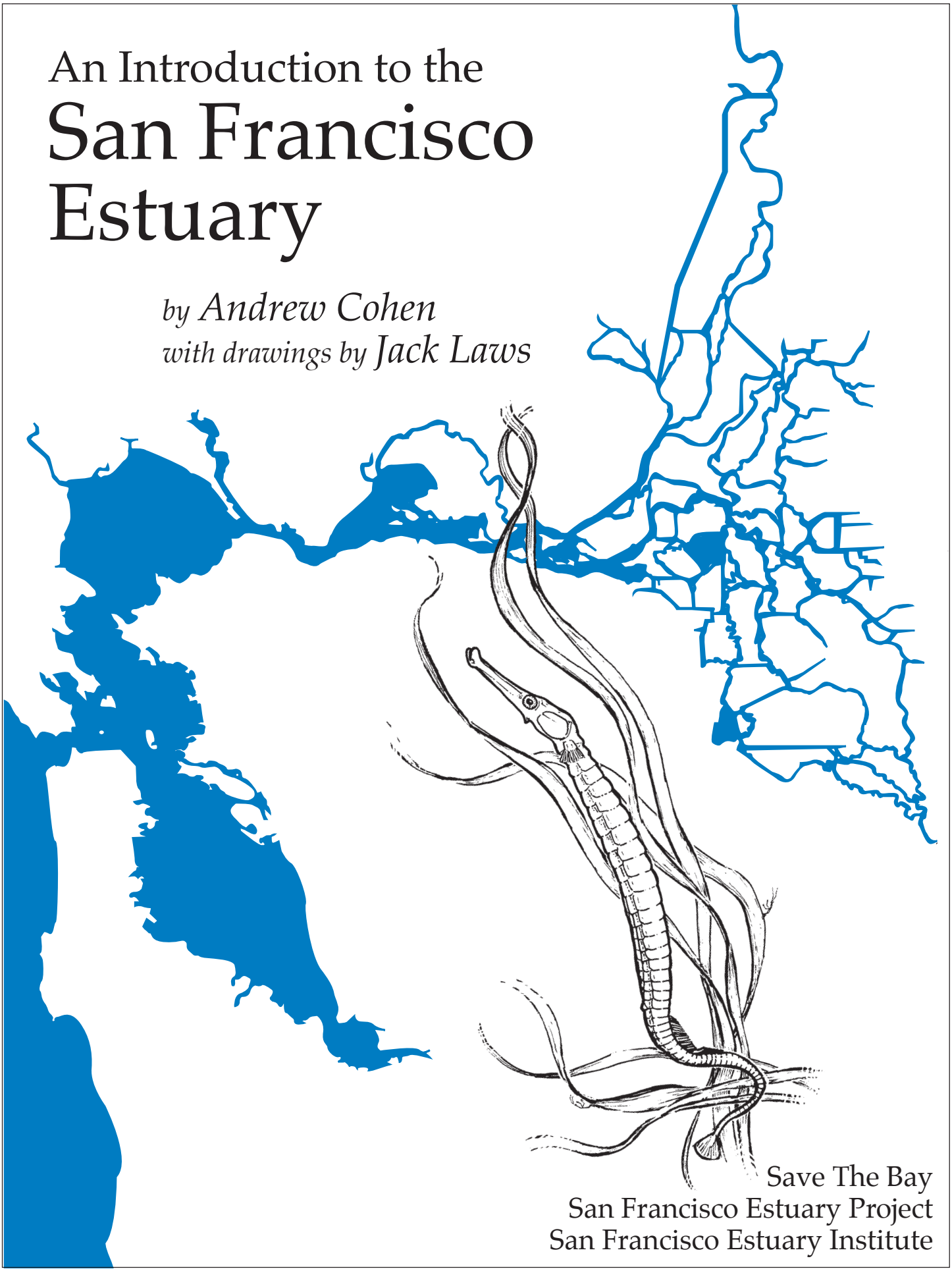
An Introduction to the San Francisco Estuary

by Andrew Cohen
with drawings by Jack Laws



Save The Bay
San Francisco Estuary Project
San Francisco Estuary Institute

San Francisco Bay enters most of our lives as an obstacle to pass over as quickly as traffic-choked bridges allow. Although this beats earlier attitudes—when we saw the Bay mainly as a dumping ground, a dam site, or a pit to fill in and pave over—we remain largely oblivious to one of the most remarkable wild resources in urban North America. Beneath our wheels lies a world of interesting and outlandish life, with much that puzzles even the scientists who regularly plumb its depths.

Farther upstream, the organisms of the Delta have also suffered from our inattention. A world of marsh and slough has been whittled down to little more than a few straightened channels jacketed in rock. The simplified ecosystem that remains is viewed as a flood threat by Delta farmers, a faulty piece of plumbing by southern water consumers, and a political nightmare by the agencies charged with managing it. But here too, life survives, though buffeted by virtually everything that California can throw at it.

And what lives here? A small fish, known from nowhere else, that smells like cucumbers. A song sparrow weaving its nest inches above the threatening tides. Tiny Dungeness crab and starry flounder, newly-spawned in the ocean, ride bottom currents *upstream* into the Bay where they develop into tasty adults. Marsh plants sweat salt. Salmon still run, barely. On the mudflats at low tide, coils of sediment spew from the surface like toothpaste squeezed from a tube, the work of unseen worms below. Diminutive, gull-like birds, swimming madly in circles, spin the water into "airspouts" and snatch at tiny crustaceans trapped in the vortex. A lugubrious fish, clad in phosphorescent buttons, sings; hidden beneath a rock, he guards golden eggs; disturbed, he undulates into the murk, mystery passing into mystery.

This booklet was written to provide a brief overview of what we know about life in this Estuary. Earlier editions were funded by the U.S. Environmental Protection Agency's National Estuary Program and published by the San Francisco Estuary Project and Save The Bay. The present edition is a joint project of the San Francisco Estuary Project, Save The Bay and the San Francisco Estuary Institute, with funding from the Mary A. Crocker Trust and the Richard and Rhoda Goldman Fund. These funds make it possible to sell the booklet at below the cost of its production. Proceeds from its sale will be used to support future editions.

Marcia Brockbank, the Director of the San Francisco Estuary Project, has been project manager on each edition, starting from her initial vision over a decade ago. It is primarily due to Marcia's unflagging efforts that we are once again able to provide this introduction to the Estuary.

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Save The Bay • San Francisco Estuary Project • San Francisco Estuary Institute
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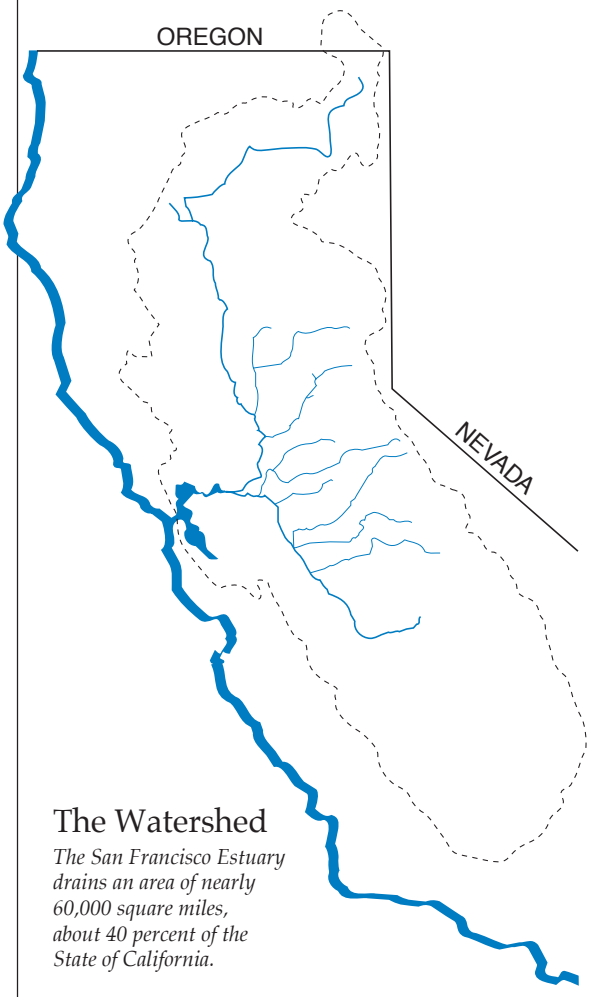
The Estuarine Environment

In the winter of 1769 a lost squad of Spanish soldiers stumbled up the ocean side of the San Francisco peninsula, looking in the wrong place for the harbor at Monterey. Struggling over the intervening ridges, they were astonished to find hidden within the coastal mountains "a most grand estuary or arm of the sea," which eventually came to be called San Francisco Bay. The Bay and the upstream, inland Delta make up the San Francisco Estuary, which in those days covered 500 square miles of open water and another 850 square miles of fresh-, brackish- and salt-water marsh. Early explorers reported an ecosystem brimming with life, with whales and sea otters playing at the water's surface, huge salmon and sturgeon cruising beneath, oysters and mussels blanketing the bottom, and sky-darkening flocks of ducks, geese and shorebirds wheeling overhead.

Unfortunately, 200 years of civilization have quite literally diminished the Estuary. Over half of the acres that were open to the tides have been diked off or filled in, destroying four-fifths of the marshes that once mantled its shores, and on average about half of the runoff from its watershed is taken to nourish cities and crops. Grizzly bear and tule elk have disappeared from the Delta, while whales and sea otter have abandoned the Bay. Many bird and fish populations have been reduced to a fraction of their former abundance, and in several habitats exotic organisms far outnumber native species.

These changes remain the focus of fierce debate. Disagreements arise regarding the importance of human-caused changes relative to natural variation, the degree of contamination in water, sediments and organisms, and the effect of freshwater diversions on the survival of endangered fish. Though tied to political maneuvering, such arguments continue in part because some aspects of the ecology of the Estuary remain so poorly known. If we are to have any hope of protecting and restoring the life in this Estuary, we need to understand how it works.



The Watershed

The San Francisco Estuary drains an area of nearly 60,000 square miles, about 40 percent of the State of California.

The San Francisco Estuary

The Estuary's watershed covers about 60,000 square miles, or about 40 percent of California. Roughly half of California's surface water supply falls as rain or snow within this region, and about half of that is diverted for use by farms, factories or households. The remainder is allowed to flow downstream through what, despite major depletions, is still the largest estuary in western North America and a biological resource of tremendous importance—providing critical winter feeding for over a million migratory birds , a productive nursery for juvenile fish and crabs, and a full-time home for many other organisms.

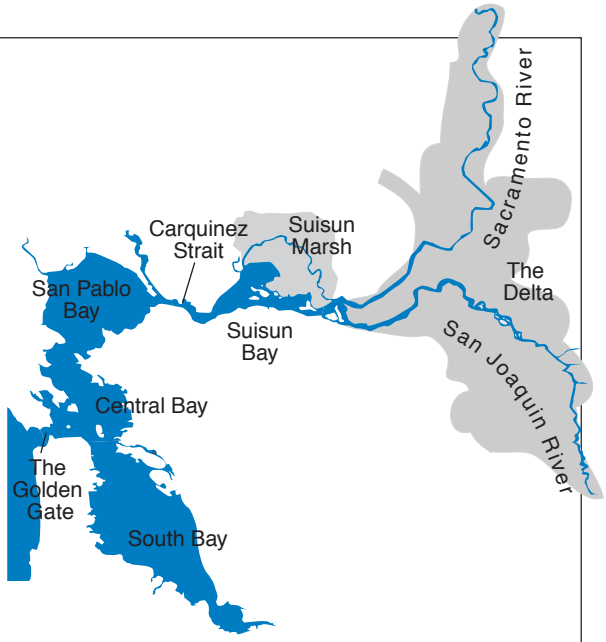
The Delta, the most upstream section of the Estuary, is a thousand-square-mile triangle of diked and drained swampland. Only the barest shreds of once-extensive tule marshes remain, now narrowly fringing sloughs and channels that wind between flat, levee-rimmed farmlands, the Delta "islands." In its natural state, the Delta pointed its hydraulic arrowhead westward from the Central Valley, gathering in waters from the Sacramento River, the San Joaquin River, and the smaller Mokelumne and Cosumnes

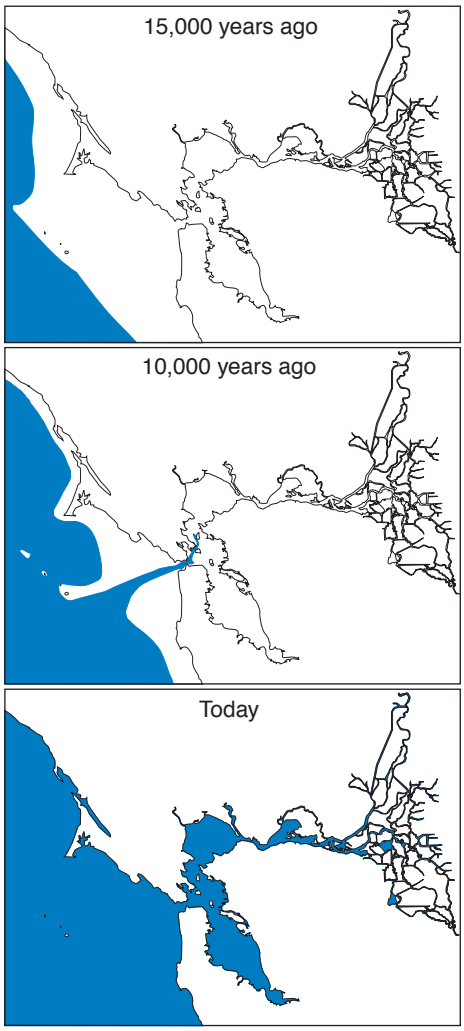
rivers and shooting them downstream into San Francisco Bay. Today, however, the Delta serves as the central valve for the world's largest plumbing system, shunting water from northern California rivers to the state's biggest water users in the south.

The plumbing includes an array of dams, reservoirs, channels and aqueducts that extends through nearly the entire state. On a precisely timed schedule, water released from northern reservoirs flows down the Sacramento Valley and into the northern Delta while immense pumps suck water from the Delta's southern end. At thousands of cubic feet per second, the water pours into concrete-lined canals leading to San Joaquin Valley farmers and to cities from the southern Bay Area to southern California. Two other systems divert water from Sierra Nevada rivers and pipe it westward past the Delta and into the Bay Area.

San Francisco Bay, the downstream portion of the Estuary, is made up of four smaller bays or basins. Suisun Bay and the diked wetlands of Suisun Marsh form the least salty of these, immediately downstream from the Delta. Saltier San Pablo Bay is next in line, west of Carquinez Strait. The saltiest basins are the Central Bay, which connects with the ocean through the Golden Gate, and the South Bay, a large shallow lobe extending off the Central Bay.

Scientists define an *estuary* as a partially enclosed body of water where fresh river water meets and mixes with the salty ocean. In the San Francisco Estuary the *mixing zone*, where fresh and salt water meet, can move tens of miles upstream and down as river flows fall and rise. The Great Flood of 1862, which temporarily turned the Central Valley and much of the Bay into a chain of freshwater lakes, pushed the mixing zone out beyond the Golden Gate for several weeks and freshened the ocean's surface 40 miles from shore. At the opposite extreme, during the dry summer and fall of 1931 the mixing zone moved inland, salting the water as far upstream as Courtland on the Sacramento River and Stockton on the San Joaquin.





Sea level has risen about 400 feet since the last Ice Age, filling the Estuary to its current depth.

Origin, Size and Structure

Twenty thousand years ago, San Francisco Bay did not exist. The world was then in the grip of the last ice age, when miles-thick glaciers blanketed northern lands. With much of the earth's water piled up on land as ice and snow, sea level dropped 400 feet and the edge of the sea retreated beyond the Farallon Islands, 20 miles west of where it is today. The Bay floor lay exposed as a chain of rolling river valleys cradled within the Coast Range, linked by rapids pouring through narrow canyons at Carquinez Strait, Racoon Strait (between Tiburon and Angel Island) and the Golden Gate. Horses, camels, mammoths, giant bison and ground sloth roamed across this landscape—animals that later disappeared from North America, but whose bones are still sometimes dug from the sand and gravel beds along the Bay shore.

Over several millenia the glaciers melted, the ocean waters rose, and the shoreline crept east. About 10,000 years ago the ocean entered the Coast Range through the Golden Gate, and seawater began to fill the Bay. At first the waters rose rapidly in a geologic sense—averaging less than an inch of rise a year, but still fast enough so that on the gently sloping floor of the South Bay the water advanced southward by several inches a day. Then, as the rise in waters slowed, sediments began accumulating in the

shallows faster than the seas could cover them. Over the last 6,000 years these accreting sediments built expanses of mudflats and marshes, whose vast extent was recorded in the last century before civilization began to reshape the Estuary.

Starting with the Gold Rush, several actions have shrunk the Estuary to a water body that is generally narrower and shallower but traversed by artificially-maintained deep channels. In the Delta, the fine silt and deep peat soils laid down by centuries of flooding rivers and flourishing marshes seemed to cry out for the planting of grain, vegetables and orchards. Between 1860 and 1930, all but a few percent of the Delta's 550 square miles of freshwater marsh were diked off and farmed to feed the state's burgeoning human population. Downstream, 80 percent of the Bay's marshes and much of its intertidal mudflats were turned into salt ponds, cow pastures, or marketable real estate. These activities reduced the area open to the tides from over 500 to about 90 square miles in the Delta, and from 800 to 500 square miles in the Bay

Meanwhile, Sierran gold-seekers were perfecting a method of environmental destruction known as hydraulic mining. Firing high-pressure streams of water from "water cannons," miners blasted the hills apart to wash away the overburden and run the buried placer deposits through sluice boxes. This trapped the heavy particles of gold, while flushing the rest of the hillsides directly into the rivers and creeks. From 1853 to 1884, when the practice was finally banned by the courts, hydraulic miners dumped over a billion cubic yards of sediment into the waterways draining the Gold Country. Sand and cobbles clogged river beds and raised them by as much as 20 feet, which led to flooding in the surrounding farms and cities. The finer mud and clay particles flushed further downstream and settled out in the northern portions of the Bay, creating extensive shoal areas and some new tidal marsh. Over the past century this sediment has continued to drift downstream toward the ocean, a massive wave of mud spilling slowly along the bottom. Meanwhile, sediment inputs to the Estuary have declined as reservoirs constructed upstream reduced floods and trapped sediments, and during the last half-century there's been a net loss of sediment over much of the Bay, so that the mudflats have been shrinking.

The Bay nevertheless remains quite shallow. A good low tide uncovers about a sixth of the Bay's total area, with the largest exposed mudflats extending across the eastern and southern parts of the South Bay and the northern parts of San Pablo and Suisun Bays. Another third of the Bay is less than six feet deep at low tide. Narrow channels 30 to 60 feet deep lead across the main basins into harbors and shipping terminals, and up through the Delta to the ports of Stockton and Sacramento. These channels are maintained partly by dredging and partly by the scouring action of river and tidal currents. The deepest spot in the Bay is under the Golden Gate Bridge, where rocky bottom lies more than 350 feet beneath the waves. A curving sandbar, built up from sediments washed out of the Bay, rises to within 20-30 feet of the surface just outside the Bay's mouth.

Bay Mussel
with Barnacles

Some channels are floored with sand, a few rocky areas ring the western part of the Central Bay and crop out elsewhere, and beds of old oyster shells pave some shallow areas, but nearly everywhere else the bottom consists of a slick, sticky ooze of fine silts and clays. Creatures that need hard surfaces to attach or cling to have a difficult time finding a home here. They attach where they can, to piers and pilings, to seawalls, breakwaters and riprapped banks, to buoys and boat hulls, and to tires, cans, bottles and other debris. But most of the Bay is mud, and its bottom-dwellers have muddy lifestyles. Microscopic plants called diatoms lend a golden hue

to the surface of the mudflat, while tall grasses and other marsh plants colonize the intertidal edge. Among animals, the bottom is primarily a place of diggers and burrowers, of worms and clams and tube-building amphipods, and all the things that feed on them.

