation (Masch and Espey, 1967; Meade, 1972), settling particulate matter may form an highly concentrated layer of suspended matter described variously as "fluff", "fluid mud" or a "turbidity flow." Turbidity flows occur when factors such as a low degree of physical mixing and electrical charge on particle surfaces may inhibit settling and consolidation, thereby prolonging the process of deposition. Masch and Espey (1967) observed that when suspended sediments exceeded concentrations of 10,000 mg L^{-1} the floccules (agglomerations of fine particles) interfered with further settling. Suspended sediment concentrations in excess of 220,000 mg L^{-1} have been observed in turbidity flows (Masch and Espey, 1967). Turbulent mixing tends to prohibit the formation of turbidity flows. Turbidity maxima in the San Francisco Estuary occur in the Northern reach (Arthur and Ball, 1979), where TSS concentrations as high as 1000 mg L^{-1} have been measured (Krone, 1966). However, current flows and turbulent mixing in the Northern reach of the Estuary are such that concentrations of TSS are unlikely to reach the critical levels at which settling is inhibited (10,000 mg L^{-1}; Masch and Espey, 1967). The highest concentration of TSS measured in the Estuary was

20,000 mg L^{-1}, a value that occurred in bottom waters at the Carquinez disposal site during a disposal operation (USCOE-SFD, 1976). While such a concentration has the potential to form a turbidity flow, observations show that it dispersed rapidly, and TSS in bottom waters decreased to ambient concentrations within 25 minutes.

82. Organisms exposed to the very high concentrations of sediments in turbidity flows may be impacted severely. The high concentrations of suspended solids may clog gills and cause asphyxia. For those organisms which can escape exposure to turbidity flows by isolating themselves from the water (i.e., bivalve molluscs, some tube-dwelling worms, etc.) survival depends upon the length of time the organism can survive under anoxic conditions (Nicol, 1960). The question of the effects of settling and deposition on substrate particle-size distribution and habitat integrity will be addressed below.

2. Direct Effects of Particles on Organisms

Phytoplankton

83. Turbidity and increased concentrations of suspended particulate matter will, by definition, decrease the transparency of water (APHA, 1976). This will reduce the amount of light available in surface waters, and will affect phytoplankton directly by reducing the depth of the photic zone, and possibly reducing net primary production. Various studies have been conducted in the field and in the laboratory to determine the relationship between suspended particulate matter in the water and primary production (Hollis, 1964; Sherk *et al.*, 1974; Cloern, 1987). Cloern (1987) stated that a large part of the spatial and temporal variability in phytoplankton biomass and productivity in estuaries, including the San Francisco Estuary, is explained by variations in the ratio of photic depth to mixed depth. Photic depth is, of course, directly determined by TSS concentrations and light penetration. Sherk *et al.* (1974) studied photosynthesis in four species of estuarine algae at different concentrations of finely ground SiO_2. He found that photosynthesis decreased as SiO_2 concentration increased from 100 mg L^{-1} to 2,250 mg L^{-1}. Most carbon assimilation in the algae was eliminated at SiO_2 concentrations greater than 250 mg L^{-1}. Sherk *et al.* (1974) stated that the higher turbidity values used in their experiments (1,000 and 2,250 mg L^{-1}) were outside the range of concentrations seen in most surface waters. However, the concentration of 250 mg L^{-1} may occur in estuaries during periods of high runoff, when wind- and current agitation resuspend large quantities of sediments, or during dredged material disposal.

84. The impact of low concentrations of TSS on phytoplankton is not necessarily negative. Odum and Wilson (1962) found, for example, that the addition of turbidity-producing materials (allochthonous sediments) to the water column can indirectly stimulate photosynthesis. This effect is due

primarily to the fact that suspended particulate material from a watershed often has nutrients adsorbed to the surfaces of mineral solids. When these nutrients desorb they become available and may stimulate growth in nutrient-limited phytoplankton populations.

85. Another direct effect of suspended particulate matter on phytoplankton was suggested by Bartsch (1960), who hypothesized that phytoplankton may be flocculated by the adherence of silt particles to algal cells which "...carry them to the bottom to die." The author knows of no studies related to the question of phytoplankton flocculation and settling due to the effects of disposed dredged material in estuarine ecosystems.

Zooplankton

86. The majority of zooplankton are filter-feeders and are well-adapted to dealing with suspensions of particulate material in the water. Few studies have been carried out to determine the negative effects of suspended particulate material on zooplankton. Studies in both marine and freshwater systems have shown that zooplankton (e.g., *Daphnia, Calanus, Acartia, Eurytemora*, etc.) will migrate vertically into regions of turbidity (Paffenhofer, 1972; Doan, 1942). Baylor and Sutcliffe (1965) showed that *Daphnia* will alter the vector of their vertical migration to bring themselves into regions where particles in the water column are absorbing a large portion of the longer wavelengths (red). Baylor has used this mechanism to explain the concentration of zooplankton in regions of high turbidity, and in oceanic and estuarine waters where zooplankton concentrate under foam lines or windrows established by wind-driven Langmuir circulation cells.

87. Robinson (1957) studied the effects of suspended material on the reproductive success of *Daphnia magna*. Using TSS concentrations up to 1,450 mg L^{-1}, he determined that small amounts of TSS were essential to survival and reproduction. Only montmorillonite clay and powdered charcoal had any toxic effect on *D. magna*. Ground glass (SiO_2), India ink, kaolinite and natural pond sediment had no effects at the concentrations tested.

88. Sherk *et al.* (1974,1976) studied the effects of suspended particulate matter on the estuarine zooplankters *Acartia tonsa* and *Eurytemora affinis*. Suspensions of fuller's earth, silica sand and estuarine muds (from the Patuxent River, MD) caused reduced feeding rates of the copepods. When TSS concentrations were above 250 mg L^{-1} algal ingestion rates decreased in *E. affinis*.. The critical concentration for *A. tonsa* was 50 mg L^{-1} TSS. However, phytoplankton concentrations of 50 and 250 mg L-1 also reduced ingestion, suggesting that the copepods were nonselectively filtering particulates from the water, and that any material (including phytoplankton) present above the critical concentration would result in reduced rates of ingestion (Sherk *et al.*, 1976).

89. The zooplankton of the San Francisco Estuary include species similar to those tested by Sherk *et al.* (1974, 1976) for responses to suspended particulate matter. Ambler *et al.* (1985) provide a description of the distribution throughout the Bay and Estuary of common calanoid copepods, such as *Eurytemora affinis*, *Acartia clausi* and *Acartia californiensis*. Based upon the results from Sherk *et al.* (1974, 1976) and the TSS concentrations in the San Francisco Estuary, it is likely that species in the Estuary would have similar responses to suspended sediments as those shown by *E. affinis* and *A. tonsa*. As non-selective filter feeders, zooplankton in the Estuary may respond to the occasional high concentrations of suspended solids by reducing filtration and ingestion rates. Such a reduction would occur in response to high TSS in Delta outflow, dredged material disposal, or a dense phytoplankton bloom. As pointed out by Sherk *et al.* (1974, 1976), a reduced rate of filtration and particle ingestion may be a mechanism to avoid "overconsumption" on the part of the zooplankton, a condition in which particles at very high concentration pass through the gut undigested, resulting in a net energy loss for the filter feeding organism.

Planktonic Life-history Stages of Fish and Invertebrates

90. Davis (1960) and Davis and Hidu (1969) studied the effects of various suspended materials on the quahog *Mercenaria mercenaria*. They showed that quahog eggs developed normally in concentrations up to 4,000 mg L^{-1} clay, chalk and fuller's earth. The proportion of eggs developing normally declined as the TSS concentration increased. Davis and Hidu (1969) found that as little as 188 mg L^{-1} natural silt caused a measurable reduction in the number of oyster eggs (*Crassostrea virginica*) that developed normally. Fuller's earth and kaolin suspensions did not affect oyster egg development until concentrations exceeded 1,000 to 2,000 mg L^{-1}. The European oyster (*Ostrea edulis*) was less affected by silt than was the North American species, *C. virginica*. Davis and Hidu (1969) noted that oyster eggs were affected more by larger particles, while clam eggs were affected more by smaller particles. It should be noted that these experiments utilized the planktonic larval stages of bivalves, not the demersal, adult forms. TSS concentrations such as those tested by Davis and Hidu (1969) are not routinely recorded in the water column in Central Bay.

91. *In situ* field studies of the effects of dredged material disposal on natural populations of planktonic fish eggs and larvae were conducted in Chesapeake Bay. As part of that study Dovel (1968) reported that turbidity associated with overboard, unconfined disposal of dredged material caused no gross effects on fish eggs and fish larvae of freshwater, estuarine and marine spawners. A similar study was conducted by Morgan *et al.* (1973), using the eggs and larvae of striped bass (pelagic eggs) and white perch (*Morone americana*) (demersal eggs). Delayed development of white perch and striped bass eggs was observed at very high concentrations of TSS (>1,500 mg L^{-1}). At 4,000 mg L^{-1} hatching of demersal white perch

eggs was delayed for one day. Egg mortality occurred for striped bass at 3,400 mg L^{-1}, and at 3,600 mg L^{-1} for white perch (Morgan *et al.*, 1973).

92. The effects of turbidity on the survival and growth of lake herring (*Coregonus artedii*) was studied by Swenson and Matson (1976). Larvae of lake herring were held in suspensions of red clay similar to that found in Lake Superior (28 mg L^{-1}). These concentrations had no negative effects upon the development or survival of herring eggs and larvae, other than the fact that larvae in higher concentrations of TSS distributed themselves closer to the surface of the experimental tanks than did control larvae. It is not known whether this distribution was a particle effect or a photoresponse.

93. Schubel and Wang (1973) examined the effects of suspended solids on the eggs of several estuarine fishes. They exposed eggs from yellow perch (*Perca flavescens*), white perch, striped bass and alewife (*Alosa pseudoharengus*) to suspensions of fine-grained sediments from natural sources. (It should be noted that the eggs of yellow perch are demersal, and develop in a gel matrix, the eggs of white perch and alewife attach to surfaces, and striped bass eggs are planktonic). TSS concentrations of up to 500 mg L^{-1} had no apparent effect on the hatching success of any of the species, although some slight time delays in hatching occurred. Schubel and Wang (1973) concluded that in a natural, well-mixed environment, suspensions of natural, fine-grained sediments would not cause adverse effects on the eggs of estuarine species.

94. The results of the studies cited above demonstrate quite clearly that egg and larval forms of invertebrates and fishes can tolerate relatively high concentrations of suspended particulate material. Especially for the estuarine species (American oyster, striped bass, white perch, alewife, etc.), spawning, development and growth take place in conditions not unlike the turbid, Northern reaches of the San Francisco Estuary. Indeed, as shown in several studies, the normal location of striped bass larvae in systems like the Chesapeake Bay and San Francisco Bay is in the zone of high turbidity (Mansueti, 1961; Arthur and Ball, 1979).

Benthos

95. Many benthic organisms are filter feeders or deposit feeders. That is, they employ specialized mechanisms to accumulate particulate food material from the water column or the mud-water interface, ingest it, and extract sustenance from it. Various species have evolved a wide assortment of mechanisms for processing food particles. In those cases where particle-processing mechanisms afford some kind of selection, the selection is generally for particle size, rather than for nutritive content (Nicol, 1960). Bivalve molluscs that are filter feeders may play a role in reducing turbidity in estuarine environments by their capacity to remove particulate matter from suspension (Nichols *et al.*, 1990).

96. The results of studies on the effects of increased turbidities on bivalve molluscs reflect the response of the organisms to increased availability of food or food-like particles. When Ingle (1952) suspended oysters in baskets adjacent to dredging operations, he found that mortalities due to increased turbidity were not statistically significant. In fact, the appearance of the oysters at the end of the experiment was described as "excellent." Ingle (1952) speculated that the increased particle concentrations in the water from the dredging operation provided additional food for the oysters in the form of organic detritus. In a similar study Macklin (1956, 1962) observed an inverse relationship between turbidity and oyster mortality; oyster survival was greatest in turbid, estuarine waters and least in less turbid marine waters.

97. Laboratory studies to assess the effects of suspended particulate matter on the benthos have concentrated on bivalve molluscs. Pratt and Campbell (1956) determined that TSS with a high silt-clay content inhibited growth in *M. mercenaria*. They attributed this effect to an increase in the energy expended for frequent cleaning of the filtering apparatus. It could also have been caused by the fact that suspensions with a higher proportion of silt and clay had proportionately less nutritive value than natural suspensions of phytoplankton or organic-rich detritus.

