The Modification of an Estuary

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The San Francisco Bay estuary has been rapidly modified
by human activity. Diking and filling of most of its
wetlands have eliminated habitats for fish and waterfowl;
the introduction of exotic species has transformed the
composition of its aquatic communities; reduction of
freshwater inflow by more than half has changed the
dynamics of its plant and animal communities; and wastes
have contaminated its sediments and organisms. Contin-
ued disposal of toxic wastes, the probable further reduc-
tion in freshwater inflow, and the possible synergy be-
tween the two provide the potential for further alteration
of the estuary's water quality and biotic communities.

E STUARIES HAVE LONG BEEN A FOCUS OF HUMAN SETTLE-
ment and activity because of their wide array of living and
nonliving resources. They have also been susceptible to
change: their tributary rivers have been dammed and diverted,
shorelines modified, fish populations reduced or eliminated, and
water quality altered by wastes (1). The San Francisco Bay estuary is
no exception.

San Francisco Bay is located at the mouth of the Sacramento–San
Joaquin river system, which carries runoff from 40 percent (153,000
km²) of California's surface area (Fig. 1). Spanish soldiers and
missionaries, first arriving in 1769, found here a complex of bays
and marshes where an estimated 10,000 to 20,000 aboriginals lived
and harvested food (2, 3). The Spanish settlement (now San
Francisco) remained an isolated trading outpost until gold was
discovered in the Sierra Nevada foothills (Fig. 1) in 1848. Within 2
years, San Francisco's population grew from 400 to 25,000, begin-
ning the California population boom.

The estuary changed as well. By 1900 the surface area and depth
of the bay had decreased, marshes were nearly gone, fresh water was
being diverted for irrigation, many exotic plants and animals
(including pest species) had been introduced, and the effects of
sewage were already apparent. With respect to diversity of change,
San Francisco Bay is today considered the major estuary in the
United States most modified by human activity (4).

In this article we describe some of the human activities occurring
in the San Francisco Bay estuary and its watershed since 1850 that
have resulted in physical, chemical, and biological changes.

Early Ecological Changes

Fish and wildlife. The best documented change that occurred in
San Francisco Bay after the Gold Rush was a decline in fish
abundances (5). Early immigrants exploited the waterfowl, fish, and
shellfish of the bay and the Delta—the low-lying region of marshes,
islands, and channels surrounding the confluence of the Sacramento
and San Joaquin rivers (Figs. 1 and 2).

Commercial fisheries in salmon, sturgeon, sardines, flatfish, crabs,
and shrimp were quickly established. However, by 1900 catches of
larger, longer lived species at upper trophic levels, such as salmon,
sturgeon, and the introduced striped bass, had declined; gradually,
these commercial fisheries were halted to protect the stocks for
sports fishing (5). Declining abundance of the Dungeness crab
(Cancer magister) in the bay forced that fishery to move offshore in
the 1880's, although the bay remained a nursery ground until the
1960's, when the nearby offshore fishery collapsed (6). Today's
commercial fishing is restricted to herring and anchovies (7, 8),
species representative of the smaller, more rapid reproducers at
lower trophic levels that dominate the fisheries of disturbed environ-
ments elsewhere (9). The shifts in San Francisco Bay fisheries
presumably have resulted from a combination of overfishing, elimi-
nation of essential habitats, and changes in water quality (5),
whereas the decline of the offshore crab fishery since 1960 is
attributed variously to increased ocean temperature, predation by
hatchery-reared salmon, and pollution (6). The specific contribution
of any of these factors to the decline of individual species has not
been quantitatively determined.

Introduced species. A less obvious but equally important change
occurred within the communities of plants and animals representing
the lower levels of the estuarine food web. Upon completion of the
transcontinental railroad in 1869, large quantities (up to 100
carloads per year) of live eastern oysters *(Crassostrea virginica)* were
shipped from the East Coast to California for maturing on coastal
bay mud flats. By the late 1890's the imported oyster was Califor-
nia's most valuable fishery product (10).

Although the eastern oyster never became naturalized in San
Francisco Bay (transplanted adults failed to produce young), other
East Coast invertebrates, unintentionally shipped with the oyster,
became fully established (Fig. 3). Additional species that had bored
into ship hulls or were carried in ship ballast were also released into
the bay (7). In total, approximately 100 invertebrate species were
introduced, including the only two mollusk species in today's bay
sports fishery [the eastern soft-shelled clam *(Mya arenaria)* and the
Japanese little-neck clam *(Tapes japonica)*] and pest species [such as
the oyster drill *(Urosalpinx cinerea)* and the shipworm *(Teredo
navalis)*, the latter causing large-scale destruction of piers and
bridges soon after its introduction (11)]. Now, nearly all common
macroinvertebrates present on the inner shallows of the bay, and
some planktonic invertebrates and algae, are introduced species (7,
12, 13). The remarkable success of the introduced invertebrates has
been attributed to (i) the lack of a diverse native fauna because of the
estuary's geologic youth and geographic isolation (7) and (ii) the

opportunistic characteristics of many of the introduced species that made them well suited to rapidly colonize the bay's underexploited habitats (12).