Tides, River Flows and Salinity

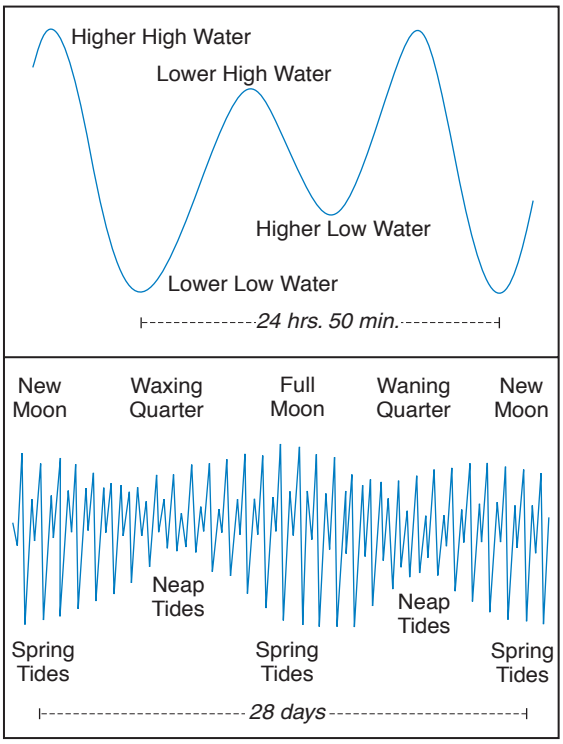
Hydrologists often visualize the Estuary as composed of two more-or-less independent sections linked to the ocean. In the northern reach, which runs from the Delta through Suisun, San Pablo and Central bays, the pattern of water circulation and salinity is strongly influenced by fresh water flowing in from the Sacramento and San Joaquin rivers. The southern reach, consisting of the South Bay, receives much less water from its tributaries and is often dominated by the combination of ocean water and northern reach water that enters it from the Central Bay. When considering the Estuary's biota, it is often useful to think in terms of three broad salinity regions: the Delta or freshwater region; an upper bay or lower salinity region, which includes Suisun Bay and sometimes extends through the Carquinez Strait into San Pablo Bay, plus areas along Napa Creek and Petaluma River at the north end of San Pablo Bay and along the sloughs and creeks entering the southern end of the South Bay; and a lower bay or higher salinity region, consisting of the main parts of South, Central and San Pablo bays.

Tides. *Mixed, semi-diurnal tides*, with two unequal high tides and two unequal low tides in each roughly twenty-five hour period, are typical of the West Coast. Twice a day, on each tidal cycle, a huge volume of salt water moves in and out of the Estuary—a quantity known as the *tidal prism*—averaging about 1,300,000 *acre-feet*, or nearly a quarter of the Estuary's total volume (one acre-foot of water will cover an acre to a foot deep, and is equal to about 326,000 gallons). In contrast, the average daily flow of freshwater into the Estuary is only about 50,000 acre-feet.

The volume of water brought in by the tides is split about evenly between the northern and southern reaches, but the tidal patterns are very different. In the northern reach the tidal range (the difference in height between high water and low water) drops with distance from the ocean, from a mean range of about five-and-a-half feet at the Golden Gate to only three feet at Sacramento. In contrast, in the southern reach's more enclosed basin the tides cause the water to slosh back and forth like water in a bathtub, amplifying the range at the southern end to eight-and-one-half feet.

The tides are raised by the gravitational pulls of the moon and the sun, with the tidal range changing in a regular pattern as the moon circles the earth every 28 days. The tides with the greatest range, called *spring tides,* occur during full and new moons, when the moon, sun and earth are nearly aligned and the pulls of the moon and the sun reinforce each other. *Neap tides*, with the least tidal range, occur during the moon's quarters, when the gravitational pulls from the moon and sun tend to cancel each other. Tide ranges also vary over the year, with the highest highs and the lowest lows typically occurring around June and December. Extreme low tides expose many organisms that live on the bottom of the Bay, attracting both shorebirds and human clam-

The Tides near San Francisco



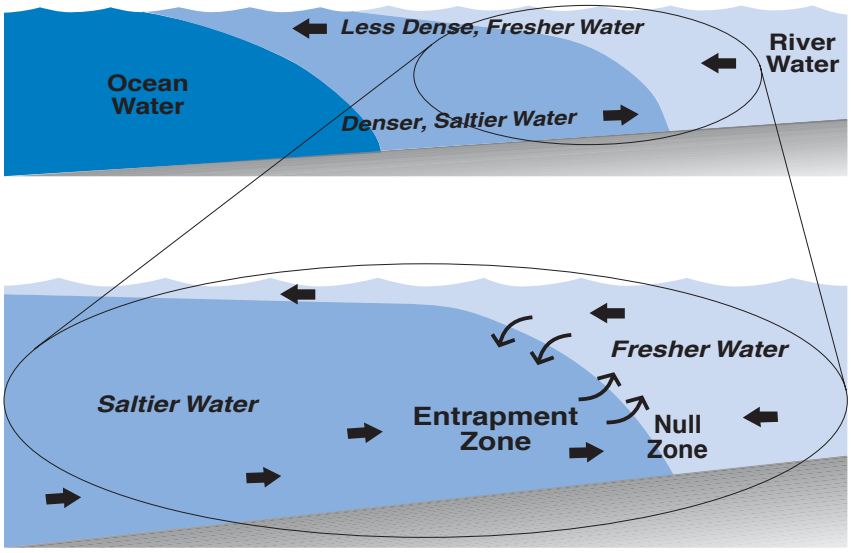
diggers looking for food, anglers sucking ghost shrimp from their burrows to use as bait, and scientists poking among the rocks for whatever it is that scientists look for. Extreme high tides force salt marsh residents, like clapper rails and harvest mice, onto the higher parts of the marsh where they are more easily captured by predators and spotted by wildlife viewers.

Northern Reach. The northern reach receives most of the Estuary's river inflow, though the amount varies greatly from year to year with changes in the weather and in water system operations. Because fresh water is lighter than salty ocean water, the river water tends to float on top of and only gradually mixes with the salt water in the Bay. The presence of water masses with distinct characteristics at different depths is called *stratification*. In the Estuary, stratification is usually stronger in the winter and in wet years when river flows are greater, and mainly occurs in the deeper channels. In the shallows, currents generated by the tides and wind generally keep the water mixed throughout the water column, preventing stratification in those areas.

River flows also create horizontal salinity gradients. The fresh water flowing in through the Delta has less than one part by weight of salt per thousand parts of water (referred to as parts per thousand or ppt). The salinity increases as one proceeds downstream, usually reaching about 30 ppt near the mouth of the Bay, nearly the salinity of the coastal ocean. At any particular spot, the salinity is usually lower when river flows are high.

Twice each day, the tides push the water in the northern reach 2 to 6 miles upstream and down. Superimposed on this back-and-forth tidal motion is the downstream flow of the freshwater surface layer, which induces a slightly smaller upstream return current of saltier water near the bottom of the channels, a pattern known as *estuarine circulation*. The region where the upstream and downstream currents meet and cancel out along the bottom is called the *null zone*. Estuarine circulation is often well-developed in Carquinez Strait, with a null zone typically found near the upper end of the Strait.

As suspended sediments are carried in by the rivers they encounter higher salinities, causing them to clump up and settle



Estuarine Circulation

In the channels of the northern reach, fresh river water flows downstream near the surface, and a net current of saltier water flows upstream near the bottom.These currents meet and cancel out in the null zone. An entrapment zone, where small particles and organisms accumulate, may form at and just downstream of the null zone, but is sometimes located elsewhere.

out. It was thought that downstream of a null zone the clumped sediments, along with phytoplankton, zooplankton, and the drifting eggs and larvae of fish, would sink down into the bottom current and be carried back upstream—so that suspended sediments and organisms would become concentrated in an *entrapment zone* at and just downstream of a null zone. However, recent studies suggest that things are a bit more complicated in the northern reach. While there often is a region where suspended sediments, nutrients and small organisms accumulate, usually in Suisun Bay during spring and summer in the area where the salinity is about 2 ppt, this is not always close to a null zone. At this time researchers are still working out the relationships between the salinity gradient, estuarine circulation, bottom topography and the formation of an entrapment zone.

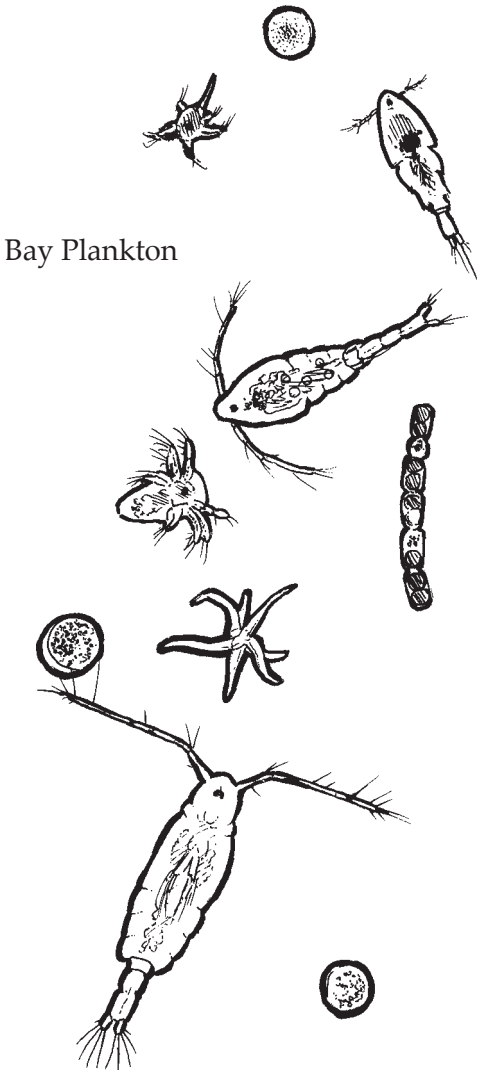
Southern Reach. The southern reach's tributaries provide less than a tenth as much fresh water as do the northern reach's, which is usually too little to stratify the water and cause estuarine circulation. Salinities are generally more uniform and higher than in the northern reach, and evaporation sometimes makes the South Bay saltier in the su mmer than the coastal ocean. With little fresh water coming in, the southern reach is relatively stagnant, especially south of the Dumbarton Bridge. Overall, the *residence time* (the average length of time it takes for a water molecule or a dissolved contaminant to leave the system) is about three to six times greater in the southern than in the northern reach. This is of concern because the southern reach receives about as much wastewater effluent as the northern reach, and in the southernmost part the water quality is relatively low and sediment contamination high.

In wet winters, however, flood flows coming down from the Delta can surge through the Central Bay and enter the southern reach, temporarily causing two-layered estuarine flow (with the fresher surface water flowing southward, and the saltier bottom water flowing northward towards the mouth of the Bay). By some calculations, this reduces the residence time from around five months in the summer to two or three months in the winter. Thus, large flows through the Delta in winter and spring may help to flush pollutants out of the South Bay.

Ocean. In the coastal ocean outside of the Estuary, conditions change regularly over the course of the year. Oceanographers describe these changes in terms of three "seasons." During the April-to-July upwelling season, persistent winds from the north cause strong southward currents and the upwelling of cold bottom water along the coast, lowering the surface temperature. Moist ocean air passing inland over this chilled surface water creates San Francisco's infamous summer fog (which led Mark Twain to declare that the coldest winter he ever spent was a summer in San Francisco). During the relaxation season, from August to November, the winds diminish, weaker currents run northward, upwelling stops and surface waters grow warmer, dissipating the fog. In the winter season, from December to March, winter storms bring intermittent strong winds from the west and southwest, and cold water returns. Inside the Bay, the seasonal temperature swings are even greater due to the shallower water and changes in river flows, so that the Bay is generally colder than the ocean during the winter, and warmer than the ocean during the rest of the year.

The Southern Reach

Life in the Estuary



Bay Plankton

All forms of life in the Estuary are linked through the intertwining chains of "who eats whom" that ecologists call the food web. At the base of the web, green plants use energy captured from the sun to combine simple nutrients absorbed from water or sediments into complex organic compounds that form the plants' tissues (a process called *photosynthesis*). Plant tissue is thus a type of storage battery for solar energy, energy that feeds the Estuary's small animals, which in turn are eaten by larger ones.

Microscopic drifting plants called *phytoplankton* are an important food source for many of the Estuary's animals. The concentration of phytoplankton is controlled by a suite of factors, including the size of river flows, the tidally-forced mixing of water between channels and shallows, the clarity and temperature of the water, the availability of nutrients, and the rate at which phytoplankton are eaten. When conditions are right, some phytoplankton can double in number every day or two, resulting in population surges known as *blooms*. In the fresh and brackish waters of the northern reach, blooms have typically occurred in the late spring, summer or fall, dominated by a group of single-celled algae called *diatoms*. Diatoms come encased in shells of silica, the same substance that window glass is made of. In the South Bay, blooms occur in the spring and include both diatoms and small *flagellates*, which move about by whipping a long, threadlike hair called a flagellum.

The drifting phytoplankton are eaten by a variety of minute animals called *zooplankton*, including copepods, water fleas and tiny opposum shrimp, plus the larvae of fish, crabs, mollusks, barnacles and other creatures. The zooplankton and larger phytoplankton are eaten by grass shrimp, by several wholly *planktivorous* fish including anchovies, herring, shad and smelt, and by other fish that eat plankton when young, such as salmon, sturgeon and striped bass. Some of these shrimp and fish are, in turn, eaten by predatory fish, by fish-eating birds, and by river otters, harbor seals or people.

Phytoplankton and zooplankton are also eaten by *benthic*, or bottom-dwelling, invertebrates (invertebrates are multicellular animals that lack a backbone). Many aquatic invertebrates live on or in the mud, including numerous species of worms, clams and little crustaceans called amphipods. Some of these live in burrows or in small tubes constructed from glued-together mud or sand, or lie buried in the mud. Others, including mussels, barnacles, sea squirts and sponges, attach to hard surfaces like rocks or pilings. Many of these benthic animals are *filter-feeders*, pumping large volumes of water through their bodies or in and out of their burrows in order to catch food particles on their gills or in nets spun from mucus. Others use tiny hairs to sweep food towards their mouths, or net-like or comb-like arrangements of limbs and hairs to capture food from the water. The barnacle, for example, sits upside-down in a bony shell while combing through the water with a dozen hairy legs.

Other clams, snails and worms sift through the mud, graze on its surface, or siphon up the slurry at the mud-water interface. Their food includes plankton that settle out of the water, micro-

organisms that live within the mud, and diatoms and other algae that grow in patches on the surface. Other worms, crabs and carnivorous snails such as the oyster drill and the channeled whelk feed on benthic invertebrates, as do bat rays, leopard sharks, sturgeon and starry flounder. The abundant worms, clams and crustaceans of the intertidal mudflats are also the primary attraction for hundreds of thousands of hungry shorebirds that descend on the Estuary each winter.

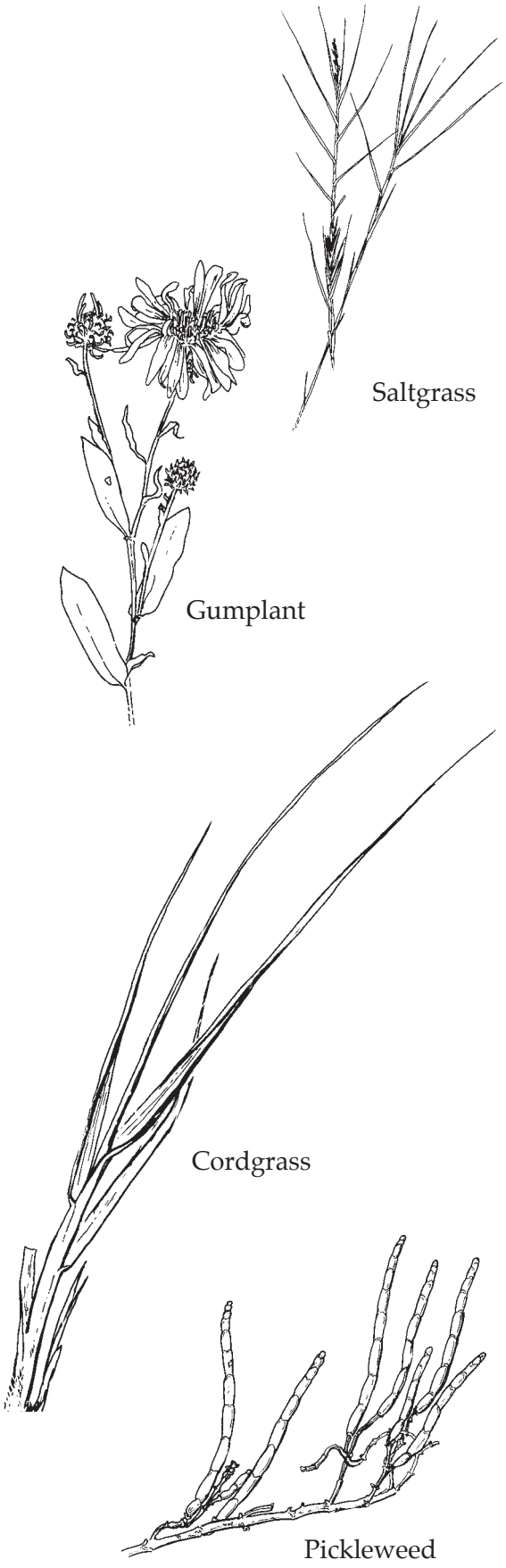
Benthic invertebrates and zooplankton also feed on another important strand of the food web, the *detrital chain.* This begins with leaves and other bits of vegetation washing in from the rivers, with marsh plants fringing the Estuary's edge, and with eelgrass and seaweeds growing beneath the water in the saltier parts of the Estuary. While a few animals feed on live marsh plants, eelgrass and seaweeds, most of the Estuary's non-planktonic vegetation dies uneaten. This dead plant material is washed back and forth by the tides and attacked by decomposing bacteria until it is broken down into small, nutrient-rich, bacteria-coated particles known as *detritus.* These detrital particles are then eaten by the filter-feeders and surface grazers, and the sifters and slurpers of mud.

Life in the Marsh

Until the Gold Rush the entire Delta was one vast freshwater marsh, while large brackish marshes and salt marshes extended across the northern portions of Suisun and San Pablo bays and the southern half of the South Bay. Smaller freshwater and seasonally flooded marshes lined the lower reaches of rivers and creeks emptying into the Bay. Marshlands then covered about 850 square miles, or nearly two-thirds of the area of the Estuary.

Tidal marsh. In the marshes that are regularly flooded and emptied by the tides, ecologists generally recognize two or three zones with distinct groups of plants growing at different elevations. Physical factors such as the length and frequency of flooding and the saltiness of the soil tend to set the lower limits for these plants, while competition from other plants usually limits their upward growth. Although from a distance the boundaries between zones seem sharp, they are often fuzzy at close range, with plant species intergrading across boundaries and cropping up outside of their nominal zone in response to subtle differences in elevation, soils or drainage.

These zones are clearest in the Estuary's salt marshes. Where exotic plants have not invaded, stands of Pacific cordgrass, which can tolerate relatively long periods of flooding, fringe the water's edge and line the lower channels. Typically, the largest section of the marsh is a flat, salty, waterlogged plain above the cordgrass, covered with the succulent, branching stems of pickleweed. Here and there, where water circulation is limited, tangled nets of orange, thread-like dodder, a parasitic vine, overgrow the pickleweed. Near the marsh's landward edge the pickleweed mixes with other low-growing plants such as saltgrass, fat hen, alkali heath, arrowgrass, jaumea and marsh lavender, along with taller shrubs of gumplant. These plants also grow on the slightly-elevated and better-drained soils alongside channels, so that otherwise hidden channels are often marked by lines of yellow-flowered gumplant winding across the pickleweed plain.