98. Stone *et al.* (1974) studied the effects of TSS on two marine bivalves, the scallop *Placopecten magellanicus* and the ocean quahog, *Arctica islandica*. Both species produced increased amounts of mucus when exposed to suspensions of kaolin. Presumably this increase in mucus production caused a depletion in energy reserves that might be used for other purposes, such as growth or reproduction (Stone *et al.*, 1974). Although no data on reproduction were provided, Stone *et al.* (1974) concluded that high concentrations of TSS could lead to impaired reproduction in marine bivalves.

99. Peddicord *et al.* (1975) studied the impact of suspended particulate matter on bivalve molluscs (*Tapes japonica* , *Mytilus edulis* and *M. californianus)* from the San Francisco Estuary. Their studies incorporated designs that tested direct sediment effects as well as the interaction of TSS and decreased oxygen concentrations in the test water. The species tested showed a wide range of sensitivities to suspended mineral solids. No studies were carried out with suspensions of natural sediments. *T. japonica* tolerated 100,000 mg L^{-1} kaolin clay for up to 10 days without a significant increase in mortality. *M. edulis* exposed to the same conditions for the same period of time experienced about 10% mortality. *M. californianus* was more sensitive than *M. edulis*, showing a 50% mortality after 200 hr exposure to kaolin at concentrations of about 96,000 mg L^{-1}. None of the concentrations of kaolin tested were representative of suspended sediment concentrations that occur in San Francisco Bay, even in the vicinity of disposal operations.

100. When the same organisms were exposed to bentonite clay suspensions in combination with reduced dissolved oxygen and two levels of temperature, higher temperatures resulted in higher mortality. Peddicord *et al.* (1975) interpreted this to mean that increased metabolic rates at the higher temperature reduced the length of time the bivalves could remain closed (avoidance of TSS), and increased their time of exposure to the bentonite particles. Peddicord *et al.* (1975) also observed decreased oxygen consumption when bivalves were exposed to bentonite clay. Their interpretation of this phenomenon was that increased concentrations of bentonite clogged the gills and impaired gas exchange across the gills.

101. Peddicord *et al.* (1975) also studied the responses of the epibenthic shrimps, *Crangon nigricauda* and *Palaemon macrodactylus*, the crab, *Cancer magister*, and the amphipod, *Anisogammarus confervicolus*. The 200 hr LC_{50} for *P. macrodactylus* and *C. nigricauda* was about 50,000 mg L^{-1} kaolin. *C. magister* and *A. confervicolus* were more sensitive to suspensions of kaolin; their 200 hr LC_{50} was approximately 35,000 mg L^{-1}. As with the bivalve molluscs, Peddicord *et al.* (1975) found that there was a complex interaction between kaolin concentration, temperature and dissolved oxygen. Survival of all test organisms was greatest under at low temperature, low suspended solids and high D.O. Conclusions derived from these studies (Hirsch *et al.*, 1978) were that optimum times for disposal of dredged material in ecosystems containing sensitive species would be during winter months when temperatures were low and dissolved oxygen concentrations would be at their highest.

102. In general it can be concluded that direct effects of suspended particles on benthic organisms are caused only by very high concentrations of particles that persist for long periods of time. Species endemic to San Francisco Bay, for example, tolerated concentrations of mineral solids close to 100,000 mg L^{-1} for up to 10 days. Unfortunately, the data from Peddicord *et al.* (1975) that relate to San Francisco Bay benthos were generated only using mineral solids. However, based upon other studies (see Section on Fishes, below; O'Connor *et al.*, 1976, 1977) it may be expected that natural suspended solids have less of an effect than mineral solids at the same concentration.

Indirect Effects of Turbidity on Benthos

103. Turbidity generated by dredged material disposal may affect benthos indirectly by altering substrate characteristics. Material that remains in suspension after disposal may settle on valuable benthic habitat, such as sandy bottoms or shoals. While it is well known that substrate alteration can affect the distribution of the benthos (e.g. Boesch, 1982), the extent to which these effects may occur in San Francisco Bay is uncertain. As stated earlier in this report, the substrates of the broad, shoal portions of the Bay are subject to large-scale resuspension and redeposition on almost a daily

basis (Conomos *et al.*, 1985). We are unaware of any studies undertaken to determine deposition of fine materials in those portions of the Central Bay where substrates are primarily coarse-grained materials; however, anecdotal reports suggest that some regions characterized by "hard" bottoms in the past may now contain mud. Additional studies of such conditions are required.

Fishes

104. Direct mortality of fish exposed to high concentrations of suspended particulate matter is due to impaired oxygen exchange (O'Connor *et al.*, 1976, 1977; DiSalvo and Peddicord, 1978; Neumann *et al.*, 1982). The exact cause of impaired oxygen exchange may be laceration and disruption of gill epithelium (Rogers, 1969), physical irritation of the gill accompanied by edema (Rogers, 1969; O'Connor *et al.*, 1976), or blockage of gas exchange by particles coating or clogging the gill (O'Connor *et al.*, 1976, 1977; Peddicord *et al.*, 1978; Neumann *et al.*, 1982). Peddicord *et al.* (1975, 1978) stress that the lethality of suspended particles is determined in part by the size distribution of the particles; a greater number of very fine particles had more of a potential to cause gill clogging than the same mass-concentration of larger particles.

105. Rogers (1969) studied the response of four species of estuarine fish to suspensions of kaolin, ground rock flour, incinerator fly-ash, diatomaceous earth, powdered charcoal, and ground glass (SiO_2). He found that mortality increased as a function of particle size and angularity. SiO_2 was the most lethal of the suspensions tested, apparently lacerating the gills, disrupting epithelial integrity and blocking respiratory gas exchange.

106. Sherk and co-workers (Sherk *et al.*, 1972, 1974; O'Connor *et al.*, 1976, 1977; Neumann *et al.*, 1982) studied the effects of fuller's earth, kaolinite, and natural sediments on estuarine fishes. The species tested included white perch, spot (*Leiostomus xanthurus*), Atlantic silversides (*Menidia menidia*), bay anchovy (*Anchoa mitchilli*), mummichog (*Fundulus heteroclitus*) and striped killifish (*F. majalis*). Lethal concentrations (24 hr LC_{50}) for these species ranged from as low as 580 mg L^{-1} (Atlantic silversides) to 24,500 mg L^{-1} for mummichogs. O'Connor *et al.* (1976) used their data to classify estuarine fishes into categories of particle sensitivity. Particle-insensitive species (e.g., the mummichog, striped killifish and spot) had 24-hr LC_{10} values greater than 10,000 mg L^{-1}. Sensitive species (white perch, bay anchovy) had 24 hr LC_{10} values between 1,000 and 10,000 mg L^{-1}, while highly sensitive species (Atlantic silversides) had a 24 hr LC_{10} value below 1,000 mg L^{-1}. Based upon these classifications, the TSS concentrations in the San Francisco Estuary would not pose a threat to even the most particle-sensitive species.

107. Peddicord *et al.* (1975) studied the effects of suspended solids, temperature and dissolved oxygen on three species of fish from San

Francisco Bay; shiner perch, *Cymatogaster aggregata*, English sole, *Parophrys vetulus*, and striped bass. Shiner perch were most sensitive to kaolin suspensions, suffering high mortality in little more than one day at concentrations of 14,000 mg L^{-1}. The bottom-dwelling English sole, on the other hand, survived as long as 10 days at kaolin concentrations of 70,000 mg L^{-1}.without mortality. When the concentration increased to 117,000 mg L^{-1}, English sole suffered 80% mortality in 10 days.

108. Peddicord *et al.* (1975) noted an interaction between temperature and bentonite concentrations. Shiner perch exposed to 400 mg L^{-1} bentonite at 10°C for 10 days experienced nearly complete mortality. English sole exposed to 60,000 mg L^{-1} bentonite at 10°C experienced no mortality in 10 days. One death was reported among English sole exposed to 60,000 mg L^{-1} at 18°C. Lowest survival among the species tested occurred when temperatures and dissolved oxygen were at their lowest, and suspended solids were at their highest. With the exception of TSS concentrations above 400 mg L^{-1}, which occur on occasion in the entrapment zone, none of the conditions causing mortality among shiner perch, English sole or striped bass (Peddicord, *et al.*, 1975) would be expected to occur in the San Francisco Estuary.

109. The sublethal effects of suspended particulate matter on fishes was investigated by Sherk *et al.* (1972, 1974; see also O'Connor *et al*, 1977; Neumann *et al.*, 1982). The respiration of the sedentary, bottom-dwelling oyster toadfish (*Opsanus tau*) was unaffected by TSS concentrations of up to 156,000 mg L^{-1}. Striped bass and white perch generally showed reduced respiration when exposed to suspended solids in a forced-swimming experimental format. Neumann *et al.* (1982) suggested that this response was related to partial clogging of the gills. O'Connor *et al.* (1977) also measured hematological parameters related to blood-gas exchange. They found that fish exposed to high TSS concentrations (>1,500 mg L^{-1}) for a short period of time showed a reduction in hematocrit (i.e., the volume percent of red blood cells in a sample of blood); however, the hematocrit value generally increased during longer exposures (five-to-ten days), suggesting a compensatory response in blood oxygen carrying capacity.

Indirect Effects of Turbidity on Fish

110. In addition to direct impacts of suspended particulate matter on fishes, particulates, or the turbidity caused by particulate matter in the water column may influence feeding behavior and choice of habitat. For example, Cyrus and Blaber (1987a, 1987b) studied the distribution of fishes in a lagoon-type estuary on the southeastern coast of Africa. They were able to distinguish five groups of fish according to preferred turbidities. These were:
- "clear water" species preferring habitats with NTU < 10;
- "clear-to-partially turbid" species preferring water less than 50 NTU;
- "intermediate turbidity" species (10 - 80 NTU);

• "turbid-water" species (NTU > 50); and
• species indifferent to turbidity.

Subsequent laboratory studies in which different species were allowed to choose water of varying turbidities confirmed their statistical evaluation of field data (Cyrus and Blaber, 1987b). Explanations of why fishes prefer habitats of varying turbidities ranged from reduced predation on young in turbid waters to easier predation for piscivorous species in turbid waters.

111. Heimstra *et al.* (1969) studied the behavior of two freshwater fishes, juvenile largemouth bass (*Micropterus salmoides*) and green sunfish (*Lepomis cyanellus*). Exposures included two different levels of turbidity: "clear" water (4 to 6 JTU) and "turbid" water (14 to 16 JTU). Activity of the bass was reduced under turbid conditions; sunfish activity was also reduced in turbid waters, but not significantly so. Feeding behavior and agonistic (attack) behavior for both species remained the same regardless of the turbidity of the water.

112. Diehl (1988) studied the foraging efficiency of three freshwater fish species in relation to light. Two types of light reduction were considered in these experiments; 1) reduction in light due to "structural complexity" (i.e., increasing amounts of vegetation), and 2) reduction in light due to turbidity. Diehl (1988) found that perch (*Perca fluviatilis*) preferred vegetated portions of habitats, and foraged efficiently in the reduced light imposed by dense vegetation. Bream (*Abramis brama*) and roach (*Rutilus rutilus*) were found to be superior foragers on chironomid larvae under dark and highly turbid conditions. The foraging of these species was especially good under turbid conditions that did not have the additional complexity of submerged aquatic vegetation.

113. Crowl (1989) found that the foraging efficiency of largemouth bass was related to the clarity of water. Largemouth bass forage visually for their prey, and Crowl (1989) found that in clear water the "reactive distance" (i.e., the distance at which the fish noticed prey [crayfish, *Procambarus acutus]*), increased linearly with increase in the size of the prey. Prey movement also resulted in an increase in the reactive distance. Neither prey size nor prey movement had any effect on reactive distance in moderately turbid water. Crowl (1989) proposed that fish may change their feeding tactics as prey visibility changes. When prey are highly visible (i.e., low turbidity), predators react only after prey recognition. When prey are less visible (i.e., high turbidity) predators attack immediately upon sighting the prey, a phenomenon which does not depend upon prey size or prey movement. Indeed, prey recognition and instigation of attack in darkness (either under highly turbid conditions or at night) may depend upon cues other than vision.

114. Breitburg (1988) conducted a series of laboratory experiments to determine the effects of turbidity on prey consumption by striped bass larvae. Striped bass larvae were placed in waters of varying turbidity (0,

75, 200 and 500 mg L^{-1} kaolin) and offered either copepods or water fleas (*Daphnia pulex*) as prey. Striped bass larvae offered copepods ingested 40% fewer prey in the more turbid water (200 and 500 mg L^{-1}), but consumption rates in 0 and 75 mg L^{-1} turbidity were similar. The results were different when *D. pulex* was offered as prey; larvae feeding on *D. pulex* consumed prey at the same rate in all turbidities. Johnston and Wildish (1982) found that larval Atlantic herring (*Clupea harengus*) took fewer *Artemia* nauplii when turbidities were increased from 0 to 20 mg L^{-1}. However, Boehlert and Morgan (1985) found that larvae of the Pacific herring (*C. harengus pallasi*) increased their capture of prey in turbidities as high as 1000 mg L^{-1}.

