Biological Report 85(7.22)
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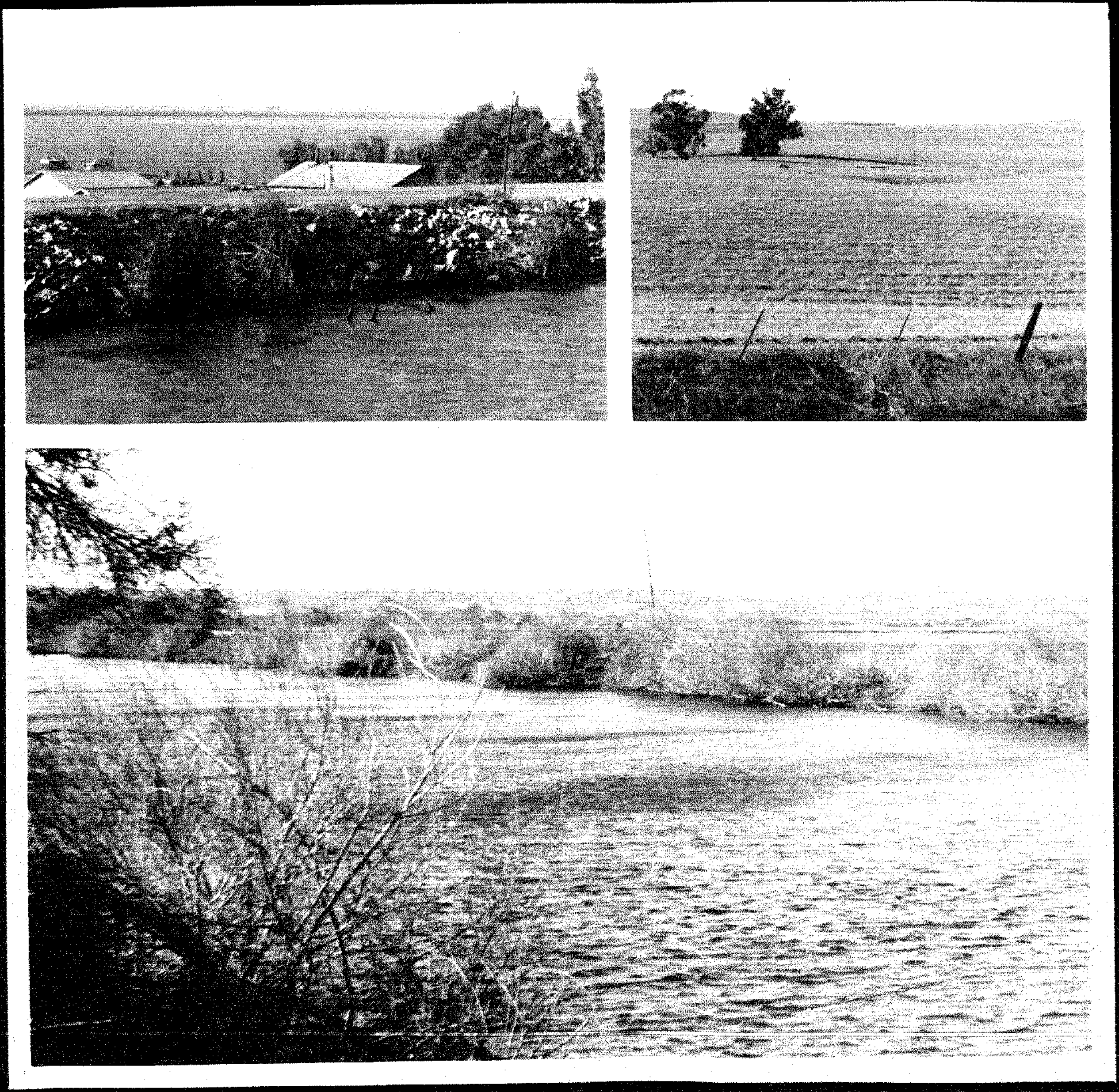

Fish and Wildlife Service

U.S. Department of the Interior **U.S. Environmental Protection Agency**

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Cover:

Upper left: Disappointment Slough, showing subsidence between dikes.
Upper right: previous upland habitat has been converted to agriculture and pasture one mile west of Rio Vista.
Bottom: the levees on Sevenmile Slough.

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THE ECOLOGY OF THE SACRAMENTO-SAN JOAQUIN DELTA: A COMMUNITY PROFILE

by

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PREFACE

This profile of the Sacramento-San Joaquin Delta is one in a series of community profiles synthesizing information pertinent to specific habitats of particular interest to environmental managers. The intent of the series is to provide scientific information in a format that is useful to a broad spectrum of users including environmental managers, college educators, water-project developers, and interested laypersons. This specific profile focuses on the delta of the Sacramento and San Joaquin Rivers, upstream of the San Francisco Bay complex. The boundaries of the delta have been legally defined, but this profile crosses those boundaries and discusses the important adjacent areas of the entire estuarine system.

A wide range of State and Federal agencies monitor the status of various aspects of the physical and biological components of the delta. The two most powerful forces affecting the biology of the delta are weather and humans. Much of the profile describes the various ways that these two forces, separately and synergistically, continue to alter the delta.

This profile should be viewed as a snapshot of the delta in the mid-1980's. Invasions of new organisms have further changed the ecosystem since this profile was written. Two new species of copepod (*Pseudodiaptomus* spp.) have become abundant. A euryhaline clam from China (*Potamocorbula amurensis*) has recently become extraordinarily abundant in Suisun Bay and may soon invade the delta. Its high filtration rates are apparently responsible for preventing phytoplankton blooms in Suisun Bay during 1987 and 1988. Native organisms continue to decline. The winter run chinook salmon was listed (1989) as endangered by the State of California and the delta smelt was listed as a candidate for endangered species status. On a more positive note, the expected invasion of white bass into the delta was apparently halted by a massive eradication effort. Political pressure continues to build around the rates and methods of diverting delta waters. Results of these pressures are apt to produce even larger shifts in the delta ecosystem. On a larger scale, if global warming raises sea levels we may find that the current system of dredged channels and islands was simply one step on the way to transforming central California from a freshwater marsh in the 1800's to a saltwater marsh in the 2000's.

CONVERSION TABLE

Metric to U.S. Customary

Multiply	By	To Obtain
millimeters (mm)	0.03937	inches
centimeters (cm)	0.3937	inches
meters (m)	3.281	feet
meters (m)	0.5468	fathoms
kilometers (km)	0.6214	statute miles
kilometers (km)	0.5396	nautical miles
square meters (m^2)	10.76	square feet
square kilometers (km^2)	0.3861	square miles
hectares (ha)	2.471	acres
liters (l)	0.2642	gallons
cubic meters (m^3)	35.31	cubic feet
cubic meters (m^3)	0.0008110	acre-feet
milligrams (mg)	0.00003527	ounces
grams (g)	0.03527	ounces
kilograms (kg)	2.205	pounds
metric tons (t)	2205.0	pounds
metric tons (t)	1.102	short tons
kilocalories (kcal)	3.968	British thermal units
Celsius degrees (°C)	1.8(°C) + 32	Fahrenheit degrees

U.S. Customary to Metric

Multiply	By	To Obtain
inches	25.40	millimeters
inches	2.54	centimeters
feet (ft)	0.3048	meters
fathoms	1.829	meters
statute miles (mi)	1.609	kilometers
nautical miles (nmi)	1.852	kilometers
square feet (ft^2)	0.0929	square meters
square miles (mi^2)	2.590	square kilometers
acres	0.4047	hectares
gallons (gal)	3.785	liters
cubic feet (ft^3)	0.02831	cubic meters
acre-feet	1233.0	cubic meters
ounces (oz)	28350.0	milligrams
ounces (oz)	28.35	grams
pounds (lb)	0.4536	kilograms
pounds (lb)	0.00045	metric tons
short tons (ton)	0.9072	metric tons
British thermal units (Btu)	0.2520	kilocalories
Fahrenheit degrees (°F)	0.5556 (°F - 32)	Celsius degrees

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At the National Wetlands Research Center, Beth Vairin edited the manuscript, Daisy Singleton prepared the camera-ready, and Sue Lauritzen designed the layout.

INTRODUCTION

The Sacramento-San Joaquin Delta is one of the 60 largest river deltas in the world and is the largest river delta on the west coast of North America. The waters of the delta principally arise from precipitation (both rainfall and snowmelt) in the Sierra Nevada Mountains. The Coast Range prevents direct movement of this water to the ocean, thereby producing two main rivers. The Sacramento River drains the northern half of this Central Valley of California while the San Joaquin River drains the southern half. Two smaller rivers enter the delta from the east: the Consumnes and Mokelumne Rivers. These four rivers merge in the delta and flow to the sea through a narrow pass in the Coast Range.

The importance of the delta to the people of California can be gauged from the following statistics (California Department of Water Resources 1987): $375 million average annual gross value of agriculture, valuation of land and improvements of $1.9 billion in 1980, 12 million estimated annual recreational user-days, and 82,000 registered pleasure boats. Recreation in the delta takes a variety of forms: fishing, windsurfing, waterskiing, and boating are all pursued throughout the year.

As the hub of California's water system, the delta is of immense municipal, agricultural, and industrial importance. Of the total state runoff, 47% passes through the delta and supplies water to Contra Costa County, the city of Vallejo, and the State and Federal pumping plants that in turn supply water to the extremely productive San Joaquin Valley and urban Los Angeles.

Legally, the delta is defined by sec. 12220 of the California State Water Code (area outlined in Figure 1). This area roughly corresponds to a triangle formed by the cities of Sacramento at the lower end of the Sacramento River, Stockton at the lower end of the San Joaquin River, and Collinsville at the easternmost edge of the San Francisco Bay complex. An important point at the border of the delta is near Tracy, where the Federal and State pumping plants draw off much of the inflowing freshwater of the San Joaquin River.

Biologically, the delta cannot be so sharply delineated. The amount of freshwater that flows through the delta controls the delta's productivity and regulates the life cycles of many of its organisms. In addition, the amount of water flowing through the delta has similar effects on downstream areas, including San Francisco Bay (Cloern et al. 1983; Cloern and Nichols 1985). Most of the organisms found in the delta are found in other parts of the estuary and rivers. Other parts of the estuary system have been thoroughly reviewed recently (Josselyn 1983; Cloern and Nichols 1985), so we will discuss the lower parts of the estuary only when they relate to the delta.

The delta has been divided variously into three to five sections. The northern delta is recognized as that portion dominated by waters of the Sacramento River. The western delta is generally described as the area near the confluence of the Sacramento and San Joaquin Rivers and is subject to the greatest tidal effects, although salt intrusion is now rare. Although the remaining portion is sometimes described collectively as the eastern delta, it is more appropriately divided into 1) a southern delta dominated by San Joaquin River waters, 2) an eastern delta that receives waters of the Consumnes and Mokelumne Rivers, and 3) a poorly defined central delta that includes the many channels where waters from all rivers mix. A cross-delta channel is opened in most years from March to November to draw Sacramento River water through part of the

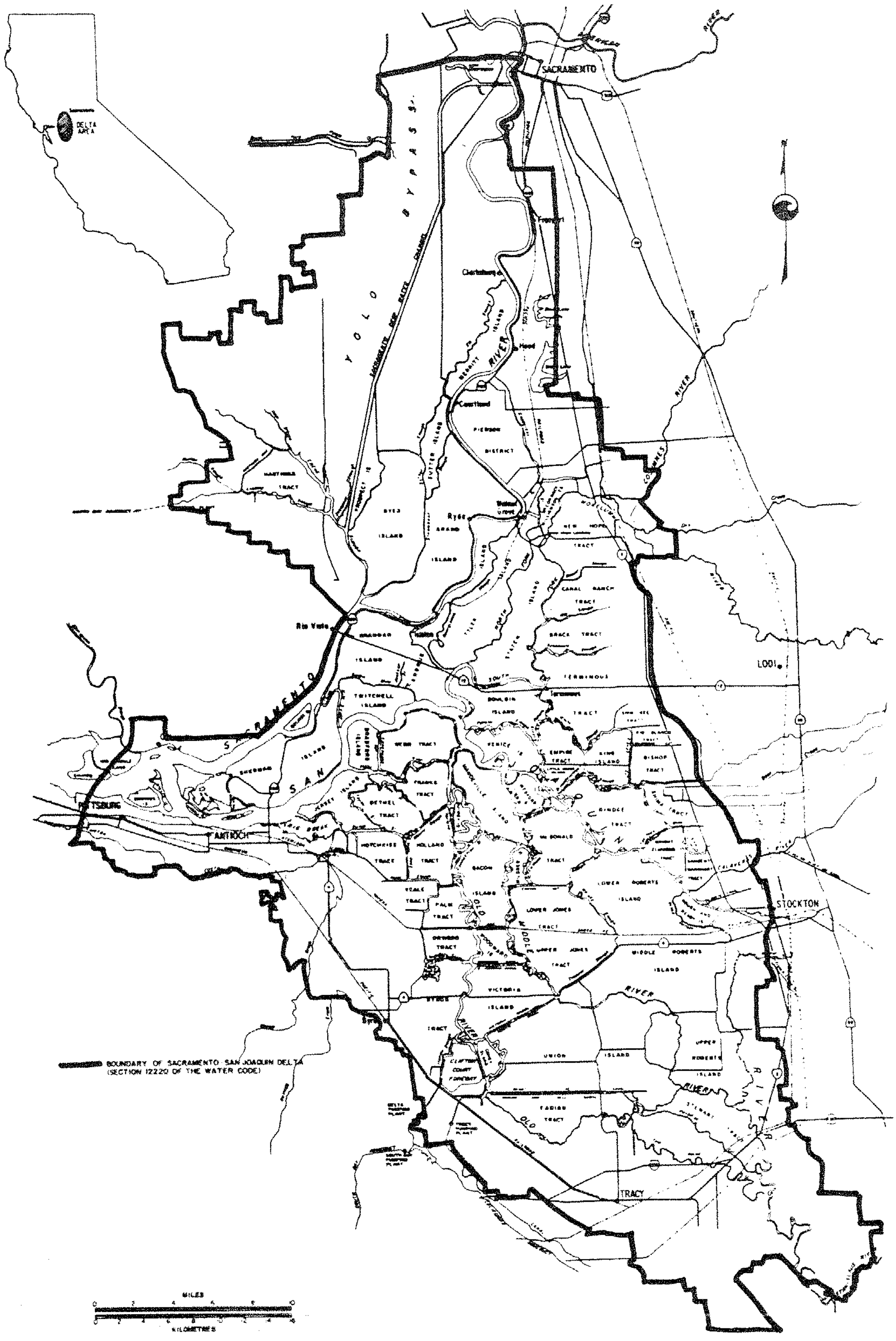

Figure 1. Legal boundary of the Sacramento-San Joaquin Delta. From California Department of Water Resources (1982).

Mokelumne River channels and into the San Joaquin River, where it can be pumped south by the State and Federal pumping plants. Opening the cross channel reduces differences among the three parts of the eastern delta. In addition, low river outflows and high export pumping rates produce a reverse flow of water in the western delta up the lower reaches of the San Joaquin River.

This report describes an ecosystem significantly different from other delta ecosystems in North America. The unique nature of the delta comes from its being far inland from the ocean and being separated from oceanic influences by an intervening series of large bays. In addition, most of the waterflows into the delta are managed to minimize oceanic factors. Although natural conditions of low summer flows produced an annual salinity intrusion into the delta, water quality is controlled by upstream releases so that most of the delta is now a freshwater system except under extreme drought conditions. Annual increases in conductivity still occur in the western and southern delta and occasionally cause problems for delta agriculture, but the increases are never of the magnitude recorded earlier in this century. The delta is primarily agricultural land with small instances of a variety of other habitats intermixed rather than a uniform and contiguous community. These characteristics combine to make this system unique in many ways.

The vast estuary of the Sacramento and San Joaquin Rivers is one of the most highly modified and intensively managed estuaries in the world (Conomos 1979; Cloern and Nichols 1985). Many of the most significant alterations, such as leveeing, diking, and agricultural practices, are not now recognized as such by most citizens, making conservation and protection of the delta difficult. Many of the alterations for water control have presumably had major effects on ecological structure and function within the delta, but in most cases there is little data available from pre-alteration periods.

Biological processes in the delta are also obscured by the temporal dynamics of the system. Weather and human activities vary widely from year to year and prevent accurate predictions of future conditions. Similar temporal dynamics in San Francisco Bay have been recently reviewed (Cloern and Nichols 1985) and have major effects on most components of the community. Variations in the Sacramento-San Joaquin Delta (such as salinity) are less in some aspects, but many of the same processes are at work in both systems or are interconnected, so that each part of the estuary controls processes in the other.

CHAPTER 1. GEOGRAPHIC BACKGROUND

1.1 GEOLOGY AND SOILS

The current Sacramento-San Joaquin Delta is the most recent in a series of deltas formed by Quaternary geologic activity (Shelemon and Begg 1975). In the Cretaceous the delta was formed principally by the channels of the Mokelumne River. The uplift of the Sierra and Coast Ranges produced two new rivers which flowed parallel to the coastline, with the delta forming at a constricted spill point into the upper end of a series of bays before reaching the ocean (Atwater 1980). Unlike other deltas, then, the Sacramento-San Joaquin narrows before reaching the sea, and its growth has been in an upstream direction. The notch in bedrock which permits the exit of delta waters into the San Francisco Bay complex has been as much as 40 m above the ground level of the delta (Shelemon and Begg 1975). The odd nature of flows through the delta has prevented the formation of the zones that usually typify delta habitats, an anomaly responsible for several unique biologic patterns.

One important consequence of the delta's narrow mouth has been that the deposition of sediments has taken place mostly within the delta instead of forming spits or mudflats in San Francisco Bay. A similar constriction at the Golden Gate, where the series of bays meets the ocean, has caused almost all sediments that leave the delta to be deposited in the bays. Thus, despite its youth compared to other deltas, the Sacramento-San Joaquin soils are very deep deltaic sediments. The advance and retreat of glaciers has interleaved glacial sands and gravels with accumulating layers of sediments (Shelemon and Begg 1975). Since the last glacial episode, islands have been formed through the deposition of natural levees along the banks of the various braided channels in the delta. Annual flooding over the top of these levees filled the central areas with sediments, producing approximately 80 atoll-like islands throughout the marsh. These regularly flooded areas supported dense growths of emergent plants such as tule (*Scirpus*), cattail (*Typha*), and rushes (*Phragmites*).