Characteristic Zonation of Tidal Marsh Vegetation

	Salt Marsh	Brackish Marsh		Freshwater Marsh
		Saltier	Fresher	
Mean Higher High Water	Saltgrass *(Distichlis spicata)*, Fat Hen *(Atriplex patula hastata)*, Alkali Heath *(Frankenia grandifolia)*	Pickleweed *(Salicornia virginica)*, Saltgrass *(Distichlis spicata)*, Fat Hen *(Atriplex patula hastata)*, Gumplant *(Grindelia humilis)*	Baltic Rush *(Juncus balticus)*, Brass Buttons *(Cotula coronopifolia)*	Arroyo, Sandbar & Gooding's Willows *(Salix* spp.*)*, Buttonbush *(Cephalanthus occidentalis)*, Dogwood *(Cornus stolonifera)*
Mean High Water	Pickleweed *(Salicornia virginica)*, Dodder *(Cuscuta salina)*	Alkali Bulrush *(Scirpus robustus)*	Olney's Bulrush *(Scirpus olneyi)*, Common Cattail *(Typha latifolia)*, Narrow-leaved Cattail *(Typha angustifolia)*	Common Tule *(Scirpus acutus)*, Common Reed Grass *(Phragmites communis)*, Common Cattail *(Typha latifolia)*
Mean Tide Level	Pacific Cordgrass *(Spartina foliosa)*	California Tule *(Scirpus californicus)*		
Mean Low Water			California Tule *(Scirpus californicus)*	California Tule *(Scirpus californicus)*, Common Reed Grass *(Phragmites communis)*
Mean Lower Low Water				

Bulrush

In more brackish marshes the zones are less distinct, but show up best on steep banks. The tall, round, grayish-green stems of California tule crowd the lowest level. Triangular-stemmed alkali bulrush dominates the middle zone in the saltier regions, with Olney's bulrush and cattails more common at this level in fresher waters upstream. In the highest zone, pickleweed and saltgrass grow on the saltier soils, with Baltic rush and brass buttons (a non-native member of the aster family) on the fresher soils. A few rare plants are found in these marshes, including soft bird's beak, Mason's lilaeopsis and Suisun thistle. While most of the Estuary's brackish tidal marsh lies within Suisun Bay, smaller brackish marshes line the Petaluma and Napa rivers north of San Pablo Bay, and some South Bay sloughs where treated wastewater discharges have freshened former salt marshes.

Although most of the Delta's freshwater marsh has been destroyed, a few channel banks, sandbars and "tule islands" are still clad in vegetation, providing cover for juvenile fish, for wading and water birds, and for aquatic mammals like river otter and the introduced muskrat. California tules and common reed grass grow lowest on the banks, with common tules and cattails abundant at slightly higher elevations, and willow, buttonbush and dogwood shrubs growing at and above the high tide level. Along some sloughs and the lower courses of rivers entering the Delta, mixed stands of willow, white alder, cottonwood, sycamore and valley oak trees, with tangled understories of buttonbush, blackberries and other shrubs and vines, form corridors of riparian forest lining the waterways.

Diked marsh. Suisun Marsh, on the northern shore of Suisun Bay, is the largest remaining marsh in California, but most of it has been walled off from the flow of the tides by a network of dikes. Duck clubs own four-fifths of the roughly 75 square miles of non-tidal marsh, and the state manages the rest as a wildlife area. Behind the dikes, salinities and water levels are manipulated to encourage plants favored by ducks and geese, mainly alkali bulrush, fat hen and the introduced brass buttons. Most of the other 25 square miles of diked wetlands in San Francisco Bay are seasonal, providing wet, marshy habitat in the winter but drying out in the summer.

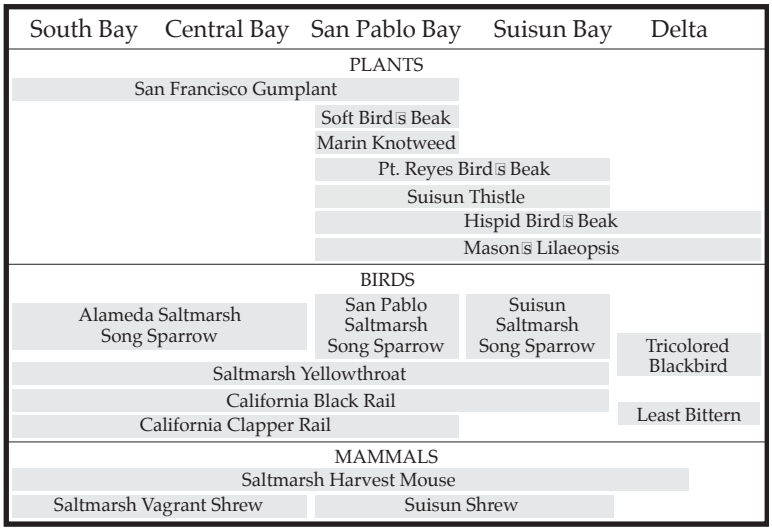
Marsh wildlife. During the first half of the 19th century fur trappers took thousands of beaver from the Delta, and during the last half commercial hunters regularly shipped freshly-killed deer, elk and bear meat and barge-loads of waterfowl and other birds from the Delta and South Bay marshes to the San Francisco markets. The Delta's freshwater marshes and the Bay's brackish marshes provided nesting areas for tens of thousands of dabbling ducks and wintering grounds for many millions of migratory waterfowl. Common winter visitors, now rarely seen in these regions, included trumpeter swans in the Delta, and tundra swans and lesser sandhill cranes in the Bay marshes

Nowadays, few waterfowl nest in the Delta's tiny remaining patches of freshwater marsh, but hundreds of thousands of ducks, geese and swans still rest and feed there in the winter, fattening on waste grains in crop fields where marshes once stood. The winter Delta hosts about three-quarters of the Pacific Flyway's tundra swans, two-thirds of the Flyway's greater sandhill cranes, a quarter of the Flyway's greater white-fronted geese, and a quarter of the nation's cinnamon teal.

Downstream, in the undiked brackish and salt marshes, wildlife activities shift in rhythm with the rise and fall of the tides. At high tide, small fish including gobies, sculpin and three-spined stickleback forage in the smaller channels and in among the cordgrass and bulrush fringing the lower portions of the marsh. The ebbing tide concentrates these and other fish in larger sloughs, where screeching terns fall upon them out of the air, dropping with head-smashing violence into the water and somehow emerging with fish between their bills. Cormorants slip beneath the surface to chase their prey, sometimes teaming up to herd the fish before them.

Along channel banks and slough edges, night herons and great egrets wait patiently for fish to come to them, while the smaller and more excitable snowy egrets stalk and pounce nearby, or plow their yellow-gloved feet through the mud, scouring up shrimp and other morsels. As the water drains from the marsh, saltmarsh song sparrows peck in the damp mud beneath the pickleweed canopy for small worms and snails to augment their

Distribution of Rare Tidal Marsh Organisms



The populations of these species have declined due to human activities, and many are listed as endangered or threatened under state or federal law.

diet of seeds, while red foxes search for the nests of rails, egrets and other birds. Harbor seals haul out on the pickleweed to loaf and sleep—a herd has hung out on Mowry Slough in the South Bay for over 70 years, birthing a new generation of pups each spring.

As the tide returns, sandpipers, dowitchers and other shorebirds are driven up from the mudflats where they feed at low tide. Sometimes the taller shorebirds such as willets and greater yellowlegs venture into the marsh to hunt for insects and other invertebrates. But most shorebirds huddle in open, unvegetated areas, where they can watch for approaching predators while waiting for the water to drop. At the highest tides, northern harriers and an occasional short-eared owl glide low over the marshes and levees, searching for rails or mice flushed from cover by the rising water.

Several rare animals make their homes in the Estuary's tidal marshes. These include the endangered saltmarsh harvest mouse and two species of shrew in the northern and southern reaches. Rare songbirds include the saltmarsh yellowthroat, with its unmistakable black mask and *witchety-witchety* call; and the Suisun, San Pablo and Alameda (South Bay) races of saltmarsh song sparrow, which have some of the smallest natural ranges of any birds in North America. The San Pablo and Alameda races live in true tidal salt marsh, which provides a refuge from competitors but only low growing vegetation to nest in, and each year these sparrows lose many nests, eggs and chicks to the rising tides.

The California black rail lives hidden under the pickleweed canopy, primarily in brackish marshes around Suisun and San Pablo Bays, where it feeds on insects and crustaceans. It is most often observed during the winter when high tides drive it out of the pickleweed and onto higher ground. The endangered California clapper rail has also been described as a secretive bird, but frequently belies its stealthy reputation by bumbling through the marsh and announcing its presence with a loud, clattering call. Clapper rails were abundant in the 1800s, when a good hunter could bag over a hundred in a day. Their numbers were first reduced by overhunting, then by destruction of their marsh habitat, and more recently by exotic predators, especially red foxes from the Midwest and Norway rats from Europe. There are only about 1,200 left today, all of them in the marshes of the Estuary. (More of the clapper rail's story is told later in this booklet.)

Although diked wetlands are artificial habitats, they are nevertheless important to wildlife. Over 200 species of birds have been seen in Suisun Marsh, and mallard, gadwall, cinammon teal, shovelers, pintail and ruddy duck nest there. Other diked wetlands in the Bay Area serve as feeding or resting areas for shorebirds and waterfowl. Some provide refuge for saltmarsh harvest mice when high tides chase them from the tidal marsh.

Life in the Water

The many types of phytoplankton, zooplankton, shrimp and fish that drift or swim in the Estuary are distributed among different salinity regions. For example, of the roughly 120 regularly occurring fish species, two are estuarine fish (delta smelt and longfin smelt), about a quarter are freshwater fish, two-thirds are marine-derived fish that range various distances into the Estuary, and the remainder are *anadromous* fish, which spend their adult lives in salt water but moving upstream into fresher water to spawn. The positions and abundances of many of these fish shift dramatically with changes in inflows, currents or tides.

Fresh waters. When the Delta was a nearly-continuous marshland, masses of decaying reeds along with leaves dropped by the willows, alders and cottonwoods that grew on the banks of the sloughs provided a larger detrital food source than exists today. Thick clouds of insects hovering over the marshes and numerous insect larvae crawling over the bottom would have provided additional food for some of the Delta fish. So the diking and draining that eliminated virtually all of the Delta's marshes must have also changed conditions for the organisms living in the adjacent open waters. Today, the Delta's food web is based primarily on organic material washed in from the rivers and on the phytoplankton growing within the Delta itself.

The phytoplankton in the Delta mainly bloom in the late spring or early summer, especially when residence times are long and nutrient concentrations, light levels and temperatures are high. River flows, channel shapes and the amount of water diverted by the water agencies all have an influence on residence times. When flows are high, phytoplankton are flushed through the Delta too quickly for much growth to occur. In most years the phytoplankton bloom only after the winter floods have passed, in wet years they bloom later in the year, and in the wettest years they may not bloom at all. The slowest currents and longest residence times occur in dead-end sloughs and within flooded islands, where phytoplankton are far more abundant than in the deeper, dredged channels. In the summer and fall when there is little water flowing into the Delta, water diversions can significantly shorten residence times in the south Delta channels by pulling through and pumping out large volumes of water, which also removes a substantial portion of the phytoplankton. Despite these diversions, phytoplankton are more abundant in the southern Delta than in the north. In the north the Sacramento River's large flows and deep, straight channels result in fast currents and short residence times, producing low phytoplankton concentrations, while in the south the slower, shallower, warmer and more nutrient-rich San Joaquin River often supports blooms that are ten times denser than in the north.

Phytoplankton concentrations affect other life in the Delta. The distribution of zooplankton—mainly water fleas, copepods and rotifers—parallels the distribution of phytoplankton. Zooplankton concentrations are typically 5 to 10 times greater in the southern Delta, reaching densities of up to 150,000 individuals per gallon. Fish are also more abundant in the southern than in the northern Delta. Exotic species dominate, including such popular

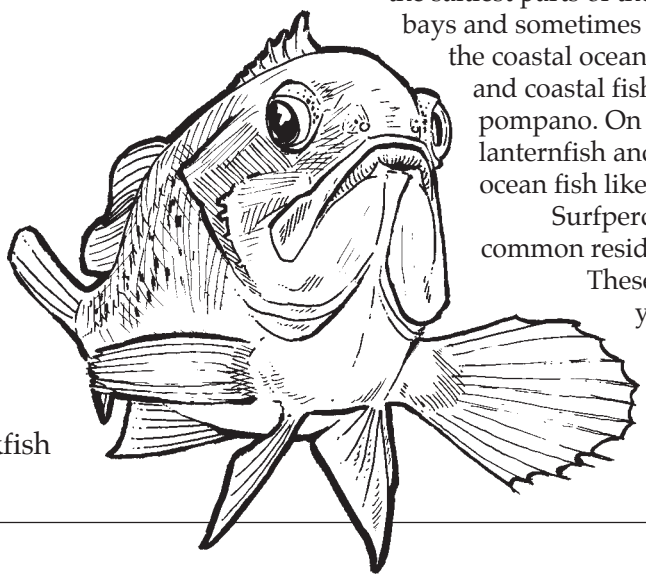
warmwater gamefish as largemouth bass, bluegill and black crappie, as well as carp, goldfish, inland silverside, threadfin shad and golden shiner. Two species of catfish introduced to the Delta in 1874 became so abundant that they supported a thriving commercial fishery for 70 years, which even shipped catfish back to Mississippi. Meanwhile, two native fish that were frequently caught by the region's aboriginal inhabitants are now absent from the Delta, the Sacramento perch and the extinct thicktail chub.

Low salinity waters. Downstream from the Delta, the broad, shallow, brackish waters of Suisun Bay historically produced abundant annual diatom blooms. These blooms supported a large crop of zooplankton, dominated by the copepod *Eurytemora affinis* and its frequent predator, the opossum shrimp *Neomysis mercedis*. The phytoplankton and zooplankton were usually concentrated around the entrapment zone (discussed above). Grass shrimp, delta smelt, American and threadfin shad, and juvenile striped bass fed on the zooplankton, and in turn were eaten by larger predators like adult striped bass.

However, several exotic invertebrates introduced in discharges of ships' ballast water have altered these food chains in recent decades. An Asian clam, *Potamocorbula amurensis*, has become so phenomenally abundant and eats so many phytoplankton that it eliminated blooms in the brackish waters of the northen reach. (Note that there are several clams from Asia that have been introduced into the Estuary, and that two have often been referred to as *the* Asian Clam: the brackish/marine clam *Potamocorbula* and the freshwater clam *Corbicula fluminea*, which is common in the Delta.) Several Asian species of copepods and opossum shrimp have increasingly dominated the zooplankton while native species have declined. At least one new copepod is better than the natives at evading capture by the Estuary's fish, and so provides a poorer food supply for them. *Potamocorbula* may have contributed to these changes both by eating larval copepods and by eating the phytoplankton that had been a major food supply for zooplankton. In addition, three species of jellyfish from the Atlantic basin, which feed on copepods and other zooplankton, have become established in this part of the Estuary. (These changes are discussed in greater detail later in this booklet.)

High salinity waters. As one moves farther downstream, fewer freshwater and more saltwater species are encountered. In the saltiest parts of the system, including the Central and South bays and sometimes San Pablo Bay, we find organisms typical of the coastal ocean including marine diatoms and copepods and coastal fish like barred surfperch, lingcod and Pacific pompano. On occasion, deep-water fish like the blue lanternfish and the northern lampfish, and wide-ranging ocean fish like the thresher shark, visit the Bay.

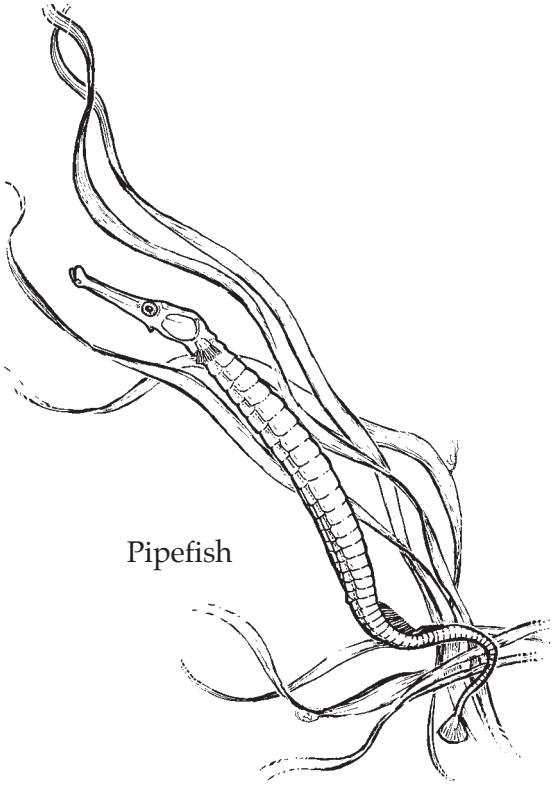
Surfperches, sculpins and gobies are the most common resident fish in the saltier parts of the Estuary. These fish provide a high degree of care for their young, with the bottom-dwelling sculpins and gobies laying eggs in nests or burrows, and surfperches giving live birth. Shiner surfperch are probably the most abundant fish around piers and pilings, accompanied



Rockfish

by other surfperch species, white croaker, brown rockfish and the peculiar bay pipefish. Like an uncoiled seahorse (a close relative), the pipefish sculls along with its fluttering dorsal fin, searching for tiny organisms to suck in through its trumpet-shaped mouth. Female pipefish lay their eggs in a pouch on the male's belly, where they remain until they hatch.

Pacific herring, northern anchovy and longfin smelt—shiny, silver-bodied fish that travel in schools and feed primarily on plankton—range through all parts of the Estuary. Herring and anchovy are ocean fish that enter the Estuary in large numbers during part of the year, the herring to spawn and the anchovy to feed. In the 1930s and 1940s, the similar Pacific sardine was also abundant in the Bay and along the central California coast, supporting a huge fishery and numerous canneries in the Bay Region and on Cannery Row in Monterey. But then the sardine virtually disappeared from these waters, apparently due to overfishing and changes in ocean temperatures, though it has started to come back in recent years.



Pipefish

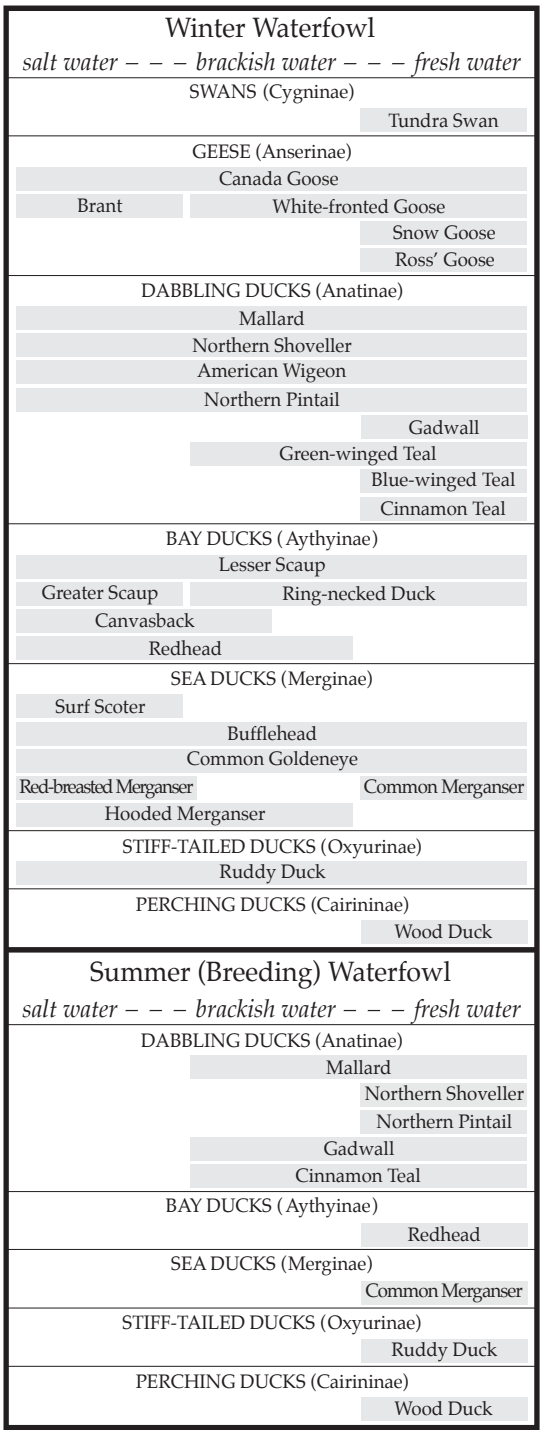
South Bay water generally contains less suspended sediment and is clearer than water in the northern reach, has a longer residence time, and receives a larger amount of nutrients from wastewater discharges. Such features suggest that the South Bay should be prone to *eutrophication*, a condition characterized by excessive blooms of phytoplankton whose subsequent decay and decomposition can deplete the oxygen in the water, sometimes to the point of killing fish. However, eutrophic incidents have not occurred in the South Bay, apparently because phytoplankton growth is limited by filter-feeding benthic invertebrates, which are about ten times more abundant here than in the rest of the Estuary and usually consume the phytoplankton faster than they can bloom.