Fish species were intentionally introduced beginning in the 1870's (5). Of the 42 fish species now inhabiting the sloughs of Suisun Bay marshes (Fig. 2), for example, 20 are introduced (14). The striped bass (Morone saxatilis), introduced from the East Coast in 1879, yielded annual catches exceeding 450 tons between 1889 and 1915. Catches declined thereafter, and commercial fishing was prohibited in 1935. The striped bass remains the primary sports fishery in San Francisco Bay (5, 7).
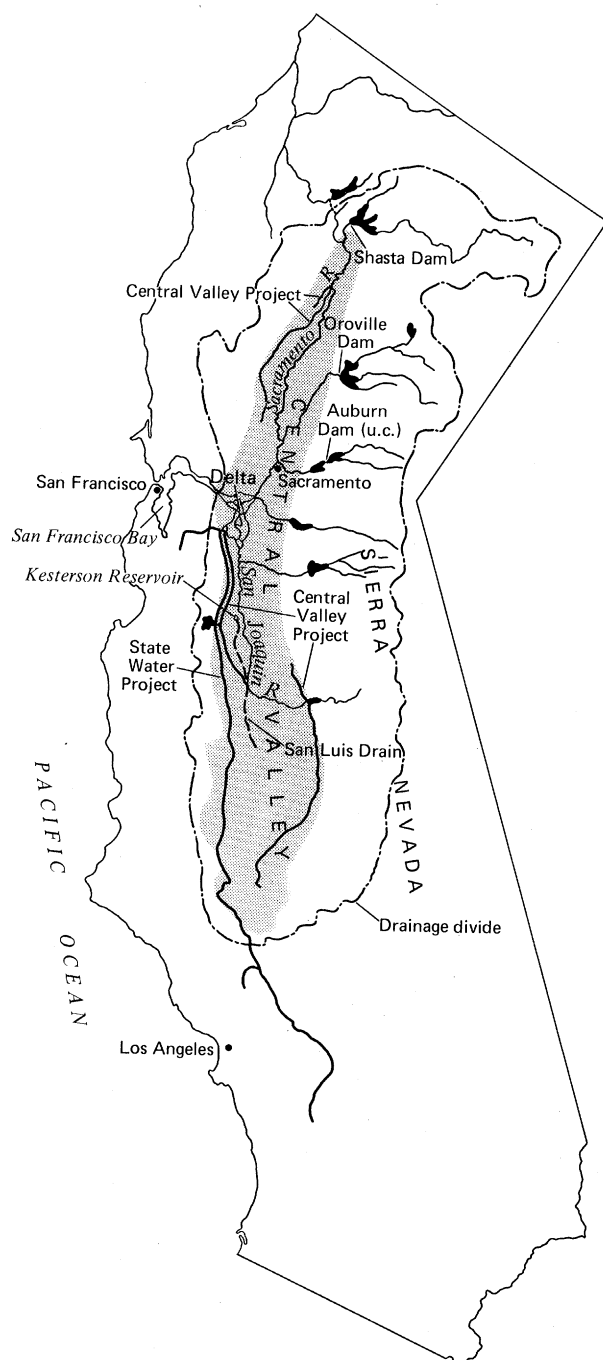

Fig. 1. Major features of California's natural and man-made water systems, including the drainage basin and major tributaries (fine lines) of the Sacramento and San Joaquin river system, major storage reservoirs (black areas), aqueducts (bold lines), the Central Valley (shaded area), the Delta, and the San Francisco Bay estuary.

Physiographic Alterations

The character of the central California landscape changed during the late 1800's as a result of the gold mining, farming, and land development that accompanied the explosive growth of population centers. Hydraulic gold mining and land reclamation resulted in particularly marked physical changes to San Francisco Bay.

Hydraulic mining debris. Hydraulic mining (the use of water under high pressure to expose ore deposits, employed from 1853 to 1884) greatly accelerated the recovery of gold from the Sierra Nevada. In the process, tens of millions of cubic meters of rock and earth were excavated annually. This debris choked creeks and rivers, silted or blocked salmon spawning streams, and obstructed navigation throughout the drainage basin (15). The obstructed river channels could not contain winter and spring runoff, and periodic massive flooding resulted (15, 16). Hydraulic mining was stopped by court injunction in 1884, but decades of winter floods and dredging were required to flush the sediments from the river channels. The Sacramento River channel did not return to its pre-mining depths until the late 1920's (11).

Although most damage from hydraulic mining debris occurred in the drainage basin of the Sacramento and San Joaquin rivers, much of the mud and sand reached San Francisco Bay. By the end of the 19th century, 1.0, 0.75, and 0.25 m of sediment was deposited in Suisun, San Pablo, and central San Francisco bays (Fig. 2), respectively (15). Acceleration of the natural sedimentation process contributed to both a permanent reduction in the open-water area of the bay through shoaling and an expansion of marshland across some of the newly formed mudflats (7). The reformed bottom topography reduced the water volume of the bay and altered tidal circulation patterns (15). No record exists of short- or long-term effects of these changes on the bay's biological communities, although oyster beds were reported to have been harmed by heavy siltation during the mining period (10).