The accumulation of sediments and dense growths of emergent plants produced organic soils: peaty-mucks with frequently high densities of fibrous materials. These soils are waterlogged in their natural state and, if permitted to dry, tend to shrink and become easily compressible. They are structurally weak and easily degraded by erosion from wind or water or by oxidation. When dry they will burn, and once ignited, they are difficult to extinguish. In islands, and in some parts of channels where peaty soils have concentrated, this type of soil can be up to 30 m deep. Generally, depths of organic soils range from 3 to 12 m (Figure 2), with the percentage of organic materials declining with depth. Structurally weak soils at the periphery of the delta are generally silty clays or clayey silts. Soils at the boundaries of the delta are typically alluvial deposits from either the late or early Quaternary (Shelemon and Begg 1975).

An additional consequence of organic soils is the presence of at least 35 natural gas deposits beneath the surface of the delta. Major gas fields are near Rio Vista and Isleton in the north delta and under Macdonald and Robert tracts in the south-central delta (Safanov 1962; Shelemon and Begg 1975). Subsidence of the western delta may have served to trap these gas deposits.

1.2 CURRENT GEOGRAPHY

The modern delta bears little resemblance to the delta of 150 years ago; it is predominantly of human construction. Its rich soils prompted agricultural development beginning in 1850. The first earthen levees were constructed in 1852 on Merritt Island

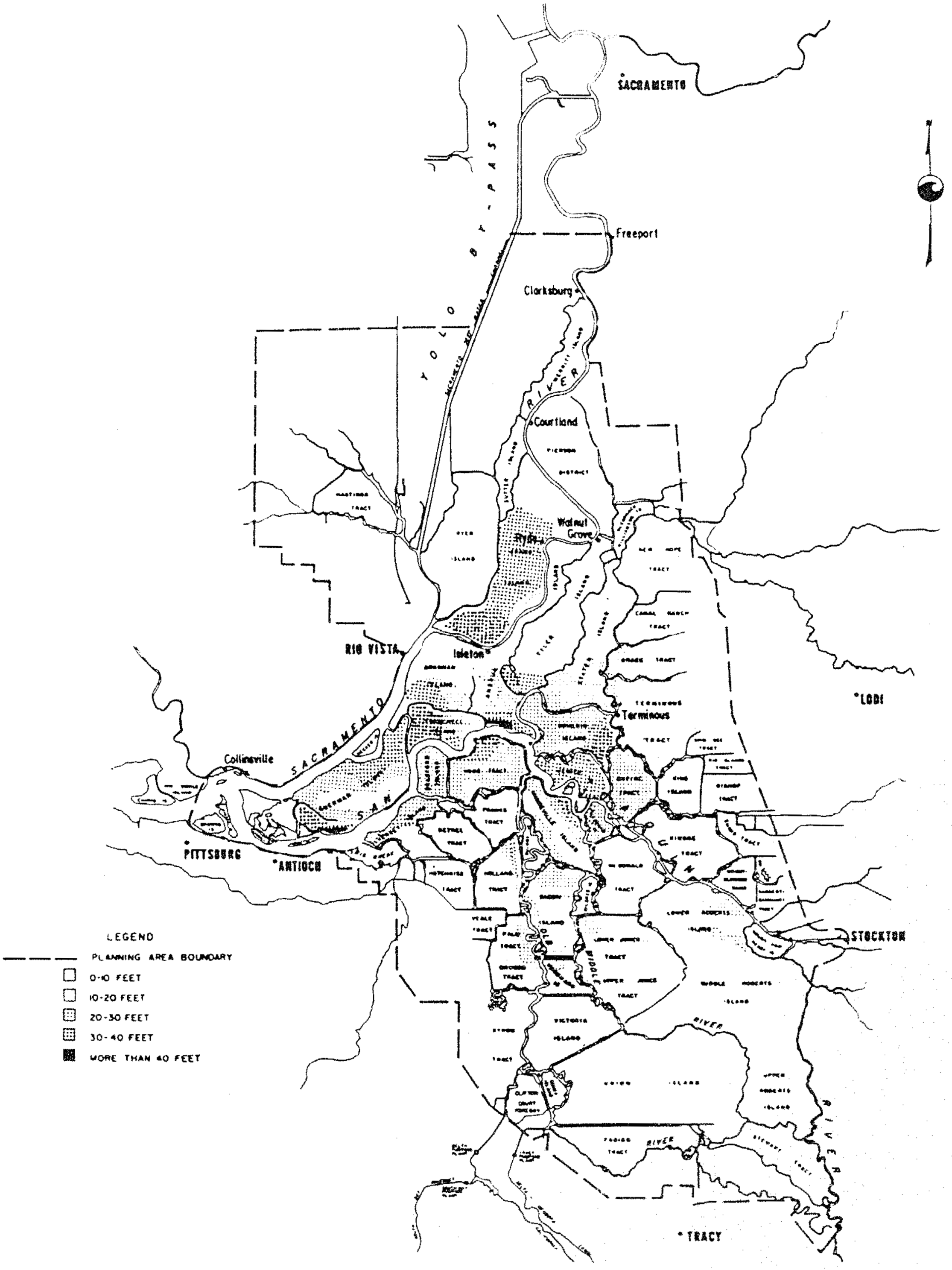

Figure 2. Depth of organic soils within the Sacramento-San Joaquin Delta. From California Department of Water Resources (1982).

(Thompson 1957) and the 60 largest islands had all been diked and drained by the turn of the century. Dikes were constructed of soils from the interior of the islands and from spoilage of dredging operations in the channels. Today, approximately 2000 km of levees line the major islands of the delta. Some are still the original levees of 100 years ago. The friability of the soil led to widespread use of rock revetments or of massive mounds of marsh soils 9 m high and 70 m wide at the base to reinforce soil levees.

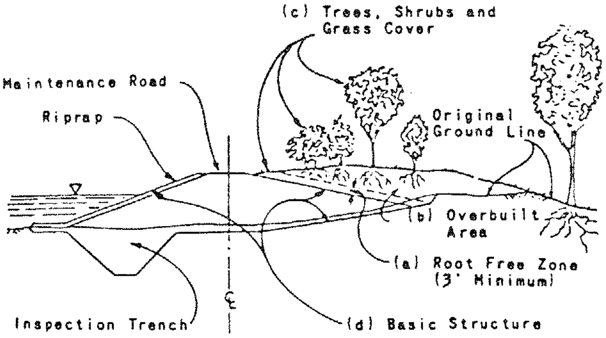

Figure 3. Normal structure of levees constructed by the U.S. Army Corps of Engineers.

Levees are typically devoid of trees and bushes, as vegetation is generally considered detrimental to the operation of the levees because it prevents easy visual inspection and because tree roots extending into the channel produce eddies that speed erosion of unreinforced soils (Nolan 1984). The possible incorporation of vegetation into the functioning of levees has been investigated (Daar et al. 1984; Whitlow et al. 1984), but has not been pursued by the regulatory agencies. Levees built by the U.S. Army Corps of Engineers (USACE) are usually of the type illustrated in Figures 3 and 4. Levees are divided into three classes: project levees are constructed and maintained according to the specifications of the USACE account, direct-agreement levees are maintained to Federal standards, and non-project levees are built and maintained to no set of standards (Figure 5). Non-project levees account for 75% of levees in the delta (Geidel and Moore 1981). The reliability of these

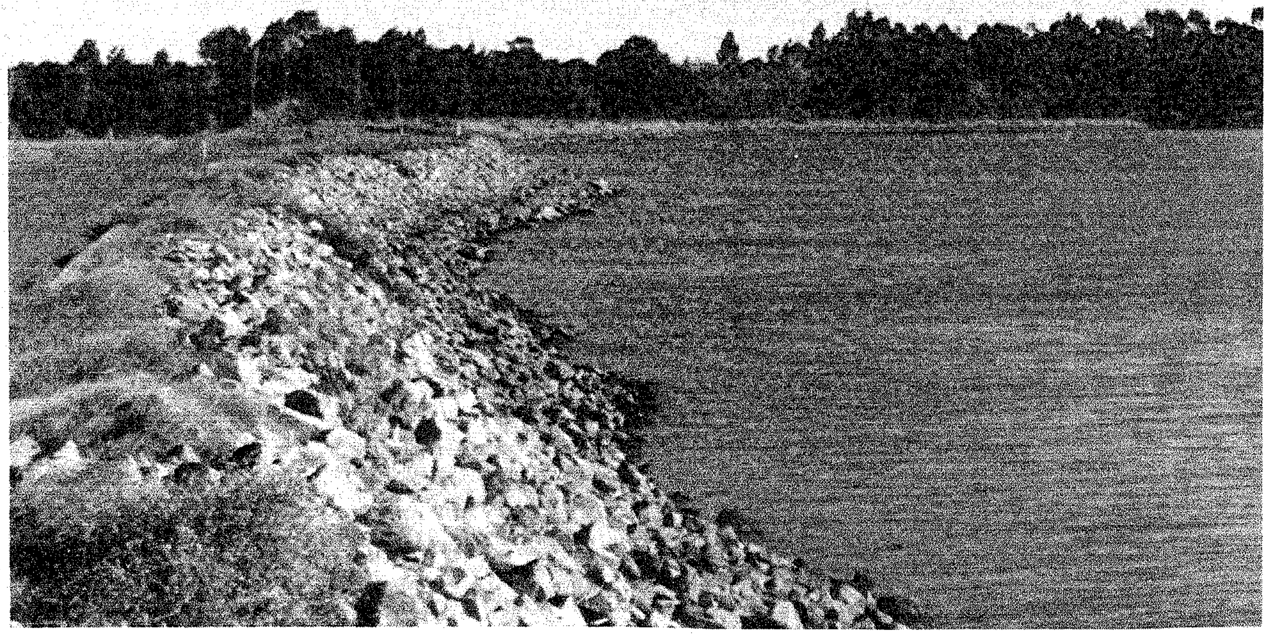

Figure 4. Project levee on north fork of Mokelumne River. Note absence of riparian or emergent vegetation.

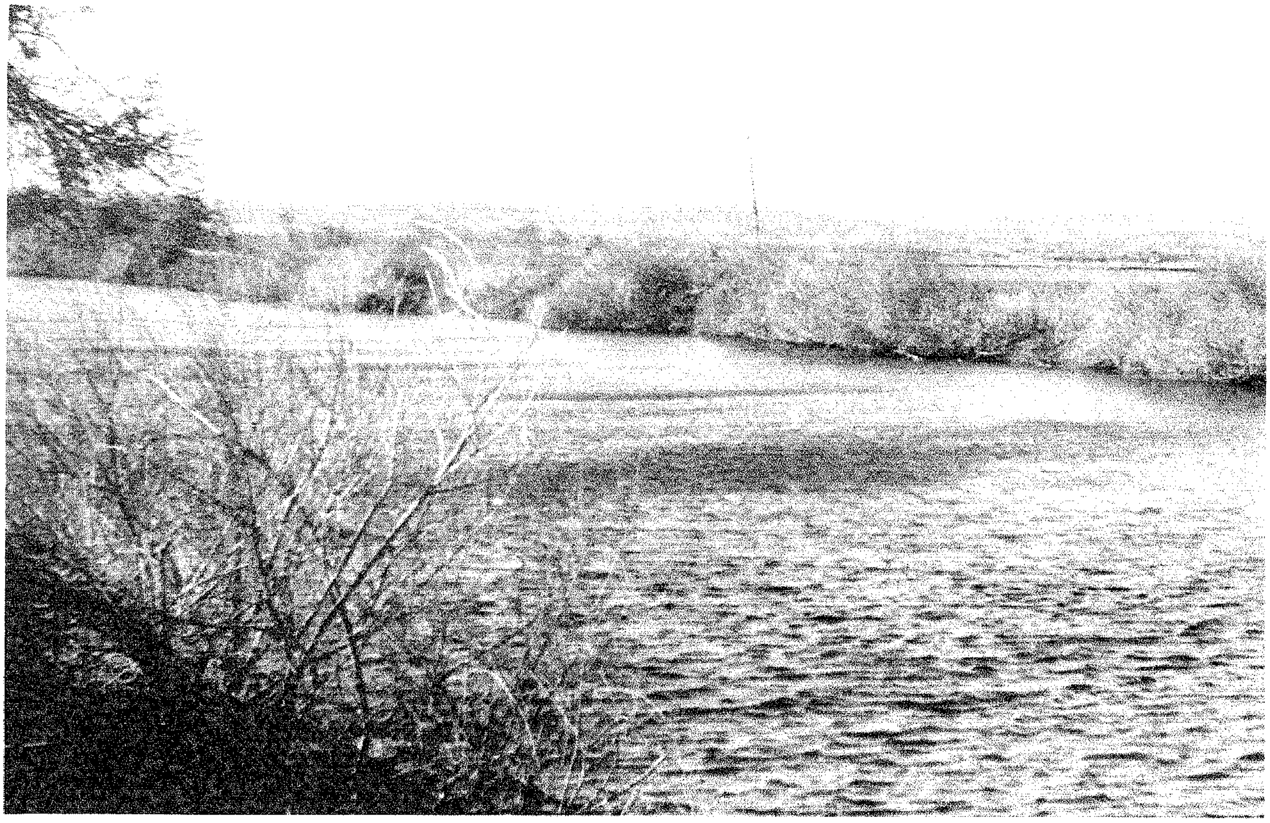

Figure 5. Privately owned and maintained levees on Sevenmile Slough. Note steepness of edge, erosion, and narrow riparian band extending into water.

non-project levees is generally much lower than project and direct-agreement levees, and they often fail.

Levee failures have been common (Figure 6). Three levee failures produced lacustrine habitats in the delta at Frank's Tract, at Sherman Lake, and at Big Break (Figure 1). Erosion of the breached levees has gradually returned these to more riverine habitats, but water currents are slower and more shallow than the surrounding channels. As subsidence continues, levee failures may become more common. Flooded islands may more frequently remain unreclaimed because the costs of reclamation are now often greater than the value of the land. A variety of plans have been put forth to reduce the incidence of levee failure, but the current plan generally involves a continuation of levee maintenance and improvements. Guidelines for the placement of vegetation on levees may permit restoration of riparian vegetation to reduce wind generated wave action.

Subsidence within the diked islands has dropped the interiors of the larger islands by as much as 7 m below mean sea level, making the islands look like holes in an inland sea (Figure 7). The depths within the islands are greatest in the western and central delta (Figure 8).

Agricultural practices have led to large-scale subsidence of these islands. The causes are numerous (Weir 1950; Broadbent 1960; Burke 1980; Newmarch 1980):

1) Drying causes the organic soils to shrink. Such shrinkages are not entirely reversible and are only a minor contributor to subsidence (Burke 1980).

2) Drying of soils leads to oxidation, which is the greatest contributor to subsidence. Oxidation of soils occurs naturally at a high rate and is enhanced by plowing and burning (Weir 1950).

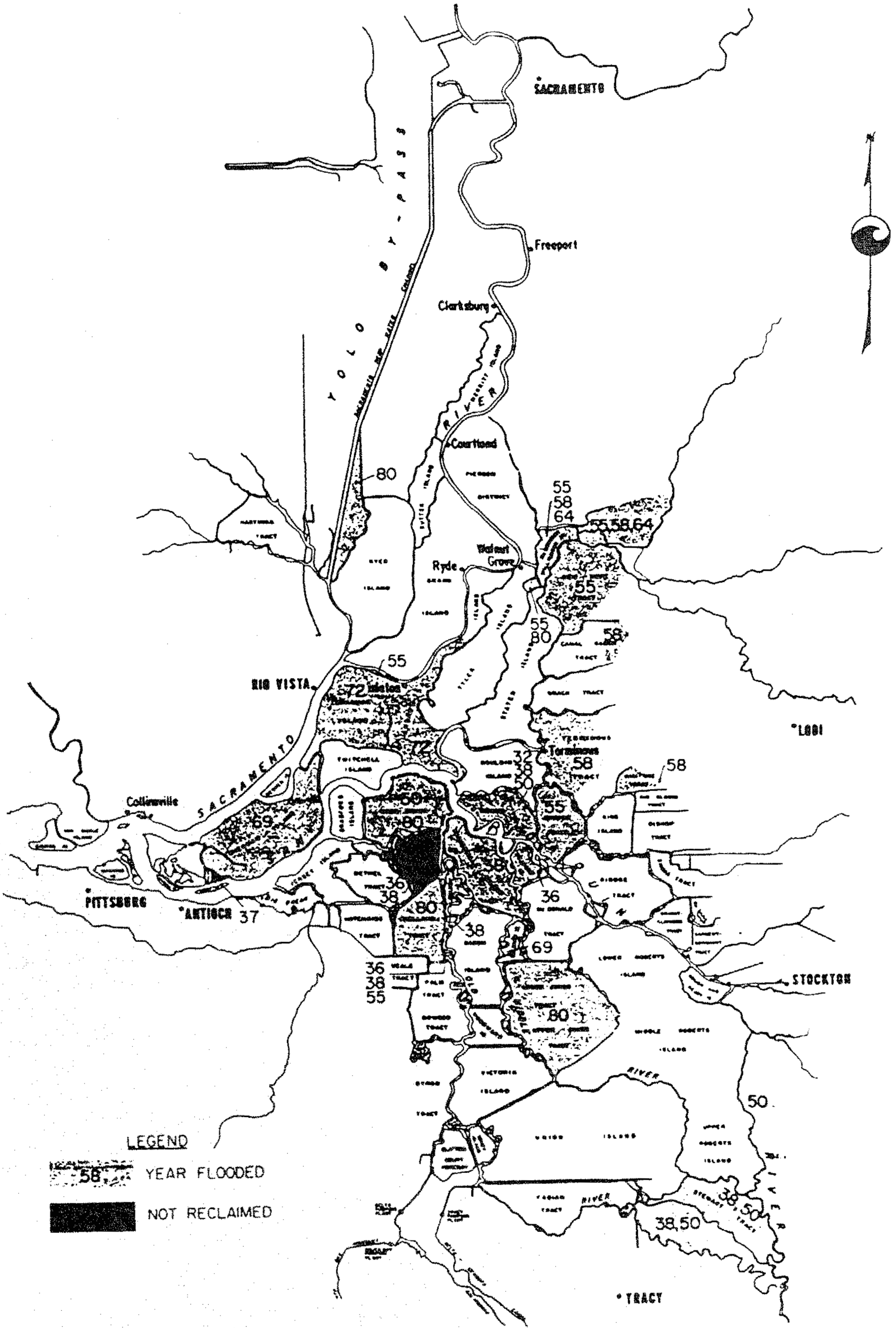

Figure 6. Years between 1930 and 1980 in which delta islands have been flooded. From California Department of Water Resources (1982).