115. Turbidity may also have effects on fish populations. Langlois (1941) and Doan (1941, 1942) suggested that turbidity in the Great Lakes was inversely correlated with commercial catches of sauger (*Stizostedion canadense*). These conclusions were the cause of some controversy since Van Oosten (1945) proposed that overfishing was the major cause of fisheries declines in the Great Lakes. Sissenwine and Saila (1974) evaluated the scup (*Stenotomus chrysops*) fishery on the Atlantic coast. While it had been proposed that the scup fishery in Rhode Island was suffering from turbidity due to open-ocean disposal of dredged material, Sissenwine and Saila (1974) were able to demonstrate that landings had declined throughout the range of the species, and that the extent to which dredged material disposal played a role in this decline was probably very small.

B. Effects of Turbidity on Fish Catch and Catchability in Central Bay

116. It has been suggested that dumping of dredged material at the Alcatraz disposal site has led to an increase in ambient turbidity in Central San Francisco Bay. Further, it has been argued that the turbidity associated with dredged material disposal has played a role in causing, or contributing to, declines in the catch of striped bass and other sport fish in the Central Bay (DFG, 1989). This section of the report evaluates this series of arguments critically. In doing so, we have reduced the logical progression of cause-and-effect to a series of hypotheses that lend themselves to technical evaluation in light of available data. The argument is framed primarily in inferential terms; that is because there are very few data that allow one to arrive at a deduction or specific conclusion based upon specific hypotheses and tests. In many cases the data necessary for evaluating the stated hypotheses are not available; we suggest a series of research studies that might be undertaken to accumulate the data necessary for a complete evaluation of the question of dredged material disposal, turbidity in the Central Bay, and fisheries.

1. <u>Increased Turbidity in Central Bay Waters</u>

117. The first hypothesis is that turbidity in the Central Bay has increased in recent years, and that some part of this increased turbidity is due to the disposal of dredged material at the Alcatraz dumpsite. The basis for concluding that there has been an increase in turbidity in Central Bay is the data collected by DFG which show a substantial decrease in Secchi disk depth (water transparency) in Central San Francisco Bay waters between 1985 and 1986, and continuing through 1988. Data are available for evaluation of this hypothesis; however, they are spotty, ill-distributed in time and space, and, with a single exception, unrelated to any direct impact of dredged material disposal or increased turbidity on fishes in the Central Bay. The data sets are those collected by DFG, historical data on turbidity and/or suspended solids in Central Bay from USGS (1989a), the Army Corps of Engineers (USCOE-SFD, 1976), SAIC (1987), Ogden Beeman Associates (1988), Johnson Offshore Services (1988), Hauck *et al.* (1990), and MEC (1990a, 1990b).

118. The only long-term information providing any measure of water clarity in Central Bay are the DFG data on Secchi disk depth measurements from samples taken at monthly intervals from 1980 through 1988. Other data have fewer observations collected over longer time intervals (e.g., USGS data on turbidity and TSS), or data collected over relatively short time intervals providing either turbidity (as NTU or FTU) and/or TSS (e.g. Hauck *et al.*, 1990; SAIC, 1987; Johnson Offshore Services, 1988; MEC, 1990a, 1990b).

119. The major advantage to the DFG Secchi data is that they have been collected continuously for nearly ten years. Furthermore, they span a period of time during which environmental factors influencing the Bay varied from very wet conditions to drought. The DFG data were also collected over a time span when dredged material disposal ranged from very low levels to the intense disposal activity of 1985 to 1987. Unfortunately, the DFG data represent only surface water transparency; they provide no information on the possible cause(s) of turbidity (i.e., whether it be phytoplankton, resuspended sediment, or particles from land runoff). Neither do they give site-specific transparency readings in various portions of the Central Bay sub-embayment.

120. We attempted to derive some relationship between Secchi disk readings and other more quantitative measures of turbidity in the Estuary. This was done in order to try to establish a frame of reference within which we could evaluate the time-series Secchi disk data from DFG. We took Secchi disk and suspended solids data from DWR water quality surveys for 1983 through 1985 and performed regression analysis on various pairs of data sets. All the turbidity and TSS data were from samples taken at 1 m depths. The DWR data from San Pablo Bay (station D41 at Point Pinole) were assumed to be representative of the same, or similar, turbidity/TSS relationships that might occur in Central Bay (see Hauck *et al.*, 1990). Turbidity and TSS were strongly correlated within samples (Figure 19; r^2 = 0.902). However, the correlation between Secchi disk and TSS data was much less strong (Figure 20; r^2 = 0.51). It can be noted in Figure 20 that TSS concentrations up to 10 mg L^{-1} (a common value in Central Bay; USGS, 1989; MEC, 1990a, 1990b) gave Secchi disk readings that varied by a factor of almost three, from 55 cm to 160 cm. We conclude from this analysis that Secchi disk data do not provide a reliable estimate of turbidity or suspended solids concentration. One would be ill-advised to attempt to derive any measure of turbidity or TSS from Secchi disk data. Water transparency, as measured by Secchi disk, is a valuable datum, but cannot be assumed to provide any information other than an estimate of the penetration of light into the surface layers of the water column.

121. MEC (1990b) provided the only other Secchi disk depth measurements available for comparison with DFG data from Central San Francisco Bay. MEC (1990b) measured water transparency in and near the plume of a sand-mining barge moored off Angel Island. Secchi disk readings were variable and differed and outside the plume. Secchi disk depths between 120 and 150 cm were common outside the sand-mining plume in June of 1990. These data are equivalent to DFG Secchi disk readings in May in the period 1980 through 1985, and higher than the values measured by DFG in 1986, 1987 and 1988. DFG (Tasto, personal communication) have noted that this observation is consistent with an increased catch of sport fish in 1988; however, DFG have no Secchi disk data for 1990.

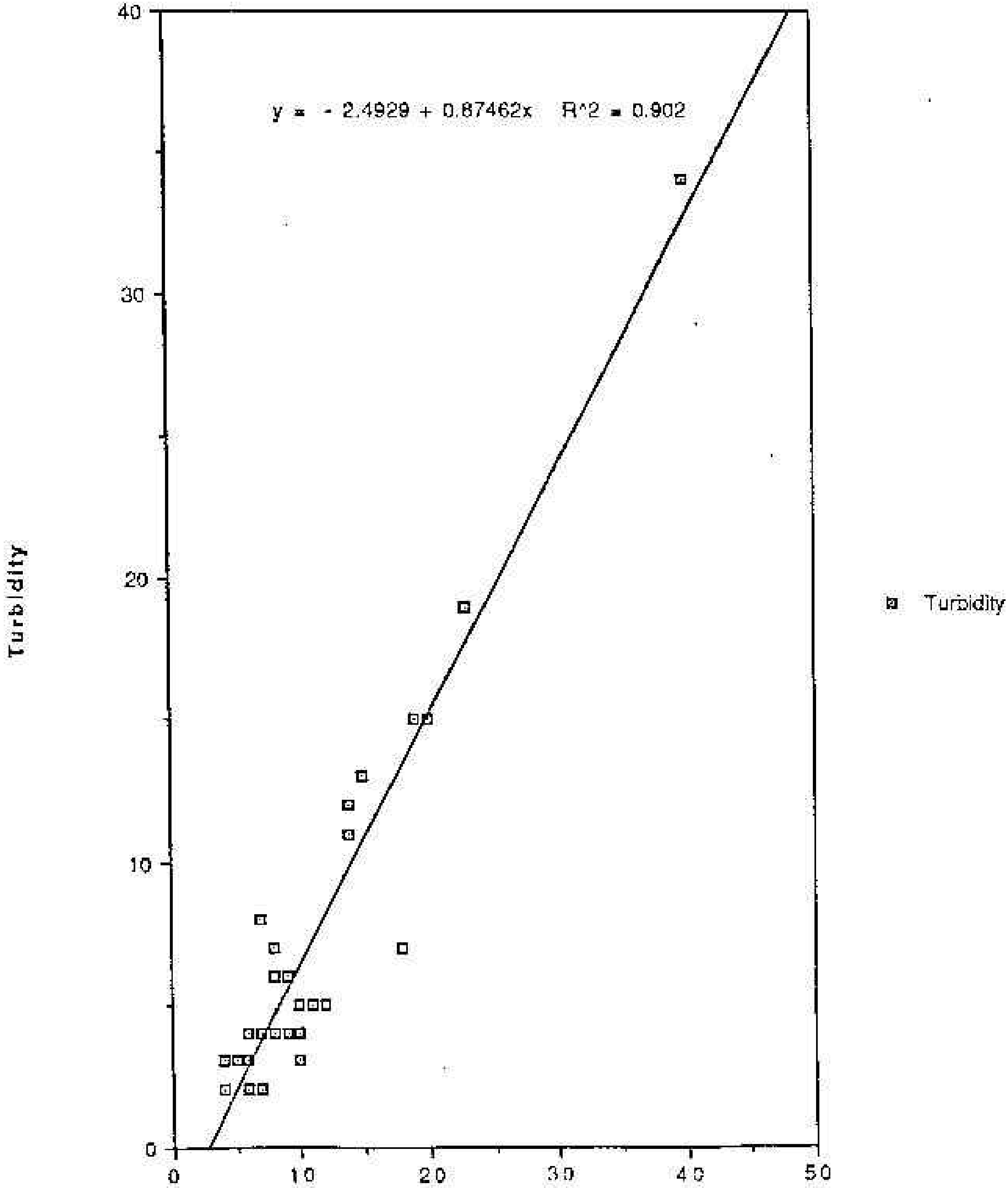


Figure 19. The relationship between measured turbidity (NTU) and total suspended solids (mg L^{-1}) in samples taken by California Department of Water Resources between 1983 and 1985 at Point Pinole (Stations D41).

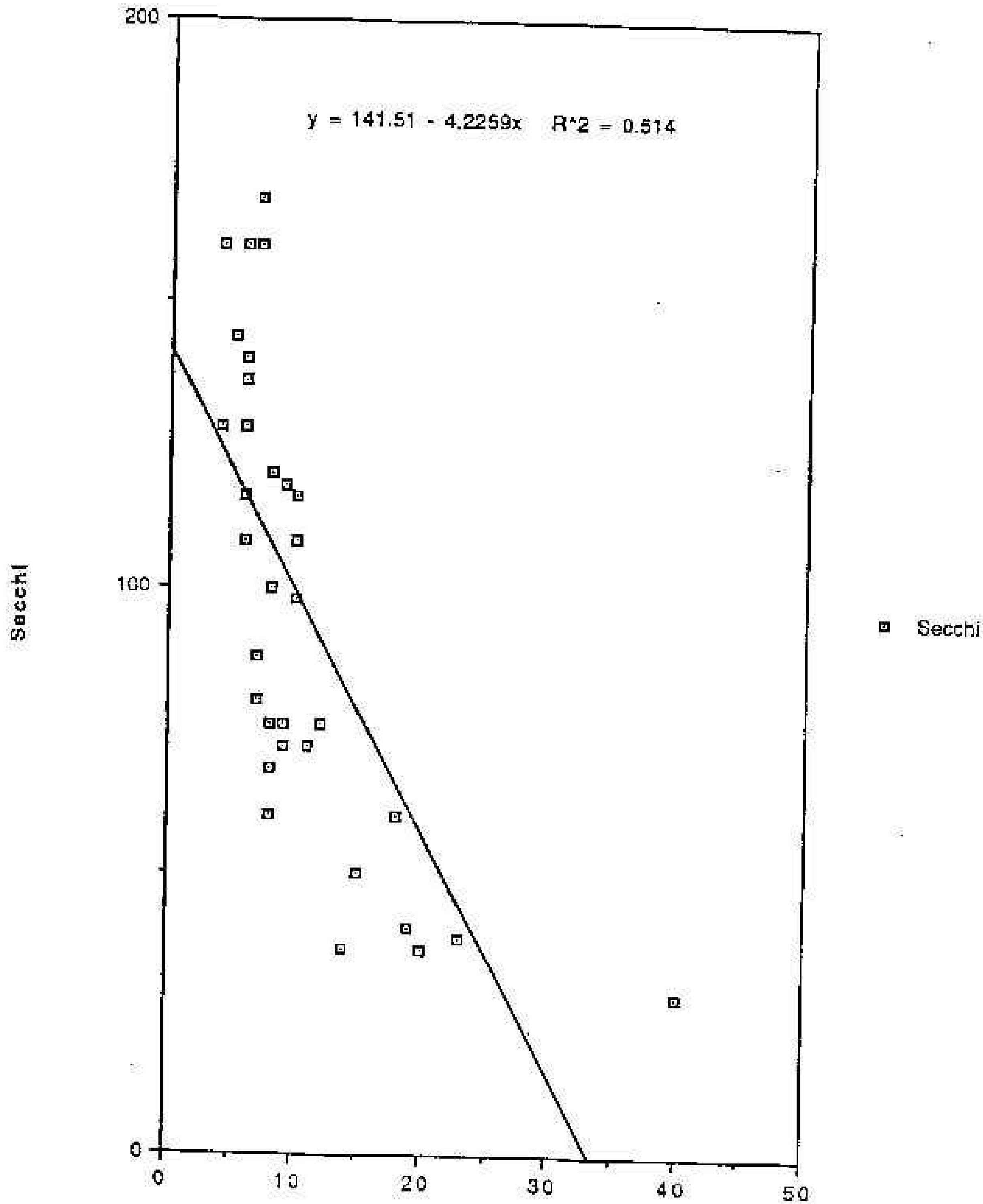


Figure 20. The relationship between measured Secchi disk transparency (cm) total suspended solids (mg L^{-1}) in samples taken by California Department of Water Resources between 1983 and 1985 at Point Pinole (Stations D41).