Short, sharp blooms do occur each year in the South Bay, with phytoplankton densities briefly increasing to 20 times or more above their normal levels. This happens when freshwater inflows are large enough to stratify the water in the channels (with the lighter fresh water floating in a layer on top of heavier salt water), the tidal currents and winds are too weak to mix the stratified water, and benthic filter-feeders are not abundant in the shallows—conditions that arise only during calm, neap tide periods in the spring season. At such times the phytoplankton in the upper water layers in the channels are separated from the filter-feeding organisms on the bottom, and thus have a chance to multiply and bloom before they are eaten up. But after a week or so, stronger tides or winds stir the water, bringing phytoplankton and the benthic organisms that feed on them back into contact, and the bloom begins to subside. Some researchers remain concerned, however, that water diversions could reduce the peak winter and spring river flows that flush contaminants out of the South Bay, thereby exposing filter-feeding organisms to higher levels of toxic contaminants, reducing their numbers and their capacity to control phytoplankton populations, and allowing eutrophication to occur.

Brine Shrimp

Salt ponds. Travellers flying in over the southern limb of the Bay marvel at the sight of enormous green, red and purple polygons covering the landscape beneath them. These colorful shapes are part of a network of salt ponds constructed over half a century

Typical Distribution of Waterfowl in the Estuary



ago, which owe their varied hues to the bacteria, algae and other organisms proliferating within them. Former salt ponds, now owned by state or federal agencies and managed as wildlife habitat, surround the southern end of the South Bay, the northeast shore of San Pablo Bay, and the lower reaches of the Napa River, while active salt-making ponds occupy the shallow margins on either side of the South Bay.

In these, Bay water is pumped or flowed from pond to pond as it is heated and evaporated by the sun to create an increasingly salty brine. After five to seven years, when the brine is sufficiently concentrated, it is pumped into smaller rectangular ponds called crystallization beds. Here the salt crystals precipitate out on the bottom, the remaining fluid is drawn off, and large, mechanical harvesters scrape up the caked salt and pile it in 90-foot-high white mounds that rise like miniature alpine peaks near Newark and Redwood City. This produces about a million tons of salt a year.

The ponds may appear desolate, even spooky, to a first-time visitor, especially on a still, summer day. Brine flies crawl over the oddly-tinted water surface and the spongy, salt-encrusted soils, rising in thick clouds at the least disturbance. This harsh environment supports relatively few species, but some of these can be extraordinarily abundant. One vascular plant, wigeon grass, grows in the less salty ponds, along with two filamentous green seaweeds and some invertebrates and fish that are common in the Bay's shallows. In saltier water an insect, the water boatman, strokes its way through the water by the thousands, while topsmelt, which can tolerate salinities of up to 90 ppt (about three times as salty as the ocean), feed on copepods and graze the bottom for amphipods and detritus. With higher salinities the ponds support even simpler ecosystems, dominated by two singled-celled algae and brine shrimp so abundant that they are netted and sold as food for aquarium fish.

The combination of quiet isolation and plentiful food attracts birds in greater concentrations than are found in other habitats on the Bay, with over 200,000 shorebirds and 75,000 waterfowl reported on the South Bay's salt ponds in the winter. Some come to the ponds to rest when the tides cover the mudflats, while others, including earred grebes, Bonaparte's gulls and white pelicans, feast on brine shrimp, brine flies and small fish. Tiny phalaropes spin round and round on the pond surface, creating eddies that trap brine shrimp and water boatmen. Small flocks of black-necked stilts forage in the shallower water, whose still surface perfectly mirrors the birds' immaculate black and white plumage and spindly, blood-red legs. At the pond's edge, snowy plovers skitter about snapping at brine flies. The levees and dried-up bottoms of salt ponds provide the only Bay Area nest sites for the plover (whose Pacific coast population is listed as threatened under the federal Endangered Species Act). Caspian and Forster's terns also nest on dikes and islands among the ponds. Many of these birds are much more common in the Bay Area than they would be without the salt ponds.

These ponds, and the question of whether to preserve them as wildlife habitat or convert them to tidal wetlands, pose a quandary for resource managers. Although the salt ponds surrounding the Bay today are artificial environments constructed on

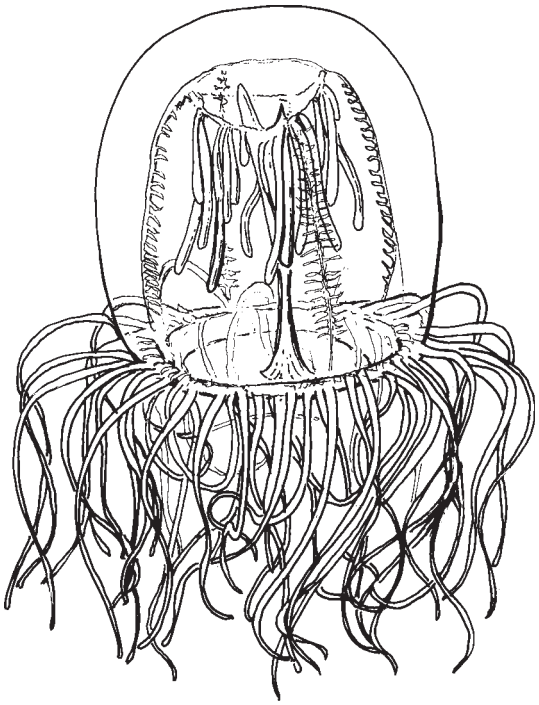
former marsh and mudflat, during the 1800s there were a few natural salt ponds that formed behind wave-built berms, especially along the Hayward shore. These natural ponds, however, were small and few, their water levels and salinity would have varied greatly with the season, and their ecology was probably quite different from today's artificial ponds. While the current ponds do augment the diversity and abundance of bird life in the region, they are largely dead-end environments for the fish, invertebrates and other aquatic organisms living within them. These organisms inevitably die as the salinity rises, neither returning nor releasing offspring back into the Bay. Except to the extent that they serve as bird food, they are lost to the larger environment.

Anadromous fish. Fish that live in salt water as adults but migrate into fresh water to spawn are classified as *anadromous* fish. Some anadromous fish have been among the most important commercial and sport fish in the Estuary, including salmon, striped bass, steelhead trout, American shad, and white and green sturgeon.

In the 1800s, staggering numbers of salmon were reported in the Estuary and its tributary rivers, with accounts of runs so thick in some streams that they scared off horses trying to cross them. Chinook salmon (also called king salmon) migrate upstream through the Estuary in four runs in the fall, late-fall, winter and spring, to spawn in the main stem and tributaries of the Sacramento River and in the Cosumnes, Mokelumne, Stanislaus, Tuolumne and Merced rivers. The salmon congregate over gravel beds, where a female begins the spawning cycle by digging a shallow pit with powerful sweeps of her tail. She is then joined by a male, and the two fish exchange a series of courtship signals and responses until they simultaneously release a cloud of eggs and sperm over the pit. The fertilized eggs fall into the gravel and the female sweeps additional gravel over them from upstream, forming a mounded nest known as a *redd*. Both fish repeat the process with other partners until they are depleted of eggs and sperm, and then they die.

The developing eggs and newly-hatched fry remain in the spaces between the gravel for about three months. Clean, cold, well-oxygenated water flowing freely through gravel of the appropriate size is essential for developing salmon. The emerged *fry* and older juveniles called *smolts* eventually migrate downstream to the Estuary, feeding along the way on insects, water fleas, amphipods and other crustaceans. After adjusting to salt water they leave for the ocean, where they may travel as far north as British Columbia and south to Monterey. After two to four years they return to the river of their birth, to spawn and die in turn.

Today, large dams block these salmon from reaching most of their former spawning grounds on the upper rivers. This has especially devastated spring-run salmon, whose life cycle depends on reaching pools in the upper rivers where they can pass the summer before spawning in the fall. Many salmon populations have also suffered from changes in flows and water temperatures and the loss of gravel beds downstream of dams and water diversions, in combination with bouts of overfishing that started in the mid-1800s. Many of the remaining runs in the watershed dropped to alarmingly low levels in the early 1990s, then recov-



A native jellyfish,
Polyorchis penicillatus

ered to varying degrees with larger river flows in the late 1990s. However, many of the salmon in the watershed come from hatcheries rather than natural spawning, and the depleted winter run of chinook salmon on the Sacramento River was listed as an endangered species in 1990.

Striped bass and American shad are native to the Atlantic and were introduced to the Estuary's watershed in the 1870s and 1880s, during a period of great disturbance and silt deposition from hydraulic mining. Both spawn mainly in the Sacramento River or its tributaries, and produce eggs that float or are carried along the bottom by currents. By the 1890s both fish had become abundant enough to support commercial fisheries, and some researchers suggest that their explosive growth was due to their producing eggs that were not smothered by silt.

Striped bass eggs hatch two to three days after spawning, and many of the larvae drift downstream and become concentrated in the entrapment zone, where they feed on copepods and other zooplankton. As they grow they feed on opossum shrimp and then increasingly on other fish. The adults live in the lower bay or the ocean, where males reach maturity in two to three years and females in four to five. The catch of striped bass declined after 1915, and since 1935 commercial fishing in the Estuary has been banned to protect the sport fishery. The population has declined in recent decades from peaks in the mid-1960s, reaching very low levels in the late 1980s and 1990s.

Hydrologic factors. The distributions and abundances of plankton, shrimp and fish in the Estuary can change dramatically from year to year with changes in freshwater inflows, which affect both salinity patterns and currents, and with changes in coastal ocean conditions, especially temperature. These factors, in combination with overfishing, pollution and changes in shoreline habitat, have created complicated patterns of population change, which researchers have labored mightily to sort out.

In recent years, several researchers have explored the relationship between the annual abundance of certain species and an index of the salinity gradient. This index, called X2, is defined as the distance in kilometers from the Golden Gate to the point in the northern reach where the salinity at one meter above the bottom is 2 ppt. X2 varies in a general way with freshwater inflows, so that it tends to move upstream with low flows and downstream with high flows.

Until around 1987, various species of zooplankton, shrimp and fish in the northern reach were consistently more abundant in years when X2 was farther downstream. However, since 1987, when the Asian clam *Potamocorbula amurensis* became abundant, researchers have found that zooplankton abundance is no longer related to X2, and disagree about whether the relationship still holds for the shrimp and fish. The issue is important to water managers, because in 1994 the X2 index was incorporated into the Delta's water flow standards.

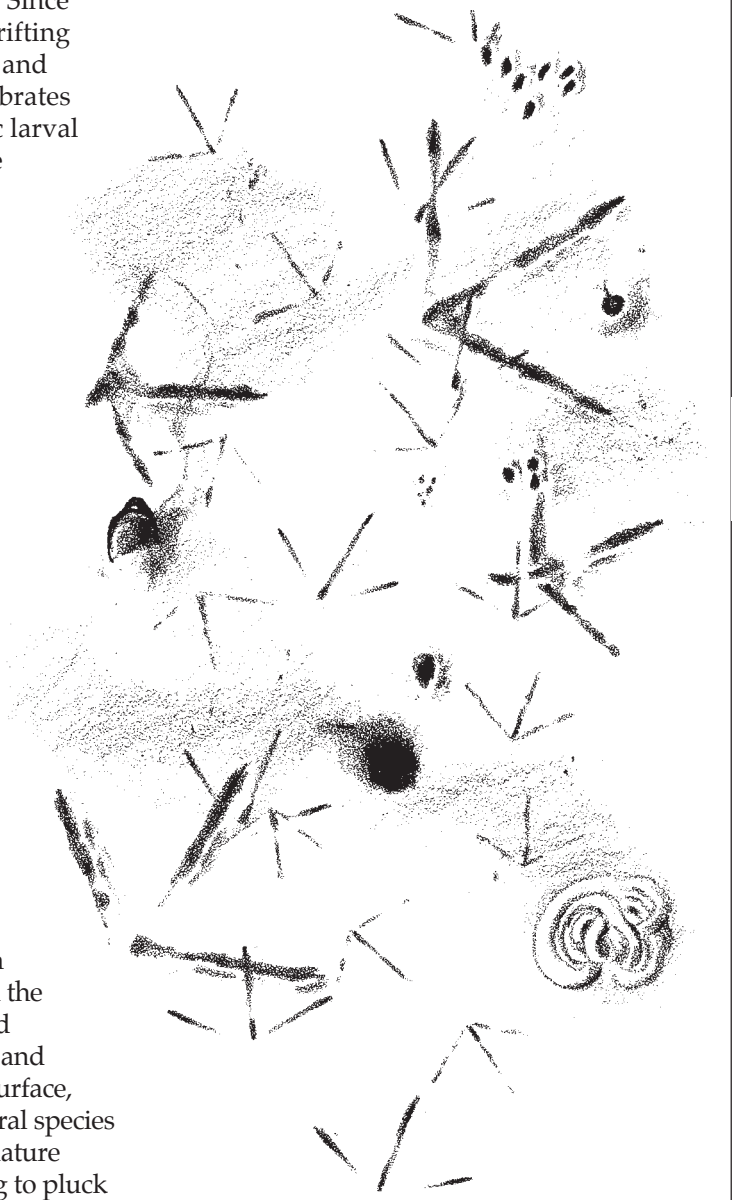
Variations in freshwater inflows may primarily affect the distribution rather than the abundance of some species. For example, some marine, bottom-dwelling fish, such as big skate, move upstream in dry years as salinities rise. In contrast, other bottom-dwelling fish, including sanddabs, turbot and sand sole, move upstream in *wetter* years, presumably carried by the strong

estuarine circulation (in the return currents flowing upstream along the bottom) generated by large freshwater inflows. A similar short-term upstream movement of bottom-dwelling English sole and starry flounder has been observed following floods.

Life on the Bottom

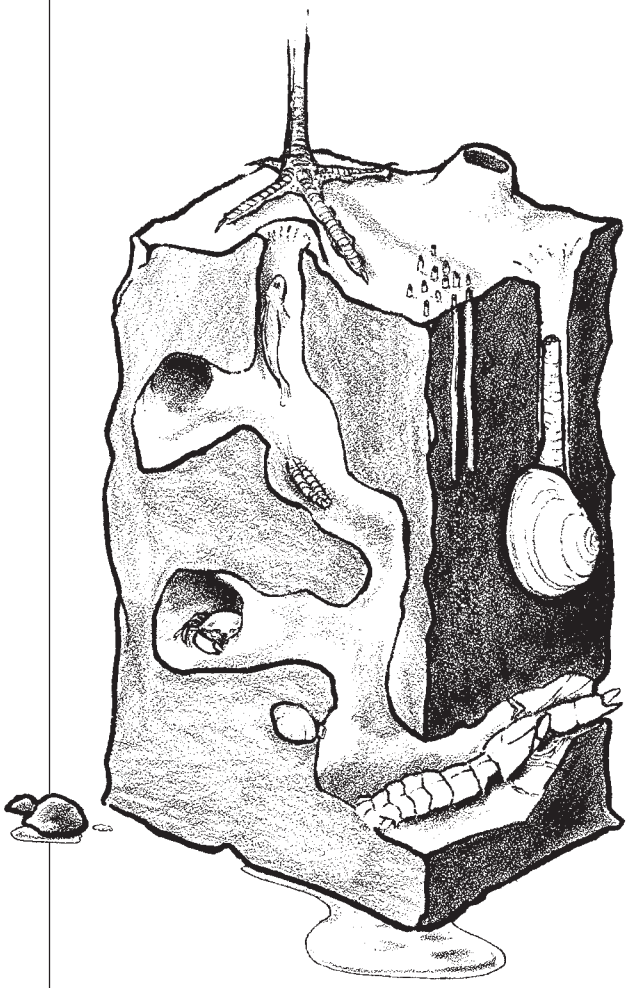
Ecologists recognize two general types of benthic habitats: "soft-bottom" habitats, which consist of muddy or sandy sediments, sometimes with gravel and rocks mixed in; and "hard-bottom" habitats, which include outcrops of natural bedrock as well as various types of artificial objects and structures. Living in these different habitat types requires different sets of skills, such as the ability to burrow if you live in sediments, versus surface-clinging or crevice-hiding abilities if you live on rocks.

In the brackish and salty parts of the Estuary, many bottom-dwelling animals—including most of the clams, crabs, barnacles and worms—spend the early (larval) part of their life as drifting zooplankton. These larvae often look nothing like the adults, but change into adult forms when they settle to the bottom. Since many of the adults are attached or sedentary, it is the drifting larvae that disperse the species throughout the Estuary and between estuaries. In contrast, bottom-dwelling invertebrates that live in fresh water usually have benthic or parasitic larval stages. These are less likely than planktonic larvae to be washed downstream toward salty water, where they or their offspring would die. Some, such as the larvae of certain freshwater clams that attach to fish, ensure that a portion of the population will be carried back upstream. Freshwater bottom-dwellers also include the larvae of dragonflies, damselflies, mayflies, water midges and other flying insects. Although these larvae may be washed downstream, some adults will fly back upstream to lay their eggs, thereby maintaining a population in fresh water.



Soft-bottom habitat. Most of the Estuary is underlain by expanses of mud. Although these vast plains of intertidal ooze appear barren at first, a closer look reveals many signs of life. Etched and embossed on the glistening surface are tracks and bulges, pits and burrows, mud-tubes and feeding-holes indicating a host of hungry creatures. Some suck and trap tiny plants and animals from the water while others sift or pluck them from the mud. Yet other creatures incessantly hunt and prey upon the suckers and sifters, who seek refuge beneath the surface of the mud.

Clams buried safely in the sediments stretch a pair of *siphons*, tubes that they use for both breathing and feeding, up into the water. Operating one siphon like a vacuum hose, they suck in water and food particles, strain out the food on their gills (which also absorb oxygen from the water), and expel water, uneaten sediment and undigested material out through the other siphon. Burrowing worms and anemones extend crowns of tentacles out upon the mud surface, ready to snare any drifting food that settles on them. Several species of amphipods and tanaids (crustaceans that look like miniature shrimp and lobsters) build mud tubes to hide in, emerging to pluck



bits of food from the surface. Mud snails, their shells fuzzy with a coat of filamentous algae, glide over the surface or plow along just beneath it, leaving tracks visible on the surface. Farther below, lugworms—a marine counterpart to earthworms—munch their way through the mud, extracting sustenance from the organic matter in the sediment as it passes through their bodies. They extrude the spent sediment at the surface, where it emerges in coils like toothpaste squeezed from a tube. The food they find in the mud includes benthic diatoms, microscopic single-celled plants that, remarkably, migrate up and down through the mud. When the tide drops in the daytime, the diatoms climb to the exposed surface to gather energy from the sun's rays, coloring the mud yellow or brown; at high tide and at night they retreat beneath the surfaceto hide from diatom-eaters.

Some larger invertebrates, including ghost shrimp, mud shrimp and innkeeper worms, dig tunnel systems under the mud. Ghost shrimp (which are actually closer relatives of hermit crabs than shrimp) are about three inches long, with pinkish- or yellowish-white, translucent bodies and one large, flattened claw, which is especially large on the males. Their burrows emerge at the surface through volcano-shaped mounds, with summit craters that periodically spew puffs of what looks like brown smoke. Ghost shrimp feed by extracting bacteria and detritus from the mud, and must continually enlarge and rework their burrows in order to get at enough mud. The volcano "smoke" is undigested sediment being expelled from the burrows, which adds up to about two cubic inches of sediment per burrow per day. In six months, a bed of ghost shrimp can completely rework the sediment down to about 20 inches, the average depth of the burrows. Anglers catch ghost shrimp for bait, sucking them from their burrows with vacuum-forming piston devices made from PVC pipe.

If undisturbed, a ghost shrimp can live for a surprisingly long time, possibly up to 16 years, attaining the status of an aged patriarch in an eclectic household. Several species of freeloading organisms—we could call them the hole-in-the-mud gang—have taken up quarters in ghost shrimp, mud shrimp and worm burrows, where they are safe from surface predators. In San Francisco Bay these organisms include scale worms and pea crabs; bright red copepods, visible as tiny dots crawling over the ghost shrimp's back; small clams that dig in alongside the burrows and extend their short siphons into them; and arrow gobies, which are visitors to the burrows rather than permanent residents.