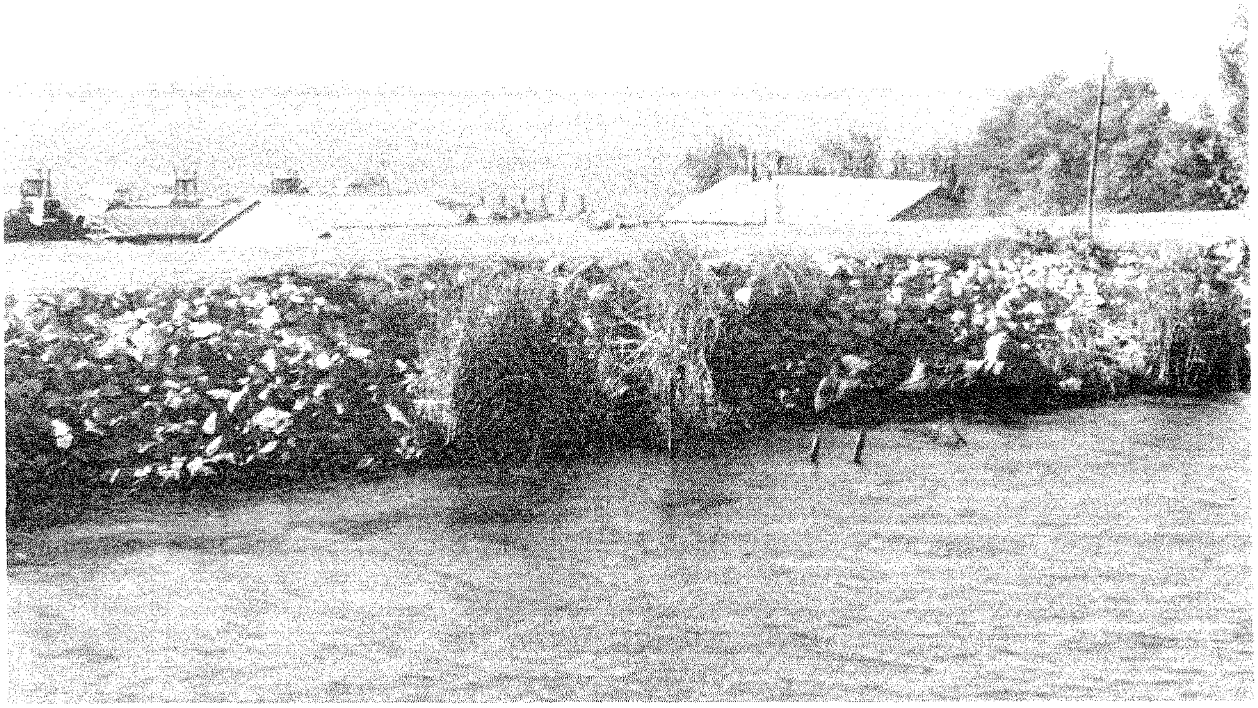

Figure 7. View across Disappointment Slough toward Empire Tract. Note tops of roofs at water level.

Prior to 1945, peat soils were regularly burned at the end of each growing season to kill weed seeds and pests. Burning was particularly common in potato cultivation because of the response of that plant to potash. Uncontrolled burnings of peat soils can occur and are difficult to control; they have become much less common in recent years because previous oxidation eliminated much of the organic material from delta soils.

3) Wind-borne erosion, or deflation, is a particular problem because of the extreme friability of peat soils when dry. Plowing can greatly increase the deflation rate. Windbreaks of planted trees are much less common than formerly.

4) Compaction of soils by the passage of heavy agricultural equipment was probably a greater cause of subsidence when these soils were first dried and graded for cultivation. Its contribution to current rates of subsidence is probably small.

5) Withdrawal of natural gas and ground water probably contributes to subsidence, as might the natural processes of geological subsidence.

6) Export of soil for sale contributes to localized subsidence.

Rates of subsidence for 18 delta islands in the period from 1911 to 1952 indicated average rates of approximately 77 mm per year (California Department of Water Resources 1982). It is unclear whether the rates of subsidence have slowed. Newmarch (1980) found that subsidence is still continuing at a rate of 71 to 77 mm per year but rates in the area where Newmarch worked may have previously been subsiding at rates of 89 mm per year (Burke 1980 citing unpublished data of Weir).

1.3 LAND USE, HABITAT TYPES, AND CHARACTERISTIC SPECIES

The delta is predominantly an agricultural region. Despite intensive cultivation, it still contains a wide

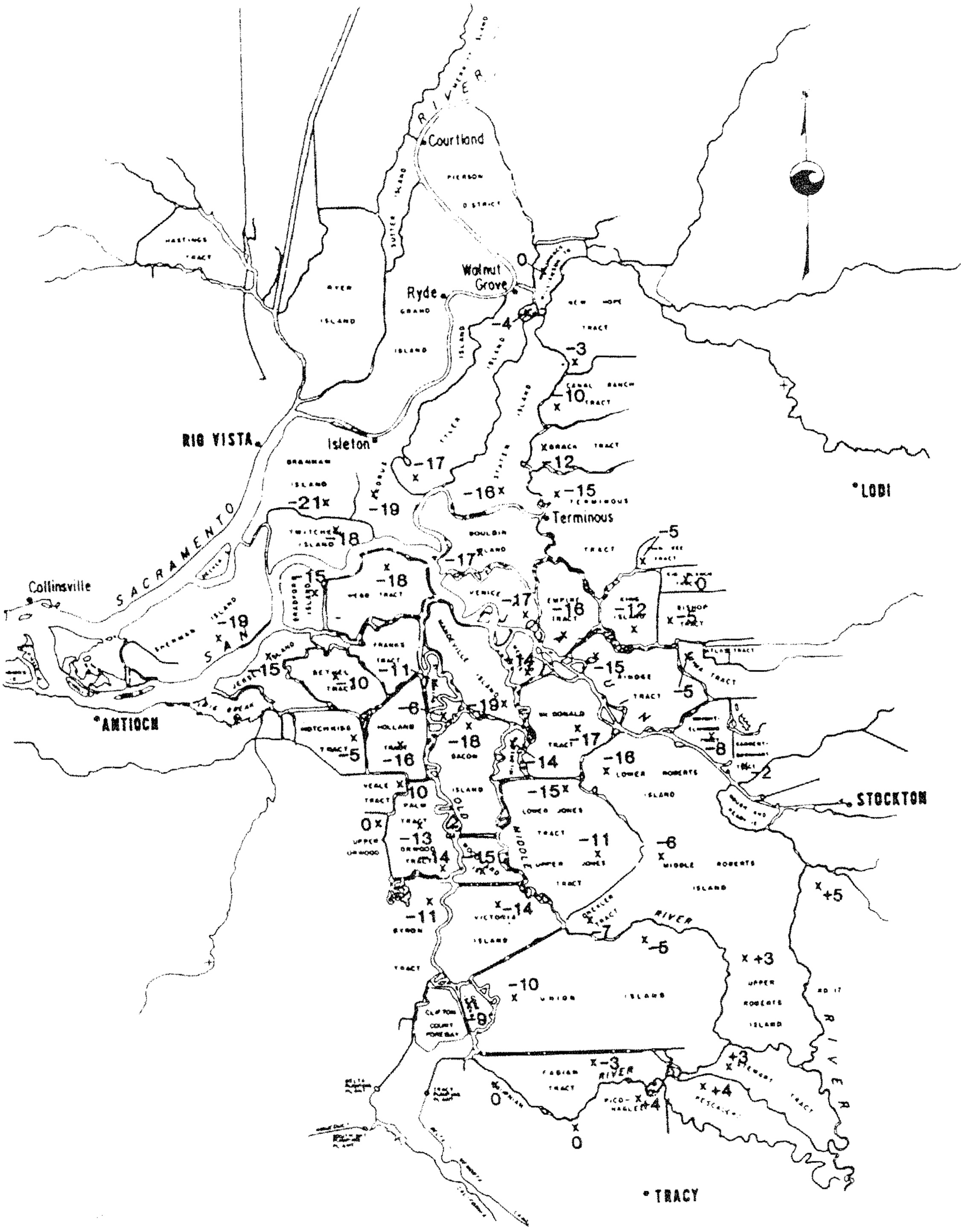

Figure 8. Depth (in feet) of subsidence in delta islands. From California Department of Water Resources (1982).

variety of habitats (Table 1) and a consequently large variety of plant species (Appendix A). Out of the delta's 679,422 acres, cultivated land has increased from 335,000 acres in 1931 to 520,518 in 1977; consequently many of the natural habitat types are represented by very small areas. In addition to the 79% of the delta which is agricultural land, another 5% comprises housing and other urban development (U.S. Army Corps of Engineers 1979) (Table 1).

Table 1. Habitat types and their abundances within the Sacramento-San Joaquin Delta (from USACE 1979).

Habitat type	Acreage in delta	Percentage
Emergent wetland	10,243	
Scrub/shrub	4,367	
Forested	2,732	
Total Palustrine (nontidal and <2m deep)	17,342	2.6
Emergent wetland	594	
Beach/bar	63	
Streambed	147	
Aquatic bed	145	
Total Riverine (channels >2m deep)	949	.1
Limnetic	5,705	
Aquatic bed	94	
Emergent wetland (perennials)	286	
Emergent (annuals)	828	
Total Lacustrine (negligible flow)	6,913	1.0
Openwater	46,720	6.9
Upland	44,446	6.5
Agriculture	531,156	78.2
Urban	31,896	4.7
TOTAL ACREAGE	679,422	100

The dominant row crops include asparagus, sugar beets, safflower, and corn; pear orchards and vineyards are also cultivated. These fields support populations of waterfowl (Anseriformes spp.), ringnecked pheasants (*Phasianus colchicus*), mourning doves (*Zenaida macroura*), yellow-billed magpies (*Pica nutalli*), ground squirrels (*Otospermophilus beecheyi*), pocket gophers (*Thomomys bottae*), moles (*Scapanus latimanus*), and garter snakes (*Thamnophis spp.*). Urban areas support the usual human symbionts: house mice (*Mus musculus*), Norway rats (*Rattus norvegicus*), roof rats (*Rattus rattus*), starlings (*Sturnus vulgaris*), house sparrows (*Passer domesticus*), and northern mockingbirds (*Mimus polyglottos*).

Riparian areas in the delta vary from grassy margins of levees to densely wooded strips 30-40 m wide. The largest concentrations of riparian habitats occur mostly in the northern and eastern delta, the Mokelumne River and the Snodgrass, Sevenmile, Trapper, and Whisky Sloughs. These areas, particularly Snodgrass Slough, are only a small part (7,100 acres) of the delta but are important to many wildlife species for the food, shelter, and breeding sites they provide. Common plants include Fremont cottonwood (*Populus fremontia*), willow (*Salix* spp.), California blackberry (*Rubus vitifolius*), and wild rose (*Rosa californica*). Also in this habitat are five species which are considered by the Fish and Wildlife Service to be candidates for listing under the Endangered Species Act (Federal Register 50:39526-39584, 1985): California hibiscus (*Hibiscus californicus*), slough thistle (*Cirsium crassicaule*), delta coyote thistle (*Eryngium racemosum*), lilaeopsis (*Lilaeopsis masonii*) and delta tule pea (*Lathyrus jepsonii* spp. *jepsonii*).

Animals dependent on the riparian areas include belted kingfishers (*Ceryle alcyon*), red-shouldered hawks (*Buteo lineatus*), Rufous-sided towees (*Pipilo erythropthalamus*), and ringtails (*Bassariscus astutus*). Some shorebirds, including great blue herons (*Ardea herodias*) and egrets (*Egretta thula* and *Casmerodius albus*), use riparian trees for nest sites. Giant garter snakes (*Thamnophis couchi gigas*), listed as rare by the California Department of Fish and Game, are highly aquatic but breed in riparian areas. Riparian areas in the delta support more species of birds and mammals than any other habitat type (Rollins 1977).

Freshwater marshes are the most decimated of delta habitats. In 1850 most of the delta consisted of freshwater marsh; by 1975 only 11,047 of the delta's 679,422 acres remained marsh. Today the freshwater marsh in the delta is largely composed of small, unleveed islands (Figure 9) along the margins of private levees. Many species of wildlife depend, wholly or in part, on these remaining bits of marsh. In the western delta these include salt marsh harvest mice (*Reithrodontomys raviventris*), listed as endangered by the California Department of Fish and Game, and California black rails (*Laterallus jamaicensis coturniculus*), listed as rare by the State.

Dominant vascular plants of the marshes include tules (*Scirpus* spp.) in the western regions where salinities intrude, and reeds (*Phragmites communis*) and cattails (*Typha latifolia*) in the more freshwater areas. Common large animals of the marshes include northern harriers (*Circus cyaneus*), herons, egrets, mallards, marsh wrens (*Cistothorus palustris*), muskrat (*Ondatra zibethicus*), otter (*Lutra canadensis*), and beaver (*Castor canadensis*).

Aquatic habitats make up 53,778 acres of the delta; these habitats include river channels, flooded islands, and the various sloughs and channels criss-crossing the delta. Freshwater marshes that annually die back to below water level also occur. The introduced floating plant, water hyacinth (*Eichhornia crassipes*), frequently covers the surface of quieter, nonsaline waters. Pondweed (*Potamogeton* spp.) and water weed (*Elodea canadensis*) makeup most of the other aquatic vascular flora. Fishes are the dominant vertebrates; the introduced striped bass (*Morone saxatilis*), white catfish (*Ictalurus catus*), threadfin shad (*Dorosoma petenense*), and carp (*Cyprinis carpio*) are particularly abundant. Mallards, grebes (Podicipedidae), gulls (*Larus* spp.), pintails (*Anas acuta*), and American coots (*Fulica americana*) are common birds.

Upland habitats, mostly fallow fields and grazing areas (Figure 10), are important to many ground-nesting birds species, including waterfowl. Vascular plants in this habitat are frequently species that are ruderal, introduced, or both such as mustard (*Brassica genicula* and *B. campestris*) wild radish (*Raphanus sativa*), foxtail (*Hordeum murinum*), cheeseweed (*Malva parviflora*), and eucalyptus (*Eucalpytus spp*). Redtail hawks (*Buteo jamaicensis*),

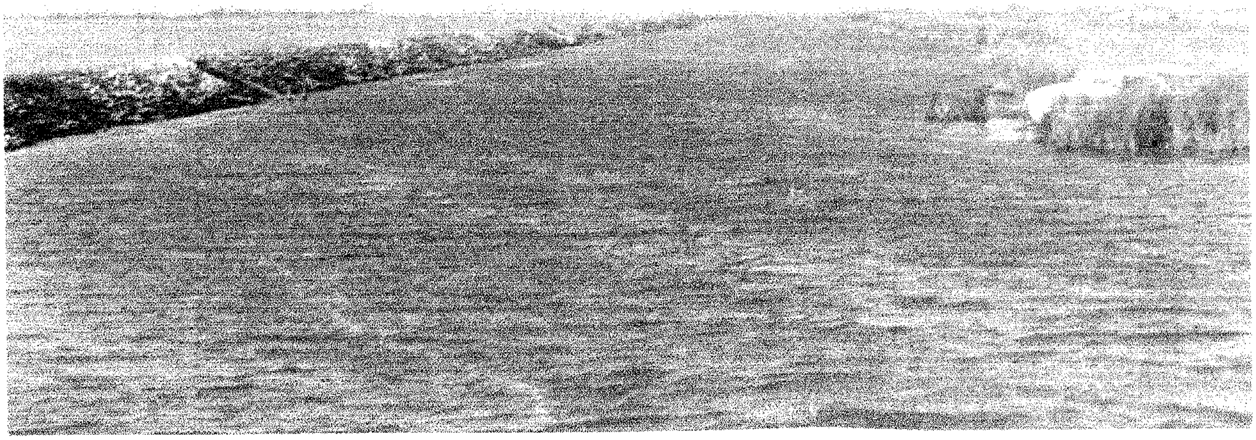

Figure 9. Unleveed island of marsh habitat in Disappointment Slough. Note absence of any similar habitat along levees.

Figure 10. Upland habitat converted to agriculture and pasturage one mile west of Rio Vista.

American kestrels (*Falco sparverius*), Western meadowlarks (*Sturnella neglecta*), fence lizards (*Sceloperus occidentalis*), and pocket gophers are abundant vertebrate species. Lange's metalmark butterfly (*Apodemis mormo langei*) and the San Joaquin kit fox (*Vulpes microtis mutica*), both listed as endangered by the U.S. Fish and Wildlife Service, occur in these habitats. Pasture habitats support almost as diverse an assemblage of vertebrates as freshwater marsh habitats (Rollins 1977).

Within the upland habitat are scattered vernal pools, which have been the objects of intensive conservation measures in recent years. These "hog wallows" fill with water each spring and dry completely in most summers. Vernal pools support a wide array of species. Solano grass (*Tuctoria mucronata*), which occurs only around these vernal pools, is listed as an endangered species by the U.S. Fish and Wildlife Service. The Service considers another plant of the vernal pools, Colusa grass (*Neostapfia colusiana*) to be a candidate for listing.