122. Turbidity, whether measured as TSS or in nephelometric units, shows wide variation throughout the Estuary, and Central Bay is no exception. From samples taken in 1980, USGS (1989a) showed a strong relationship between turbidity and TSS (r^2=0.91; Figure 21); however, turbidity in Central Bay varied between approximately 2 and 118 NTU. TSS ranged from 2 mg L^{-1} to more than 105 mg L^{-1} (Figure 21). The majority of turbidity and TSS measurements from Central Bay in 1980 were between 1 and 20 NTU, and 1 and 20 mg L^{-1} TSS.

123. This variation is reflected in other data. Surface-to-bottom composite samples analyzed for TSS by Hauck *et al.* (1990) showed concentrations in Central Bay of from 10 to 26 mg L^{-1}. Time- and depth-averaged TSS concentrations in Central Bay were between 31.9 and 32.8 mg L^{-1}. All these values are well within the range of values measured by USGS from Central Bay in 1980. Perhaps more significant in the data of Hauck *et al.* (1990), was that the standard deviation of TSS concentration at stations in Central San Francisco Bay was equal to or greater than one-half the mean in most cases. This demonstrates the high degree of variability in the parameter, even within the sub-embayment of the Central Bay. All other data on ambient turbidity or TSS from Central Bay show the same pattern of wide variability (see Section III).

124. The available data are insufficient to determine if a gradual decrease in water clarity (or a corresponding increase in turbidity or TSS concentration) has occurred in Central Bay between 1985 and 1990. During this time there has occurred a wide range of disposal activity at the Alcatraz dumpsite, as well as the institution of requirements for disposing of dredged material in slurried form (to reduce mounding at Alcatraz) and a seasonal limit on the amount of dredged material permitted for disposal on a daily basis (SFBRWQCB, 1988). With the exception of monthly DFG Secchi disk depth measurements, there has been no long-term monitoring program in place at any point in Central Bay that would make possible an evaluation of turbidity, suspended solids and dredged material disposal activity at Alcatraz. All the data show wide variability, within and between days, within and between depths, among stations, and among years. If managers and regulators determine that it is necessary to determine whether Central Bay turbidities are increasing, we recommend institution of a monitoring program that includes depth-specific water sampling for turbidity and TSS concentrations throughout the Central Bay. The program should be structured to take into account the direction of tidal flow, and should be stratified in time to be responsive to changes in freshwater outflow from the Delta. Turbidity (NTU), TSS (gravimetric) and Secchi disk depth measurements should be taken at every station so that historical data may be incorporated into future analyses.

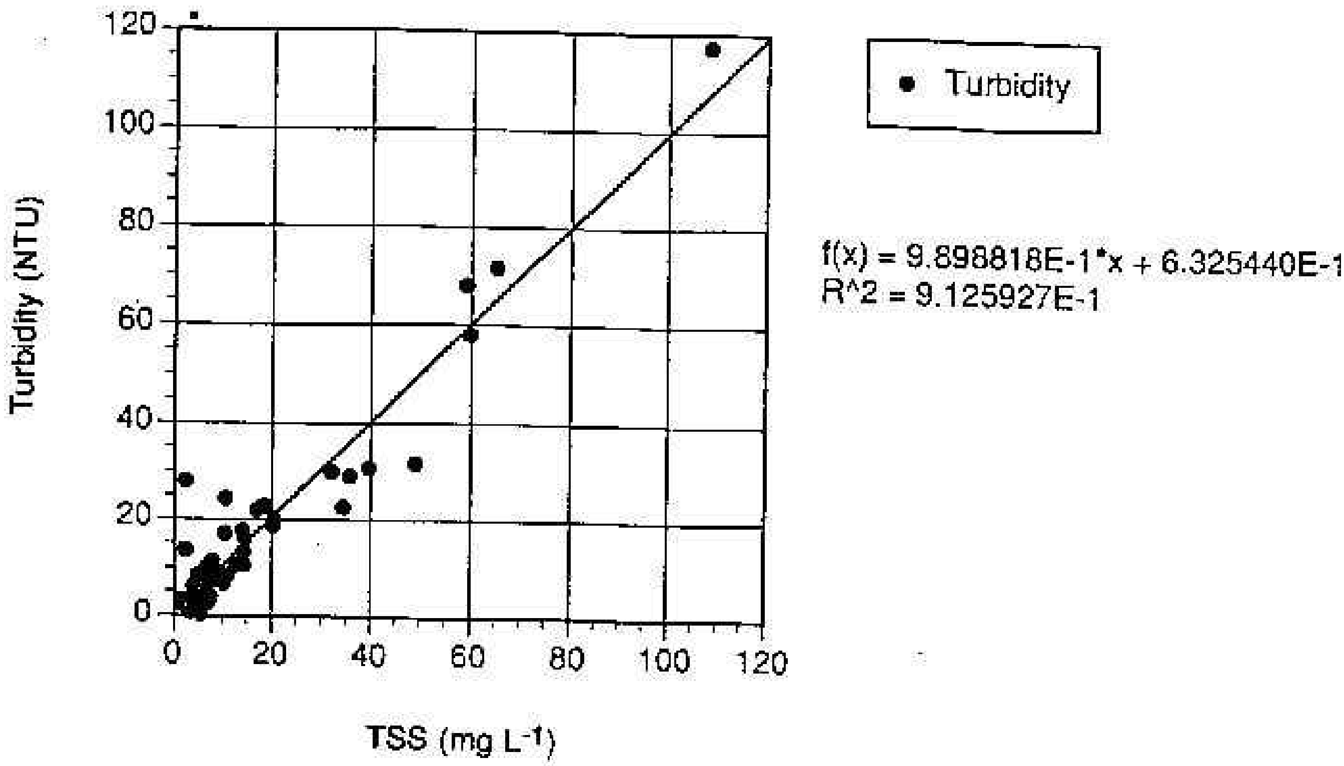


Figure 21. The relationship between measured turbidity (NTU on the vertical axis) and total suspended solids (mg L^{-1} on the horizontal axis) for stations occupied in Central Bay in 1980. Data from USGS (1989a).

2. Increased Disposal-Related Turbidity in Central Bay

125. The hypothesis must be stated that dredged material disposal at the Alcatraz site causes an increase in turbidity and/or TSS concentrations in Central Bay. As noted previously, disposal of dredged material may increase turbidity in several ways. First, finely divided material may escape during the period of convective descent, as the bolus of dredged material descends through the water column. Second, finely divided material may become suspended when the bolus of disposed material impacts the bottom. Third, unconsolidated disposed dredged material on the bottom may be subject to resuspension due to the action of wind- and tidally-driven currents.

126. Fine material that "escapes" during the dumping process causes a local increase in the turbidity of surface waters (Tavolaro, 1984;SAIC, 1977; MEC, 1990a). Typically, such turbidity disappears rapidly by virtue of settling and mixing. The time period for disappearance of turbidity from surface water after a disposal event is on the order of minutes. MEC (1990a) measured a plume established in water approximately 6 m deep extending away from disposal operations at Alcatraz. The MEC (1990a) data showed that the TSS concentration in the "mid-water" plume reached concentrations of 2 to 5 times ambient, and dispersed within some 20 minutes. These observations are similar to those of SAIC (1987), who monitored plume progress using acoustic backscattering. They noted that turbidity plumes from dredged material disposed at Alcatraz decreased to ambient within 20 to 25 minutes after disposal.

127. Gunther *et al.* (1990) evaluated the SAIC (1987) data to determine the potential for frequent dredged material disposal events to cause an increase in TSS concentrations in Central Bay. Their analysis was based upon a simple model of plume settling and the frequency of disposal events at the Alcatraz site. Their conclusion was that at very high frequencies (e.g., more than 20 disposal events per day) it would be possible for sufficient material to remain in suspension in the water column to cause an increase in turbidity in some portion of the Central Bay. The analysis by Gunther *et al.* (1990) did not account for bi-directional tides in Central Bay, contributions of turbid waters from San Pablo Bay and South Bay, upwellings of turbid bottom water, or other factors.

128. Whether disposal at the Alcatraz site caused local increases in turbidity due to impact with the bottom cannot be determined from the very few data available. The only data which address this point directly are those of MEC (1990a), in which measurements of TSS were made at multiple depths at several locations in the water column down-current from disposal operations on three dates in May, 1990. The sampling protocol was such that the plume from the disposal event was followed as it moved away from the point of discharge. The MEC (1990a) data show no particular pattern of

TSS concentration showing that impact of the disposed material with the bottom was causing large, and long-term increases in TSS at depth. For example, the plume tracking on 1 May, 1990 showed that TSS were greater in bottom waters (16 m) than in surface waters (3 m) at all stations. The differences reported ranged from 40 mg L-1 in bottom waters to 5 mg L-1 (or less) in surface waters (MEC, 1990a). On different sampling dates, however, the distribution of TSS after dumping was different. For example, on 5, 9 and 10 May, 1991, TSS in bottom waters was occasionally less than that in surface waters. While it is possible that some of the samples were taken outside, or on the fringe of the disposal plume, every precaution was taken to assure that samples were taken in the disposal plume, and the data suggest that there was no significant, long-term increase in the turbidity of bottom waters associated with dredged material disposal at the Alcatraz site (see, e.g., the data of Hauck *et al.*, 1990).

129. Some increase in the turbidity of Central Bay waters is certainly due to the resuspension and transport of disposed dredged material; the disposal site at Alcatraz, (and in the Carquinez Strait) is a dispersive site. Disposal of dredged material at the Alcatraz site was, historically, intended as an intermediate step in the removal of sediment from the San Francisco Estuary.

130. Whether turbidity plumes from disposal operations disperse rapidly may not be an important point in estimating whether dredged material disposal at Alcatraz could result in an overall increase in Central Bay turbidity. More important is the question of whether the amount of material disposed at the site is a resuspendable source of fine-grained material that can be scoured from the bottom, resuspended, and circulated throughout the Central Bay. The Alcatraz site was chosen and designated precisely because it is a dispersive site. In theory, material disposed at the site would be scoured by currents at the bottom of the Bay and transported offshore, out of the Bay system. The results of seabed and water column drifter studies show that the circulation patterns in Central Bay may be much more complex than that. In fact, net movement of bottom water - and associated particulate matter - is probably landward (Conomos *et al.*, 1970).

131. Although some mounding occurs at the Alcatraz disposal site, much of the material disposed there is scoured, resuspended, and transported elsewhere. Some fraction of that material remains in the Estuary, probably in Central Bay. The key question in evaluating whether disposal at Alcatraz causes increased turbidity in Central Bay is whether the material scoured from the disposal site remains in suspension for long periods of time, or whether it settles relatively rapidly to the floor of the Estuary. We recommend that sampling and monitoring studies of sediment transport in the lower water column be carried out to determine the direction and magnitude of sediment transport in the deeper waters of the Bay. It may be practical to conduct a tagged sediment monitoring study wherein easily detectable labels (in this case bacteriophage) are incorporated into the

sediment and then tracked throughout the Central Bay. Such data would be valuable input to the construction of mathematical models of water movement, sediment transport, and turbidity distributions in the Central Bay.