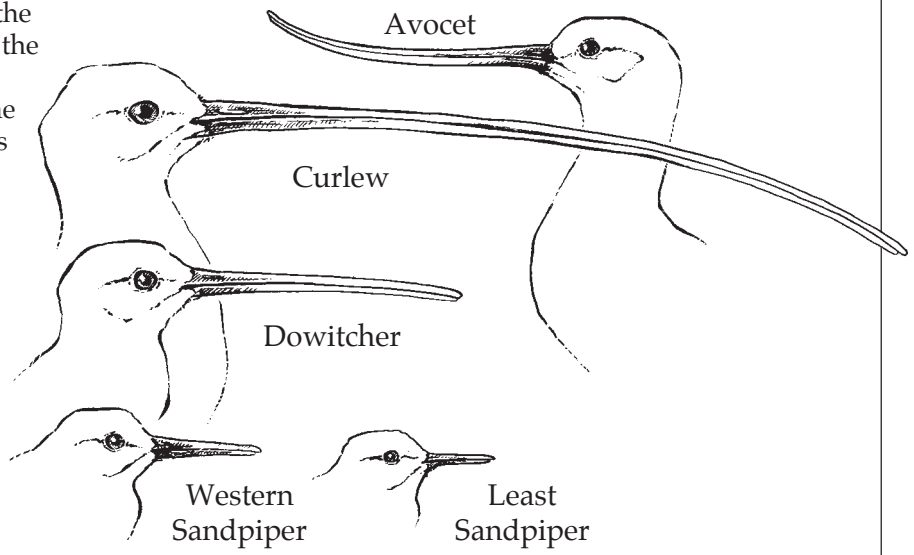
Arrow gobies grow to an inch or two in length, and can be extraordinarily abundant in the shallow pools and thin films of water on the intertidal mudflats. They dart over the sediment surface grabbing tiny organisms including copepods and the settling larvae of worms, clams and other invertebrates, whose numbers they may control. In the laboratory, arrow gobies have been seen carrying pieces of food that are too big for them to swallow to pea crabs, snatching small morsels as the crabs tear them up. Out on the mudflats, when a bird or other predator approaches, arrow gobies bolt down the nearest hole, including shrimp or worm burrows and even the narrow openings left when clams retract their siphons. One researcher collected 24 arrow gobies from a single worm burrow.

All together, the animals living on and under the mud are phenomenally efficient harvesters of the living and dead plankton sifting down from the water column, the algae living on the mud surface, and the detritus washing in from marshes and creeks. When the tide comes in, many of these creatures are feasted upon by leopard shark and starry flounder, which also bite the siphons off of feeding clams. Bat rays glide along just above the bottom and flap their "wings" to wash away the mud and expose buried clams, leaving behind a characteristically pot-holed surface.

But the real feeding frenzy begins when the tide goes out and shorebirds invade the intertidal flats. Hundreds of thousands migrate here in the winter from nesting grounds on the Canadian prairies and arctic tundra, hungry travelers from as far away as Siberia. Prowling avocets sweep their bills back and forth through the soupier mud, while willets conduct a deliberate search for small crabs. Skittering plovers and sandpipers peck shallowly for little worms and crustaceans. Dowitchers probe the middle depths, their bills going up-and-down like sewing-machine needles as they stitch their way across the mud. The godwits' four-inch bills reach deeper still, while the the curlews' absurdly long, down-curved bills grapple with worms and clams burrowing eight inches under the mud. Occasionally mallards join the shorebirds, thrusting heads and necks deep into soft, soupy patches in the mud, gobbling up clams and leaving their white, worm-like siphons scattered behind.

Many invertebrates that inhabit intertidal mudflats are also found on the muddy bottom below the reach of the tides. There they are safe from attack by shorebirds, but are fed on by diving ducks and by bottom-feeding fish such as sturgeon, which have a hose-shaped mouth for sucking up food from the mud. Eelgrass, one of the few vascular plants that has adapted to life under the sea, breaks the monotony of mud with scattered patches and beds along the shallow margins of the Bay. These provide cover for larval and juvenile fish, which feed on the invertebrates and small seaweeds that live on the eelgrass. Here and there, larger seaweeds grow attached to bits of rock, shell or debris. The most common are flat, green sheets of sea lettuce, *Ulva lactuca*, green tubes of *Enteromorpha intestinalis*, and long branching strings of a red alga, *Gracilaria sjoestedtii*.

One celebrated bottom-dweller uses the Estuary only during part of its life cycle. In the late fall, Dungeness crab spawn outside of the Bay in the Gulf of the Farallones, and the females carry large masses of fertilized eggs under their abdomens. The larvae hatch during the winter and drift in the ocean for about three months, growing and molting through several stages. They then somehow drift back close to shore, possibly carried by currents associated with the start of the upwelling season. Whatever the mechanism, large numbers of larval crabs settle to the bottom near the Golden Gate and enter the Estuary in May or June as juveniles less than half an inch



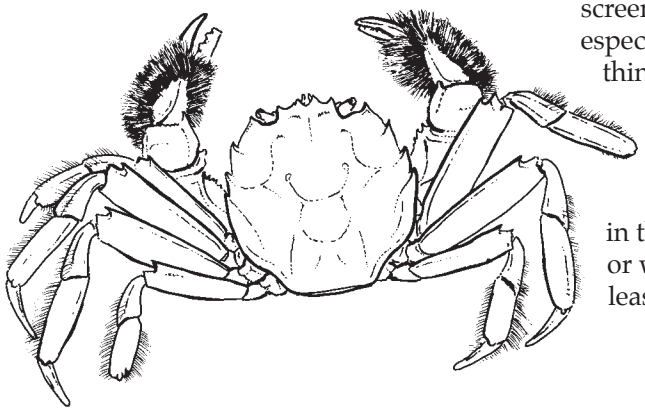
wide. They spend over a year in the Estuary, ranging upstream as far as Suisun Bay, and growing to 3-4 inches in width before returning to the ocean in August or September. After a few more years of growth they reach the legally harvestable size of six and a quarter inches. Studies have found that most of the Dungeness crab caught along the central California coast grew up in the Estuary. A closely related crab, the red rock crab, is commonly captured in ring nets at fishing piers around the Bay.

Throughout the Estuary, populations of benthic organisms can vary greatly from year to year. This is especially true in the Suisun Bay area of the northern reach, where (as with the zooplankton, shrimp and fish discussed earlier) the bottom fauna often shifts radically with each year's change in water flows. During wet years the bottom is colonized by freshwater invertebrates that are typical of the Delta. In drier years, salinity-tolerant species move in, possibly carried as floating larvae in upstream-flowing bottom currents. Since 1987, an Asian clam, *Potamocorbula amurensis,* has taken over this area, virtually excluding other clam species, and spread throughout the rest of the Bay. The hard shells of this clam, poking up through the mud, provide a new substrate that a few organisms have exploited, the most common being a white barnacle from the Atlantic Ocean.

Farther upstream, the Delta's benthic populations are dominated by five filter-feeding invertebrates: two tube-dwelling amphipods, a tube-dwelling and a burrowing worm, and the freshwater Asian clam *Corbicula fluminea*. These organisms may occur in densities of up to 10,000 individuals per square foot, providing sustenance for bottom-feeding vertebrates like catfish and sturgeon. Although the region's only native crayfish, the sooty crayfish, is extinct, two exotic crayfish are common in the Delta and in streams flowing into the Bay and Delta. The red swamp crayfish was introduced from the lower Mississippi River area and the signal crayfish from the Pacific Northwest. Typically, 50 to 250 tons of primarily signal crayfish are harvested from the Delta each year.

The recently introduced Chinese mitten crabs could offer competition to these crayfish. Mitten crabs live as adults in freshwater rivers and go down to the sea to spawn, a migration pattern known as *catadromous*, opposite to that of anadromous fish like salmon and striped bass. These crabs were first collected on the Pacific Coast in the South Bay around 1992, and have since become abundant throughout the Estuary and many of its tributaries. Large numbers of mitten crabs are caught each year at the fish screens of the federal and state water pumps in the southern Delta, especially during the fall migration when unsuspecting crabs, thinking they are headed downstream, follow the water being drawn into the pumps. Mitten crabs were first seen in the Delta in 1996 and turned up in huge numbers in the fall of 1998, when tens of thousands of crabs per day clogged the fish screens. Although fewer crabs showed up at the screens in the following year, a large population could affect food webs or weaken stream banks or levees with extensive burrows, at least in the saltier parts of the Estuary.

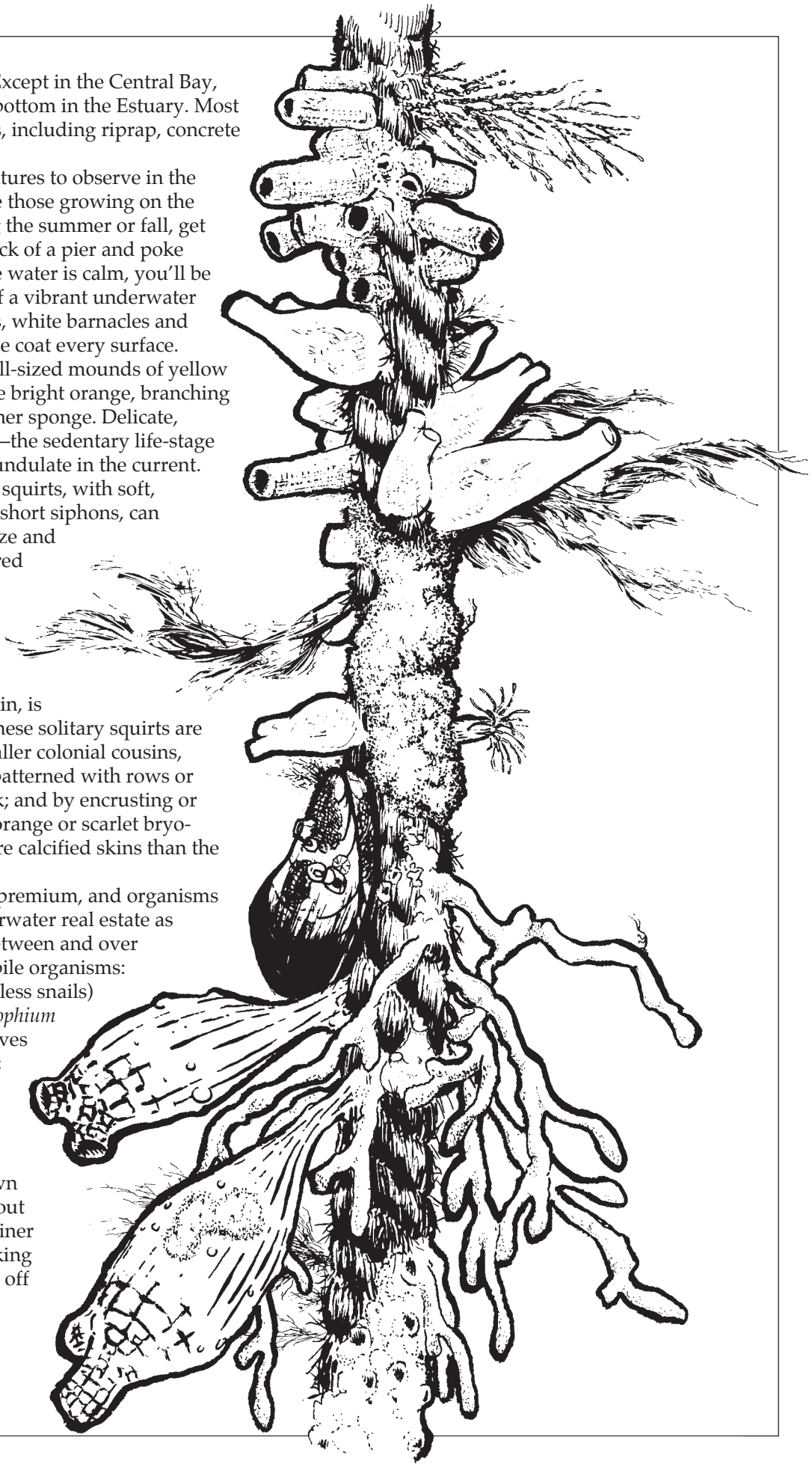
Chinese Mitten Crab



Hard-bottom habitat. Except in the Central Bay, there is little naturally rocky bottom in the Estuary. Most consists of artificial substrates, including riprap, concrete seawalls, piers and pilings.

Perhaps the easiest creatures to observe in the saltier parts of the Estuary are those growing on the sides of floating piers. During the summer or fall, get down on your belly on the deck of a pier and poke your head over the side. If the water is calm, you'll be rewarded with a close view of a vibrant underwater world. Dark blue bay mussels, white barnacles and pale-green sheets of sea lettuce coat every surface. Overgrowing these are softball-sized mounds of yellow "breadcrust" sponges, and the bright orange, branching "dead-man's fingers" of another sponge. Delicate, translucent hydroid colonies—the sedentary life-stage of a type of jellyfish—gently undulate in the current. Several species of solitary sea squirts, with soft, sack-like bodies and a pair of short siphons, can be distinguished: one is the size and shape of a large marble, covered with silt and detritus; a larger species is transparent, its internal organs showing clearly through its skin; yet another, up to six inches long with a tough, warty brown skin, is attached by a narrow stalk. These solitary squirts are partially covered by their smaller colonial cousins, which form gelatinous mats patterned with rows or starbursts in orange and black; and by encrusting or branching colonies of white, orange or scarlet bryozoans, which have stiffer, more calcified skins than the colonial squirts.

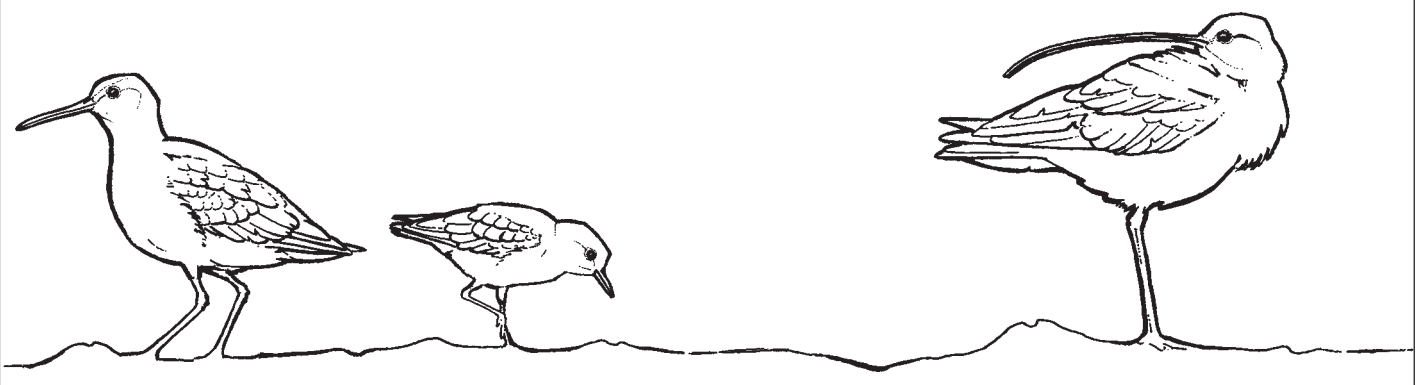
Space is obviously at a premium, and organisms pack onto this desirable underwater real estate as thickly as they can. Roving between and over them are several types of mobile organisms: iridescent nudibranchs (shell-less snails) laying large coils of eggs; *Corophium* amphipods dragging themselves about by their stout antennae; and thousands of bizarre-looking skeleton shrimp clinging to hydroids and seaweeds with three pairs of rear legs, bowing up-and-down in the current and looping about like inchworms. Schools of shiner surfperch swarm about, plucking at skeleton shrimp or nipping off the feeding legs of barnacles.



The organisms in these "float-fouling" communities vary with the type, depth and orientation of the substrate, with the salinity and temperature of the water, and with the season and other factors. An associated community found on wood and concrete pilings is a little more constant. Unlike the sides and bottoms of the floats, the upper part of each piling is exposed to the air at low tide, and fewer kinds of organisms can survive here. The most abundant is usually a white barnacle, *Balanus glandula*, joined at higher levels by a smaller grayish-brown barnacle and sometimes by two types of snail, a limpet and a small black periwinkle. Lower down there is often a band of bay mussels, and below that, where they are rarely or never uncovered by the tides, live many of the same seaweeds, sea squirts, hydroids and bryozoans that grow on the floating piers.

Many parts of the Bay shore have been "hardened" with a covering of rocks and boulders called riprap, like those used in the construction of jetties, and the adjacent mudflats often have a scattering of smaller rocks that have washed or rolled onto the mud. The brown seaweed thickly mantling the larger rocks in the lower intertidal zone is *Fucus*, recognized by its flattened, bifurcating blades with bulbous tips. The larger oval blades covered with small bumps are a red seaweed *Chondracanthus*, sometimes called Turkish towel; and thin, translucent olive sheets are *Porphyra*, better known as the edible seaweed *nori*. The smaller rocks are coated with green seaweeds, especially the flat sheets of sea lettuce and the irregular tubes of *Enteromorpha*, both of which tolerate low salinities.

At low tide the yellow shore crab, which grows to about an inch in width and is often more green than yellow, crowds underneath the rocks lying on the mud. Toward the Estuary's mouth it is joined under the rocks by its cousin, the purple shore crab, and upstream in fresher waters by an introduced Atlantic mud crab. Another exotic species found among these rocks is the European green shore crab, which is usually a dirty orange. Clambering about on the boulders and bedrock one encounters perhaps the nastiest crab in the Bay, the lined shore crab. It's a beautiful crab, up to 2-3 inches wide, with a purplish-red back decorated with fine transverse lines and a startling teal green flap of flexible inner shell showing at its elbow. But it is quick with its claws, snapping at any effort to catch it, or wedging backwards into a crack in the rocks with claws spread menacingly outward, daring the rash collector to reach closer.



Human Activities

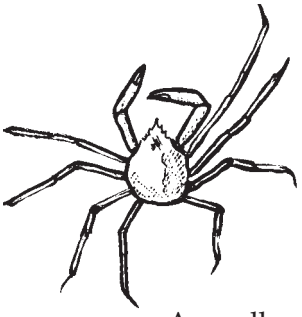
Commercial, industrial, agricultural and mining activities have unquestionably altered the types and numbers of organisms living in the San Francisco Estuary. However, due to the complexity of the ecosystem, including large natural fluctuations in river flows and associated variation in species composition, distribution and abundance, it may be difficult to determine whether any particular change indicates a long-term trend. And because the Estuary has been affected in so many different ways, proving that a specific activity is the cause of a particular change may in some cases be impossible. These difficulties are compounded by our ignorance of historic conditions. Serious scientific study began only after the Estuary had already been substantially altered.

Still, a few effects are clear. The destruction of 80 percent of the Estuary's marshes has cut its carrying capacity for migratory waterfowl and for some resident birds and mammals, and probably reduced its value as a nursery and feeding area for certain fish and shellfish. The few remaining marshlands are thus of heightened importance, and any further degradation or loss could be expected to have increasingly harmful effects.

The construction and operation of flood control and water supply systems have had many environmental consequences. Dams built on major tributaries have blocked salmon and steelhead from reaching spawning grounds, wiping out magnificent runs. This has been exacerbated on some rivers by water diversions that reduce critical flows. Large pumps in the south Delta can reverse the flow in some channels, further disrupting migrations. Pumps also remove or kill large numbers of plankton and the eggs and young of fish. Reductions in flows into the Estuary can have numerous effects, although there is disagreement on the specific mechanisms and consequences. It is clear, however, that some species of fish do better when flows are high.

Improved treatment of municipal and industrial waste water over the past three decades has dramatically improved water quality, particularly in the South Bay. But despite these improvements, contaminated bottom sediments along with wastewater discharges and other inputs from the watershed still result in elevated contaminant levels in fish, shellfish and other organisms. And we have barely begun to address the large pollutant loads in runoff from cities, farms and historic mining areas, which release pulses of contaminants washed from the land during and after storms.

Intentional and incidental introductions of hundreds of exotic species have altered the biotic landscape, with exotic organisms almost entirely replacing native organisms in several habitats. Although this is an old problem, its magnitude has only recently been recognized, and little has yet been done to address it. Despite potentially irreversible impacts, discharges of these "biological pollutants" occur with little regulatory control, and new exotic species continue to arrive and become established at an alarming rate.