1.4 CLIMATE

The Mediterranean climate of California is particularly marked in the delta region because the Coast Range prevents almost all summer storms from reaching the inland areas. In the winter, storms are often kept within the valley, locked between the Coast Range and the Sierra Nevadas. Thus, summers are uniformly hot and dry, while winters are usually cold and wet. Mean monthly temperatures and precipitation for Stockton and San Francisco for the years from 1964 to 1974 are presented in Figures 11 and 12. These two cities represent the geographic extremes of the estuary. The climates in the two cities are similar, but the delta region (Stockton) experiences more extreme values of temperature due to greater continental effects. On the other hand, the variability within months is greater in San Francisco (at the mouth of the estuary) where oceanic storms can move in and out more freely.

The most common variations of weather within this climatic pattern occur in two forms. Warm, tropical, wintertime storms are responsible for the heaviest rainfalls and abnormally warm winter months. Cold, polar storms produce the coldest times on record and usually lead to little rainfall. The water year of 1985-86 contained examples of both phenomena. In December 1985 the delta received very little precipitation and was wrapped in cold fogbanks for 22 days. Two months later the delta received a tropical storm bringing new records for rainfall as well as anomalous high temperatures.

The years 1976-85 in the delta were remarkably variable because of the occurrence in some years of

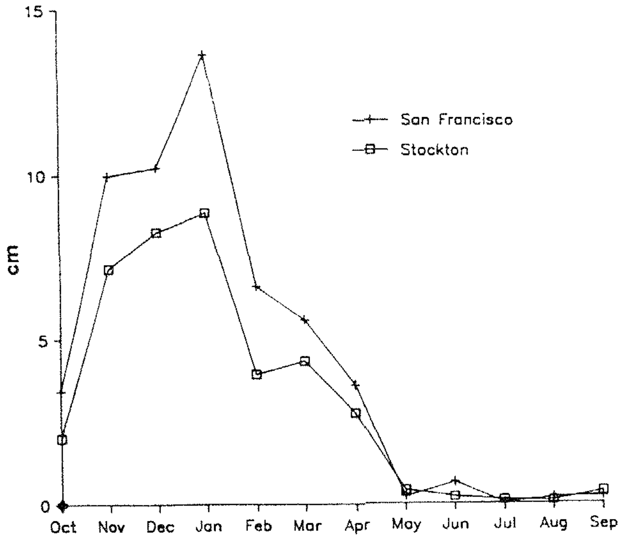

Figure 11. Mean monthly precipitation rates in centimeters for Stockton and San Francisco.

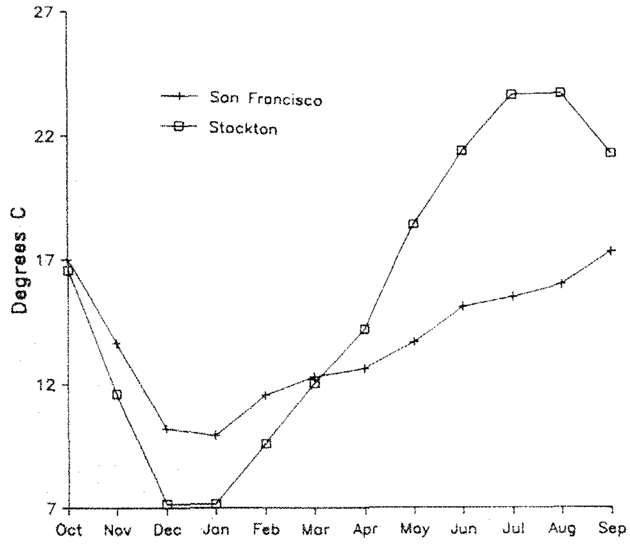

Figure 12. Mean monthly temperatures in degrees Celsius for Stockton and San Francisco.

polar, tropical, or both types of winter storms. This led to the driest years on record (1976-77) and the wettest year on record (1983). Earlier weather patterns were more consistent, but a similar period of extreme conditions characterized the 1860's. At that time the ecological consequences were probably more pronounced because control structures on the rivers were absent.

Annual incursions of saline water into the delta still occur each summer as they did historically (at much higher levels). Water diversions and management practices have substantially changed the dynamics of these incursions. Diversion of up to 80% of normal outflow can cause longer residences of saltwater in the delta due to the paucity of freshwater available to dilute it or push it downstream. On the other hand, upstream control structures (principally Shasta Dam) retain water during the rainy season and release it during the dry season. These practices have greatly reduced the extent and degree of maximum salinity intrusion into the delta (Figure 13). Thus, the decreased range of salinities experienced in the delta is one of the most pronounced changes. Electrical conductivities of delta waters still increase slightly through the summer, but this is largely due to increased proportions of agricultural waste waters rather than tidal intrusions.

The northern delta is dominated by large quantities of low conductivity, relatively unpolluted water from the Sacramento River. Total dissolved solids in the San Joaquin River generally are at much higher concentrations than the Sacramento (Figure 14); however, the San Joaquin carries much less water into the delta. When the San Joaquin is in flood, the conductivity of its water drops dramatically. The east side streams are exemplified by the Mokelumne River, which runs over a short distance down the Sierra slopes carrying small quantities of water of exceptionally low conductivity.

1.5 WATERFLOWS

The Sacramento River provides most of the delta's water. Water quantities have varied from 5 to 35 million acre-ft with a wide variability throughout the last 29 years (Figure 15). This seven-fold variability

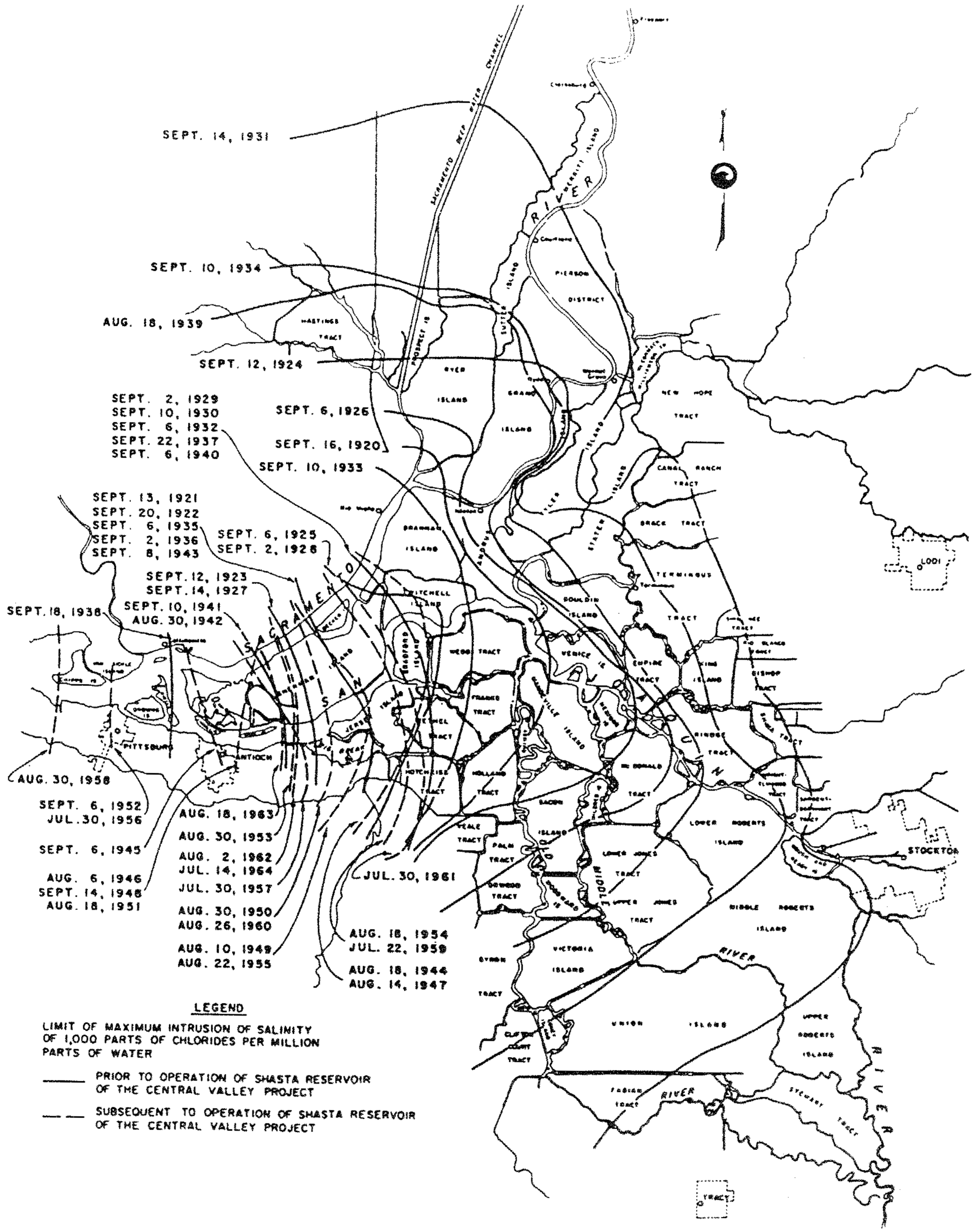

Figure 13. Historical extents of salinity intrusion within the Sacramento-San Joaquin Delta. Shasta Dam was first operational in 1943. From California Department of Fish and Game (1972).

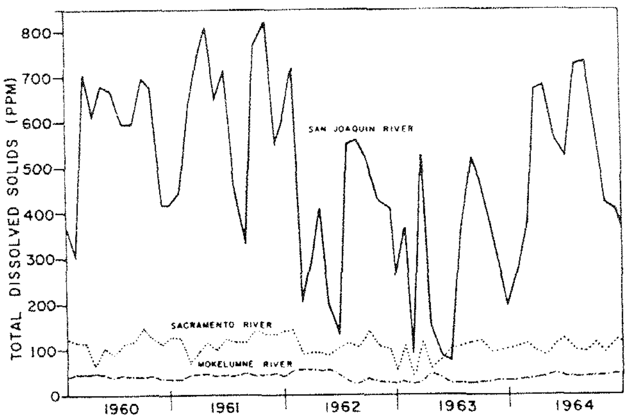

Figure 14. Conductivities of waters entering the delta from three principle rivers. From California Department of Fish and Game (1976).

in flows makes the Sacramento very unusual among the major rivers of North America. The distribution of total annual flows has little central tendency and appears bimodal. The San Joaquin River seldom contributes more than 20% of delta waters. The variability in San Joaquin outflow is even more erratic than that of the Sacramento, with the same scarcity of years falling near the mean (Figure 16).

Seasonal distributions of river flows, on the other hand, are quite consistent. The water year runs from October to September (Figure 17). As already noted, water management strategies have reduced some of the variability in this system, particularly by maintaining the minimum flows necessary to prevent saltwater intrusion throughout the summer. The peak in discharge of the Sacramento River rises sharply with the onset of winter rains and falls to a plateau through the summer. The peak of San Joaquin flows is smoother, with a continuous decline through the summer.

Direction of waterflow within channels is also seasonally variable. During winter and spring, when both main rivers are at their peaks of discharge, flows are uniformly downstream into the western

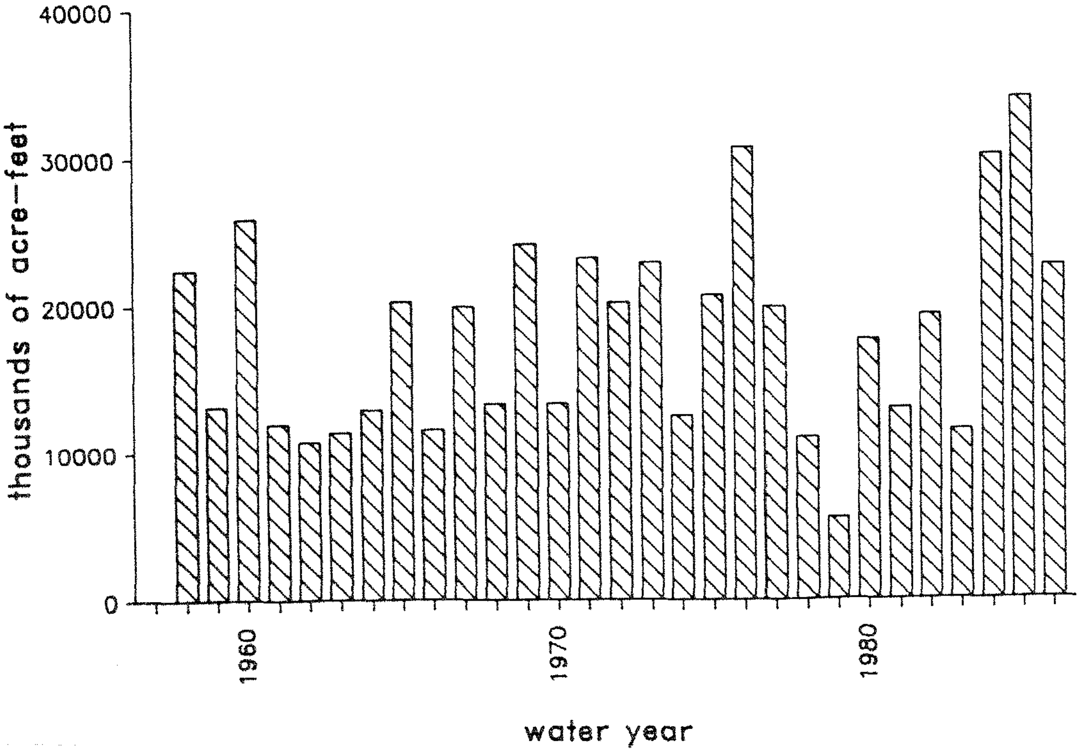

Figure 15. Annual flows in the Sacramento River over 29 years.

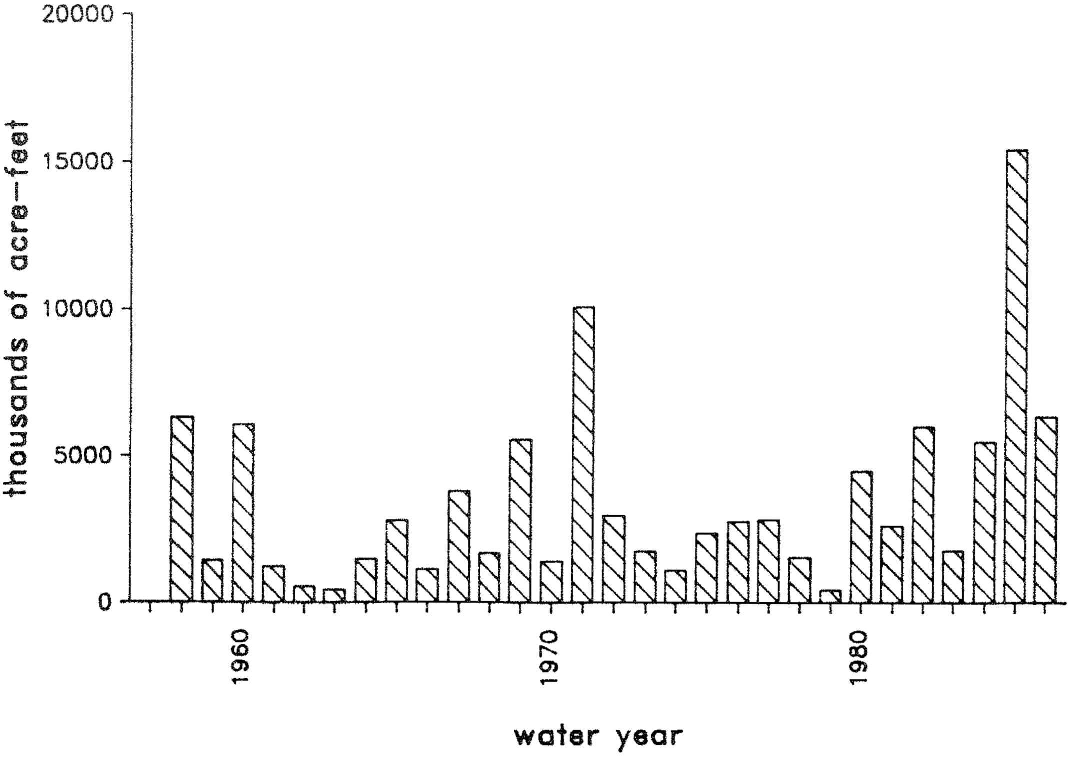

Figure 16. Annual flows in the San Joaquin River over 29 years.

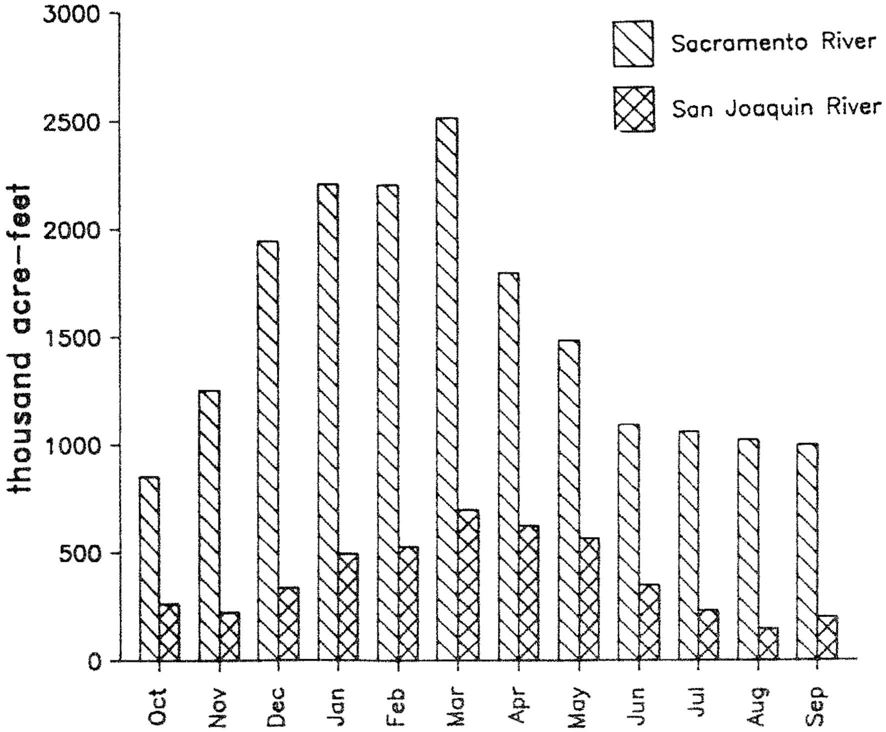

Figure 17. Mean monthly flows of the Sacramento and San Joaquin Rivers over the years 1975-84.

delta (Figure 18). From late spring to early fall, the pumping plants at Tracy withdraw more water than is delivered into their area by the San Joaquin River. As pumping starts to alter flow patterns in the delta, a cross channel is opened between the Sacramento River and the lower Mokelumne River. Sacramento River water can then flow south through the central delta channels (Figure 19). As the quantity of water exported continues to increase relative to Sacramento River outflow, water in the lower Sacramento River is drawn around Chipp's Island and upstream through the lower channels of the San Joaquin (Figure 20). These reverse flows have a variety of effects on the distribution of plankton and the migrations of fish.