3. Direct Impacts of Increased Turbidity on Central Bay Biota

132. Assuming that turbidity in Central Bay waters has increased, we must evaluate the hypothesis that an increase in turbidity of the magnitude suggested may have a direct, negative impact on the biota in the system. Direct, negative impacts may be expressed in one or more of several ways. In order of decreasing severity these are:

- Mortality (imposition of direct, acute lethality);
- Imposition of physiological stress; and
- Environmental disturbance leading to avoidance.

Mortality

133. The literature on the subject of direct, lethal effects of suspended solids and turbidity on estuarine organisms, including numerous species endemic to the San Francisco Estuary, is extensive. As summarized by Hirsch *et al.* (1978), most organisms are very resistant to the effects of sediment suspensions in the water. Lethal effects of sediment suspensions on estuarine invertebrates and fishes due to turbidity from dredging or dredged material disposal in estuarine systems is not of major ecological concern. Of the many species tested for direct, lethal effects only Atlantic silverside (*Menidia menidia*) was classified as being highly sensitive to suspended solids at concentrations that would exist in the vicinity of dredged material disposal operations (LC_{10} < 100 mg L^{-1}; O'Connor *et al.*, 1976). The topsmelt (*Atherinops affinis*), common to surface waters on the shores of Central Bay might provide an appropriate sensitive species for bioassay studies. Even at the highest disposal frequencies observed (up to 41 per day; Gunther *et al.*, 1990) calculated increases in turbidity in that part of the Central Bay immediately around the Alcatraz site would be on the order of 7 mg L^{-1}. An increase in ambient TSS concentrations from 20 or 30 mg L^{-1} to 27 or 37 mg L^{-1} would be most unlikely to cause mortality in any fish or invertebrate populations in Central Bay.

134. After review of the literature, it is our conclusion that direct, lethal effects of suspended solids on fishes and invertebrates in the San Francisco Estuary will not occur under circumstances where TSS values average between 10 and 100 mg L^{-1} of natural particulate materials in suspension. Ambient TSS concentrations in Central Bay are highly variable, and, from the limited data available, range from about 10 to 50 mg L-1. TSS concentrations due to dredged material disposal are greater (30 to 100 mg L-1), but decrease rapidly to ambient levels due to settling and mixing in Bay waters. The reader is referred to the research results of Rogers (1971),

Sherk *et al.* (1976, 1977), O'Connor *et al.* (1976, 1977) and Peddicord *et al.* (1978) and Peddicord and McFarland (1978) reviewed in this report.

Imposition of Physiological Stress

135. Suspended solids alone, or in combination with elevated temperatures and low dissolved oxygen concentration have the potential to impact respiration of fishes and invertebrates. The mechanism of impact of suspended solids on respiration would appear to be clogging or coating of the gills, rather than physical damage to respiratory epithelia (O'Connor *et al.*, 1977; Neumann *et al.*, 1982). However, the conditions under which respiratory impairment occurs include TSS concentrations substantially greater than the concentrations observed in Central Bay (including those in the vicinity of dredged material disposal operations), and exposures of much greater duration than those which might occur in Central Bay. Even in those cases in which respiratory responses to suspended particulate matter have been shown to be significant, researchers have concluded that the responses observed (e.g., depression of oxygen consumption in striped bass) are apparently the first stage in a multi-stage response whereby organisms can eventually compensate for reduced oxygen exchange across the gill surface.

136. The possibility exists that the oxidation of sulfiderous disposed sediments may cause a decrease in dissolved oxygen in the water column. Studies to determine the extent and duration of such phenomena have been limited. MEC (1990a) measured sulfide concentrations in disposed dredged material plumes and recorded no significant increases. Studies of dissolved oxygen in plumes from material disposed in San Francisco Bay showed no significant or enduring declines (MEC, 1990a).

Environmental Disturbance Leading to Avoidance

137. Ecological studies have demonstrated many instances in which freshwater, marine, and estuarine fishes will avoid regions of excessively high turbidity, or will alter their distribution to conform to some preferred or tolerated range of suspended particulate matter. Among the more sensitive species the response to suspended solids might be characterized as a "fright" response. Less sensitive species will gradually alter position until they are in waters of preferred TSS concentrations. A plot of the data showing total striped bass catch in Central Bay (Block 488) compared to mean Secchi disk depths from DFG shows no apparent relationship between water transparency and catch (Figure 22). Some of the lowest catches (1980 to 1982) occurred during years when mean Secchi disk depth was very high; in 1983, when mean transparency was less than 100 cm, total catch was 5000 fish. None of the available data include studies with other species of concern in the San Francisco Bay ecosystem.

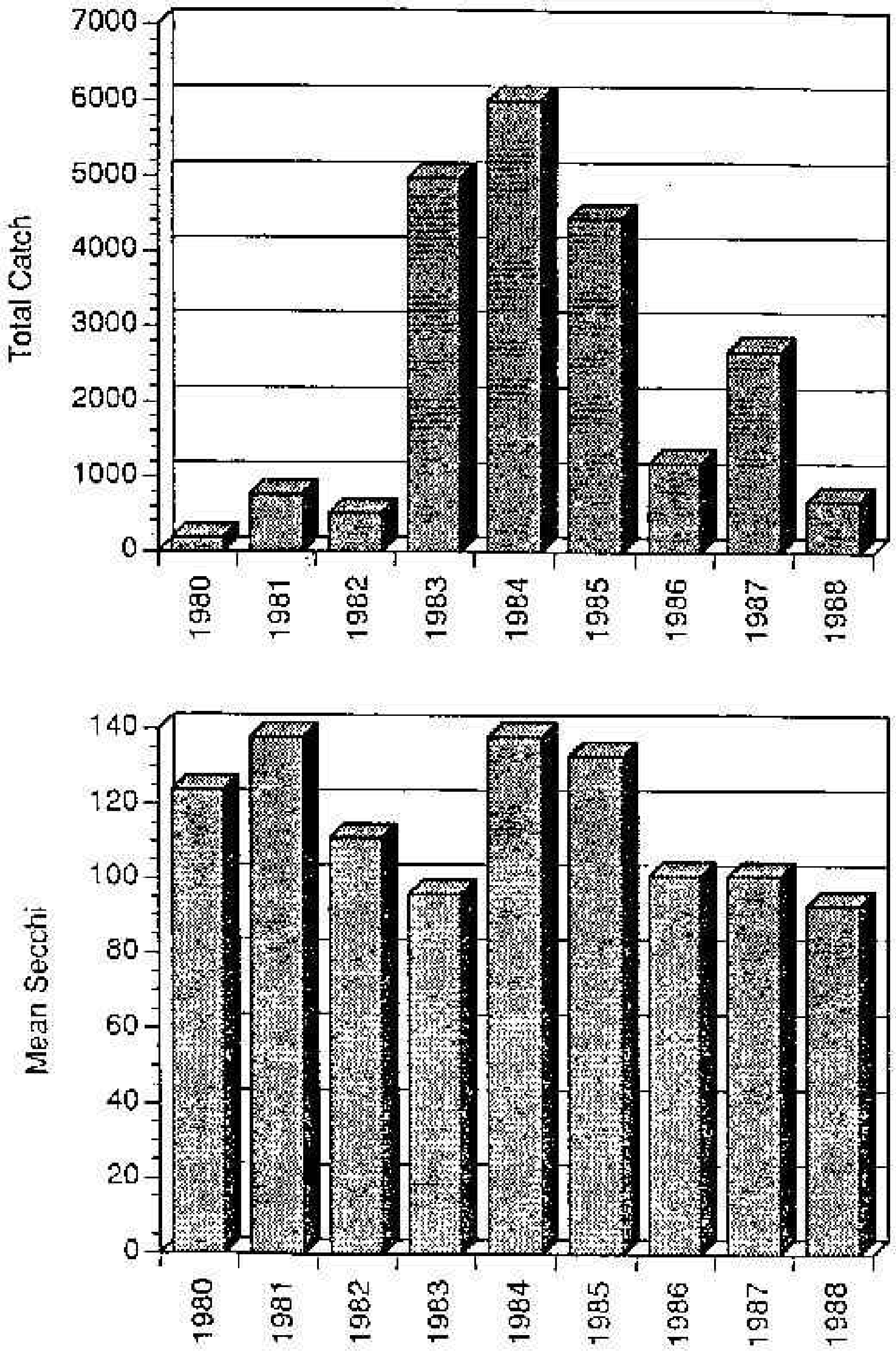


Figure 22. Plot of annual total catch of striped bass in Central Bay (top) and annual average Secchi disk transparency measurements (cm) made by DFG.

138. Studies recently performed in Central Bay have documented the movement of fish schools in Central Bay, and the local responses of fish schools to dredged material disposal events (MEC, 1990a). These studies included hydroacoustic monitoring of fish school movements at and near the Alcatraz disposal site, as well as sampling to identify the species in the schools, TSS concentrations in the water column at various depths, and chemical constituents in the water column (e.g., total sulfides, dissolved oxygen, etc.; MEC, 1990a). Species represented in "ground truth" samples included northern anchovy (*Engraulis mordax*), white croaker (*Genyonemus lineatus*) and shiner perch (*Cymatogaster aggregata*), all species that serve as forage for striped bass (Curtis, 1949; Skinner, 1962). Preliminary analysis of the data shows that fish schools active at the Alcatraz site either dispersed or moved away in response to a disposal event. However, continued monitoring showed that the fish schools returned to the site within an hour or two after the disposal event. It is impossible to tell from the available data whether the fish schools responded to suspended material in the water, or whether the response was to pressure waves produced as dredged material was dumped. MEC (1990a) suggested that the response of fish schools to disposal events was a response to physical factors (noise, pressure waves) rather than to suspended solids. This conclusion was based upon the immediacy of the response, which made it likely that the fish were responding to a rapidly transmitted physical event (e.g., noise, or a pressure wave), rather than detecting, or being exposed to, any suspended material from the barge.

139. The dispersal of fish schools in response to disposal events at Alcatraz, and their subsequent return, is a descriptive phenomenon that cannot be used to test the hypothesis under consideration. It is not known, for example, how far the fish schools moved after a disposal event; the distance of movement can only be characterized as "...outside the range of detection of the hydroacoustic gear." An evaluation of fish school dispersal and fishing success in Central Bay would require analysis of fish movements throughout Central Bay. The fact that fish returned to the Alcatraz site within one or two hours suggest that dispersal outside Central Bay had not occurred.

140. These few data are not conclusive evidence that forage fish are unaffected by dredged material disposal at Alcatraz, or that the potential for increased turbidity due to disposal might result in their movement to other portions of the Estuary. However, they are the first data showing that single disposal events cause a rapid, evasive response, followed by a return to the site a short time later. It is possible that numerous disposal events could result in fish schools remaining at some distance from the Alcatraz site; Gunther *et al.* (1990) reported disposal frequencies in excess of 20 events per day in 1986 and 1987. The question of the cumulative effect of such disposal frequencies on fish distribution in Central Bay has not been addressed. We recommend that additional studies be undertaken to determine the distribution and abundance of fishes in Central Bay. Sampling should be

designed such that fish distribution can be evaluated in relation to the natural changes in Central Bay turbidity that occur on an interannual, annual and tide-related basis, as well as that due to dredged material disposal. Such studies might well be feasible using hydroacoustic techniques and limited trawl sampling for ground truth information.

Effects on Sensitive Life History Stages

141. Juveniles of fishes and invertebrates, including egg and larval stages, are considered to be more sensitive to environmental perturbation than are adults. The studies of Davis (1960) and Davis and Hidu (1969) showed that eggs of oysters and clams tolerated TSS concentrations up to 188 mg L^{-1} of natural silt, and larvae developed at silt concentrations as high as 4,000 mg L^{-1}. Eggs and larvae are of fishes are generally capable of withstanding exposure to TSS concentrations of in excess of 200 mg L^{-1} before effects are apparent. Even then, as shown by Morgan *et al.* (1973), the severity of effects is debatable; white perch exposed to high TSS concentrations showed a one-day delay in hatching. Eggs of the species tested by Schubel and Wang (1973) showed similar, if not less severe, responses.

142. Larval stages of striped bass also showed tolerance to high concentrations of TSS. Breitburg's (1988) data demonstrated that larval striped bass could capture prey (copepods and cladocerans) at TSS concentrations between 75 and 500 mg L^{-1}. At higher TSS concentrations the efficiency of copepod capture was reduced; however, young striped bass were not only able to survive well in TSS of 500 mg L^{-1}, but were able to capture *Daphnia* with as much facility as at 0 mg L^{-1}.