Land reclamation. Before 1850, 1400 km² of freshwater marsh surrounded the confluence of the Sacramento and San Joaquin rivers, and another 800 km² of saltwater marsh fringed the bay's shores (Fig. 2) (15). As population increased, tidal marshes were diked to create farmland (primarily in the delta), evaporation ponds for salt, and, later, residential and industrial land. Reclamation of freshwater marshlands in the Delta was essentially complete by the early 1920's, but filling of the bay's saltwater marshes continued into the early 1970's (8). Of the original 2200 km² of tidal marsh, only about 125 km² of undiked marsh remains today (Fig. 2) (7). Long-term effects of marshland elimination on estuarine water chemistry and productivity are possible (17), but, again, no appropriate records predating these changes exist. Nonetheless, because half of the migratory birds on the Pacific Flyway winter on or near San Francisco Bay (18), we assume that the loss of food and habitat provided by the bay's former marshes has been detrimental to these bird populations.

Water Development and Altered Freshwater Inflow

California's climate consists of a wet winter (November through April) and a dry summer (May through October). The absence of summer rainfall necessitates irrigation of Central Valley farmlands with water diverted from the Sacramento or San Joaquin rivers and their tributaries. Further, because about 70 percent of the state's annual runoff occurs north of Sacramento (Fig. 1) and 80 percent of water consumption occurs south of that city (19), increased management of the water that flows toward San Francisco Bay has

accompanied the state's growth (16). One result has been a greatly reduced freshwater flow into the estuary.

The Sacramento and San Joaquin rivers discharged about 34 km³ of fresh water into San Francisco Bay annually before 1850 (20). As California's population grew (Fig. 4A), the area under irrigation increased by about 30,000 ha per year (Fig. 4B), creating demands for both flood protection and reliable water supplies. In response, state and federal agencies built dams, reservoirs, and canals to increase storage capacity (Fig. 4C) and annual export rates (Fig. 4D). These facilities represent the world's largest man-made water system (Fig. 1), with a water-storage capacity of about 20 km³ (16). At present, nearly 40 percent of the historic (1850) flow of the Sacramento–San Joaquin river system is removed for local consumption upstream and within the Delta. Another 24 percent is pumped from the Delta and exported in aqueducts for agricultural and municipal consumption in central and southern California (Fig. 5). Now, the flow into San Francisco Bay is less than 40 percent of historic levels. To minimize up-estuary salt intrusion that results from lowered freshwater flows (and that is exacerbated by dredged channel deepening between San Pablo Bay and the Delta) (11), inflow during summer has been increasingly augmented (Fig. 6).

Nearly 86 percent of California's managed water supply is used in agriculture (21). If the state's reservoir capacity increases as projected (Fig. 4C) and conversion of arid land to new farmland through irrigation continues to be profitable, demands for water export will increase (Fig. 4D). As a result, average freshwater inflow to the bay in the year 2000 is projected to drop to 30 percent of the historic average (Fig. 5).

Ecological consequences of reduced river inflow. Both the physical process of diverting water and the changes in flow patterns resulting from water management have affected biological communities of the San Francisco Bay estuary. Disruption of the natural flow of water has most noticeably affected migratory fish—species dependent on the rivers for spawning. Construction of Shasta Dam (Fig. 1) in 1944 eliminated half of the salmonid spawning habitat in the Sacramento River system (5), requiring the augmentation of natural stocks with hatchery-reared fish. The operation of water diversion pumps at the southern end of the Delta during summer periods of low river flow causes water in Delta channels to flow upstream. Thus, hundreds of millions of juvenile salmon and striped bass (31 and 25 percent of typical year classes, respectively) are drawn into the water diversion pumps each year (22). Equal numbers are lost to numerous small siphons and pumps that collect irrigation water for local consumption in the Delta (23). These losses have contributed to a decline in the abundance of adult striped bass to less than 25 percent of that in the mid-1960's (24).

Effects of water diversions on the biology of the bay itself, although more difficult to identify or quantify because of simultaneous changes due to land reclamation, fishing, and waste disposal, can be deduced from observations made during two consecutive years of naturally low flows (1976 and 1977). Normally, fresh water is released during summer at a controlled rate between 100 and 400 m³/sec (Fig. 6). Under these conditions, the downstream-flowing river currents are balanced, in Suisun Bay, by the upstream-flowing bottom currents carrying salt water (Fig. 7). This convergence, or null zone, is a point where suspended particles, including sediment and planktonic diatoms, accumulate (7, 25, 26). Associated with this phytoplankton maximum are high abundances of pelagic herbivores (copepods and the mysid shrimp *Neomysis mercedis*) that are important food sources for larval or juvenile fish (27). During 1977, when Sacramento–San Joaquin river discharge in summer dropped below 100 m³/sec (Fig. 6), phytoplankton biomass in the upper estuary was reduced to 20 percent of normal levels (26), zooplankton abundance was significantly reduced, and both *Neomysis* abundance

and striped bass recruitment fell to their lowest recorded levels (27, 28). Suppression of the pelagic food web during this natural occurrence of extremely low flow suggests that (i) production of some pelagic fishes in the upper estuary may depend on a high biomass of primary producers and (ii) high phytoplankton biomass develops only when freshwater inflow exceeds 100 m³/sec (26).