Discharge rates control the location of the area where inflowing sea water meets outgoing freshwater. This region is referred to as the entrapment, or null, zone. Conflicting flows produce a concentration of suspended sediments and high settling rates (Ingles and Allen 1957; Meade 1972). At high discharge rates (2,000 m^3/sec) the null zone in the Sacramento-San Joaquin Estuary is 20 km above the Golden Gate. At low flows (100 m^3/sec) the zone is another 60 km upstream, within the delta itself. At intermediate flows the null zone typically occurs in broad, shallow Suisun Bay, just west of the delta (Peterson et al. 1975; Arthur and Ball 1979).

1.6 ANTHROPOGENIC CHANGES

The Sacramento-San Joaquin Delta is part of the most modified and intensely managed estuary in North America (Cloern and Nichols 1985). Many of the currently abundant species of angiosperms, invertebrates, fish, and mammals were introduced in the last 110 years. Many introductions were made with the cooperation of government agencies, but in recent years most of the introductions have been accidental or without official sanction. Most terrestrial habitat types have been converted to agriculture. Consequently, aquatic habitats have been changed from meandering channels lined with dense riparian growth into dredged sloughs with banks reinforced with rock revetments. Any understanding of the ecology of the delta must begin with a realization of the intensity and thoroughness with which the system has been altered.

The California gold rush, which began in 1848, entailed the first and harshest modifications of the delta. Hydraulic mining in the Sierras delivered millions of cubic meters of silt into the river channels, raising the bottom of the river by as much as 9 m in places and triggering widespread flooding. This flooding was the primary motivation behind the subsequent ban on hydraulic mining (1884). In addition, the flooding led to widespread demands for dredging and flood control.

No data are available on the ecological effects of hydraulic gold mining in the delta, but two major impacts can be reasonably surmised. Silty substrates support low diversities and densities of invertebrates in the delta (Hazel and Kelley 1966), so it is reasonable to assume that there was little benthic production or nutrient recycling during the years of hydraulic mining. Salmonid populations are severely depressed by siltation on redds (nests), so at least some of the decline in catch of trout and salmon can probably be attributed to hydraulic mining. The introduction and rapid spread of striped bass and American shad at nearly the same time may be partly ascribed to their more silt-tolerant type of eggs.

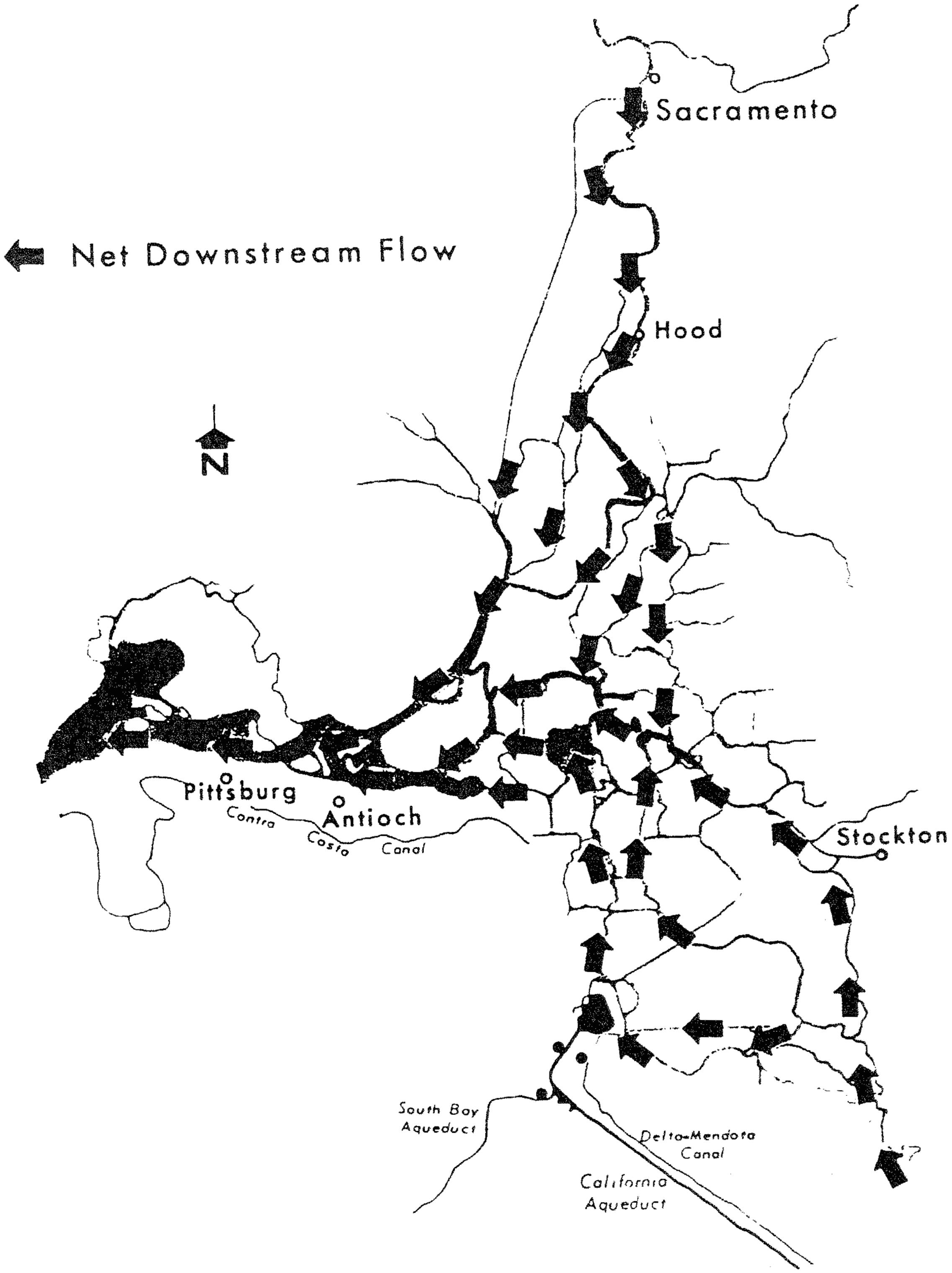

Figure 18. Pattern of waterflow through the Sacramento-San Joaquin Delta during typical winter conditions. From Geidel and Moore (1981).

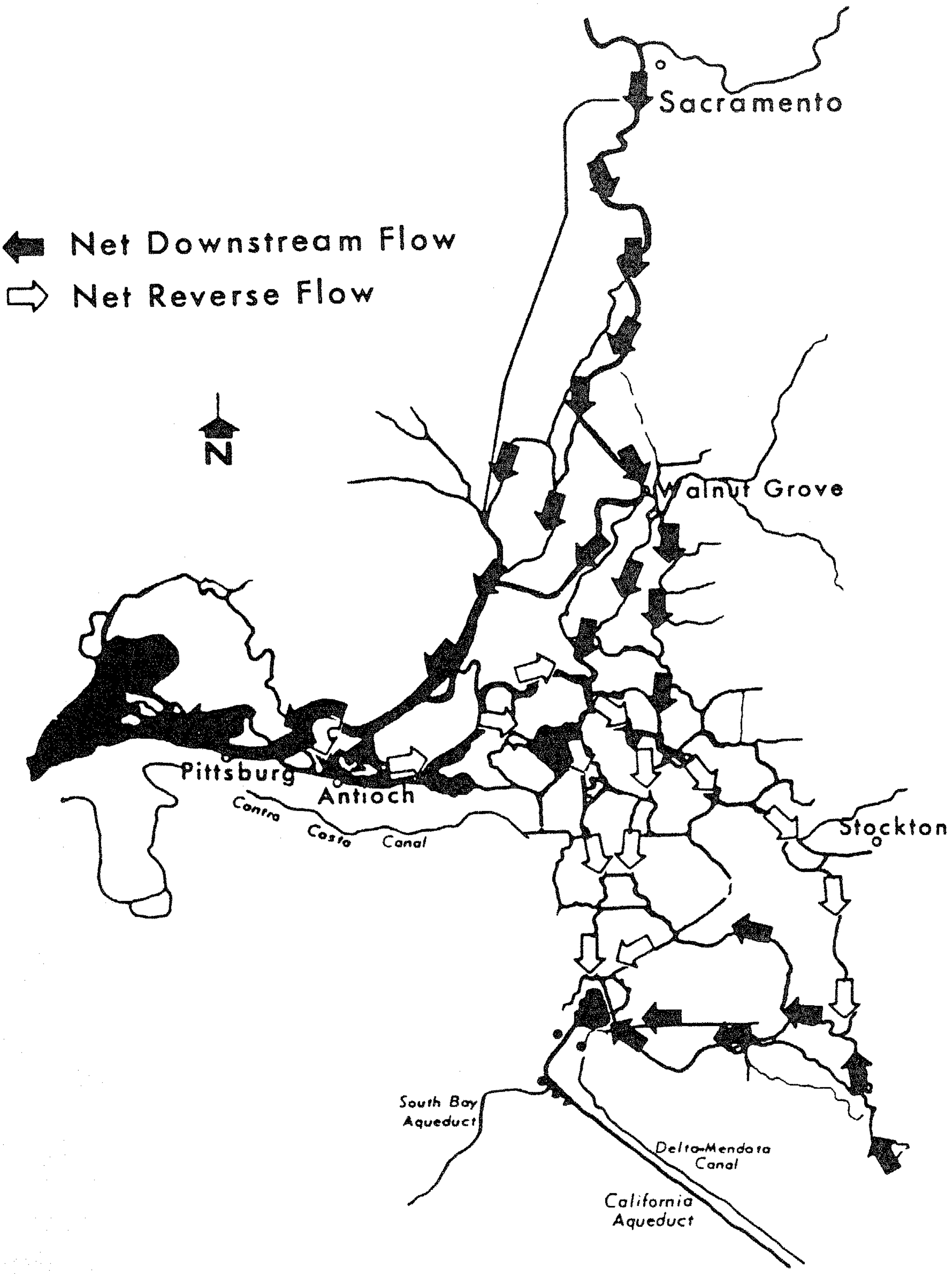

Figure 19. Pattern of waterflow through the Sacramento-San Joaquin Delta in early summer when the cross-delta channel is opened. Modified from Geidel and Moore (1981).

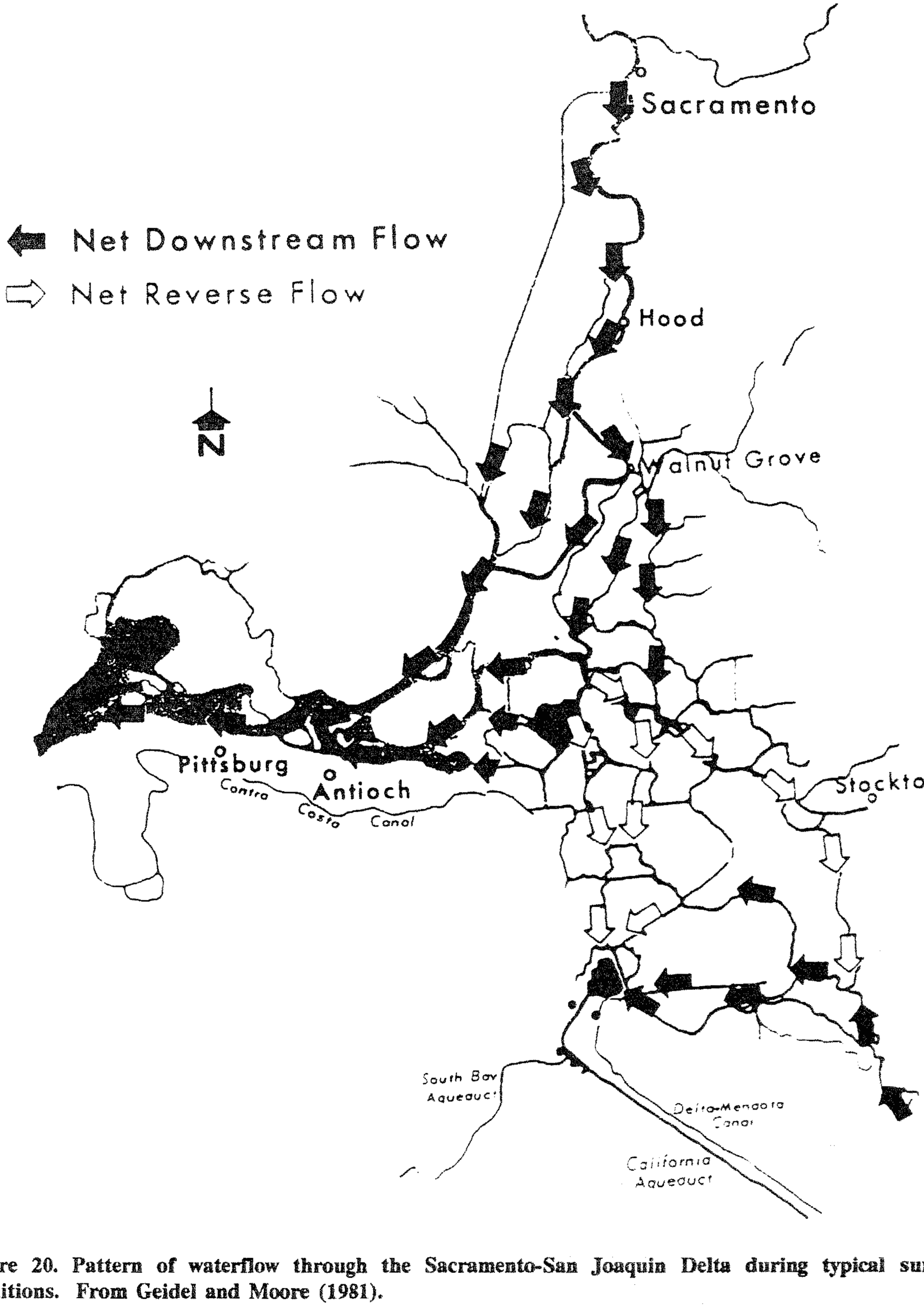

Figure 20. Pattern of waterflow through the Sacramento-San Joaquin Delta during typical summer conditions. From Geidel and Moore (1981).

CHAPTER 2. PHYTOPLANKTON

2.1 PATTERNS OF PRIMARY PRODUCTIVITY

Phytoplankton species are the dominant source of primary productivity in the delta. The steep-sided banks of the dredged sloughs and channels (see section on riparian habitats) have greatly reduced the former contributions of emergent vegetation and their attached assemblages of algae and their consumers (aufwuchs). Benthic algae are very limited in the delta because of the combination of turbid water and depths that usually keep the euphotic zone well above the bottom. As with other Pacific estuaries (Simenstad 1983), San Francisco Bay derives significant amounts of primary productivity from bentho-phytoplankton of exposed mud flats. However, filling has transformed many of the flats of the bay into commercial real estate, while dikes and dredges have removed such habitats from most of the delta.

Substantial in situ production of phytoplankton occurs in the delta. As it enters the delta, water from the Sacramento River seldom contains phytoplankton concentrations greater than 6 μg/L; halfway through the delta, chlorophyll *a* concentrations average 10-12 μg/L, and as it enters Suisun Bay it may carry from 10 to 60 μg/L (Chadwick 1972; Ball 1975). This pattern of increasing phytoplankton abundance at greater distance downstream occurs throughout the length of the Sacramento River (Figure 21; Greenberg 1964).

Conversely, at times when San Joaquin River water carries phytoplankton concentrations of 240 μg/L into the delta at Vernalis, phytoplankton populations in more downstream sites are only 40-60 μg/L. These results are primarily a result of the pumping stations at Tracy which withdraw almost all the plankton-rich waters of the San Joaquin (Ball 1975), thereby causing the less fertile waters of the Sacramento to flow up the lower channels of the San Joaquin.

2.1.1 Controlling Processes

Phytoplankton productivity is generally controlled by six factors: residence times, nutrient concentrations, insolation, temperature, animal grazing, and toxicant concentrations. Figure 22 provides a conceptual model of the operation of these factors. Which factor limits phytoplankton abundance varies in both time and space.

Hydraulics. Residence time is the average time of passage for a unit of water. If plankton are considered as free-floating particles within a water mass, then they are limited in their productivity by the number of generations that can be produced in the residence time of the water. This is an overly simple view because particles concentrate in eddies and backwaters of streams, thus greatly increasing their period in the delta. In addition, the density of most species of plankton is greater than that of water, so they tend to settle for various periods before turbulence reinjects them into the water column. Settling rates are higher in the delta than in upstream areas because of the slower water velocities. In the western delta, settling rates of diatoms increase with increasing chloride concentrations. This response may be part of the reason for the decline in diatom abundance in the western delta during the last major drought, for the bottom is well below the euphotic zone in almost all of the delta. However, landward flowing currents along the bottom of Suisun Bay usually serve to keep the water column in the western delta thoroughly mixed (Arthur and Ball 1979; Ball and Arthur 1979).