143. While it is true that eggs and larvae of estuarine biota are more sensitive to suspended solids, the sensitivity measured in experimental studies shows that the concentrations at which eggs and larvae of fish and bivalves begin to suffer ill effects are above those expected to occur for any extended period of time in Central Bay.

4. Indirect Impacts of Turbidity on the Biota

144. The indirect impacts of turbidity on biota may include reduction of light leading to decreased feeding efficiency and selection of specific habitats based upon ambient turbidity.

Reduction of Light and Decreased Feeding Efficiency

145. Many studies of the feeding efficiency of fishes have concluded that increased turbidity can lead to reduction in visual prey detection and reduced foraging success. The relationship of turbidity to light penetration in Central Bay waters and associated "catchability" of striped bass and other species cannot be assessed directly from the available data.

However, by using data from other portions of the Estuary it is possible to evaluate the possibility that reduced light penetration might result in reduced catch of striped bass or other sport fishes.

146. The historical record for the striped bass fishery in the San Francisco Estuary shows that between 1938 and 1956 the majority of striped bass were taken upstream; i.e., in San Pablo Bay, Carquinez Strait, Suisun Bay, and in Carquinez Strait. It was only upon introduction of deep trolling that the Central Bay fishery became dominant. If light penetration and visual identification of prey (or bait) is a major factor in striped bass catchability, then it should also be true that striped bass catchability in the more turbid upstream waters should be low. The historical data suggest that this is not the case; while catch has varied from year-to-year, striped bass catchability in the turbid portion of the Estuary has been good historically. It is only with the recent decline in striped bass numbers that fishing (catchability) has declined.

147. It is unlikely that increases in turbidity, if they have occurred, would have any impact on the ability of striped bass to detect prey (or bait) visually. Most of the striped bass caught in the Estuary are taken from bottom waters (especially in the Central Bay deep-trolling fishery). Turbid estuaries such as the San Francisco Bay-Delta system typically show a very high degree of light attenuation, as is obvious from the low Secchi disk readings that occur throughout the Estuary. Light transmission at depth (i.e., below approximately 3 m) in the Estuary is essentially zero. Therefore, it can be concluded that most of the striped bass taken in the Estuary are taken in waters where light transmission is essentially zero. Thus, the ability of striped bass to detect and strike prey may be assumed to be under the control of senses other than sight; e.g., olfactory, pressure, etc. A change in surface water turbidity would be unlikely to have any impact on the ability of striped bass to detect and take prey or bait in the absence of light in deep waters.

148. Whether the major striped bass forage species respond to reduced light in their environment cannot be determined. However, species such as anchovies and Pacific herring are filter-feeders, feeding upon zooplankton in the water column. Filter feeding strategy among estuarine fishes is such that vision is not a major factor in obtaining prey, and zooplankton have been shown to be unaffected by low-level changes in turbidity (Sherk *et al.*, 1976). Thus, it is unlikely that slight increases in turbidity in the Estuary would lead to decreases in striped bass forage species, or in the zooplankton populations that support the forage species.

V. Conclusions and Recommendations

149. The evidence available to evaluate whether turbidity has increased in Central San Francisco Bay is equivocal. On the one hand, the DFG Secchi disk data demonstrate an apparent reduction in transparency after 1985. Transparencies during some months were as low as 50 cm. The apparent change in water transparency from previous years was most noticeable in the late summer and fall months; the historical data showed that transparency typically increased during the latter part of the year. In years previous to 1986, Secchi disk depths often approaching 150 to 200 cm were measured during the fall months. In 1986 and thereafter DFG measured Secchi disk depths that were apparently much lower. On the other hand, other investigators measured turbidity and TSS in Central San Francisco Bay in 1987, 1988, 1989 and 1990 that showed that turbidity in the Central Bay was highly variable, and no greater than at any time during the 1970's and the 1980's.

150. DFG Secchi disk depths were measured once per month, and there are few other Secchi disk data with which to compare them. It is difficult to determine the representativeness of once-monthly Secchi disk depth measurements. Total suspended solids in Central San Francisco Bay were shown to be highly variable; standard deviations of measurements made at a single station were, typically, equal to more than 50% of the mean. This suggests that any study of transparency or turbidity in Central Bay would require large numerous replicate measurements in order to discriminate any changes that might occur.

151. Secchi disk depth data did not correlate well with quantitative estimates of light scattering in water. This is because Secchi disk depth measurements are not a measure of turbidity. Even as a measure of transparency, Secchi disk readings suffer from the effect of dissolved materials in the water, the skill of the observer, surface conditions (wind, waves, etc.), time of day, and other factors. Any conclusions regarding increases in turbidity in Central San Francisco Bay should be based upon TSS data or quantitative turbidity measurements, rather than Secchi disk readings.

152. The MEC (1990) data from May and June of 1990 show Secchi disk depths of 120 to 150 cm, values very similar to those observed by DFG prior to 1986. In support of the MEC (1990) observations are data from 1987, 1988 and 1989 on TSS concentrations and turbidity, throughout the Central Bay, and at the Alcatraz site in particular. These data show that TSS and turbidity in the Central Bay were variable from 1987 through 1990, but similar to data collected prior to 1986.

153. The data for the entire Estuary show that TSS, turbidity, and Secchi disk depths vary from year-to-year, season-to-season, day-to-day, tide-to-tide, and among depths at a single sampling point. Therefore, any attempt to

determine changes of turbidity in the Estuary must be based upon a thorough and detailed monitoring program with sufficient samples to accommodate the variability that is expected in the data, and identify real changes that have occurred.

154. The range of TSS concentrations in the Estuary may be from about 2 mg L^{-1} to 1000 mg L^{-1} under natural conditions, and up to 20,000 mg L^{-1} directly adjacent to dredging operations (at the Carquinez disposal site). High TSS concentrations from dredging and dredged material disposal have been shown in field studies to dissipate or become diluted rapidly under the influence of turbulent mixing due to freshwater inflow, tides, and winds. Under conditions of frequent dredged material disposal at Alcatraz, it is possible that sufficient residual solids may remain in suspension to cause a measurable increase of turbidity. The data to evaluate this hypothesis are not available; a long-term monitoring program keyed to disposal at the Alcatraz site is needed in order to make such a determination.

155. TSS concentrations in Central Bay may vary from less than 10 mg L^{-1} to about 100 mg L^{-1} due to natural influences and the local, transitory effects of dredged material disposal. The higher TSS concentrations that occur during dredged material disposal have been shown to dissipate within 20 to 25 minutes. The lowest TSS concentration recorded to have any impact, even on sensitive life history stages of aquatic biota was about 100 mg L^{-1}, for periods of time lasting from 10 hr to more than 24 hr. Such conditions have never been observed in Central Bay. The potential for impact on sensitive biota in the Central Bay is very small; however, considering the variability seen in TSS and turbidity data, we suggest strongly that monitoring programs be instituted to ascertain the range of TSS concentrations at all depths at a variety of stations in Central Bay.

156. The possibility that increased turbidity in Central Bay, if it were occurring, would affect sport fish "catchability" is considered to be very small. The turbidities measured in Central Bay are typical of, or lower than, turbidities in striped bass habitat throughout the rest of the Estuary, and throughout the range of the species.

157. It is possible that sport fish are less abundant in Central Bay due to some effect of increased turbidity. Thus, if striped bass prey were sensitive to and avoided areas of high turbidity, it is possible that the bass would choose to occupy portions of the Estuary in which food was available, and not Central Bay. There are few data that can be used to evaluate this hypothesis. The MEC data (1990a) on disposal events, TSS concentrations, and fish school behavior suggests that prey avoidance may not play a role in reduced catches of striped bass. These data suggest that forage fish in Central Bay respond to dredged material dumping rapidly, and briefly, returning to disposal locations in an hour or two. The question remains, therefore, what happens during periods of intensive use

of the dumpsite, when 20 to 30 disposal events may occur each day? It would be very useful to expand the existing data set in order to gather additional information on dredged material disposal, turbidity, and fish school behavior, particularly during periods of frequent disposal.

158. It is possible that the reduced catchability of sport fish in Central Bay could be related to a decrease in the amount of available light, which could make prey (and bait) location more difficult. However, this is unlikely. Striped bass fishing in Central Bay uses deep trolling as a primary capture method. This technique places bait at a depth where light penetration, even in the least turbid water, ranges from very low to zero. It is unlikely, therefore, that slight increases in turbidity in Central Bay, if they were occurring, would have any impact on the ability of striped bass to detect and capture prey, or their ability to detect and strike bait.

159. Striped bass populations in the San Francisco Estuary have been in decline for many years. Possible reasons for this decline have been stated as water diversion from the Sacramento-San Joaquin Delta, toxicity in the San Francisco Bay-Delta system that affects both juvenile and adult striped bass, and the accumulation by striped bass of pollutants introduced from domestic and industrial sources. One effect of the striped bass decline has been reduced catch to sport fishermen in all portions of the Estuary. It is our conclusion, based upon evaluation of the available data, that the reduction in striped bass catch in Central Bay is reflective of the overall decline in striped bass stocks in the Estuary, and is not related to turbidity, water transparency, or suspended particulate matter in Central Bay waters.

160. All these conclusions rest upon a severely limited data base. If the question of dredged material disposal, turbidity and catchability of fish is to be addressed, then it will be necessary to bolster our current knowledge. The major requirements of any future monitoring at the Alcatraz site, or in Central San Francisco Bay, would be making sufficient measurements so that a statistical evaluation of turbidity as it relates to dredged material disposal could be performed ; i.e., additional measurements of Secchi disk depths and TSS concentrations, additional sampling of striped bass, other sport fish, and forage fish in the area, and additional detailed information gathered from partyboat fishermen.

References

Ambler, J.W., J.E. Cloern, and A. Hutchinson. 1985. Seasonal cycles of zooplankton from San Francisco Bay. In: J. Cloern and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay*. Hydrobiologia 129: 177-198.

APHA (American Public Health Association). 1976. Turbidity. *Standard Methods for the Examination of Water and Wastewater*. 14th ed. Amer. Pub. Health Assn., Washington, D.C. pp.131-139.

Armor, C. and P. Herrgesell. 1985. Distribution and abundance of fishes in the San Francisco Bay estuary between 1980 and 1982. In: Cloern, J., and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay*. Hydrobiologia 129: 211-228.

Arthur, J.F. and M. Ball. 1978. *Entrapment of suspended material in the San Francisco Bay-Delta Estuary*. U.S. Dept. of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento CA. 106 pp.

Arthur, J.F. and M. Ball. 1979. Factors influencing the entrapment of suspended material in the San Francisco Bay-Delta Estuary. In: Conomos, T.J. (Ed.) *San Francisco Bay: The Urbanized Estuary*. Pacific Div. AAAS, San Francisco. pp. 143-174.

Atwater, B.F. 1979. Ancient processes at the site of southern San Francisco Bay: movement of the crust and changes in sea level. In: *San Francisco Bay, the Urbanized Estuary*. T.J. Conomos (Ed.). American Association for the Advancement of Science, San Francisco, California. pp. 31-45

Austin, R.W. *et al. (sic)*. 1974. *Conclusions and recommendations*. In NOAA/NOIC Turbidity Workshop, May 1974. U.S. Dept. of Commerce, NOAA, National Oceanographic Instrumentation Center. 216 pp.

Barnard, W.D. 1978. *Prediction and Control of Dredged Material Dispersion Around Dredging and Open-Water Pipeline Disposal Operations*. Technical Report DS-78-13. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Bartsch, A.F. 1960. Settleable solids, turbidity, and light penetration as factors affecting water quality. Pp. 118-127 in C. Tarzwell (ed.), *Biological Problems in Water Pollution*. U.S. Public Health Service Pub. No. W60-3.

Baylor, E. and W. Sutcliffe. 1963. Dissolved organic matter in seawater as a source of particulate food. *Limnol. Oceanogr.* 8: 369-371.

Boesch, D. 1982. Ecosystem consequences of alterations of benthic community structure and function in the New York Bight region. In: G.F. Mayer (ed.) *Ecological Stress and the New York Bight*. Estuarine Res. Fed. Charleston, S.C. pp. 543-568..

Boehlert, G.W. and J.B. Morgan. 1985. Turbidity enhances feeding abilities of larval Pacific herring, *Clupea harengus pallasi*. *Hydrobiologia* 123: 161-170.

Breitburg, D.L. 1988. Effects of turbidity on prey consumption by striped bass larvae. *Trans. Amer. Fish. Soc.* 117: 72-77.