A small spider crab, *Pyromaia tuberculata*

Population and Land Use

The shores of the Estuary were inhabited by aboriginal Californians for thousands of years before the coming of Europeans. Archaeologists believe that over 50,000 native people lived in villages and camps in this region, but nearly the only enduring marks that they left on the landscape are the remains of 400 garbage dumps, called shell mounds or middens, containing large quantities of mussel, clam and oyster shells.

The Spanish government established a mission and a fort (The Presidio) at San Francisco in 1776, but there were few settlers in the region until 1848, when James Marshall plucked a nugget of gold ore from the tail race of a sawmill on the American River. Within two years a flood of miners and speculators had swelled the Bay Area's non-native population from 400 to 25,000 people. The region's population has continued to climb, although less explosively, and today around eight-and-one-half million people live in the twelve counties bordering the Estuary.

Over the same period, nearly half of the Estuary's watershed has been turned into farms and range land, with about a fifth of the watershed irrigated for crops. About four percent of the watershed is urbanized, with industrial sites occupying about a tenth of that. These changes in population and land use are the ultimate cause of many changes in the Estuary, including the diking and filling of wetlands, the discharge of pollutants and the diversion of water.

Loss of Vegetated Wetlands

Over the past 200 years, most of the Estuary's vegetated wetlands have been destroyed. The riparian woodlands along the Delta and Central Valley waterways were initially cut down to power steamboats and provide fuelwood and charcoal for industry and homes, and then further extinguished by the levee construction and bank protection activities of flood control and land reclamation projects. The levees separated the rivers from their floodplains, which when inundated by floods served as important rearing areas for juvenile salmon and spawning areas for splittail and other native fish. Nearly all of the Estuary's tidal marshes, which at one time covered nearly two-thirds of its surface, have been destroyed, extensively altered, or cut off from the tides. Between 1860 and 1930, 97 percent of the Delta's 550 square miles of freshwater marsh were diked off and plowed for farms. Of the 300 square miles of brackish and salt marsh that fringed the Bay's shores before 1850, perhaps 60 square miles of undiked tidal marsh remain, along with 100 square miles of diked wetlands and 60 square miles of salt ponds. Incremental destruction of remaining marsh and riparian habitat can occur when projects are approved on wetlands, when levees and banks are covered with protective riprap, and when tributary creeks are stripped of vegetation or lined with concrete in the name of flood control, although mitigations for these projects can also restore or create new wetland habitat. Wetlands may also suffer from invasions by exotic plants.

The loss or degradation of wetlands affects native flora and fauna. Tidal marshes are an important source of dead plant material for the detrital food chain, which has become less productive as marshes have been lost. The brackish, diked wetlands of Suisun Marsh still provide nesting areas for many waterfowl, but the destruction of

freshwater and seasonally flooded marshes in the Delta eradicated nesting populations of shorebirds, rails, herons, ibises and terns. The construction of levees and riprapped banks and associated destruction of riparian vegetation have largely or entirely eliminated bank swallow, willow flycatcher, yellow-billed cuckoo and least Bell's vireo from the region. Several rare or endangered species in the Estuary now depend on the few remaining wetlands. Tidal salt marshes are critical to the California clapper rail, the California black rail, the Alameda and San Pablo races of saltmarsh song sparrow, and the saltmarsh wandering shrew. Brackish marshes support the Suisun race of saltmarsh song sparrow, the Suisun ornate shrew and several rare plants. Both salt and brackish marsh are important to the saltmarsh harvest mouse, the saltmarsh yellowthroat nests in freshwater or brackish marsh and winters in salt marsh, and the giant garter snake lives in freshwater sloughs and marshes.

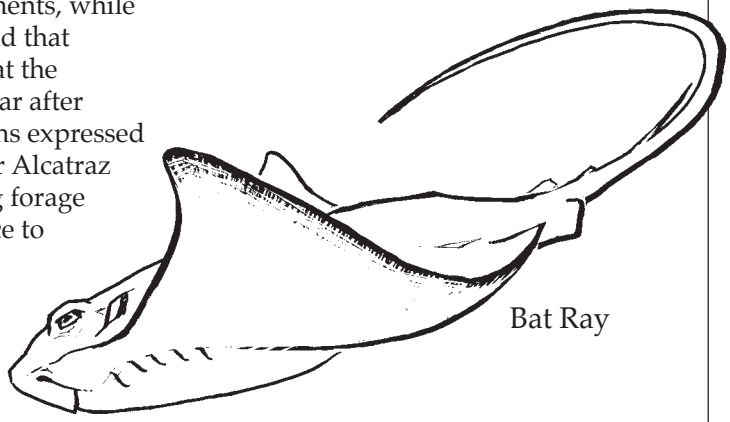
The diked, managed wetlands of Suisun Marsh and most of the remaining tidal marsh are now either in government ownership and managed by resource agencies, or are protected by a combination of state and federal laws. Piecemeal destruction or alteration of these wetlands still occurs, however, and virtually all have been or could be invaded by one or another species of aggressive, exotic plant. In addition, the unmanaged, diked wetlands in the Estuary remain at significant risk of outright destruction, especially those that are only wet in the winter or spring. These seasonal wetlands serve as important feeding and resting areas for shorebirds and as refuges for tidal marsh animals. Unfortunately, these wetlands also have potentially enormous monetary value as developed real estate, and the existing mix of laws may prove inadequate to protect them.

Dredging

On average, over 7 million cubic yards of sediment are dredged from the Estuary's waterways each year in order to enlarge or maintain shipping channels, marinas, and flood control or water-delivery channels. Concerns have been aired over the potential for dredging and the disposal of dredged sediments to harm organisms either through disturbance effects or through the mobilization of contaminants.

Benthic communities may be harmed when organisms are removed by dredging or buried by the disposal of sediments. However, even under natural conditions the Estuary's sediment is exposed to a substantial amount of disturbance, which the organisms living here must be able to tolerate. The winds and tides constantly stir the shallow water and suspend and redistribute bottom sediments, while the rivers discharge new sediment. Researchers have found that dredging and disposal sites are rapidly recolonized, so that the benthic community is generally re-established within a year after operations cease. About a decade ago, fishing organizations expressed fears that the dumping of dredged sediments at a site near Alcatraz Island was increasing the turbidity in the area and driving forage and sport fish out of the Estuary, but there is little evidence to either support or refute that hypothesis.

Over the years, some areas in the Estuary have received massive quantities of pollutants from industrial and urban waste discharges and surface runoff. Studies have identified several "hot spots" where sediments



Bat Ray

have especially high concentrations of contaminants including metals (such as mercury, lead, copper, silver and chromium) and organic compounds (including various pesticides, polychlorinated biphenyls [PCBs] and polycyclic aromatic hydrocarbons [PAHs]). At these sites, dredging operations could release toxic contaminants that are currently sequestered in the mud.

Pollution

Pollution has been recognized as a problem in the Estuary since at least 1879, when a California resource agency bemoaned the "constant fouling of the waters and consequent destruction of life by the foetid inpourings of our sewers." Mining activities contributed other pollutants, especially mercury in runoff from mercury mines in the Bay Area and from gold mines in the Sierra Nevada, where mercury was used to process the ore. Oil became a concern after the first of the Estuary's refineries was constructed in 1896, contamination from raw sewage was blamed for the decline of the Bay's oyster and soft-shell clam fisheries in the early 1900s, and farm runoff carried increasing amounts of fertilizers and pesticides as their use became more widespread after World War II. Over the years, the volume of municipal and industrial waste discharges steadily grew and contamination problems increased, particularly near wastewater outfalls located in shallow waters or in areas with poor water circulation.

In the 1950s, municipal wastewater plants began installing facilities for the primary treatment of sewage (the removal of floating and settleable solids, and disinfection), followed by secondary treatment (biologic breakdown of organic material) beginning in the 1960s, with some plants installing tertiary treatment (that targeted persistent pollution problems or treated the effluent for reclamation) starting in the late 1970s . Wastewater outfalls were moved to deeper water, where larger water volumes and stronger currents more effectively diluted and dispersed discharges. Between 1955 and 1985 the population served by the treatment plants doubled and the wastewater volume more than doubled, but improvements in treatment cut the overall discharge of organic matter by over 70 percent, which reduced coliform levels (an indicator of contamination by human waste) and raised dissolved oxygen concentrations in the Estuary, particularly in the South Bay.

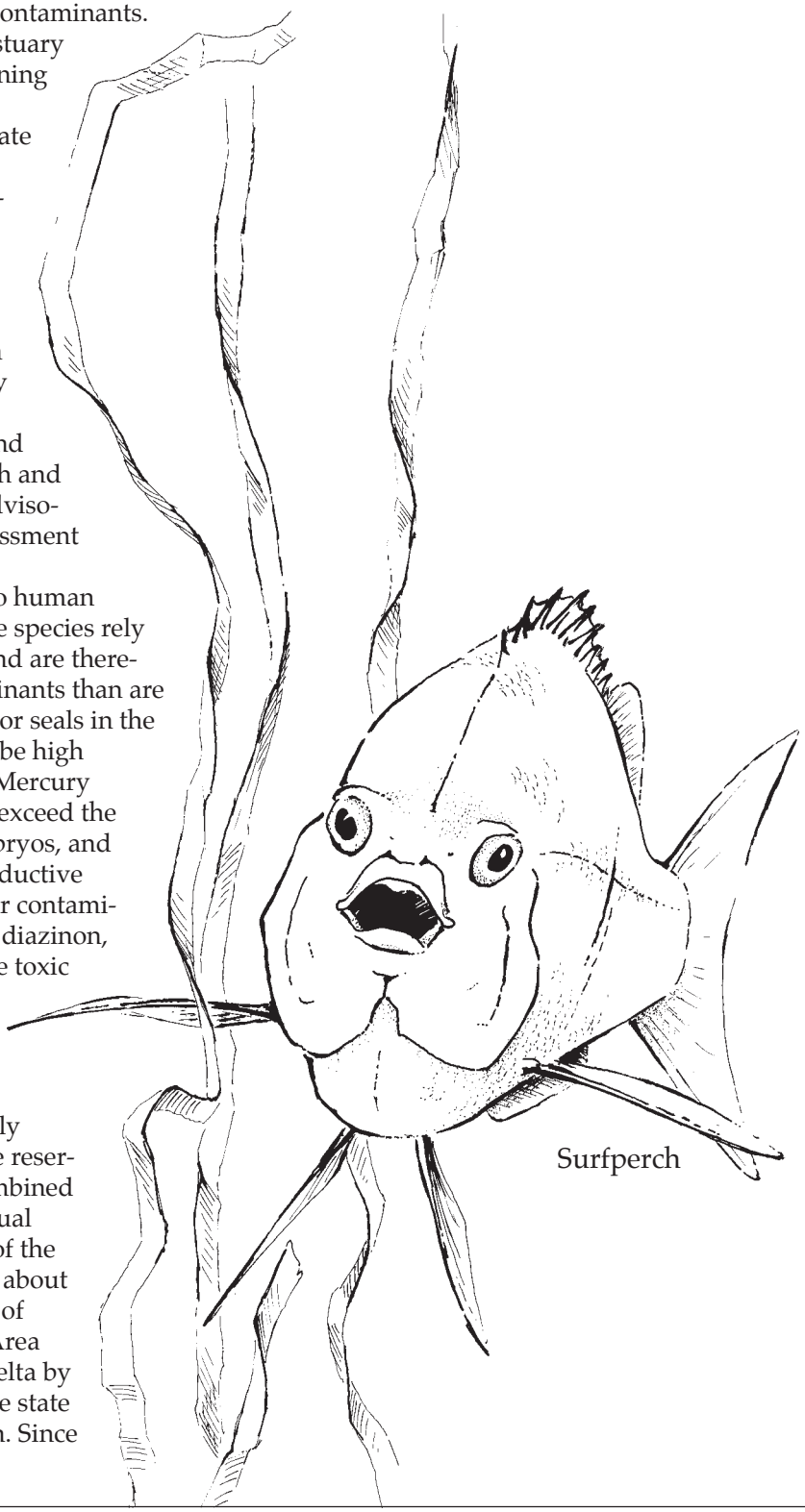
These treatment improvements also reduced the discharge of toxic metals and organic pollutants. For example, between 1975 and 1985 municipal treatment plants cut their discharge of each of nine metals by 37 to 92 percent. Industrial waste loads also dropped. From 1961 to 1984, refineries reduced their discharge of organic waste by 93 percent, oil and grease by 95 percent, and chromium and zinc by more than 99 percent. However, despite such major improvements, about 50 municipal and 65 large industrial facilities still dump substantial quantities of wastes into the Estuary, including an average of 300 tons of trace metals each year.

Large amounts of pollutants also enter the Estuary from stormwater runoff. Urban runoff carries metals, PAHs, PCBs and pesticides washed from streets, lawns and industrial properties. Agricultural runoff contains pesticides and herbicides, nitrates and phosphates applied as fertilizer, and selenium leached from the soil. Runoff from historic mining districts carries large amounts of mercury and other toxic metals. Oil and petroleum products enter the Estuary from

accidental spills, leaks from boat and ship engines, and from storm sewers when used motor oil is dumped into storm drains and gas and oil are washed off the streets. Other sources of pollutants include chemical spills, leachate from landfills, pesticides sprayed into the water to control aquatic weeds, and contaminants that are washed or settle out from the air. Past discharges have left significant pollutant concentrations in the Estuary's sediments, which may be available to biota in varying degrees. As noted above, sediments at various "hot spots" show elevated concentrations of contaminants.

Recent analyses of various fish in the Estuary found several contaminants in excess of screening values—defined as concentrations that are of potential public health concern and that indicate a need for more intensive monitoring or evaluation of health risks. Mercury concentrations were higher in the larger fish species (especially leopard shark and striped bass) and in the larger individuals within most species. Organochlorine compounds—PCBs, DDT, chlordane and dieldrin—were higher in species with high lipid (fat) content, especially white croaker and shiner surfperch. Based on these and other data, state agencies recommend that people limit their consumption of Bay fish and North Bay waterfowl. (For the latest health advisories, contact the Office of Health Hazard Assessment at 510-622-3200.)

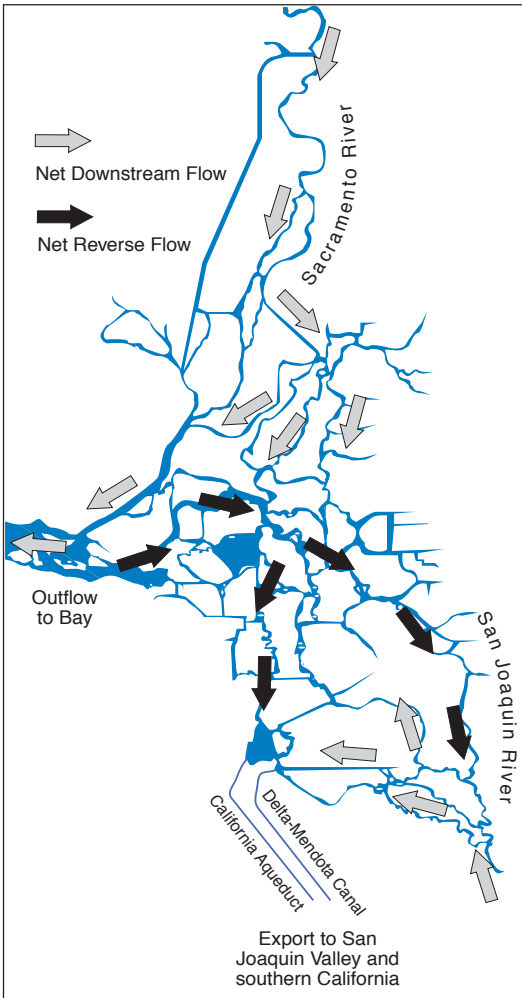
The contaminants that represent risks to human health also pose hazards to Bay wildlife. Some species rely almost exclusively on Bay fish for their diet and are therefore much more exposed to food web contaminants than are humans. Studies of fish-eating birds and harbor seals in the Bay found PCB concentrations that appear to be high enough to impair the health of these species. Mercury concentrations in California clapper rail eggs exceed the thresholds for toxic effects on developing embryos, and may partially explain the relatively low reproductive success of this species. Concentrations of other contaminants, such as the pesticides chlorpyrifos and diazinon, occasionally appear to be high enough to have toxic effects on zooplankton and other species at the base of the food web.



Surfperch

Dams and Diversions

Water storage and diversion have greatly altered the flow of water into the Estuary. The reservoirs constructed in the watershed have a combined storage capacity greater than the average annual inflow to the Bay, and on average about half of the runoff in the watershed is diverted. Typically about two-thirds of the diversion is taken upstream of the Delta (for upstream users and some Bay Area cities), and the remainder is taken from the Delta by local farmers or pumped from the Delta by the state and federal water projects and exported south. Since



the total runoff in the watershed varies greatly from year to year while the amount of water diverted is relatively constant, the percentage diverted can increase substantially in dry years. For example, less than one-sixth of Delta inflow was diverted in recent wet years, but about one-third to one-half was diverted in dry years.

The effect of water operations also varies seasonally. The reservoirs generally store water from the rivers between January and June, and release water back into the rivers from July to December. Diversions from the southern Delta usually peak between June and August. The net result is to reduce the overall flow into the Estuary, especially in winter and spring, and reduce peak flows. Reductions in annual flows tend to lower the abundance of zooplankton and some fish; reductions in peak flows could lessen the flushing of contaminants from the South Bay; and reductions in spring flows, especially in dry years, could impede the migrations of salmon and other fish.

Diversions within the Delta cause particular problems. Each year a substantial part of the Delta's plankton and hundreds of thousands of eggs, fry and juvenile fish are removed from the Estuary when they are sucked into the pumps and siphons operated by water agencies and Delta farmers. The state and federal water projects pump so much water that at times they have reversed the flows in South Delta channels, confusing fish that are migrating upstream to spawn, and interfering with the downstream drift of eggs and young.

Finally, the decrease in flows has altered salinities, including raising the average salinity by an estimated 1-2 ppt over the Estuary. This affects the distribution and abundance of many organisms, and may threaten the survival of endangered plants in the Suisun marshes.

Species Introductions

Researchers have so far documented about 250 organisms—including algae, marsh plants, protozoans, many types of invertebrates and dozens of fish species—that live in the Estuary but are not native to it, and there are certainly many others that we don't yet know about. These organisms traveled to the Estuary by a variety of mechanisms, the most important being intentional introductions for food, sport or other reasons, and accidental transport of organisms as fouling attached to the hulls of ships, as planktonic larvae or adults drifting in the ballast water carried by ships, and as "hitchhikers" with organisms imported for stocking, for aquaculture or for bait.

Half of the fish species in the Delta are exotic, and frequently over 90 percent of the individual fish collected in the southern Delta are exotic. Many of these species were brought in to establish commercial or sport fisheries, including the striped bass and American shad (which are anadromous fish that range throughout the Bay), and several species of freshwater catfish, sunfish and bass. Threadfin shad were introduced to provide forage for gamefish, fathead minnow and golden shiner arrived as bait, and mosquitofish and inland silverside were released to control mosquitos, gnats and other insects. Yellow perch were introduced in the 1890s as gamefish, did well for a while, but then disappeared from the Delta by the 1950s. Four species of Asian gobies that arrived accidentally in recent decades, possibly introduced in ballast water, have become very abundant in different parts of the Estuary.

Over 160 exotic invertebrates are known from the Estuary, most of which were introduced unintentionally. The earliest known arrival

was a white Atlantic barnacle, collected in 1853, followed by a pair of Atlantic hydroids reported in 1859. These and other fouling organisms probably traveled attached to the hulls of ships, while yet other fouling and benthic organisms were accidentally included in barrels of live eastern oysters that were shipped across the country after the transcontinental railroad was completed in 1869, or accompanied Japanese oysters that came by ship after 1930. Both of these oyster species were planted on the floor of the Bay to be grown to market size, and though the oysters never became established, several organisms that had traveled with them did. Later organisms arrived as plankton drifting in ballast water, and more recently a few organisms, including a periwinkle and perhaps the green shore crab, arrived in the algae that is used to pack marine baitworms shipped from Maine.