In the Sacramento-San Joaquin Delta the effects of residence times can be seen in several ways. The higher flows and straighter channels of the Sacramento River as it passes through the delta give rise to the lowest algal concentrations measured.

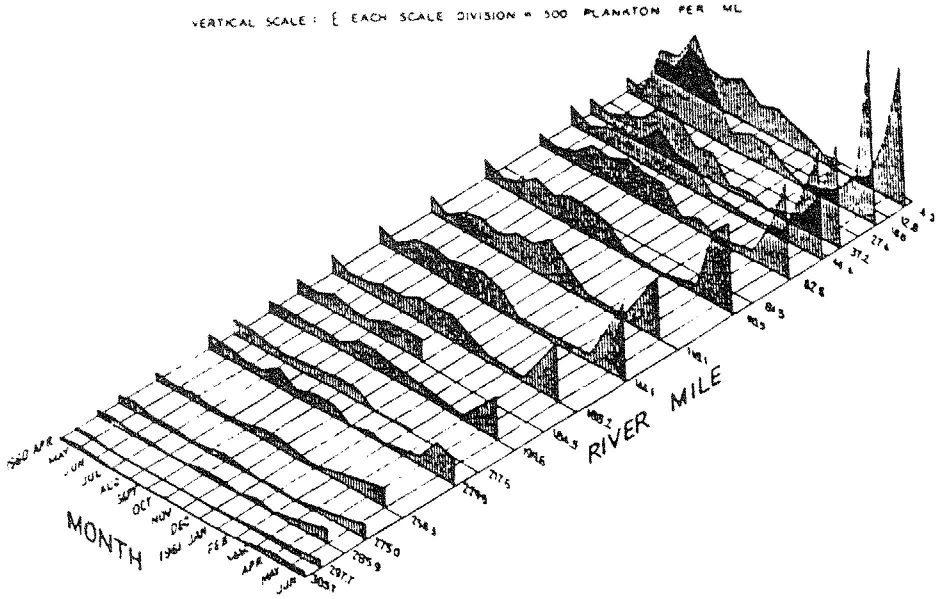

Figure 21. Concentration of phytoplankton at various distances up the Sacramento River over 18 months of sampling. From Greenberg (1964).

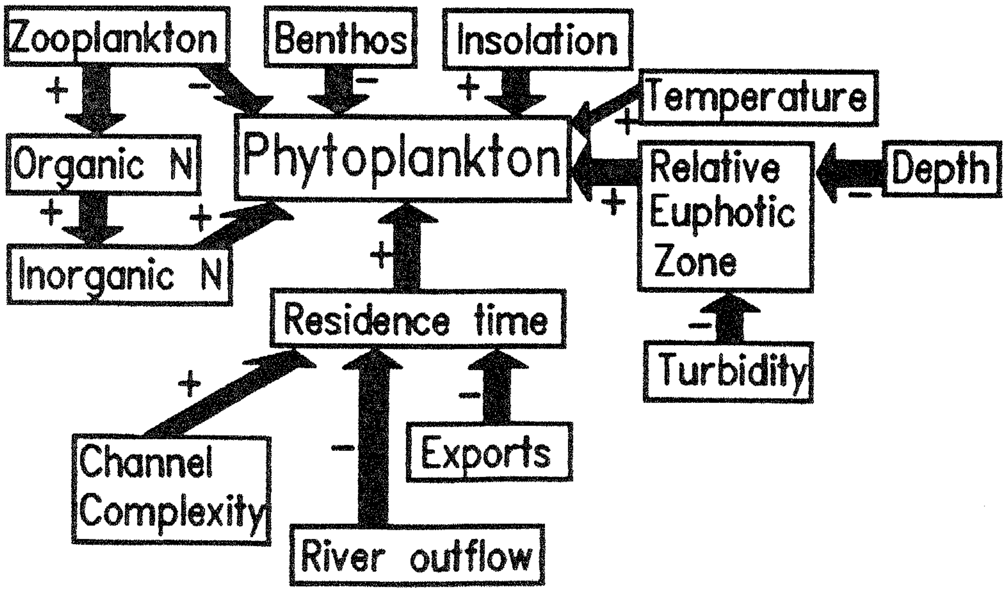

Figure 22. Conditions controlling phytoplankton abundance. Positive and negative signs indicate the effect of increasing the source element on the target element.

Residence time is the controlling parameter as indicated by the relationship between timings of spring blooms and volume of flows. For the years 1969-72, the spring bloom was in various months but always later in years of high flow than in years of low flow. Spring blooms in the Sacramento River always occurred after the flows had leveled out (Figure 23; Ball 1975). During the drought of 1976-77, Sacramento River chlorophyll *a* levels were several times greater than normal. These higher chlorophyll *a* levels were predominantly an effect of increased residence times, although temperatures were also higher (California Department of Water Resources 1976-86a,b; see 1978 data). Flows of the San Joaquin River are much less than those of the Sacramento, and phytoplankton populations are correspondingly greater at almost all times. Evidence that residence times are important lies in comparisons of the channels that pass water to the Clifton Court forebay with dead-end sloughs where water may be held for extended periods. These dead-end sloughs consistently harbor higher phytoplankton populations than their flow-through counterparts. On the other hand, dead-end sloughs are usually the first recipients of nitrogen-rich agricultural waste water and they tend to be some of the shallowest channels in the delta; these factors also contribute to greater productivity.

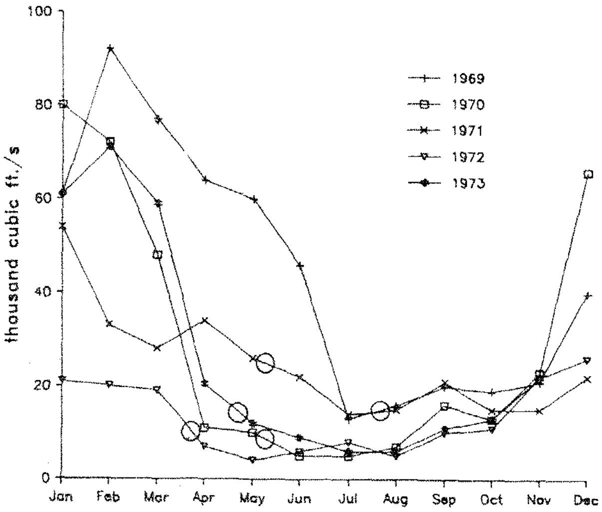

Figure 23. Comparison of peak spring algal abundance with amount of spring outflow for years from 1969 to 1972. Circles indicate periods of highest chlorophyll *a* concentrations in west central delta. Modified from Ball (1975).

Residence times of water, and associated algal populations, are determined by three main factors. Upstream river outflows control the water velocities in channels. Downstream diversions (principally at the Tracy pumping plants) remove water from the delta and accelerate flows in some channels. Finally, the morphology and placement of channels control flow rates because flooded islands or dead-end sloughs are much more efficient water traps than dredged channels or canals. River outflow and delta exports are frequently inversely related so that in winter and spring, when residence time is brief because of river inflow, delta exports are least. During the dry season, river outflows decline, but exports increase so that residence time is kept short.

At extreme flows, residence times are the primary control of phytoplankton production. In 1983 northern extensions of a seasonal warm tropical current, *El Niño*, brought long and heavy rainfall to California resulting in the wettest year on record. Flows through the delta were almost 400,000 ft^3/s and never dropped below 20,000 ft^3/s during the whole water year. San Joaquin River flows were particularly higher than usual. These conditions resulted in a complete absence of plankton blooms in the delta, with concentrations of algae never higher than the usual background level of 10 $\mu g/L$. The plankton failed to produce blooms in spite of suitable levels of light, temperature, water transparency, and macronutrient concentrations (California Department of Water Resources 1978-86a,b; see 1984 data).

Nutrients. Different nutrient concentrations appear to limit phytoplankton growth in different parts of the delta at different times. Nitrogen is the nutrient most frequently implicated in the control of algal growth. In laboratory trials, the addition of nitrogen to delta waters stimulates the growth of phytoplankton. In addition, the decline of phytoplankton production in an area usually coincides with a drop in the concentration of nitrogen. Silicate concentrations drop as diatom populations bloom, but rarely to levels associated with limiting diatom growth. Phosphorus is rarely, if ever, a limiting factor on primary production in the delta for its concentrations are generally several times higher than algal requirements.

Light Availability. Insolation and light penetrance seem to be the most direct control of phytoplankton abundance in the delta. Because of its latitude of 35° N, the delta seasonally undergoes fivefold fluctuations in the amount of available light. While high temperatures can cause rapid increases in phytoplankton growth, blooms in the delta (prior to 1980) usually occur in late spring when the duration of daylight is approaching its maximum, but the peak of temperature is still two months away.

Turbidity alters the effects of light and river discharge rates on phytoplankton growth; higher flow rates carry more sediments and thereby increase turbidity (Ball 1975). Blooms are in late spring or early summer when insolation approaches a maximum (Chadwick 1972). In addition to reducing residence times, high discharge rates may control phytoplankton growth by decreasing the depth of the euphotic zone (Figure 24).

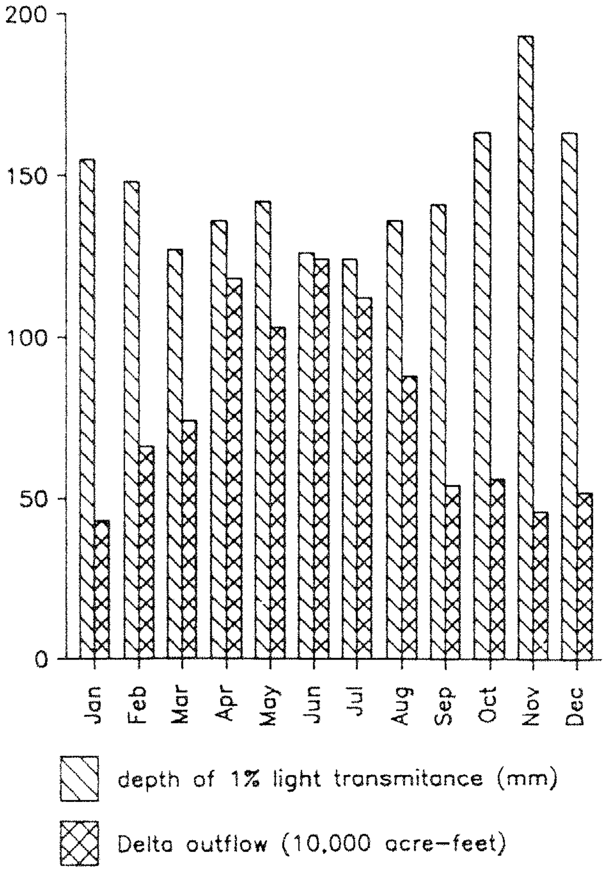

Figure 24. Mean monthly depth of 1% light transmittance (euphotic zone) with mean monthly delta outflow rates.

The euphotic zone in the delta is rarely more than 2 m deep (Figure 24). On the other hand, average depth of the channels is generally 10-13 m. Thus, the euphotic zone constitutes less than 20% of the water column. Because the water column is thoroughly mixed, no more than 20% of the phytoplankton in delta channels receives enough light for growth. The significance of depth is shown by the much higher algal concentrations in those parts of the delta where depths are least. Where it enters the delta, the San Joaquin River is only about 3 m deep and supports chlorophyll *a* concentrations five to six times those found in most delta channels. Flooded islands and dead-end sloughs are other habitats where the euphotic zone makes up as much as 30%-40% of the water column.

The relative depth of the euphotic zone is most important in the entrapment, or null, zone (Peterson et al. 1975; Arthur and Ball 1978; Cloern et al. 1983). If delta outflows push the null zone out of the delta and into the broad, shallow reaches of Suisun Bay, phytoplankton growth is much higher than in years of low flow when the entrapment zone lies within the deep channels of the western delta. The effect of the null zone in increasing residence time of plankton and mixing the water column apparently permits more efficient use of insolation, but its role in concentrating nutrients may also be important. Throughout the delta there is usually only one (spring) plankton bloom. When the null zone is in Suisun Bay there is often a larger second (summer) bloom.

Grazing. The role of herbivore grazing on phytoplankton abundance has been a subject of debate. Phytoplankton dynamics are modeled more accurately if zooplankton grazers are included (HydroQual 1984), but the models are still rather poor predictors. Phytoplankton concentrations have been observed to be inversely related to the density of benthic, filter-feeding clams (*Corbicula*), but the same periodicity of algal abundance occurs in areas of very low grazer abundance (California Department of Water Resources 1978-86a,b; see 1983 data). In the upper reaches of the San Francisco Bay complex immigration by marine benthos during dry years has been strongly linked to low phytoplankton biomass (Nichols 1983).

Toxicants. Toxicants do not seem to affect delta phytoplankton. Experiments with two common agricultural herbicides, Ordram and Bolero, failed to show any effect on the growth rates of *Melosira granulata* and *Coscinodiscus spp*. Tests were run at both low and high levels of the herbicides. Low levels were in the ranges found in delta waters; high levels equaled the concentrations found in rice fields. The possible effects of other toxicants are undetermined.

2.1.2 Recent Changes

Phytoplankton patterns in the delta have been drastically different over the last 10 years from all previous samplings. After the drought of 1976-77 no phytoplankton blooms were recorded until 1980. A double peak in chlorophyll *a* concentrations, an event usually seen in Suisun Bay, occurred in the western delta in 1982 although the entrapment zone was in Suisun Bay (California Department of Water Resources 1978-86a,b; see 1983 data). The timing of the double peaks, as well as their distribution, were different. Since 1980 most phytoplankton peaks have occurred later in the year.

Since the drought of 1976-77, phytoplankton abundances in the delta have been generally lower and differently distributed than in earlier years, so references to earlier studies must be viewed cautiously. Also, in this last decade the zooplankton community has acquired new dominant species of copepods, but the effect of these changes on the phytoplankton community is undetermined.

Phytoplankton peaks since 1980 have been dominated by *Melosira granulata*. Similar changes in the relative abundance of *M. granulata* in Lake Michigan and Lake Erie occurred earlier in this century (Hohn 1969; Stroemer and Yang 1970). Part of the reason for the success of *M. granulata* may rest on its natural history: it is especially tolerant of pollutants; it can survive long periods of dormancy in the sediments; and it is not a preferred food of most zooplankton (Ball 1987). The size of its valves and filaments are larger than the mouthparts of most species of zooplankton.

The apparent preferred temperature of *M. granulata* is higher and the range narrower than for many of the other common diatom species found in the delta (Stoermer and Ladewski 1976). In many eutrophic habitats of Europe, *M. granulata* peaks in the summer or early fall (Huber-Pestalozzi 1942). In Clear Lake, the natural lake closest to the delta, *M. granulata* blooms in August and September (Horne 1975). In the western and central delta, chlorophyll *a* peaks since the 1976-77 drought have occurred later in the year, never beginning in March or April as they frequently had before the drought (Ball 1987). The high and narrow preferred temperature regime of *M. granulata* may be part of the reason for the shift in seasonal abundance of chlorophyll *a*. No reason has been put forward for the lack of a spring bloom of other species since the drought, but changes in water quality since 1980 may explain the recent increase in importance of *Melosira granulata*.

Ball (1987) put forward a possible explanation for the increasing dominance of *Melosira granulata*. *M. granulata* is a large-celled, cylindrical diatom that forms longer cylinders by the adhesion of valves; the total length of these colonies can be greater than 1 cm. Large cell size and thick walls result in a high silica consumption rate and a high settling rate for this species. The high settling rate produces a large "seed bed" for *M. granulata* on the bottom. Since 1973, water transparency has been increasing in the delta, so in shallow areas the bottom is more often in the photic zone. The large dormant population of *M. granulata* could respond rapidly to adequate light levels by rapid growth and reproduction. Peaks since 1980 have been more sudden and of shorter duration than those before the drought, which is consistent with activation of a large dormant population. In further support of the importance of a dormant population is the occurrence of blooms at higher cross-delta flows than in earlier years; higher cross-delta flows reduce residence times and used to be important limitations on population growth rates. The sudden declines following recent chlorophyll *a* peaks have been accompanied by drops in available nitrogen to very low levels.

Water transparency has steadily increased in the central and western delta; average Secchi depths in 1973 were 20-40 cm, and now they are more often 40-80 cm. Several possible mechanisms behind the increasing transparency of delta waters have been suggested: trapping of sediments by upstream dams, transport of sediments out of the estuary that had been introduced by hydraulic gold mining during the last century, export pumping of water carrying suspendable sediments, export pumping causing disruption of sediment trapping in the entrapment zone, and changes in agricultural practices that may have formerly injected more sediment into the delta waters (Ball 1987).

2.2 SPECIES COMPOSITION AND DISTRIBUTION

In this section detailed reference is made to the phytoplankton abundances measured by the California Department of Water Resources for 1984 (Table 2). Weather in this year was not as unusual as in many preceding years, so its phytoplankton communities may have been more typical. Wintertime phytoplankton of the delta are frequently dominated by cryptomonads (Ball 1975) or the diatom *Achnanthes* (California Department of Water Resources 1978-86a,b; see 1985 data). However, these wintertime populations are usually at low densities so the emphasis in the following discussion is on those species that dominate the productive period from spring to fall.

The distribution of species can be masked by their simultaneous growth periods. The 1984 peak in chlorophyll *a* (Figure 25; California Department of Water Resources 1978-86a,b; see 1985 data) showed a maximum in the south central delta with a more rapid decline toward the west and north than toward the south, suggesting a single bloom. In fact, this bloom varied in species composition as much as in density (Figure 26; California Department of Water Resources 1978-86a,b; see 1985 data). In 1982 there was a similar situation (California Department of Water Resources 1978-86a,b; see 1983 data) when three more-or-less simultaneous blooms were responsible for the high June concentrations of chlorophyll *a* throughout the delta. Because of the formation of transition zones, five different algal communities constituted this bloom (Figure 27;

Table 2. Genera of phytoplankton collected by California Department of Water Resources in monthly collections in 1984 at 15 stations throughout the delta.