Brown, R. 1987. *Toxics and Young Striped Bass*. California Department of Fish and Game. A working paper for the Interagency Ecological Studies Program's Striped Bass Report (DFG 25). 35 pp.

Brown, R. 1989. Interagency Ecological Study Newsletter. September, 1989. p.5.

Cairns, J., Jr. 1968. Suspended solids standards for the protection of aquatic organisms. 22nd Purdue Indust. Waste Conference. *Purdue University Eng. Bull.* 129: 271-274.

Carlton, J.T. 1979. Introduced invertebrates of San Francisco Bay. In: Conomos, T.J. (ed.) *San Francisco Bay, the Urbanized Estuary*. American Association for the Advancement of Science, San Francisco, California. pp. 427-444.

Carlton, J., J. Thompson, L. Schemel and F. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the asian clam *Potamocorbula amurensis*. I. Introduction and dispersal. *Marine Ecol. Progr. Series*. 66:81-94.

Chadwick, H.K. 1962. Catch records from the striped bass sportfishery in California. *Calif. Fish and Game* 48: 153-177.

Cloern, J.E. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. *Continental Shelf Research* 7: 1367-1381.

Conomos, T.J. 1979. Properties and circulation of San Francisco Bay waters. In: *San Francisco Bay: The Urbanized Estuary*. T.J. Conomos (Ed.). American Association for the Advancement of Science, San Francisco, California. pp. 47-84.

Conomos, T.J. and D.H. Peterson. 1977. Suspended particle transport and circulation in San Francisco Bay: An overview. In: M. Wiley (ed.) *Estuarine Processes. Vol. 2.* Academic Press, New York. pp. 82-97.

Conomos T.J., D.H. Peterson, P.R. Carlson and D.S. McCulloch. 1970. Movement of seabed drifters in the San Francisco Bay estuary and the adjacent Pacific Ocean: a preliminary report. *U.S. Geological Survey Circular 637B*. 8 pp.

Conomos, T.J., R. Smith and J. Gartner.1985. Environmental setting of San Francisco Bay. In: J. Cloern and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay*. Hydrobiologia 129: 1-12.

Crowl, T.A. 1989. Effects of crayfish size, orientation, and movement on the reactive distance of largemouth bass foraging in clear and turbid water. *Hydrobiologia* 183: 133-140.

Curtis, B. 1949. The warm-water game fishes of California. *Calif. Fish and Game* 35: 255-279.

Cyrus, D.P., and S.J.M. Blaber. 1987a. The influence of turbidity on juvenile marine fishes in estuaries. Part 1. Field studies at Lake St. Lucia on the southeastern coast of Africa. *J. Exp. Mar. Biol. Ecol.* 109: 53-70.

Cyrus, D.P., and S.J.M. Blaber. 1987b. The influence of turbidity on juvenile marine fishes in estuaries. Part 2. Laboratory studies, comparisons with field data and conclusions. *J. Exp. Mar. Biol. Ecol.* 109: 71-91.

Davis, C.O. 1982. The San Francisco Bay ecosystem: A retrospective overview. In: Kockelman, W.J., T.J. Conomos and A.E. Leviton (Eds.). *San Francisco Bay Use and Protection*. San Francisco, AAAS, Pacific Division. pp. 17-38.

Davis, H.C. 1960. Effects of turbidity producing materials in sea water on eggs and larvae of the clam *Venus (Mercenaria) mercenaria*. *Biol. Bull.* 118: 48-54.

Davis, H.C. and H. Hidu. 1969. Effects of turbidity-producing substances in sea water on eggs and larvae of three genera of bivalve molluscs. *The Veliger* 11: 316-323.

Davis, J.A., A.J. Gunther, J.M. O'Connor, B.J. Richardson, R.B. Spies, E. Wyatt, E. Larson, and E.C. Meiorin. 1990. *Status and Trends Report on Pollutants in the San Francisco Estuary*. San Francisco Estuary Project, U.S. Environmental Protection Agency, Oakland, CA.

DFG (California Department of Fish and Game). 1987. *Exhibit 60: Delta Outflow Effects on the Abundance and Distribution of San Francisco Bay Fish and Invertebrates, 1980-1985*. Report for the State Water Resources

Control Board 1987 Water Quality/ Water Rights Proceeding on the San Francisco Bay/Sacramento-San Joaquin Delta. 345 pp.

DFG (California Department of Fish and Game). 1989. *Striped Bass Restoration and Management Plan for the Sacramento-San Joaquin Estuary. Phase I*. State of California, Department of Fish and Game, Sacramento, CA. 39 pp.

Diehl, S. 1988. Foraging efficiency of three freshwater fishes: effects of structural complexity and light. *Oikos* 53: 207-214.

Doan, K.H. 1941. A relationship between increased turbidities and heavier sauger catches in Lake Erie. *Ohio J. Sci.* 41: 440-452.

Doan, K.H. 1942. Some meteorological and limnological conditions as factors in the abundance of certain fishes in Lake Erie. *Ecol. Monogr.* 12: 293-314.

Dovel, W.L. 1968. *Fish eggs and larvae*. Project E. Ref. No. 69-122. 12 pp.

Duchrow, R. , and M. Everhart. 1971. Turbidity Measurement. *Trans. Amer. Fish. Soc.* 100: 682-690.

DWR (California Department of Water Resources). 1984. *Sacramento-San Joaquin Delta Water Surveillance Program, 1983 Monitoring Results Pursuant to Delta Water Rights Decision 1485* , Volume 1. 203 pp.

DWR (California Department of Water Resources). 1985. *Sacramento-San Joaquin Delta Water Surveillance Program, 1984 Monitoring Results Pursuant to Delta Water Rights Decision 1485*, Volume 1 126 pp.

DWR (California Department of Water Resources). 1986. *Sacramento -San Joaquin Delta Water Surveillance Program, 1985 Monitoring Results Pursuant to Delta Water Rights Decision 1485*, Volume 1. 138 pp.

EIFAC. 1964. *Water quality criteria for European freshwater fish.* Technical Paper No. 1. European Inland Fisheries Advisory Commission, Working Party on Water Quality Criteria for European Freshwater Fish, Rome, Italy.

Ellis, M.M. 1936. Erosion silt as a factor in aquatic environments. *Ecology* 17: 29-42.

Gilbert, G.K. 1917. *Hydraulic mining debris in the Sierra Nevada*. U.S. Geological Survey Professional Paper 105. 148pp.

Gordon, R.B. 1974. Dispersion of dredge spoil dumped in near-shore waters. *Estuarine and Coastal Marine Science* 2: 349-358.

Gunther, A.J., J.A. Davis and D.J.H. Phillips. 1987. *An Assessment of the Loading of Toxic Contaminants to the San Francisco-Bay Delta.* Aquatic Habitat Institute, Richmond, California. 330 pp.

Gunther, A., J. Davis, J. O'Connor, D. Phillips, K. Kramer, B. Richardson, and P. Williams. 1990. *Status and Trends Report on Dredging and Waterway Modification in the San Francisco Estuary.* Report to the San Francisco Estuary Project, Oakland, CA. 250 pp.

Hatfield, S. 1985. Seasonal and interannual variation in distribution and population abundance of *Crangon franciscorum* in San Francisco Bay. In: Cloern, J. and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay.* Hydrobiologia 129:199-210.

Hauck, L., A. Teeter, W. Pankow and R. Evans, Jr. 1990. *San Francisco Bay Suspended sediment movement report No. 1. Summer condition data collection program and numerical model verification.* Technical Report HL-90-6. 85 pp. USACE Waterways Experiment Station, Vicksburg, MS.

Heimstra, N.D., D.K. Damkot, and N.G. Benson. 1969. *Some effects of silt turbidity on behavior of juvenile largemouth bass and green sunfish.* Tech. Paper 20. U.S. Bureau of Sport Fisheries and Wildlife, Washington, D.C.

Herbich, J., S. Brahme and C. Andrassy. 1989. Generation of re-suspended sediment by dredges. In: Wilson, J. and V. van Dam (eds.) *Dredging: Technology, Environmental, Mining.* Western Dredging Association. pp.253-266.

Herrgesell, P., R. Schaffter and C. Larsen. 1983. *Effects of freshwater outflow on San Francisco Bay biological resources.* Tech. Rept. 7. Interagency Ecological Study Program. DO/SFB/BIO-4ATR/83-7. 86 pp.

Hirsch, N.D., L.H. DiSalvo and R.K. Peddicord. 1978. *Effects of dredging and disposal on aquatic organisms.* Technical Report DS-78-5. U.S. Army Engineer Waterway Experiment Station, Vicksburg, MS.

Hollis, E.H., J.G. Boone and C.R. DeRose. 1964. *A literature review of the effects of turbidity and siltation on aquatic life.* Staff Report, Dept. of Chesapeake Affairs, Annapolis, MD.

Ingle, R.M. 1952. *Studies on the effect of dredging operations upon fish and shellfish.* Tech. Ser. No. 5. State of Florida, Board of Conservation, Tallahassee, FL.

Johnson Offshore Services, Inc.. 1988. *Water Monitoring Program, Alcatraz Dredge-Dump Site.* Johnson Offshore Services Group. Report to Port of Oakland , California.

Johnston, D.D. and D.J. Wildish. 1982. Effects of suspended sediment on feeding by larval herring (*Clupea harengus harengus* L.). *Bull. Env. Contam. Toxicol.* 29: 261-267.

Kohlhorst, D. 1973. *An Analysis of the Annual Striped Bass Die-Off in the Sacramento-San Joaquin Estuary, 1971-72.* Anadromous Fisheries Branch Administrative Report No. 73-7. 21 pp.

Kohlhorst, D. 1975. *The Striped Bass* (Morone saxatilis) *Die-Off in the Sacramento-San Joaquin Estuary in 1973 and a Comparison of its Characteristics With Those of the 1971 and 1972 Die-Off.* Anadromous Fisheries Branch Administrative Report No. 74-13. 13pp.

Krone, R.B. 1966. *Predicted suspended sediment inflows to the San Francisco Bay System.* Central pacific River Basins Comprehensive Water Pollution Control Project, Federal Water Pollution Control Administration, Southwest Region, Davis, CA.

Krone, R.B. 1979. Sedimentation in the San Francisco Bay system. In: *San Francisco Bay, the Urbanized Estuary,* T.J. Conomos (Ed.) American Association for the Advancement of Science, San Francisco, California. pp. 85-96.

Langlois, T.H. 1941. Two processes operating for the reduction in abundance or elimination of fish species from certain types of water areas. *Trans. N. Amer. Wildlife Conf.* 6: 189-201.

Macklin, J.G. 1956. *Studies on the effect of suspensions of mud in sea water on oysters.* Report No. 19. Texas A&M Research Foundation Project 23., College Station, TX.

Macklin, J.G. 1962. Canal dredging and silting in Louisiana bays. *Pubs. Inst. Mar. Sci., Univ. Texas* 7: 1-131.

Mansueti, R.J. 1961. Effects of civilization on striped bass and other estuarine biota in Chesapeake Bay and tributaries. *Gulf and Caribbean Fisheries Institute, Proc.* 14: 110-136.

Masch, F.D. and W.H. Espey. 1967. Shell dredging - A factor in sedimentation in Galveston Bay. Tech. Rept. No. 7. Center for Research in Water Resources, Univ. of Texas. 168pp.

McLaren, P., and D. Little. 1987. The effects of sediment transport on contaminant dispersal: An example from Milford Haven. *Marine Poll. Bull.* 18: 586-594.

MEC Analytical Systems, Inc. 1990a. *Results of the Larkspur Landing Dredge Disposal Monitoring Program.* Report to Golden Gate Bridge District. November, 1990. 50pp.

MEC Analytical Systems, Inc. 1990b. *Environmental effects of sand mining at Point Knox Shoal.* Report to Tidewater Sand and Gravel, Oakland, CA. October, 1990. 38pp.

McKechnie, R.J. and L.W. Miller. 1971. The striped bass partyboat fishery: 1960-1968. *Calif. Fish and Game* 57: 4-16.

Mead, R.H. 1972. Transport and deposition of sediments in estuaries. *The Geological Society of America, Inc., Woods Hole, MA Mem.* 133: 91-120.

Morgan, R.P. II, V.J. Rasin, and L.A. Noe. 1973. *Effects of suspended sediments on the development of eggs and larvae of striped bass and white perch.* Ref. No. 73-110. Univ. Md. Nat. Res. Inst., College Park, MD.

Morton, J.W. 1976. *Ecological Impacts of Dredging and Dredge Spoil Disposal: A Literature Review.* MS Thesis, Cornell University. 112 pp.