Two theories have been proposed to explain the absence of a summer phytoplankton bloom in northern San Francisco Bay during extremely low inflows. The first theory (26) holds that the typical summer biomass maximum is dependent on a circulation pattern that positions the null zone adjacent to the productive shallows of Suisun Bay, where light availability is sufficient to sustain algal growth. When river discharge falls below 100 m³/sec, the null zone moves upstream into the deeper Sacramento River, where light availability is insufficient to sustain net photosynthesis and phytoplankton biomass remains low. The second theory (29) holds that reduced phytoplankton biomass during periods of persistent low river flow and high salinity results from increased grazing losses to immigrant benthic suspension feeders that are normally excluded from this region by winter freshets.

Both mechanisms, direct consequences of reduced freshwater inflow, probably contributed to the absence of a summer bloom during the 1977 drought. These findings illustrate the sensitivity of northern San Francisco Bay biological communities to persistent low river flow and suggest that further reductions in freshwater inflow (Fig. 5) could permanently alter the pelagic food web and fisheries yield there.

Other consequences of reduced inflow. Reduced freshwater inflow from the Sacramento–San Joaquin river system may also reduce the estuary's capacity to dilute, transform, or flush contaminants that are discharged into San Francisco Bay. Estimated residence time of water in northern San Francisco Bay ranges from a minimum of 1
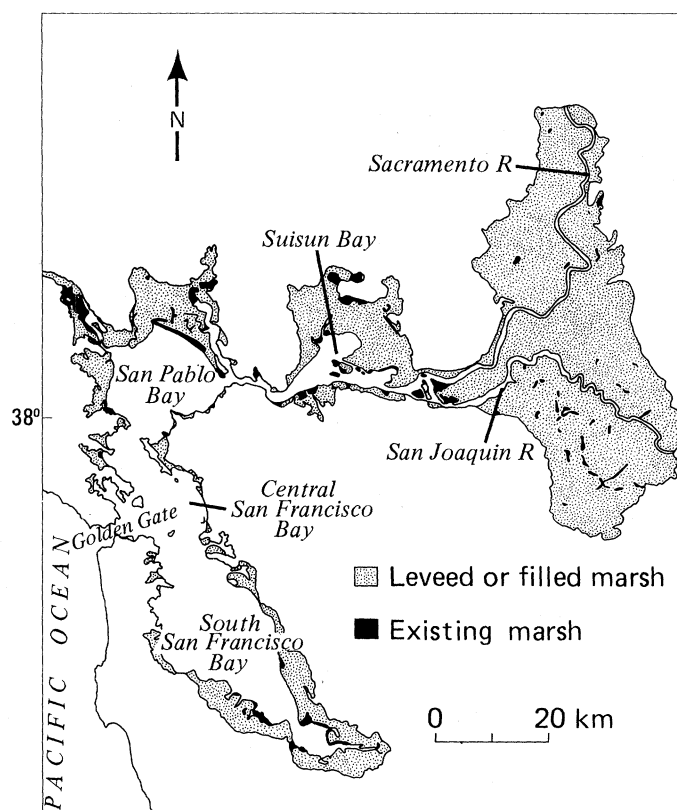