Besides barnacles and hydroids, exotic fouling species in the Estuary include Atlantic sponges and mussels, tube-worms from the southern hemisphere, and anemones and sea squirts from Asia and the Atlantic, so that most of the organisms found living on the sides of floating piers, buoys and boat bottoms are exotic species. Over most of the Estuary, more than 90 percent of the total weight of invertebrates living in or on the bottom mud are exotic species. These include the Atlantic soft-shelled clam and the Manila clam (both of them introduced with oyster shipments), which are the most common clams harvested recreationally in the Estuary; the channelled whelk, the largest snail in the Estuary; an Asian clam *Potamocorbula amurensis*, a small Atlantic gem clam, and several species of tube-building amphipods and polychaete worms, all of which are extraordinarily abundant in the Estuary; and another Asian clam, *Corbicula fluminea,* the most common freshwater clam in the Estuary. Planktonic invertebrates introduced through ballast water in recent decades include eight copepods and four opossum shrimp from Asia and three jellyfish from the North Atlantic basin that have frequently dominated zooplankton assemblages in the northern reach.

Manila Clam

The Estuary's migratory shorebirds and the endangered California clapper rail primarily feed on exotic invertebrates, and native hermit crabs have learned to set up house in the shells of introduced snails. Though beneficial in these regards, exotic species can also have a variety of harmful impacts. Introduced shipworms (which are actually highly-modified clams) and gribbles (small isopod crustaceans) bore into wood, damaging piers, pilings and boat hulls in the Estuary. An Australian isopod that burrows into mud banks may hasten the erosion of pickleweed marshes, and also bores into and damages the styrofoam blocks used as floats under piers. Exotic aquatic plants, including water hyacinth and *Egeria*, can clog flood control channels, block the passage of boats, reduce dissolved oxygen concentrations and degrade fish habitat.

A general concern is that exotic species could reduce or eliminate populations of native species. This can happen through predation, such as when exotic striped bass and black bass fed on and probably helped eliminate the thicktail chub and Sacramento perch from the Delta, and when exotic red foxes and Norway rats feed on the eggs or chicks of the endangered clapper rail. Or it can happen through competition, as occurred when an Atlantic mudsnail displaced a native hornsnail from the mudflats, restricting it to the harsher and more limited environment of shallow, salty, high marsh pools. The impacts of *Potamocorbula* on food webs and the Atlantic cordgrass *Spartina alterniflora* on habitat structure are discussed elsewhere in this booklet.

Atlantic Mudsnail

The Changing Ecology of the Estuary

The Estuary's ecological state is affected by the physical and chemical conditions in the environment, the interactions of plants and animals, and the actions of human society. The interplay of these elements is evident in the history of changes in the Estuary and in changes that we might expect or influence. A few examples are described below.

Damming the Estuary

An estuary is where fresh and salt water mix, but for much of this century engineers have been trying to keep them separate, so that untainted fresh water can be diverted for use by farms, factories and cities. The simplest approach, some have said, would be to put a dam across the Estuary.

It began with the drought years of 1917 and 1919, when exceptionally low flows pulled salt water into the Delta, contaminating Antioch's water supply. The city sued the farmers, arguing that their diversions had caused the problem. The Army Corps of Engineers offered to settle the conflict by damming the Estuary at the upper end of Suisun Bay. A dam, the Corps argued, would keep salt out of the Delta while storing fresh water for cities and farms.

Others agreed, but wanted the dam built farther downstream to hold more water, ease navigation by raising water levels, support a road and railway across the Bay, and (as a bonus) eliminate the wood-destroying, salt-water-requiring Atlantic shipworm from the northern part of the Bay. And so, state and federal engineers examined eleven potential dam sites from the mouth of the Delta to the sandbar outside the Golden Gate. For six years they surveyed alignments, poked holes in the Bay floor, designed floodgates, invented new types of ship locks, argued that fish ladders were a waste of water, drafted plans, estimated costs, and finally issued a report.

It turned out that damming the Estuary was a more complicated and expensive proposition than anyone had imagined. For example, one of the more promising options involved a mile-long, earth-fill dam stretching from Benicia to Martinez, which would have to 'float' on the Estuary's mud bottom since the nearest bedrock was more than 150 feet below. Thirty floodgates, each forty feet wide and six stories high, would be needed along with four sets of ship locks and a 1,000-foot-wide flood channel cut through the middle of Suisun Point. The total price tag was 15 times the estimate made by the Army Corps' just a few years before.

Despite aggressive boosting, enthusiasm for the project waned as people confronted the consequences. Farmers worried about competition from crops grown on diked and drained marshlands above the dam. Delta residents feared floodwaters that could back up behind it. A dam—even one with four ship locks—would impede access to Delta ports, and Stockton's businessmen declared that the entire concept was just a plot to shift trade to downstream ports at the expense of their own. By the 1930s, caught between economic conflicts and disagreements over the appropriate site, support for a dam had crumbled.

Soon, however, the dam idea attracted a new and remarkably effective champion in John Reber, an unemployed actor and theatrical producer. Not content with merely resolving a water crisis, Reber saw his role as "stage-managing San Francisco Bay, the greatest pageant on earth." He presented the public with a vision of colossal earthworks stitching Oakland to San Francisco and Richmond to San Rafael that would transform the unruly waters of San Francisco Bay into a chain of placid lakes. Corte Madera and Richardson bays and the eastern half of the Central Bay would be plugged with earth and converted into real estate, military bases and an airport.

John Reber was a gifted huckster who rekindled interest in damming the Estuary, and inspired scores of competing designs for remodelling it: crosswise barriers at Junction Point, Chipps Island, Dillon Point, Point San Pablo, Candlestick Point, Dumbarton Point and virtually every point in-between; massive earth-and-rock "Diagonal Baffles" and "Longitudinal Barriers" in the South Bay, and "Parallel Barriers" along Suisun Bay and Delta channels; plans that linked dams with pipelines and expressways to Los Angeles; the Walker Plan creating "Lake San Francisco;" the Weber Plan's dikes and polders, inspired by the Dutch; the Nishkian Plan's "Causeway to the Future;" the Savage Plan, the Biemond Plan, and many others. But none caught the public's attention like the Reber Plan.

But once again, after an initial burst of enthusiasm, support began to waver. East Bay cities contemplated a bleak future with their bustling waterfronts stranded behind dams and ship locks, abandoned by the tides of commerce. Echoing Stockton's earlier outrage, Oakland's leaders described the Reber Plan as "a clever, diabolical scheme to build up the San Francisco harbor at the expense of all other Bay region ports." The Army and the Navy opposed the plan on military grounds. Calculations showed that the dams couldn't hold enough water to replace losses to evaporation and ships locks and produce the supplies that Reber had promised, without flooding the Delta. The direct costs were daunting, and the indirect costs mounted even higher.

In 1953 the state reviewed three decades of dam plans and rejected most, including the Reber Plan, as unworkable. After

briefly considering a Chipps Island Dam, the state focused on a plan that involved building a dam at Junction Point on the Sacramento River, running water south through the Delta in a few isolated channels, and draining all the other Delta waterways dry. Thus, over the years the state shifted its interest in physical barriers to points farther and farther upstream.

In 1966 the state moved the concept of a salinity barrier as far upstream as possible by proposing the Peripheral Canal, which would loop around the east side of the Delta to carry northern California water to southern California, bypassing the Delta entirely. Voters rejected the Peripheral Canal in 1982, and after several more years of conflict the water agencies agreed in 1994 to increase flows through the Delta—the type of solution sought by the plaintiffs in the Antioch lawsuit back in 1920. As a new century dawns, however, the wrangling continues over where and how the Estuary's fresh and salt water should meet, and whether their mingling should be regulated by physical barriers or by flows.

Interactions in the Salt Marsh

California clapper rails are an endangered species, with a total current population of about 1,200 birds. But at one time they were abundant enough to be targeted by market hunters, who sometimes shot over a hundred birds a day. The rails were reduced first by overhunting and later by the destruction of their saltmarsh habitat, while their lives became progressively more entangled with three exotic species.

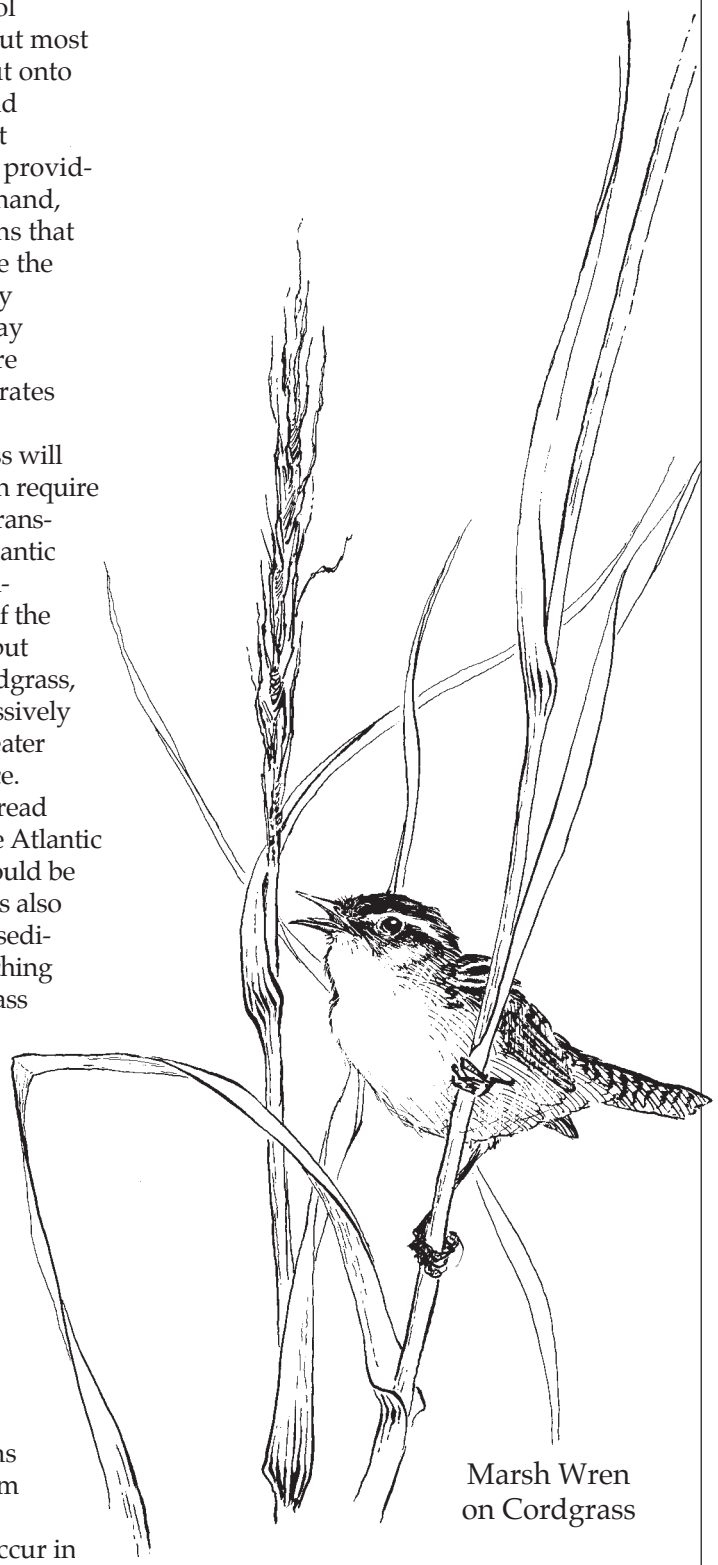
Clapper rails nest in cordgrass and pickleweed marsh, and at low tide forage for mollusks, crabs and other invertebrates along the sloughs and channel banks. The Atlantic ribbed horse mussel, which was introduced into San Francisco Bay around the 1890s with shipments of Atlantic oysters, is one important prey species. The horse mussel typically lies buried at the base of cordgrass plants, attached by tough threads to the stems beneath the surface, with the ends of its slightly gaping shells poking up just above the mud. In the 1920s, biologists noticed that foraging rails sometimes accidentally stuck their toes or inserted their bills into these shells, and that the mussels tended to clamp down, so that rails could be found walking about with mussels hanging from their toes or bills or with the tips of these appendages damaged or missing. Noting that a chick caught by a horse mussel would be unable to pull it from the mud and would drown at the next high tide, some biologists estimated that clapper rails suffered substantial losses from this cause. Although clapper rails in the Bay continue to show damage from horse mussels, there are no recent studies to indicate the extent to which capture by these mussels might affect rail populations.

Another exotic species, red fox from the Midwest, became established in California's Central Valley by the 1870s, having either escaped from fur farms or been released to provide stock for fox hunting. By the 1980s, the foxes had spread to the Bay's salt marshes, where they ate small rodents and the eggs and young of birds, including rails, least terns, Caspian terns, egrets and herons. In the early 1990s, the U.S. Fish and Wildlife Service concluded that the foxes were a threat to the clapper rail, and after some

public debate and controversy, began killing the foxes in the salt marshes in order to protect the rails.

Yet another exotic species arrived in the salt marshes in the early 1970s when the Army Corps of Engineers planted the Atlantic smooth cordgrass, *Spartina alterniflora*, in a marsh restoration project that was intended to mitigate for a flood control channel. The Atlantic cordgrass has since spread throughout most of the South Bay, where it grows over native marsh and out onto the mudflats below. The Atlantic cordgrass grows taller and denser than the native marsh vegetation, and might benefit clapper rails by extending the marsh over larger areas and providing better cover in which to hide from foxes. On the other hand, the Atlantic cordgrass may overgrow the small tidal sloughs that serve the rail as foraging areas and escape routes; and since the mud surface is more deeply shaded in marsh dominated by Atlantic cordgrass than in native marsh or mudflat, this may inhibit the growth of benthic diatoms and seaweeds that are important sources of food for the clams and other invertebrates that clapper rails feed on.

Meanwhile the mudflats invaded by Atlantic cordgrass will no longer be used for feeding by migrating shorebirds, which require open, unvegetated spaces to forage in. The marshes will be transformed into monocultures of cordgrass, superficially like Atlantic Coast salt marshes and utterly unlike the low-growing, open-canopied and floristically more diverse native salt marshes of the Pacific coast. The transformation may benefit some species, but others will suffer. One big loser will clearly be the native cordgrass, *Spartina foliosa*, which is thoroughly outcompeted and aggressively hybridized by the Atlantic cordgrass, whose enormously greater pollen production swamps the native's attempts to reproduce. Although the native cordgrass is still a common and widespread plant today, its future in the Estuary is in jeopardy, and if the Atlantic cordgrass spreads to other bays along the coast, the native could be put at risk throughout its entire range. The Atlantic cordgrass also alters the topology and hydrology of the marsh by trapping sediment, raising the surface elevation of the marsh, and encroaching on and shrinking channels and sloughs. The Atlantic cordgrass has had its most ironic impact as a hydro-geological agent, for it has invaded the very same flood control channel that it was originally intended to mitigate for, impeding the flow of water and silting up the channel, and leading to expensive aerial herbicide applications in a largely unsuccessful attempt to control it.

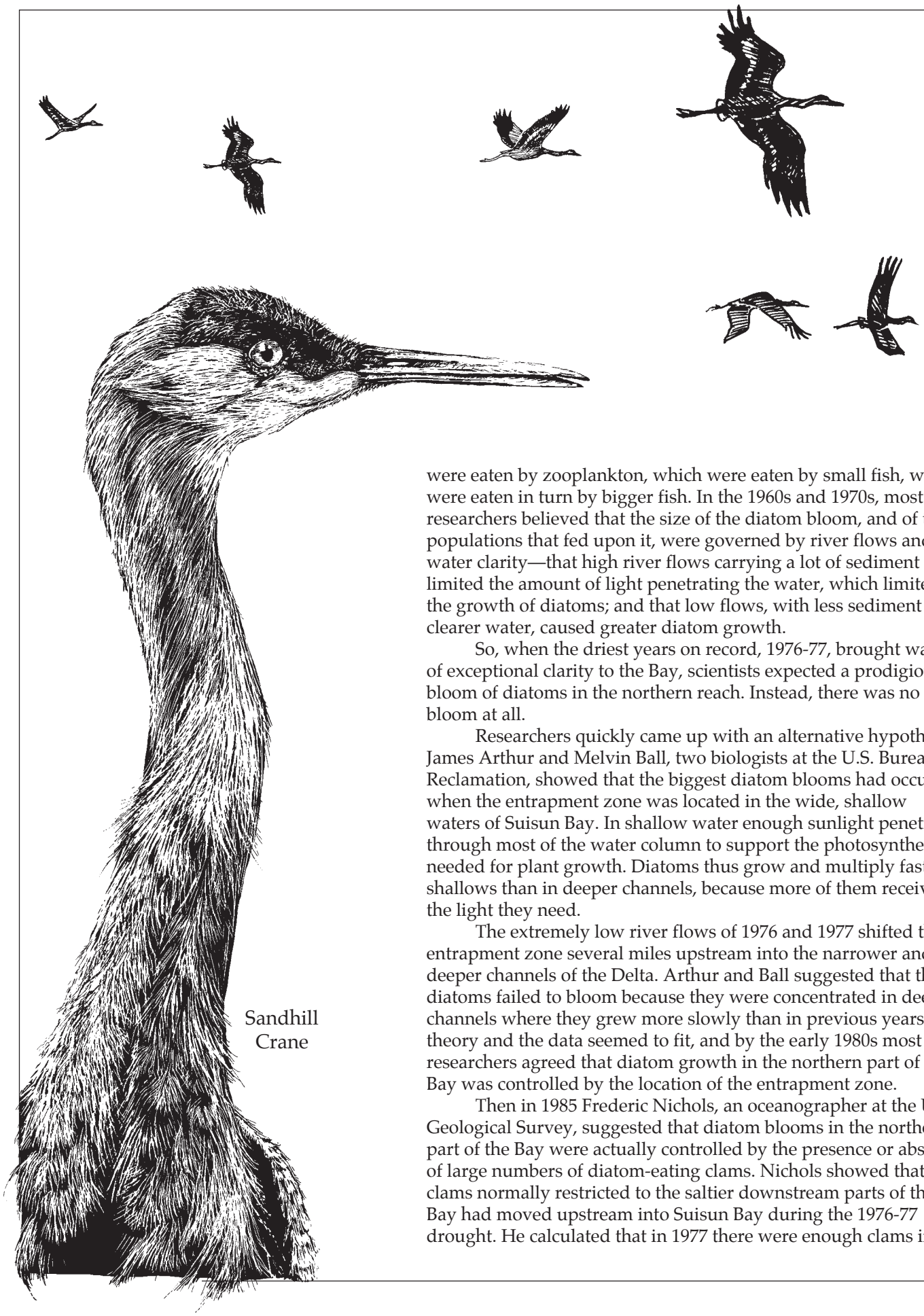


Marsh Wren on Cordgrass

Productivity in the Northern Reach

Estuaries tend to be highly productive habitats, where warm, shallow water, abundant nutrients and tidal mixing result in rapid growth of plants and animals. This estuarine productivity also supports life in ocean waters outside of the estuary. The biological diversity of coastal ecosystems may thus depend in part on the web of relations between estuary and ocean, and on the energy flowing from sunlight to plant to animal within the estuary.

As described earlier, a large diatom bloom used to occur in the Estuary's northern reach during most summers. The diatoms



Sandhill Crane

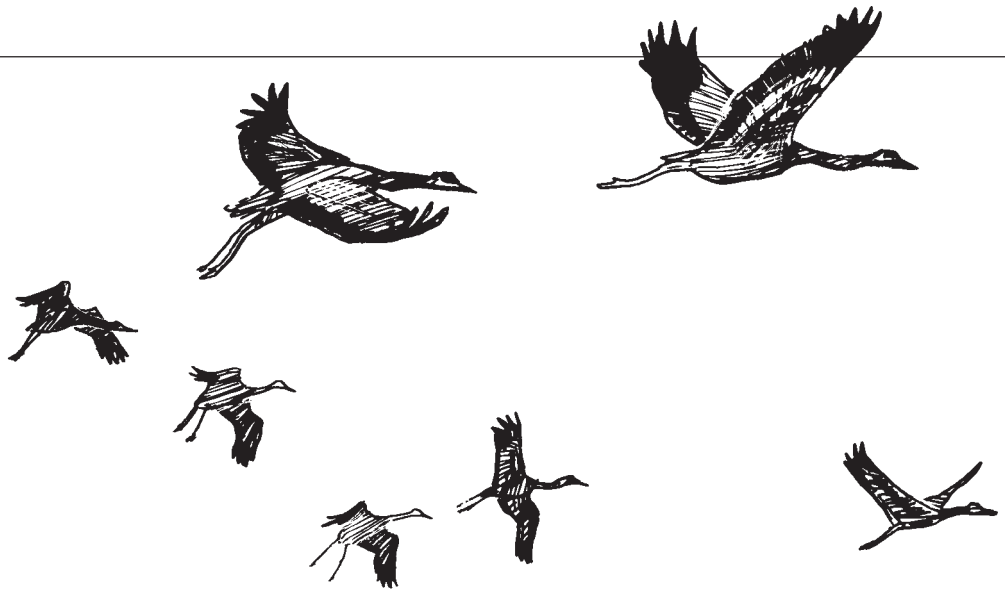
were eaten by zooplankton, which were eaten by small fish, which were eaten in turn by bigger fish. In the 1960s and 1970s, most researchers believed that the size of the diatom bloom, and of the populations that fed upon it, were governed by river flows and water clarity—that high river flows carrying a lot of sediment limited the amount of light penetrating the water, which limited the growth of diatoms; and that low flows, with less sediment and clearer water, caused greater diatom growth.