Neumann, D.A., J.M. O'Connor and J.A. Sherk, Jr. 1982. Oxygen consumption of white perch (*Morone americana*), striped bass (*M. saxatilis*) and spot (*Leiostomus xanthurus*). *Comp. Biochem. Physiol.* 69(A): 467-478.

Nichols, F.H. 1979. Natural and anthropogenic influences on benthic community structure in San Francisco Bay. In: Conomos, T.J. (ed.).*San Francisco Bay, the Urbanized Estuary.* American Association for the Advancement of Science, San Francisco, California. pp. 409-426.

Nichols, F.H. and J.K. Thompson. 1985. Time scales of change in the San Francisco Bay benthos. *Hydrobiologia* 129: 121-138.

Nichols, F., J. Cloern, S. Luoma and D. Peterson. 1986. The modification of an estuary/ *Science* 231: 567-573.

Nichols, F., J. Thompson and L. Schemel. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the asian clam *Potamocorbula amurensis.* II. Displacement of a former community. *Marine Ecol. Progr. Series.* 66:95-101.

Nicol, J.A.C. 1960. *The Biology of Marine Animals.* Interscience, New York, NY. Pp. 135-201.

O'Connor, J.M., D. A. Neumann and J.A. Sherk, Jr. 1976. *Lethal effects of suspended sediments on estuarine fish.* Tech. Paper 76-20. U.S. Army Engineers Coastal Engineering Research Center. 38 pp.

O'Connor, J.M., D.A. Neumann and J.A. Sherk, Jr. 1977. *Sublethal effects of suspended sediments on estuarine fish.* Tech. Paper 77-3. U.S. Army Engineers Coastal Engineering Research Center. 90 pp.

O'Connor, J.M., J.B. Klotz and Theo. J. Kneip. 1982. Sources, sinks and distribution of organic contaminants in the New York Bight ecosystem. In: G.F. Mayer (ed.) *Ecological Stress and the New York Bight.* Estuarine Res. Fed. Charleston, S.C. pp. 631-653.

Odum, W.E. and R.F. Wilson. 1962. Further studies on reaeration and metabolism of Texas bays, 1958-1960. *Pub. Inst. Mar. Sci., Univ. Texas* 8: 23-55.

Ogden Beeman and Associates, Inc. 1988. *Letter Report to United States Army Corp of Engineers, San Francisco District on sampling at Alcatraz Dredge Spoil Disposal Site in 1988.*

Ogden Beeman and Associates, Inc. 1989. *Letter report to United States Army Corp of Enginereers, San Francisco District on sampling at Alcatraz Dredge Spoil Disposal Site in 1989.*

Paffenhofer, G. 1972. The effects of suspended red mud on mortality, body weight, and growth of the marine planktonic copepod *Calanus helgolandicus. Water Air and Soil Poll.* 1: 314-321.

Peddicord, R., V. McFarland, D. Belfiori, and T. Byrd. 1975. *Dredge Disposal Study, San Francisco Bay and Estuary.* Appendix C. Effects of Suspended Solids on San Francisco Bay Organisms. US Army Engineers, San Francisco District, San Francisco CA.

Peddicord, R.K. and V.A. McFarland. 1978. *Effects of Suspended Dredged Material on Aquatic Animals.* Technical Report D-78-29. Dredged Material Research Program, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Peterson, D., R. Smith, S. Hagar, D. Harmon, R. Herndon and L. Schemel. 1985. Interannual variability in inorganic nutrients in northern San Francisco Bay estuary. In: J. Cloern and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay.* Hydrobiologia 129: 37-58.

Pickering, R.J. 1976. *Measurement of "turbidity" and related characteristics of natural waters.* U.S. Geological Survey Open-file report 76-153. USGS Water Resources Division, Reston, VA. 6 pp plus appendix.

Pratt, D.M. and D.A. Campbell. 1956. Environmental factors affecting growth in *Venus mercenaria. Limnol. and Oceanogr.* 1: 54-60.

Pritchard , D. 1967. What is an Estuary: Physical Viewpoint. In: Lauff, G. (ed.) *Estuaries.* American Association for the Advancement of Science. Washington,D.C.

Reid, G. and R. Wood. 1976. *Ecology of Inland Waters and Estuaries*, Second Edition. Van Nostrand Company, New York, N.Y.

Remane, A., and C. Schlieper. 1971. *Biology of Brackish Water.* J. Wiley, New York. 372 pp.

Robinson, M. 1957. The effects of suspended materials on the reproductive rate of *Daphnia magna. Pubs. Inst. Mar. Sci., Univ. Texas* 4: 265-277.

Rogers, B.A. 1969. *The tolerance of fishes to suspended solids.* M.S. Thesis, Univ. Rhode Island.

SAIC. 1987a. *Alcatraz Disposal Site Survey. Phase I. San Rafael Clamshell/Scow Operation. Technical Report.* Report of Science Applications International Corporation. Newport, Rhode Island to the San Francisco District, U.S. Army Corps of Engineers, San Francisco, California.

SAIC. 1987b. *Alcatraz Disposal Site Survey, Phase 2, Richmond Channel Hopper Dredge Operation.* Report of Science Applications International Corporation, Newport, Rhode Island to the San Francisco District, U.S. Army Corps of Engineers, San Francisco, California.

Schubel, J.R. and D.J. Hischberg. 1982. The Chang Jiang (Yangtze) estuary: Establishing its place in the community of estuaries. In: Kennedy, V. (ed.) *Estuarine Comparisons.* Academic Press, New York. pp. 649-654.

Schubel, J. and J. Wang. 1973. *The effects of suspended sediment on the hatching success of* Perca flavescens *(yellow perch),* Morone americana *(white perch),* Morone saxatilis *(striped bass), and* Alosa pseudoharengus *(alewife) eggs.* Special Rept. 30. Chesapeake Bay Institute, Johns Hopkins Univ. Baltimore, Md.

Segar, D.A. 1989. *An assessment of certain aspects of the environmental impacts of dredged material dumping in San Francisco Bay.* Prepared for

Division of Ecological Services, U.S. Fish and Wildlife Service, Sacramento, CA.

SFBRWQCB. 1989. *Tentative resolution No. 89-. Policy for the Regulation of Dredged Sediment Disposal in the San Francisco Bay Region.* San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Sherk, J.A., J.M. O'Connor, and D.A. Neumann. 1972. *Effects of suspended and deposited sediments on estuarine organisms, Phase II.* Ref. No. 72-9E. Natural Resources Institute, University of Maryland Chesapeake Biological Laboratory, Solomons, MD.

Sherk, J.A., J.M. O'Connor, and D.A. Neumann. 1974. *Effects of suspended and deposited sediments on estuarine organisms, Phase II.* Ref. No. 74-20. Natural Resources Institute, University of Maryland Chesapeake Biological Laboratory, Solomons, MD.

Sherk, J.A., J.M. O'Connor, and D.A. Neumann. 1976. *Effects of suspended solids on selected estuarine plankton.* Misc. Report No. 76-1. U.S. Army Coastal Engineering Research Center, CE, Fort Belvoir, VA.

Sherk, J.A., Jr., J.M. O'Connor and D.A. Neumann. 1977. *Effects of suspended solids on selected estuarine plankton.* Misc. Rept. 76-1. U.S. Army Engineers Coastal Engineering Research Center. 50 pp.

Sissenwine, M. and S. Saila. 1974. Rhode Island Sound dredge spoil disposal and trends in the floating trap fishery. *Trans. Amer. Fisheries Soc.* 103: 498-506.

Skinner, J.E. 1962. *An historical review of the fish and wildlife resources of the San Francisco Bay area.* Calif. Fish and Game, Water Project Branch Report No. 1. 226 pp.

Smith, S. and S. Kato. 1979. The fisheries of San Francisco Bay: Past, present and future. In: Conomos, T.J. (Ed.) *San Francisco Bay: The Urbanized Estuary.* Pacific Div. AAAS, San Francisco. pp. 445-468.

Stern, E. and W. Stickle. 1978. *Effects of Turbidity and Suspended Material in Aquatic Environments, Literature Review.* Tech. Report D-78-21. Report to Office, Chief of engineers, U.S.Army, Washington, D.C. pp.117.

Stevens, D. 1977. Striped bass (*Morone saxatilis*) year class strength in relation to river flow in the Sacramento-San Joaquin Estuary, CA. *Trans. Amer. Fish. Soc.* 106: 134-142.

Stevens, D. 1980. Factors affecting the striped bass fisheries of the west coast. In: Clepper, E. (ed.) *Marine Recreational Fisheries. 5.* Washington D.C. The Sport Fishing Institute. pp. 15-28.

Stevens, D. 1981. *An evaluation of factors affecting abundance of striped bass in the Sacramento-San Joaquin estuary.* Calif. Dept. of Fish and Game. Bay-Delta Fishery Project. Stockton, CA.

Stevens, D. ,L. Miller, and D. Kohlhorst. 1989. *Where Have California's Striped Bass Gone?* Bay-Delta Project. California Department of Fish and Game.

Stone, R.L., R. Palmer, and W.T. Chen. 1974. *A study of the effects of suspended particulate matter on some marine bottom-dwelling invertebrates.* Northeastern Univ. Mar. Sci. Center. Final Rept. U.S. Army Engineer Division, New England, CE, Boston, MA.

Swenson, W.A. and M.L. Matson. 1976. Influence of turbidity on survival, growth, and distribution of larval lake herring (*Coregonus artedii*). *Trans. Am. Fish. Soc.* 105: 541-545.

SFBRWQCB, 1986. *Water Quality Control Plan: San Francisco Bay Basin.* San Francisco Bay Regional Water Quality Control Board, Oakland, CA.

Tavolaro, J.F. 1984. A sediment budget study of clamshell dredging and ocean disposal activities in the New York Bight. *Environ. Geol. Water Sci.* 6:133-140.

Thomson-Becker, E.A. and S.N. Luoma. 1985. Temporal fluctuations in grain size, organic materials and iron concentrations in intertidal surface sediment of San Francisco Bay. In: J. Cloern and F. Nichols (eds.) *Temporal Dynamics of an Estuary: San Francisco Bay.* Hydrobiologia 129: 1-12.

Tramontano, J.M. and W. F. Bohlen. 1984. The nutrient and trace metal geochemistry of a dredge plume. *Estuar. Coast. Shelf Sci.* 18: 385-401.

USBR (U.S. Bureau of Reclamation). 1987. *River flows, water project exports and water quality trends in the San Francisco Bay-Delta Estuary.* Exhibit 111. Bay Delta Hearings. US Bureau of Reclamation, Mid-Pacific Region, Sacramento CA. September, 1987.

USCOE. 1976. *Dredge Disposal Study, San Francisco Bay and Estuary.* U.S. Army Corps of Engineers, San Francisco District, San Francisco, California.

USEPA/USCOE. 1977. *Ecological Evaluation of Proposed Discharge of Dredged Material into Ocean Waters: Implementation Manual for Section*

103 of Public Law 92-532 (Marine Protection, Research, and Sanctuaries Act of 1972). U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. NTIS #ADA143776.

USEPA/USCOE. 1990. *Ecological Evaluation of Proposed Discharge of Dredged Material into Ocean Waters.* Draft Report. USEPA, Office of Marine and Estuarine Protection and US Army Corps of Engineers, Office of the Chielf of Engineers.

USGS. 1979. Physical and Chemical Properties of San Francisco Bay Waters, 1969-1976. U.S. Geological Survey Open-File Report 79-511.

USGS. 1986. *Physical and Chemical Data for San Francisco Bay, California, September Through November, 1984.* U.S. Geological Survey Open-File Report 86-228. 32 pp.

USGS. 1989. *Physical and Chemical Properties of San Francisco Bay, California, 1980.* U.S. Geological Survey Open-File Report 89-421.

Van Oosten, J. 1945. Turbidity as a factor in the decline of Great Lakes fishes with special reference to Lake Erie. *Trans. Am. Fish. Soc.* 75: 281-322.

Vellinga, T. 1989. Environmental Effects of Dredging and Disposal Operations. In: Wilson, J. and V. van Dam (eds.) *Dredging: Technology, Environmental, Mining.* Western Dredging Association. pp.235-252.

Wagner, D.B. 1978. *Environmental history of central San Francisco Bay with emphasis on foraminiferan paleontology and clay mineralogy.* Ph.D. Thesis. Univ. California, Berkeley, CA. 274 pp.

Winzler and Kelly. 1985. *Oceanographic Investigation at the Alcatraz Disposal Site, San Francisco Bay, California.* Report prepared by Winzler and Kelly, Consulting Engineers, for the U.S. Army Corps of Engineers, San Francisco District, San Francisco, California.