Fig. 2. Distribution of undiked tidal marshes around San Francisco Bay before 1850 and at present (7).
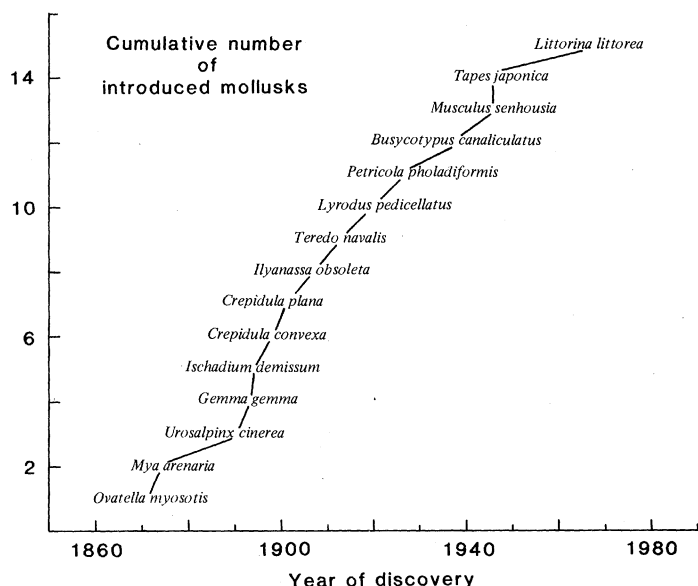
Fig. 3. Cumulative number of introduced mollusks by date of discovery (7). The period of most rapid increase, the 1890's, coincides with the period of maximum oyster importation.
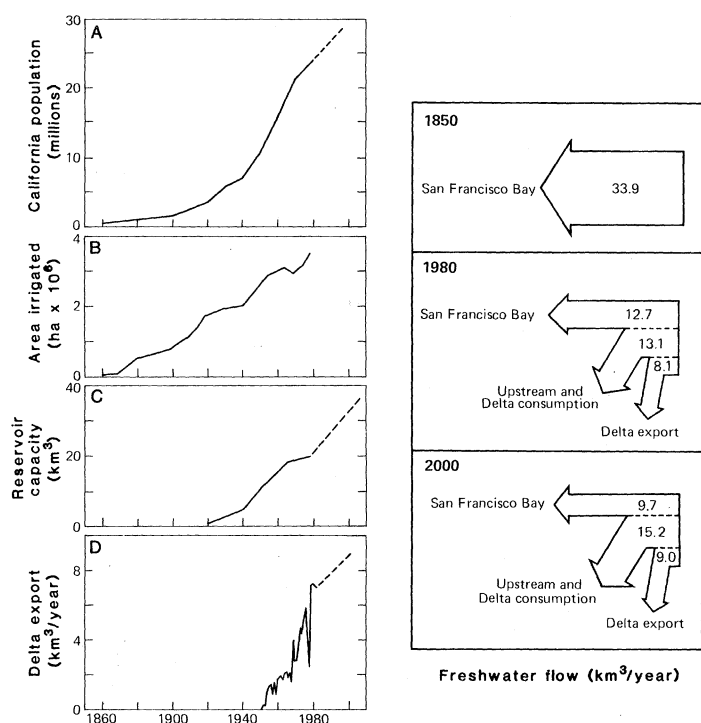

Fig. 4 (left). (A and B) California population growth and land under irrigation (50); (C) water storage capacity of reservoirs in the Sacramento and San Joaquin river basin exclusive of those smaller than 8000 ha (dashed line represents an estimated increase of 15.2 km³ in the year 2005 for the Auburn Reservoir now under construction and the proposed increased height of Shasta Dam) (51); (D) historic and projected export of water from the delta by the federal Central Valley and state water projects (19, 52). The effect of the 1976–77 drought on Delta export is clearly seen. Fig. 5 (right). Disposition of Central Valley runoff (exclusive of transpiration and other natural losses) before about 1850, in 1980, and projected for the year 2000. Water removed in the watershed and within the delta for local irrigation and domestic consumption is shown as upstream and delta consumption; that withdrawn from the Delta for export to central and southern California is shown as Delta export (19, 20).

day during peak winter flows to a maximum of 2 months during sustained low summer flows (30). Winter peaks in river inflow also carry fresh water into the semienclosed embayment of South San Francisco Bay (hereafter called South Bay) (Fig. 2), which has no other important source of freshwater inflow. In the process, salinity of South Bay drops from about 30 to 15 per mil (well below that of seawater at the Golden Gate). The resulting horizontal water-density gradient causes the fresher surface layer to move seaward and more saline bottom water to move landward (30, 31). This increase (up to tenfold) of nontidal currents following periods of high river discharge accelerates the exchange of water between South Bay and Central Bay, decreasing water residence time in South Bay from several months to several weeks (30).

Changes in circulation that accompany freshwater intrusion into South Bay apparently affect concentrations of dissolved constituents, including trace contaminants. Silver and copper concentrations in benthic organisms near a waste outfall in South Bay decrease after winter floods, when salinity drops (30). Moreover, less silver accumulates in the organisms during years of highest freshwater inflow in winter (Fig. 8). Although mechanisms are not well understood, such evidence suggests that (i) concentrations of biologically available metals may be linked to the river-driven circulation of South Bay and (ii) a significant reduction of river inflow could reduce the effectiveness of processes that facilitate waste assimilation in South Bay.

Waste Disposal

Wastes from municipal and industrial outfalls and in runoff from urban and agricultural lands have flowed into the estuary since the Gold Rush. Nonetheless, determining their effects on the bay's aquatic life has been difficult.

Agricultural waste. Beginning in the late 1940's, use of fertilizers, soil amendments, herbicides, and pesticides in Central Valley farmlands became widespread and altered the composition of river water, most notably in the San Joaquin River. The San Joaquin River Valley is arid, with a discharge per unit area about one-third that of the Sacramento River Valley. Agricultural waste water (residual irrigation water, containing salts leached from the soil, that is returned to the river in subsurface pipe drainage systems) makes up more than 20 percent of the total San Joaquin River flow (32). Maximum annual concentrations of sulfate and nitrate in the river, normally occurring during the irrigation season, have increased nearly threefold and fivefold, respectively, since 1950 (Fig. 9). The increases reflect, in large part, expanding irrigation of soils containing natural sources of gypsum ($CaSO_4 \cdot 2H_2O$) and the addition of fertilizers as well as gypsum and other forms of sulfate as soil amendments.