Bacillariophycae
- *Achnanthe*
- *Amphora*
- *Asterionella*
- *Cocconeis*
- *Coscinodiscus*
- *Cyclotella*
- *Cymatopleura*
- *Cymbella*
- *Diatoma*
- *Epithemia*
- *Fragileria*
- *Gomphoneis*
- *Gomphonema*
- *Melosira*
- *Navicula*
- *Neidium*
- *Nitzschia*
- *Pinnularia*
- *Pleurosigma*
- *Rhoicosphenia*
- *Rhopalodia*
- *Skeletonema*
- *Surirella*
- *Synedra*
- *Thalassiosira*

Chlorophycae
- *Actinastrum*
- *Ankistrodesmus*
- *Carteria*
- *Chlamydomonas*
- *Chodatella*
- *Closterium*
- *Coelastrum*
- *Crucigenia*
- *Elaktothrix*
- *Kirchneriella*
- *Nephrocytium*
- *Oocystis*
- *Pediastrum*
- *Pyramimonas*
- *Scenedesmus*
- *Schroederia*
- *Selenastrum*
- *Spermatozopsis*
- *Sphaerocystis*
- *Tetraedron*
- *Tetrastrum*

Chrysophycae
- *Chrysocromulina*
- *Synura*

Cryptophycae
- *Cryptomona*

Dinophycae
- *Gymnodinium*
- *Hemidinium*
- *Massartia*
- *Peridinium*

Cyanophycae
- *Agmanellum*
- *Anabaena*
- *Anabaenopsis*
- *Anacystis*
- *Aphanizomenon*
- *Dictyosphaerium*
- *Glenodinium*

Euglenophycae
- *Euglena*
- *Phacus*
- *Trachelmonas*

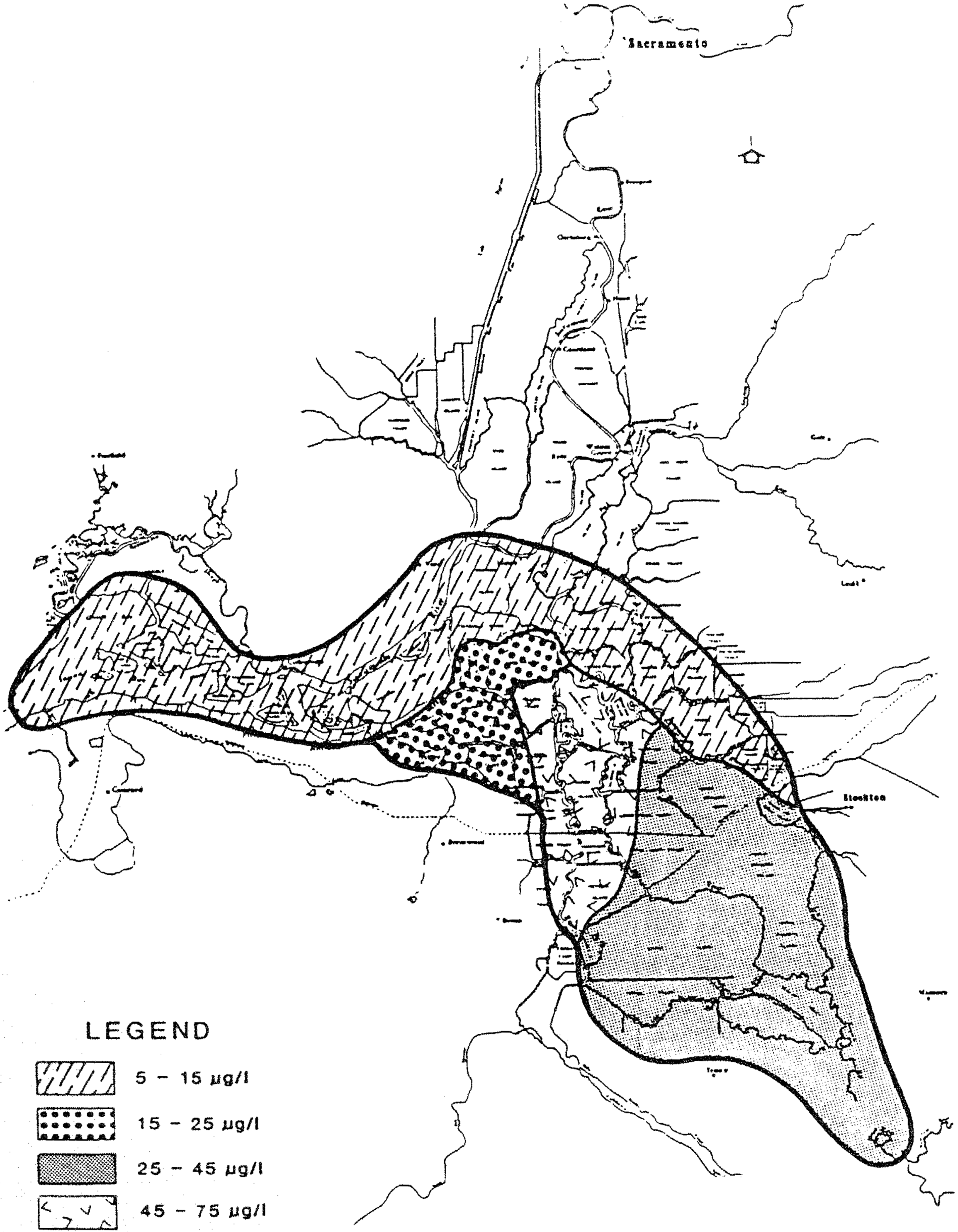

Figure 25. Distribution chlorophyll *a* concentrations within the delta during the spring bloom in 1984. From California Department of Water Resources (1978-86a,b; 1985 data).

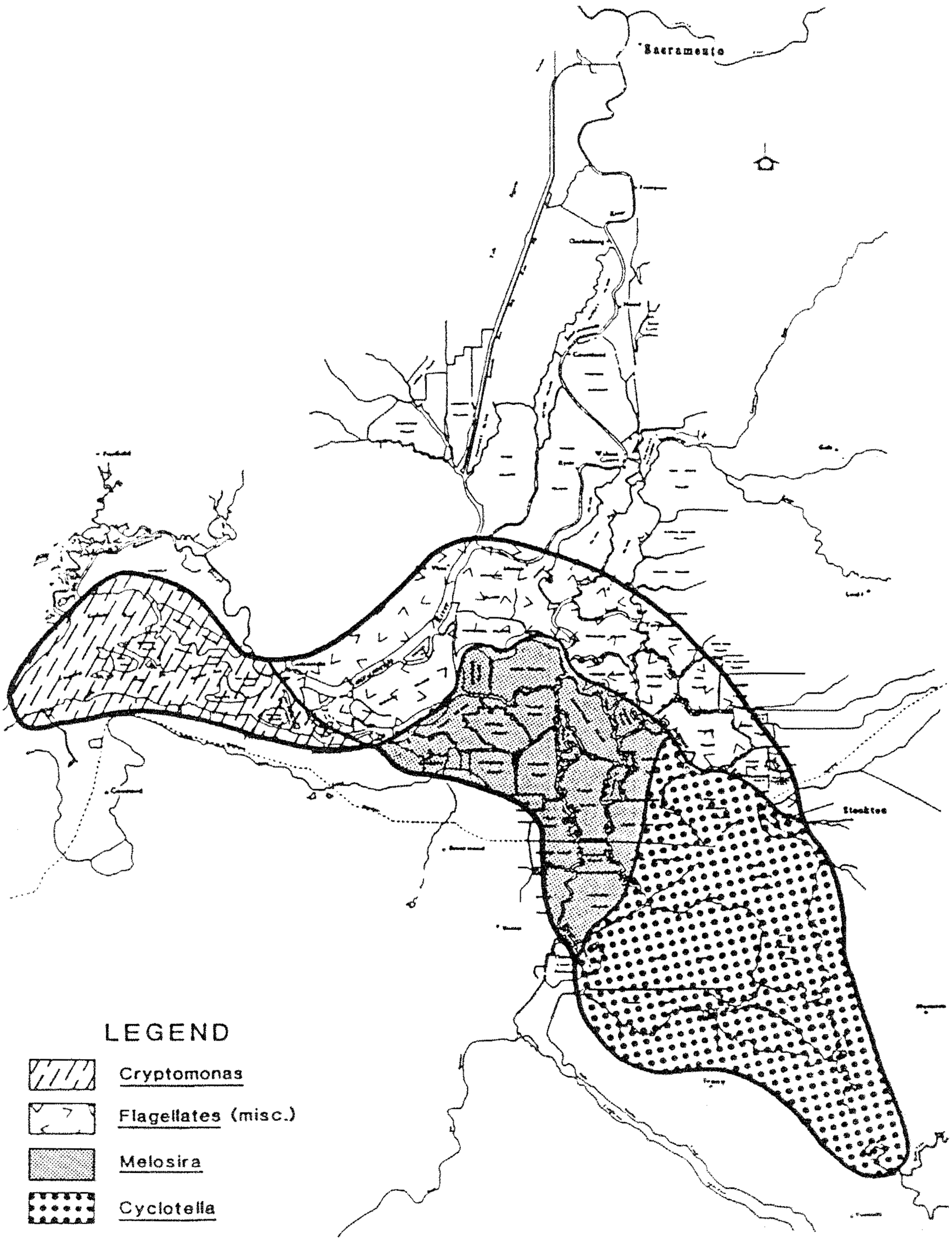

Figure 26. Distribution of species of phytoplankton during the spring 1984 bloom. From California Department of Water Resources (1978-86a,b; 1985 data).

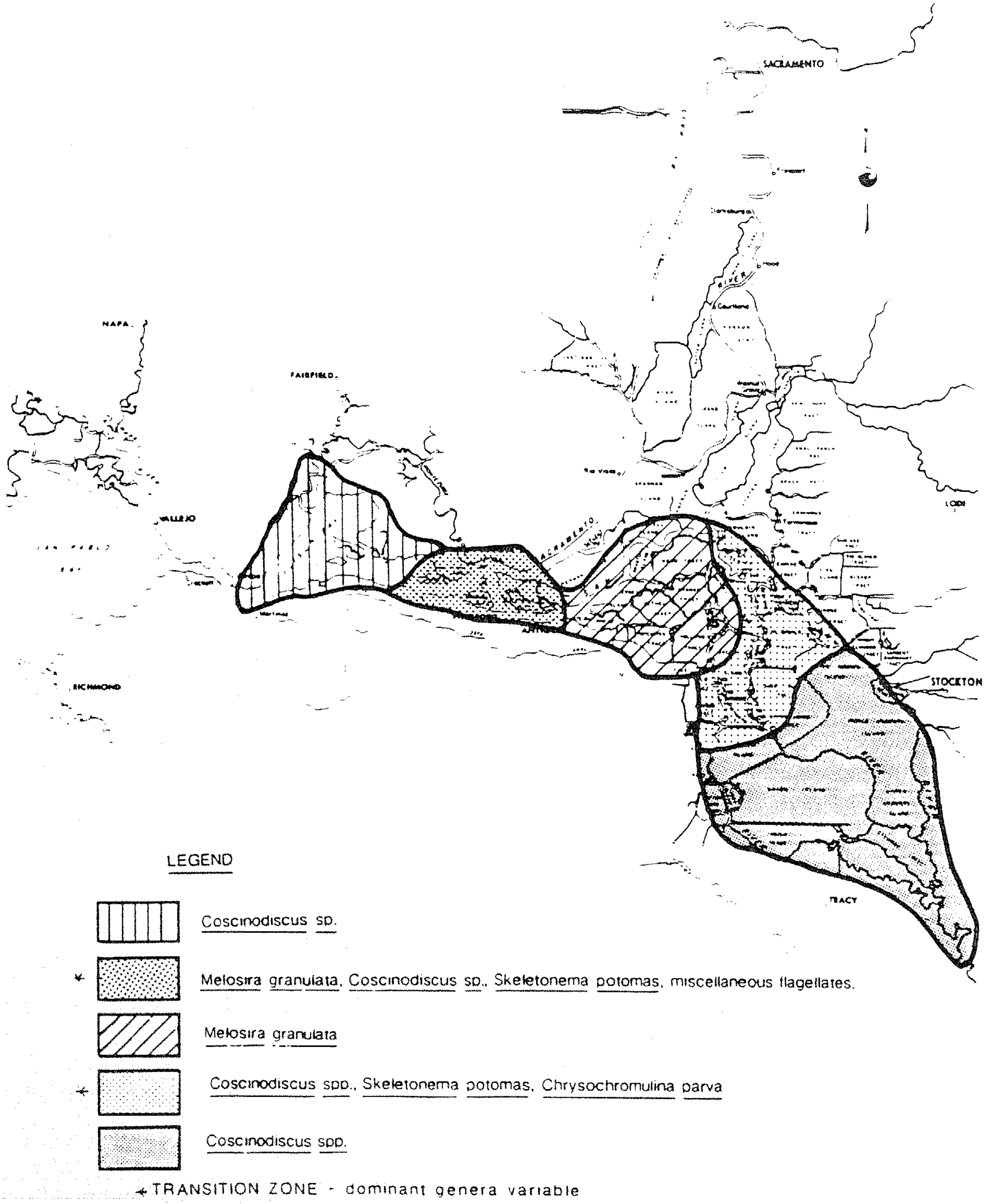

Figure 27. Distribution of species of phytoplankton during the spring 1982 bloom. From California Department of Water Resources (1978-85a,b; 1983 data).

California Department of Water Resources 1978-86a,b; see 1983 data). Small-scale discrepancies in timing of the peaks within these associations (California Department of Water Resources 1978-86a,b; see 1983 data) suggested that they were controlled by different environmental factors. The different growth rates of the different species responsible for these blooms have probably been the largest stumbling blocks in developing a predictive model of delta phytoplankton (HydroQual 1984; Brown 1987).

2.2.1 *Northern Delta*

The northern delta is dominated by the waters of the Sacramento River and associated Yolo Bypass that support the lowest phytoplankton concentrations of the area. As described above, water from the Sacramento River enters the delta carrying chlorophyll *a* at concentrations seldom greater than 6·μg/L in the summer. During the winter, when water residence times, insolation, and temperature are lowest, chlorophyll *a* concentrations are frequently as low as 1 μg/L. As the water flows through the delta to Green's Landing, these concentrations are generally doubled. The low flows during the 1976-77 drought generated phytoplankton concentrations several times greater than these. High-flow years can prevent any measurable phytoplankton growth.

This area, like most of the delta, is dominated by diatoms (Bacillariophycae) but flagellates are occasionally abundant (Figure 28). Abundances peak in the spring, although in 1984 there was a wintertime peak of *Asterionella* in January and *Cyclotella* in February. From 1969 to 1974 the dominant phytoplankton were *Coscinodiscus*, *Cyclotella*, and *Melosira* (Ball 1977; Ball and Arthur 1979).

2.2.2 *Southern Delta*

The southern delta is dominated by waters of the San Joaquin River. The San Joaquin is generally shallower, warmer, slower, and richer in nutrients than the Sacramento and supports much greater concentrations of phytoplankton. Peak plankton abundances in the south delta are regularly 10 times as dense as those in the rest of the delta (Figure 29). Because of the recirculation of agricultural water through the San Joaquin Valley, the south delta has higher conductivities than most of the rest of the delta. In fact, conductivities here are similar to the saline areas of the western delta. Consequently, the algal community is frequently more similar in these two areas than in the rest of the delta. The algal community from 1969 to 1974 was dominated by *Coscinodiscus*, *Cyclotella*, *Stephanodiscus* (=*Skeletonema*?), and *Melosira*. The

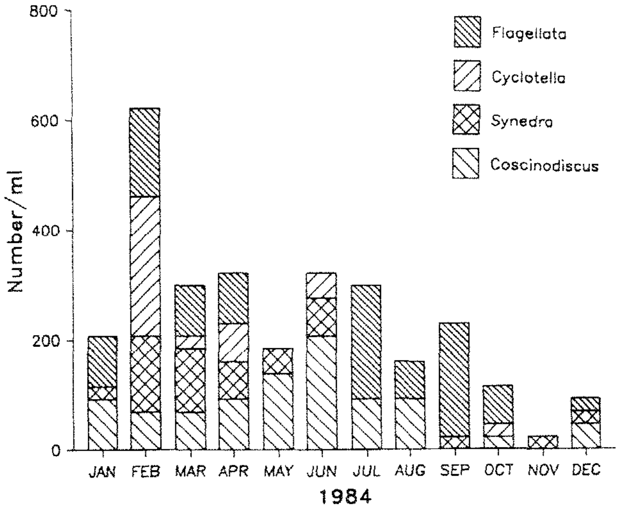

Figure 28. Density and species composition of phytoplankton in the northern delta (Sacramento River at Green's Landing).

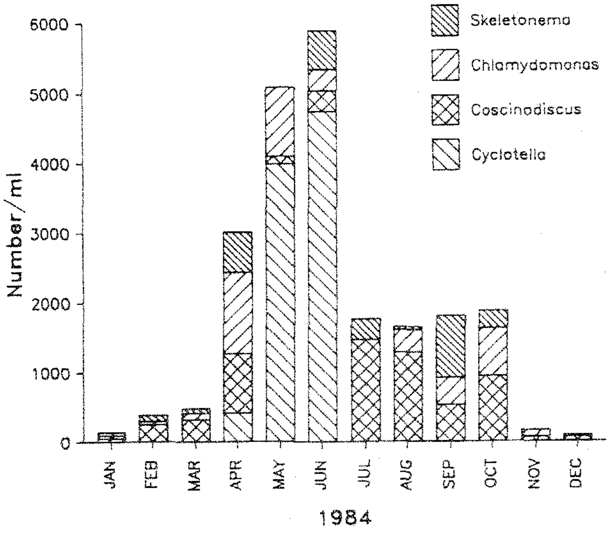

Figure 29. Density and species composition of phytoplankton in the southern delta (San Joaquin River at Mossdale bridge).

1984 community was similar, but at times *Chlamydomonas* was abundant while *Skeletonema* was not reported.