So, when the driest years on record, 1976-77, brought waters of exceptional clarity to the Bay, scientists expected a prodigious bloom of diatoms in the northern reach. Instead, there was no bloom at all.

Researchers quickly came up with an alternative hypothesis. James Arthur and Melvin Ball, two biologists at the U.S. Bureau of Reclamation, showed that the biggest diatom blooms had occurred when the entrapment zone was located in the wide, shallow waters of Suisun Bay. In shallow water enough sunlight penetrates through most of the water column to support the photosynthesis needed for plant growth. Diatoms thus grow and multiply faster in shallows than in deeper channels, because more of them receive the light they need.

The extremely low river flows of 1976 and 1977 shifted the entrapment zone several miles upstream into the narrower and deeper channels of the Delta. Arthur and Ball suggested that the diatoms failed to bloom because they were concentrated in deep channels where they grew more slowly than in previous years. The theory and the data seemed to fit, and by the early 1980s most researchers agreed that diatom growth in the northern part of the Bay was controlled by the location of the entrapment zone.

Then in 1985 Frederic Nichols, an oceanographer at the U.S. Geological Survey, suggested that diatom blooms in the northern part of the Bay were actually controlled by the presence or absence of large numbers of diatom-eating clams. Nichols showed that clams normally restricted to the saltier downstream parts of the Bay had moved upstream into Suisun Bay during the 1976-77 drought. He calculated that in 1977 there were enough clams in the

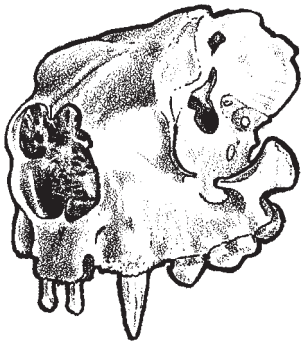


northern reach to filter the entire water column over the shallows in less than two days, preventing a bloom from ever getting started. Then the return of normal river flows in 1978 pushed the clams back downstream, and diatom blooms returned.

A year after Nichols published his hypothesis, a Diablo Valley College biology class dredged from the bottom of Suisun Bay three small, yellowish clams that had never before been seen in North America. These were later identified as *Potamocorbula amurensis*, a native of China, Japan and Korea, which had probably traveled to America as larvae drifting in the ballast water of a cargo ship. The clam found the Estuary to its liking and, reproducing with enthusiasm, quickly became the most abundant mollusk in the ecosystem, reaching peak densities of over four thousand clams per square foot. *Potamocorbula* is also a more efficient diatom-feeder than the other clams in the Estuary, and tolerates a wider range of salinities, maintaining large populations in wet years as well as in dry. Ever since the clam became abundant in the summer of 1987, there have been no substantial diatom blooms in the northern reach.

Other possible impacts of *Potamocorbula*'s arrival are still being debated. The zooplankton composition in the northern reach has changed dramatically since the early 1970s, with one Asian species after another becoming established and several of them dominating parts of the zooplankton community. Some of these changes began before *Potamocorbula* arrived, but others may be due to *Potamocorbula*'s reducing the supply of phytoplankton or eating the young of some zooplankton species. More generally, *Potamo–corbula* might alter the Estuary's food web, from one that supports large numbers of water-column-feeding fish to one that favors bottom-feeders like sturgeon and diving ducks, although no boom in bottom-feeders has yet been detected. Other impacts could result from *Potamocorbula*'s accumulating higher concentrations of selenium in its tissues than do other clams in the Estuary. The selenium is then passed on to *Potamocorbula*-eating sturgeon and ducks at levels which some studies suggest may interfere with reproduction. An important future challenge will be to determine

Sea otter bones dug from a shell midden on the shore of San Francisco Bay



if this clam's unusual capacity for accumulating a toxin might be poisoning the animals that feed on it.

Finally, researchers have a new puzzle to ponder. If there are practically no phytoplankton growing in the northern reach, then what are the billions of *Potamocorbula* feeding on now? It may turn out that phytoplankton or detritus washing in from the rivers or Delta, or the growth of tiny bacterioplankton, are more important to the Estuary's food web than had been thought. The changes wrought by *Potamocorbula* have sparked investigations of these possibilities.

Welcome Back, Otter?

Most people think of California sea otters as hanging out in kelp forests and rocky coves, munching away on abalone and sea urchin. But San Francisco Bay, with no kelp, a muddy bottom and water too brackish for urchins or abalone, nevertheless was once home for large numbers of otters. Sea otter bones are common in aboriginal middens on the Bay shore. When Father Pedro Font stood on the cliff at Fort Point in the spring of 1776, he saw sea otters playing in the surf below, and it is said that in the early 1800s General Mariano Vallejo placed a herd of sea otters in San Pablo Bay under his personal protection. The Bay's original sea otter population numbered in the thousands, with otters frequenting the mouths of creeks from the south end of the Bay to the Sonoma River, and frequently hauling out on the shore.

But sea otter pelts fetched a high price in China, and in the 1780s the Spanish government began trading otter pelts for Chinese quicksilver (mercury), which it needed to process the ore from Mexican mines. English ships also hunted California otters until 1790, when they were barred by a treaty with Spain. Meanwhile, the Russians began hunting in Alaska and worked their way southward, establishing a station on Kodiak Island in 1781, then one at Sitka in 1804, and finally erecting Fort Ross on the Sonoma County coast in 1812. Some American ships chased the otters during this period, often working on contract with Russian companies. Most of these hunts were illegal under Spanish law, and typically were multicultural affairs: a Boston-built ship commanded by a New England captain and manned by a Hawaiian crew would ferry a squad of Aleutian Island hunters and their skin boats, under the command of a Russian lieutenant, down to Bodega Bay or Drake's Estero. From there the Aleuts would paddle down the coast and enter San Francisco Bay, either sneaking through the Golden Gate past the guns of the Presidio, or portaging across the lower end of the Marin peninsula.

Otter hunting in the Bay must have been pretty good to attract these hunters, since many paid with their lives. Spanish soldiers staked out the springs and creeks around the Bay, and shot or captured the Aleuts when they came ashore for water. Although the records of this illegal trade are necessarily sketchy, we know that at times there were over a hundred Aleutian boats hunting in the Bay, taking hundreds of sea otter per week. As elsewhere on the Pacific Coast the otter population declined, especially after a period of intense hunting in the 1820s, although a few animals continued to be taken from boats or shot or even lassoed from shore. With the otters disappearing the Russians

abandoned Fort Ross in 1841, and the last known sea otters in the Bay were shot in 1846. However, since the 1970s sea otters have occasionally been sighted in the Bay and nearby waters, and some people have begun to wonder if they might come back. Could otters re-establish here? What would they eat? What threats would they face?

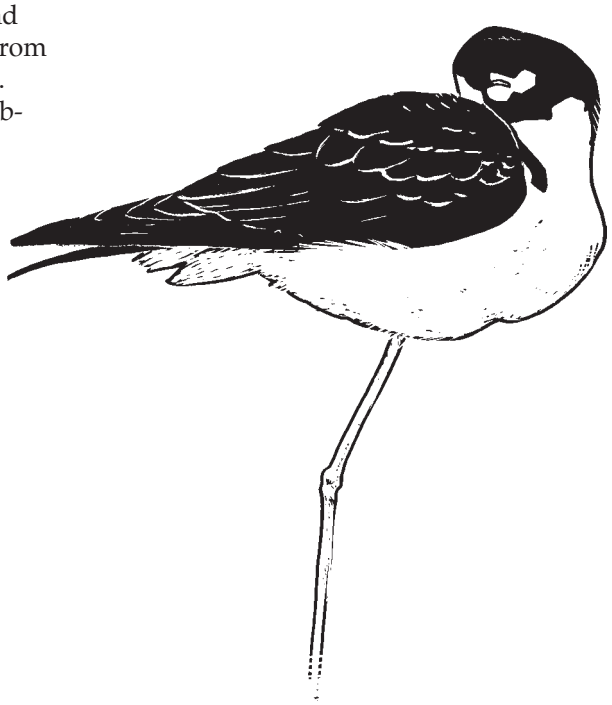
Otters readily adapt to most human activities. Efforts to develop techniques for scaring sea otters away from oil spills found that they quickly acclimate to air horns and other loud noises, and are attracted rather than repelled by boats, nets, oil booms and other artifical objects. Within their range, sea otters are common around harbors and marinas and seem generally unperturbed by boating, swimming, diving and other activities.

Although primarily creatures of the rocky coast, sea otters do sometimes live in muddy bays such as Elkhorn Slough in Monterey Bay, where they feed on clams dug from the mud. Otters have also been observed digging for large worms, and gathering discarded aluminum cans from the bottom to extract octopuses and other animals hiding within them. In some parts of Alaska, fish such as sculpin, flatfish and greenling form a significant part of their diet, the first two of which are also common in San Francisco Bay. Otters also eat mussels, which are abundant on docks and pilings in the Bay, and crabs, which are common in the Bay. However, if otters were to feed heavily on the Bay's young Dungeness crabs, they might harm the central California crab fishery.

Otters have few predators, mainly great white sharks in California and orcas, grizzly bears, coyotes and bald eagles (feeding on young otters) in Alaska. These are unlikely to become a problem in San Francisco Bay.

As discussed elsewhere, fish and invertebrates in the Bay often have elevated levels of organic or metal contaminants. Otters feeding on these animals might accumulate harmful levels of these substances, though currently there is not enough evidence to judge the likelihood of this. A greater problem might be the risk of a substantial oil spill in the Bay, or the ongoing smaller leaks and spills of oil and gas from motor boats and commercial ships, from tanker and refinery operations, and in runoff from city streets. Unlike other marine mammals, sea otters have no layer of blubber to protect them from cold Pacific waters. Instead they are insulated by air trapped in their remarkably dense fur, but in order to work their fur has to be *clean*. Dirty fur provides poor insulation, and poor insulation means rapid death. So sea otters spend a huge amount of time grooming their fur, on the order of 10-30 percent of their waking hours. But even constant grooming may not be enough in waters routinely contaminated by oil and gas.

However, given a sufficient effort, these problems could be addressed. Sea otters once thrived in this Estuary, and if offered a fair chance they might do so again. Maybe, if we continue to clean it up, they'll come home.



Glossary

Acre-foot – A volume equal to an acre covered to one foot of depth, or 325,900 gallons.

Amphipods – Small and often abundant crustaceans, usually with a body flattened from side to side; includes both tube-dwelling and mobile forms; sometimes called "scuds;" jumping types found on beaches are called "sand fleas."

Anadromous – Organisms such as salmon, striped bass, shad or sturgeon, which spend most of their adult life in the ocean or the saltier parts of an estuary, and migrate upstream into fresher water to spawn.

Benthic – Occurring on the bottom of a water body.

Bloom – A sudden increase in a phytoplankton population.

Catadromous – Organisms such as mitten crabs, which spend most of their adult life in fresh water and migrate down to salt water to spawn; the opposite pattern to anadromous.

Copepod – A tiny, crustacean zooplankton.

Crustacean – A type of invertebrate with a hard, segmented exoskeleton and jointed legs; includes crabs, shrimp, amphipods, isopods, copepods, barnacles and other forms.

Detritus – Small particles of organic matter, largely derived from the breakdown of dead vegetation.

Detrital chain – The part of the food web that begins with detritus as a food source.

Diatoms – Single-celled algae with a silica shell. Diatoms are among the most common phytoplankton in the Estuary, and some types ("benthic diatoms") grow on and in the mud.

Entrapment zone – A region where suspended particles and small floating organisms are concentrated by estuarine circulation or other factors; also called the **turbidity maximum**.

Estuarine circulation – A pattern of water circulation characterized by a net downstream flow of fresher water near the surface anda net upstream flow of saltier water near the bottom; also called **gravitational circulation**, **density currents** or **two-layered flow**.

Estuary – A partially enclosed body of water where river water meets and mixes with ocean water.

Filter-feeders – Organisms that feed by filtering out small food items such as detrital particles and plankton that are suspended in the water column; distinguished from **deposit feeders** that glean such items from the bottom.

Flagellate – A type of single-celled organism; sometimes considered to be an animal because it moves by whipping a long hair about, and sometimes a plant because it photosynthesizes.

Food web – The array of organisms in an ecosytem, including plants, herbivores and carnivores, diagraming "who eats whom."

Invertebrates – Animals without a backbone; includes clams, snails, shrimp, crabs, insects, starfish, jellyfish, sponges, worms and others.

Neap tides – The tides around the quarter moon, when the tidal range is smallest.

Null zone – In estuarine circulation, the area near the bottom where the currents of net upstream-flowing saltwater and downstream-flowing freshwater meet and cancel out.

Opossum shrimp– A small, crustacean zooplankton; named for the pouch on its chest in which it broods its eggs; also called a **mysid shrimp**.

Ostracode–A minute crustacean enclosed in a pair of shells; looks like a tiny clam with legs.

Photosynthesis – The process by which green plants use the sun's energy to produce carbohydrates from carbon dioxide and water.

Phytoplankton – Small, usually single-celled plants that drift in the water.

Planktivorous – Plankton-eating.

Plankton – Small drifting organisms; includes plants (phytoplankton) and animals (zooplankton); derived from *planktos*, the Greek word for "wandering."

Polychaete – A class of segmented worms with bristly appendages.

Redd – The gravel nest of a salmon or trout.

Residence time – The average time it takes for a discrete component, such as a molecule of water, a molecule of a contaminant, or a drifting organism, to leave a system such as a body of water.

Riparian – On the bank of a river or lake.

Riprap – Rock placed on a bank to prevent erosion.

Spring tides – The tides occurring around the full or new moon, when the tidal range is greatest.

Stratification – A condition where water masses with distinct characteristics (typically differing in salinity or temperature) are present at different depths.

Tidal prism – The volume of water that moves in or out of an embayment with each tide.

Tidal range – The difference in height between high and low water.

Turbidity – The opacity of the water, an indicator of how much sediment, plankton or other organic matter is suspended in the water.

Water column – The water between the surface and the bottom of a body of water.

Zooplankton – Small, often microscopic animals that drift in the water. They feed on detritus, phytoplankton or other zooplankton.

Sources and Further Information

Three *Community Profile* reports published by the U.S. Fish and Wildlife Service provide thorough summaries of some of the major habitats in the Estuary: *The Ecology of the San Francisco Bay Tidal Marshes*, Michael Josselyn, Oct. 1983; *The Ecology of the Soft-Bottom Benthos of San Francisco Bay*, Frederic H. Nichols and Mario M. Pamatmat, Sept. 1988; and *The Ecology of the Sacramento-San Joaquin Delta*, Bruce Herbold and Peter B. Moyle, Sept. 1989.

An Island Called California (Elna Bakker, University of California Press, 1984) is a highly readable description of ecological communities on a transect across northern California, including chapters on salt marsh, freshwater marsh and riparian forest.

The San Francisco Estuary Project's *Status and Trends Reports* are useful compilations of information on Dredging and Waterway Modification (Aquatic Habitat Institute and Philip Williams & Assoc. Ltd., 1990), Wetlands (Emy Chan Meiorin and others, 1991), Pollutants (Jay A. Davis and others, 1991), Land Use and Population (Jeanne B. Perkins, Sandi Potter and Linda Stone, 1991), Aquatic Resources (Bruce Herbold, Alan D. Jassby and Peter B. Moyle, 1992) and Wildlife (Thomas E. Harvey and others, 1992). The Project's *State of the Estuary* report (Michael W. Monroe and Judy Kelly, 1992) provides an overview of these issues.

Several well-written natural history guides focus on intertidal invertebrates, including some that are found in San Francisco Bay: *An Introduction to Seashore Life of the San Francisco Bay Region and the Coast of Northern California*, Joel W. Hedgpeth, University of California Press, 1962; *Between Pacific Tides*, Edward F. Ricketts, Jack Calvin and Joel W. Hedgpeth, revised by David W. Phillips, Stanford University Press, 1985; *Seashore Life of the Northern Pacific Coast*, Eugene N. Kozloff, University of Washington Press, 1983; *Natural History of Marine Animals*, G. E. MacGinitie and Nettie MacGinitie, McGraw-Hill Book Company, 1968; and *Intertidal Invertebrates of California*, Robert H. Morris, Donald P. Abbott and Eugene C. Haderlie, Stanford University Press, 1980. Books from Sea Challengers Press of Monterey provide photographs and brief descriptions of Pacific Coast nudibranchs (David W. Behrens, 1991), crabs and shrimp (Gregory C. Jensen, 1995), and pelagic invertebrates, mainly jellyfish (David Wrobel and Claudia Mills, 1998).

Information on the region's aquatic vertebrates can be found in several books from the University of California Press: *Freshwater Fishes of California*, Samuel M. McGinnis, 1984; *California Marine Food and Game Fishes*, John E. Fitch and Robert J. Lavenberg, 1971; *Water Birds of California*, Howard L. Cogswell, 1977; and *Marine Mammals of California*, Robert T. Orr and Roger C. Helm, 1989. Detailed though somewhat outdated information on the harvesting of organisms from the Estuary is provided in *An Historical Review of the Fish and Wildlife Resources of the San Francisco Bay Area*, John E. Skinner, California Department of Fish and Game, June 1962.

Exotic species in the Estuary are covered in the U.S. Fish and Wildlife Service report *Nonindigenous Aquatic Species in a United States Estuary: A Case Study of the Biological Invasions of the San Francisco Bay and Delta*, Andrew N. Cohen and James T. Carlton, 1995.

Several scientific papers on the Estuary are collected in two books published by the American Association for the Advancement of Science (*San Francisco Bay: The Urbanized Estuary*, T. John Conomos (ed.), 1979; and *San Francisco Bay: The Ecosystem*, James. T. Hollibaugh (ed.), 1998), and in a volume reprinting articles from a special issue of the journal *Hydrobiologia* (*Temporal Dynamics of an Estuary: San Francisco Bay*, James E. Cloern and Frederic H. Nichols (eds.), Kluwer, Dordrecht, Netherlands, 1985). The first of these is the easiest read for the non-scientist. (The maps showing the Estuary from 15,000 years ago to today, on page 3, are based on Brian Atwater's article in this volume.)

"The Modification of an Estuary" by Frederic H. Nichols, James E. Cloern, Samuel N. Luoma and David H. Peterson, an article in *Science,* Vol. 231 (7 Feb. 1986), pp. 567-573, gives a succinct summary of the ways in which civilization has changed the Estuary. (The tidal marsh map on page 26 is based on a figure in this article.)

Shoreline access points, trails and sites of interest around the Bay shore are described in the *San Francisco Bay Shoreline Guide*, Rasa Gustaitis and Jerry Emory, University of California Press, 1995.

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— Andrew Cohen

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The San Francisco Estuary Project is a local/state/federal partnership established under the Clean Water Act's National Estuary Program to develop and carry out the Comprehensive Conservation and Management Plan for the Bay-Delta Estuary. Its goals are to restore water quality and natural resources through effective management and public/private partnerships, while maintaining the region's economic vitality.

Save The Bay

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Save The Bay has been working for four decades to protect and restore the San Francisco Bay-Delta, to improve public access to its shoreline, and to educate a new generation of Bay stewards. Save The Bay is committed to keeping the Bay alive, healthy and beautiful.

San Francisco Estuary Institute

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The San Francisco Estuary Institute is a non-profit organization that aims to improve environmental decision-making by developing and communicating the scientific information needed to protect, enhance and successfully restore a healthy ecosystem. The Institute runs monitoring and research programs dealing with trace substances, wetlands, watersheds and biological invasions.

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