To dispose of the increasing volume of agricultural waste water (including water used to flush salts from salinated soils), an artificial channel connecting the Central Valley with San Francisco Bay near Suisun Bay—the San Luis Drain (Fig. 1)—was authorized for construction by Congress in 1960 (33). As proposed, the drain would discharge natural and agriculture-related chemicals into the bay, including an estimated 17 tons of nitrogen per day (34), a rate equal to that from all point sources north of San Francisco (7).

A portion of the San Luis Drain that serves about 3000 ha of farmland (less than 10 percent of the area proposed to be served) was constructed. In 1978 drain water began to flow into a temporary holding facility, the Kesterson Reservoir—a marshy lowland used also as a wildlife refuge (33). In 1982 dying vegetation and declining wildlife abundances were noted in the reservoir. A year later, unusually high incidences of physical deformities, reproductive

failure, and mortality were observed in aquatic birds using the reservoir: greater than 40 percent of nests contained at least one dead embryo and 20 percent contained at least one embryo with obvious external abnormalities (35). Subsequent chemical analyses of animal and plant tissues taken from reservoir populations showed mean selenium concentrations ranging from 22 to 175 μg/g (dry weight), or up to 130 times those found at a nearby control site (35). Samples of waste water from the San Luis Drain and the Kesterson Reservoir also contained very high selenium levels (140 to 1400 μg/liter) (36).

Selenium, occurring naturally in alluvial soils of the arid western San Joaquin Valley, is leached by irrigation water and concentrated, with other salts, in the topsoil by evaporation. The selenium is mobilized when the soils are drained to remove all accumulated salts and is carried into the reservoir. There, it causes the reproductive failures and deformities in resident birds (33, 35).

The discovery of bird mortalities and deformities in the Kesterson Reservoir has resulted in recent state and federal decisions to halt work on the San Luis Drain project and to close the reservoir in 1986. In the meantime, agricultural waste water from west San Joaquin Valley farmlands not served by the existing San Luis Drain continues to flow into the San Joaquin River. High concentrations of selenium have recently been found in ducks in South Bay (37). Whether the selenium originates in the San Joaquin River or from local sources in the bay area remains to be determined.

Domestic and industrial waste. Significant changes in the composition of bay waters have occurred because of the urbanization and industrialization of the bay's shore. At present, industrial and domestic wastes, as well as urban runoff, enter the bay at more than 100 locations. The known point sources of waste include more than 30 municipal and 40 industrial waste treatment facilities and an additional 100 smaller industrial dischargers. Together, these facilities discharged 0.7 km³ of waste water in 1978, or nearly 4 percent of the average annual freshwater inflow to the bay. The annual waste input contains, among numerous constituents, 300 metric tons of trace metals (38). The ratio of wastewater to freshwater inflow is expected to double by the year 2000 (8). Untreated urban runoff also enters the bay through more than 50 small local streams because most runoff and sewage systems are separated. Additional contamination results from daily accidental spills of industrial chemicals and oil; small oil spills alone account for 200 to 300 spills annually (8).

Adverse ecological effects of waste discharge have been suspected since the early 1900's, when industrial wastes were implicated in the gradual failure of the oyster industry (2, 5). A detailed analysis of pollution effects was not undertaken until 1951, when a study showed that (i) few or no benthic invertebrates were present immediately adjacent to several waste outfalls, (ii) the number of species nearby was depressed below area averages, and (iii) industrial wastes suppressed the number of species more than did domestic wastes (39).

Improvements in sewage treatment facilities beginning in the 1960's reduced some of the adverse effects of wastes. Concentrations of oxygen-consuming organic matter and ammonia in South Bay have been reduced to the point that the summer depletion of dissolved oxygen, typical two to three decades ago, no longer occurs (8). Summer concentrations of enteric bacteria have declined in South Bay from 800 per 100 ml of water in 1964 to 4 per 100 ml in 1977 (38, 40). Collection of shellfish for human consumption, banned for decades, has recently been permitted during summer on selected mud flats well removed from outfalls or other sources of hazardous waste.

Despite greatly upgraded sewage treatment, bay sediments and organisms are contaminated to various degrees with trace organic and inorganic materials. Average concentrations of trace metals in

bay organisms, when compared with averages in organisms from other estuaries, are not especially high, reflecting the many locations in the bay unaffected by local discharges and the rapid dilution of those wastes discharged by the major cities near the mouth of the estuary. On the other hand, localized patches of metal contamination, with concentrations as high as those observed anywhere in the world, occur near past and present waste disposal sites (8, 41).
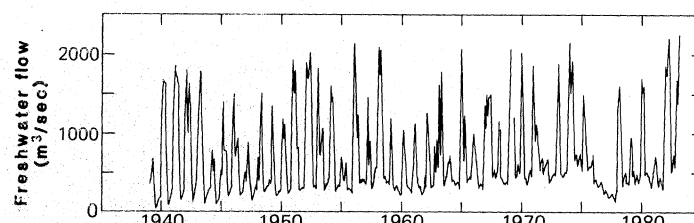

Fig. 6. Mean monthly freshwater flow in the Sacramento River at Sacramento since 1938. Note the progressive increase in the summer flow rate and the major anomaly associated with the 1976–77 drought [from T. J. Conomos *et al.*, figure 9A, in (30)].
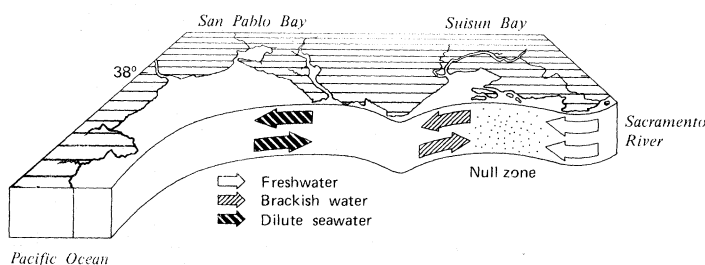

Fig. 7. Nontidal estuarine circulation and the null zone in northern San Francisco Bay. Suspended particles (stippled area) accumulate in the null zone where the upstream flow of salt water at the bottom meets the downstream flow of fresh water and net movement is minimal. This zone moves up and down the estuary in response to river discharge.

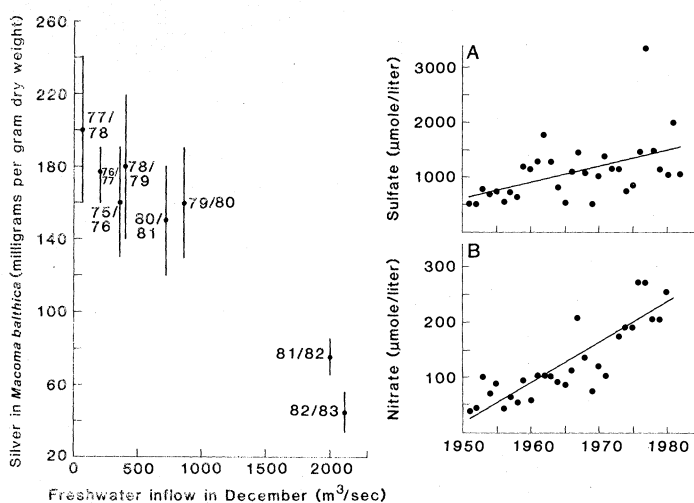Fig. 8 (left). Maximum concentrations of silver found in the clam *Macoma balthica* living in a metal-enriched mud flat in South San Francisco Bay as a function of freshwater inflow in December [from S. N. Luoma *et al.*, figure 9, in (30)]. Fig. 9 (right). Maximum annual concentrations of dissolved sulfate (A) and nitrate (B) in the San Joaquin River near its mouth (53). Lines are least-squares regressions.

Phosphate ☐ 0 - 3   ☰ 6 - 10   ☰ > 20
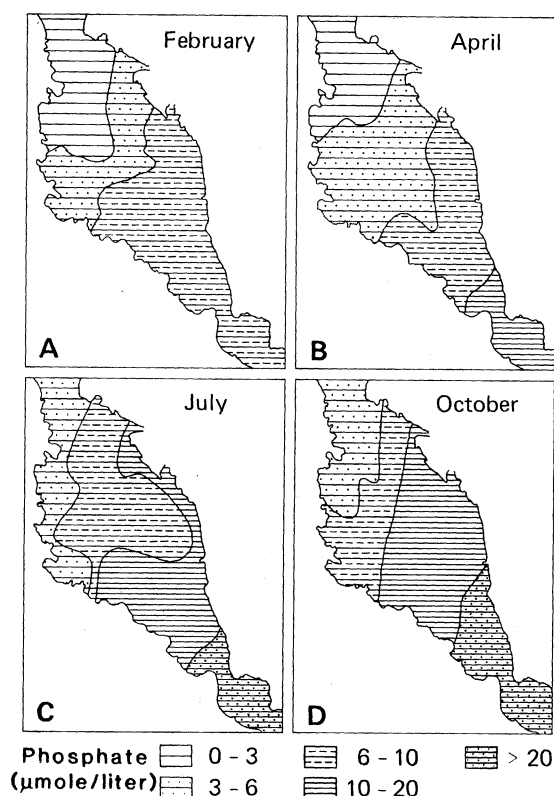(μmole/liter)☰ 3 - 6   ☰ 10 - 20

Fig. 10. Dissolved phosphate distributions in South San Francisco Bay at four times of year (54).

Distributions of toxic organic materials [polychlorinated biphenyls (PCB's) and petroleum hydrocarbons] are also patchy, with concentrations in some organisms reaching levels comparable to those in highly contaminated estuaries. For example, PCB concentrations observed in the blubber of bay harbor seals (Phoca vitulina richardii) in 1977 (42) equaled those concentrations thought to cause reproductive failure in Baltic Sea gray seals (43). Concentrations of petroleum hydrocarbons in mussels collected in central San Francisco Bay nearly equal those in Los Angeles and San Diego harbors, which are subjected to frequent petroleum contamination (8).

Although no studies have clearly linked trace contaminants to the permanent elimination of any species population, elevated tolerances to trace metals have been observed in the clam Macoma balthica and the copepod Acartia clausi from contaminated locations in the bay (44). These results imply an importance of adaptive flexibility to the survival of some populations. Studies near a South Bay sewage outfall also indicate that physiological stress caused by trace metal contamination occurs even in highly adaptable bivalves when metal availability is highest (30). High incidences of skin lesions, tumors, and increased parasitism in the bay's striped bass may be consequences of exposure to synthetic organic compounds; moreover, the concentrations of petroleum-derived hydrocarbons found in striped bass are as high as those that adversely affect the hatching success of eggs in the laboratory (45). Physiological indicators of stress in mussels transplanted along a transect in South Bay increased coincident with a gradient of increasing trace metal concentrations in water, sediment, and organisms (46).

Nutrient enrichment of the bay. Stimulation of plant growth through nutrient enrichment, with subsequent declines in oxygen content of the water as the plant material decomposes, is another potentially important result of waste discharge. Sewage-derived nutrient inputs in northern San Francisco Bay are not easily distinguished from the large riverine inputs. Waste-derived nutri-

ents are more apparent in South Bay, where storm drains and waste treatment plants are the principal sources of freshwater inflow (7). During the winter-spring period of high river runoff, levels of nutrients [for example, phosphate (Fig. 10A); nitrate concentrations vary similarly] in South Bay are low because of dilution with low-salinity water in central San Francisco Bay (7). During the rest of the year, when runoff is low and dilution and mixing with central bay water diminish, nutrient levels increase (Fig. 10, B to D) to a summer-autumn maximum that is often the highest level found in San Francisco Bay.

Although nutrient concentrations are periodically high, the bay does not exhibit symptoms of eutrophication—nuisance phytoplankton blooms and associated depletion of oxygen [although localized, episodic blooms of drift macroalgae occur in some years (30)]. Benthic filter feeders in South Bay are apparently sufficiently abundant to reduce the standing crop of phytoplankton well below expected levels (47). Thus the benthos may act as a natural biological control on eutrophication—a process employed in aquaculture (48)—by converting sewage-derived nutrients to animal biomass. It follows, therefore, that events that selectively disturb the benthos (for example, exposure to contaminants) could promote the development of noxious blooms.

In Perspective

Few of the changes we have described are unique to San Francisco Bay. Many estuaries, such as those of the Delaware, Hudson, Potomac, Rhine, Susquehanna (Chesapeake Bay), and, until recently, Thames rivers, have seasonal or permanent oxygen depletion resulting from high organic waste loading or nutrient enrichment as well as contamination by toxic wastes (49). Other estuaries in arid regions around the world are also affected by river water impoundment and diversion (4).

Measured in terms of concerns that attract public attention or interfere with commerce, the problems of San Francisco Bay appear less severe than those of other large urbanized estuaries. This appearance results, in part, because (i) much of the urban and industrial development in the bay area has occurred near the estuary mouth, where dilution and dispersal of wastes are greatest, rather than on the tributary rivers; (ii) corrective actions taken since the 1960's have eliminated oxygen depletion and greatly reduced pathogenic bacteria; and (iii) many of the major changes (such as the disappearance of wetlands, introduction of exotic species, and loss of many commercial and sports fisheries) occurred decades ago and have been forgotten.

Despite the difficulties in measuring ongoing, human-induced changes, it is clear that San Francisco Bay is sensitive to diverse human activities. Toxic wastes derived from agricultural and industrial activities have been locally detrimental to birds and bottom-dwelling invertebrates. Suggested links between the striped bass decline and contamination with synthetic organic compounds or between physiological stress in bivalves and trace metals, although largely circumstantial, indicate that chronic regional effects of contamination exist in San Francisco Bay. There is also evidence that decreased freshwater inflow can contribute to altered balances among plant and animal communities that may lead, for example, to decreases in some fish stocks. In addition, there is an apparent link between river flow and the capacity of the estuary to assimilate wastes.

The future well-being of this estuary (like that of other urbanized estuaries) lies in achieving an increased understanding of its interacting physical, chemical, and biological processes and how these processes are affected by specific human activities. The effects of

increased toxic waste inputs and further reductions in freshwater inflow, and particularly the possible synergy between the two, are among the critical topics requiring increased research and management efforts. Meanwhile, economically important issues, such as changes in the treatment and disposal of industrial and agricultural wastes, deepening of channels to accommodate larger ships, and increasing river water diversion, are being considered without sufficient quantitative understanding of the effects of these actions on the estuary.

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