Agricultural return waters are rich in nitrogen and other nutrients, but it is unclear whether these have any effect on phytoplankton growth. Modeling of phytoplankton growth rates showed no effect of agricultural runoff even at extreme levels (HydroQual 1984); however, these models are poor predictors of phytoplankton dynamics in the delta. Experimental addition of nitrates to cultures of delta waters has stimulated growth in almost all cases.

Summertime densities of phytoplankton in the lower reaches of the southern delta usually decline sharply when increased exports from Tracy decrease residence times and draw the less-productive waters of the Sacramento up the lower reaches of the San Joaquin (Ball 1975). Residence times are also lowered by wintertime high flows that limit algal growth (California Department of Water Resources 1978-86a,b; see 1983 data).

Since 1978, chlorophyll *a* abundances in the southern delta have been markedly lower (Ball 1987). Increased outflows of water from the New Melones Dam have kept San Joaquin River flows over 1000 ft^3/s at all times. Prior to 1978, flows were frequently less than 100 ft^3/s. The increased input of cool, clear water has decreased standing crops by dilution of the algal population and their nutrients, by decreasing residence times, by slowing the growth rates, and by reducing the percentage of the water column in the photic zone. Improved sewage treatment by the city of Modesto may also have reduced algal growth (Ball 1987).

2.2.3 Eastern Delta

Almost no generalities can be made about the eastern delta. It is usually dominated by the waters of the northern delta with additional inputs from the Cosumnes, Mokolumne, and Calaveras Rivers; thus, the source waters seldom support chlorophyll *a* concentrations greater than 10 μg/L (Ball 1975). However, the smaller rivers generally have low flows, and they flow into a number of dead-end sloughs with high residence times and high nitrogen contributions from neighboring farmlands (Ball 1975). This conflict of factors produces a very heterogeneous array of plankton densities (Ball and Arthur 1979). Depending on export rates and inflow rates, the area may also receive much of its water from the San Joaquin River. Dominant algal species during the spring and summer seasons of 1969-74 were *Coscinodiscus, Cyclotella, Skeletonema,* and *Melosira* (Ball 1977). In the dead-end sloughs the phytoplankton is frequently dominated by green algae that seldom account for more than 20% of the phytoplankton in the rest of the delta.

2.2.4 Central Delta

The hydrology of the central delta is dependent on the relative and absolute flows of the inflowing rivers and the rate of export by the pumps in Tracy. It is not surprising, then, that densities of phytoplankton vary widely through the year (Figure 30). Attempts to model delta phytoplankton populations have focused primarily on the central and western delta (HydroQual 1984). A consistent pattern in several recent years has been seen in the dense blooms of *Melosira granulata*. Recent studies (Brown 1987) have shown that *Melosira granulata* is one of the slowest growing of the algal species in the delta; incorporation of different growth rates may allow greater predictive accuracy for the models.

2.2.5 Western Delta

The seasonal influx of saline waters from the broad, shallow waters of Suisun Bay causes the

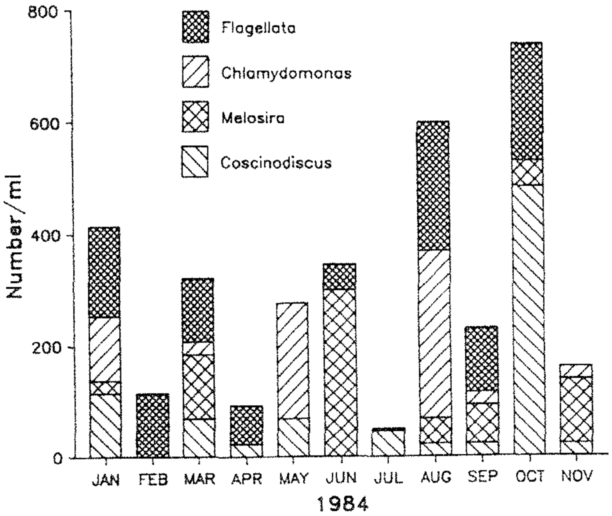

Figure 30. Density and species composition of phytoplankton in the central delta (San Joaquin River at Potato Point).

western delta to exhibit patterns in phytoplankton productivity different from the southern or northern portions of the delta. In the western delta, higher flows push the null zone into Suisun Bay, where conditions are extremely good for algal growth (Arthur and Ball 1979; Cloern et al. 1983). Tidal movements can then bring much of this phytoplankton productivity into the western delta (Sitts and Knight 1979). Low flows keep the null zone within the deep channels of the western delta where only a small fraction of the algal cells are in the euphotic zone at any time. Consequently, while the drought of 1976-77 was associated with higher than average phytoplankton populations in most of the delta (Ball and Arthur 1979), the western delta had lower phytoplankton densities than for any other year on record (Siegfried et al. 1979; Arthur and Ball 1980). Since the 1976-77 drought, phytoplankton blooms, even in years when the null zone is in the optimum position, are not as productive as in earlier years (California Department of Water Resources 1978-86a,b; see 1985 data). Peak chlorophyll *a* concentrations have been high, but they do not last as long (Ball 1987).

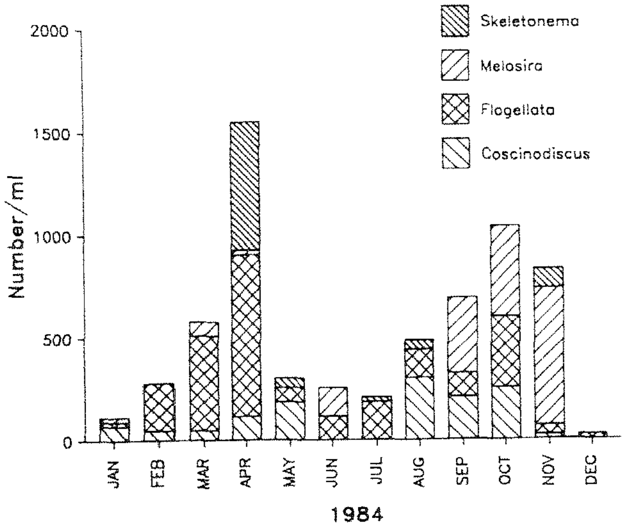

Figure 31. Density and species composition of phytoplankton in the western delta (San Joaquin River at Antioch ship channel).

The invasion by more saline bay waters also contributes to different dynamics and composition of algal species in the western delta. Multiple peaks of phytoplankton densities are a frequent feature of the western delta (Ball 1975). The dominant genera of the western delta in 1984 included *Skeletonema, Melosira, Cyclotella*, and *Coscinodiscus* (Figure 31), with *Skeletonema* dominating in the spring and *Melosira* in the fall. Earlier years supported similar assemblages (Ball 1977; Ball and Arthur 1979). More saline species such as *Chaetoceros* are occasionally abundant during very dry years. During the drought year 1976, the dominant genera of algae switched from diatoms in the spring to blue-greens in the summer (Siegfried et al. 1979).

CHAPTER 3. ZOOPLANKTON

3.1 SMALLER ZOOPLANKTON

3.1.1 Overview

The distribution of smaller zooplankton closely parallels the distribution of phytoplankton with, in general, more plankton in the waters with the greatest levels of total dissolved solids. Thus, concentrations are densest in the shallow areas of the San Joaquin River in the south delta; lowest densities occur in the waters of the Sacramento River in the north delta (Turner 1966e). It is most likely that residence times are the controlling factor on zooplankton populations (Turner 1966e; Chadwick 1972) within the waters of each river. Examining the waters within a dead-end slough, Turner (1966e) found that zooplankton, total dissolved solids, residence times, and temperature all covaried over the length of the slough and over the course of the seasons. It was impossible to sort out the effects of each factor on zooplankton densities, but all apparently contribute to productivity. In the drought year 1976, the zooplankton peaked in March, predominantly because of the abundance of rotifers (Siegfried et al. 1979).

In 1913, Allen (1920) found over 116 zooplankton species in parts of the San Joaquin River near Stockton. Of these, as for most freshwater ecosystems, the vast majority were ciliate protozoans, rotifers, copepods, and cladocerans. There was much variability among his four sampling sites in both the relative and total abundances of these groups. Later studies (Chadwick 1972) have found that the same four groups continue to predominate throughout the delta.

Ciliate protozoa. Ciliate protozoans are particularly similar to phytoplankton in their geographic distribution. In the San Joaquin River densities range from 14,000 to 40,000/L, whereas in the Sacramento River they rarely approach 6,000/L and are more commonly found at densities less than 2,000/L (Chadwick 1972). Chadwick (1972) reported no apparent seasonal trends within this group, despite wide temporal variability. In the western delta the ciliate *Tintinnopsis* showed a strong peak in abundance in February (Sitts and Knight 1979), but it is impossible to say whether this represented a seasonal phenomenon since the study encompassed only one year.

Rotifera. Rotifers are primarily a freshwater group of animals and so are rarer in the lower portions of the Sacramento-San Joaquin Estuary, but they sometimes occur at high densities within the delta. Densities range from as many as 14,000/L during their peak in the lower San Joaquin River to not more than 10,000/L in the rest of the delta (Chadwick 1972). Most of the species identified are substrate-oriented species and were collected generally in shallow habitats (Chadwick 1972). In the western delta the genera *Keratella* and *Notholca* were most abundant in early spring when salinities were minimal. A secondary peak, composed mainly of increased abundances of the brackish-water species *Synchaeta bicornis*, occurred in the late fall (Siegfried et al. 1978). In the far western delta, *Synchaeta* constituted a large part of the total zooplankton population in diel samples in February, May, and September of the drought year (Sitts and Knight 1979). In the eastern delta, *Asplanchna girodi* and *A. priodonta* were found to prey on an assemblage of other rotifers including *Synchaeta, Brachionus, Gastropus, Platyias, Trichocerca, Keratella, Polyarthra, Monostyla, Filinia,* and *Difulgia* (G. Salt, University of California, Davis; pers. comm.).

Copepoda and Cladocera. The greatest average densities of copepods and cladocerans coincide with the peak of temperature (Turner 1966e). Thus, the densest populations of these zooplankters seem to occur later in the year than the densest populations of phytoplankton, but it is unclear to what extent grazing pressure may contribute to the decline of the phytoplankton. It is particularly noticeable in Figure 32 that the temperature decline exactly corresponds to the timing and rate of decline in the abundance of these smaller zooplankton species. The 1966 study on temporal distribution of zooplankton only covered 1 year, so how these patterns actually represent recurrent seasonal distributions is still unknown.

A special situation exists at Stockton in the southern delta where the California Department of Fish and Game has been sampling in most months of all years from 1972 to the present. This portion of the delta is least affected by the pumping plants at Tracy, so waterflows and residence times do not vary as greatly from month to month or from year to year as in the rest of the delta. Thus, the data from this area can be used to identify the species of plankters most sensitive to temperature and photoperiod (J. Orsi, California Department of Fish and Game; pers. comm.; Orsi and Mecum 1986). *Diaptomus* and *Diaphanosoma* are the genera most closely controlled by temperature; they show distinct summer-fall abundance peaks in most years. *Bosmina* normally has one peak in abundance in spring and another in fall, but these peaks are depressed if chlorophyll *a* concentrations are below 10 μg/L. Rotifers, while generally unpredictable, do not seem to become abundant unless chlorophyll *a* concentrations exceed 20 μg/L. *Daphnia* spp. and cyclopoid copepods show no apparent pattern with season or with chlorophyll *a* concentrations.

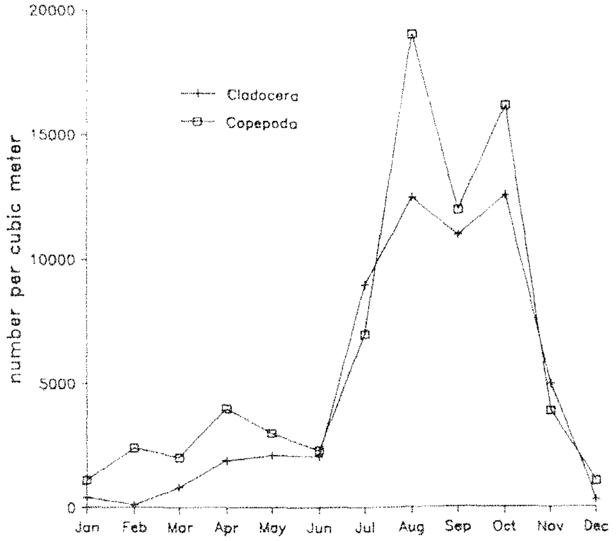

Figure 32. Densities of copepods and cladocerans through 1963. Modified from Turner (1966e).

Turner (1966) reported that zooplankton were most abundant from June to November; copepods dominated the earlier part of the peak and cladocera the later portion. The dominant species of cladocera were *Bosmina longirostrus*, *Diaphanosoma brachyurum*, and *Daphnia* spp.; the dominant copepods were *Cyclops* spp. (Turner 1966e), *Eurytemora affinis (=E. hirundoides)* (Heron and Damkaer 1976) and *Diaptomus novamexicanus* (California Department of Water Resources 1978-86a,b; see 1986 data).

3.1.2 Recent Changes

Native species. From 1972 to 1978 the association of small zooplankton was made up of many of the same species described by Turner (1966e), but better measures of their environmental requirements were possible through the extensive collections made by the California Department of Fish and Game (Orsi and Mecum 1986). The delta zooplankton comprised a freshwater group and a brackish water group. The freshwater group was dominated by cyclopoid copepods (primarily *Acanthocyclops vernalis* with *Cyclops scutifer* and *C. bicuspidatus thomasi*), cladocerans (mostly *Bosmina longirostris*), and the rotifer genera *Keratella, Polyartha, Trichocerca,* and *Synchaeta*. The brackish water group was characterized by the copepod *Eurytemora affinis* and the rotifer *Synchaeta bicornis* (Table 3). In dry years copepods of the marine genus *Acartia* also associated with the brackish water group. These were not exclusive associations. Even in the most seaward parts of the delta, where *E. affinis* dominated the plankton assemblage, *Synchaeta bicornis* was never found to be the most abundant rotifer. Both species were also found throughout the delta in most years.

Chlorophyll *a* was strongly correlated with most measures of zooplankton abundance. The year 1974 was extremely wet, and the year 1977 was extremely dry. Because of peculiarities of flow, 1974 produced very high concentrations of zooplankton and chlorophyll *a* in the San Joaquin River at Stockton

Table 3. Fauna collected in zooplankton samples from the western edge of the Sacramento-San Joaquin Delta from January to November 1976, a drought year (Siegfried and Kopache 1980).

COPEPODA
- *Eurytemora affinis*
- *Acartia calusii*
- *Diaptomous* spp.
- *Cyclops* spp.
- *Ectinosoma* sp.
- *Scottalana* sp.
- *Harpacticoida* (2 spp.)

CLADOCERA
- *Bosmina longirostris*
- *Daphnia laevis*
- *D. pulex*
- *D. schodleri*
- *D.galeata*
- *Monospilus dispar*
- *Diaphanosoma leuchtenbergianum*

MISCELLANEOUS CRUSTACEA
- *Rithropanopeus harrisii* zoea
- *Balanus* spp. nauplii
- *Palaemon macrodactylus* larvae

ROTIFERA
- *Polyarthra spp.*
- *Kellicottia spp.*
- *Filinia spp.*
- *Synchaeta spp.*
- *Keratella spp.*
- *Notholca spp.*
- *Brachionus spp.*
- *Platyias spp.*
- *Asplanchna spp.*
- *Ascomorpha spp.*
- *Tetrasiphon spp.*
- *Pleurotrocha spp.*
- *Trichotria spp.*
- *Wigrella spp.*

but, simultaneously, much lower concentrations in the Sacramento River at Hood. In 1977, Hood samples contained many more plankters and more chlorophyll *a*, while all were depressed at Stockton. More disturbingly, an overall decline in chlorophyll *a* in the delta from 1972 to 1978 was reflected in a general decline in zooplankton densities (Orsi and Mecum 1986).

The species composition and relative abundances of the smaller species of zooplankton are changing drastically. Between 1972 and 1978 the dominant rotifer shifted from *Keratella cochlearis* to *Synchaeta bicornis* (Orsi and Mecum 1986).

Introduced species. In 1978-79 two new species of copepods were found in the delta, *Sinocalanus doerrii* and *Limnoithona sinensis*. Presumably these species arrived from the waters of their native China Sea via the ballast holds of commercial ships (Orsi et al. 1983; Ferrari and Orsi 1984). The introduction of these species may be responsible for the switch in abundance from dominance by the summer-form *Diaptomus novamexicanus* to the winter-spring form, *D. franciscanus* (California Department of Water Resources 1978-86a,b; see 1986 data). The general decline in zooplankton abundance in the years prior to 1979 (Orsi and Mecum 1986) may have facilitated the invasion of the delta by these new species.

Limnoithona sinensis was first found near Stockton in August 1979 and had spread throughout the freshwaters of the delta by October of the same year. It is particularly abundant from October to November and is rarest in March and April (Ferrari and Orsi 1984). *Limnoithona sinensis* has attained densities of 71,176/m^3 and is more abundant in the waters of the San Joaquin than the Sacramento River. Salinities of more than 1.2 parts per thousand (ppt), which roughly coincide with the salinities of the null zone, appear to limit its seaward distribution.

Sinocalanus doerrii was first captured in May 1978 at the western edge of the delta near Pittsburg (Orsi et al. 1983). *Sinocalanus doerrii* occupies areas of higher flows than had been occupied by native species. In fact, its spread upstream from Pittsburgh took place from December 1978 through March 1979 when outflows were quite high.

Recent measures of chlorophyll *a* and pheopigments in water samples from the Sacramento River have indicated a decrease in chlorophyll *a* relative to other pigments (Ball 1987). The ratio of chlorophyll *a* to other pigments is frequently interpreted as a measure of the health of the phytoplankton population (Ball 1975) and the percentage of chlorophyll *a* can decline as zooplankton grazing increases. The invasion by *Sinocalanus doerrii* of Sacramento River channels, which had previously supported very few zooplankters, coincides with the reduction in relative abundance of chlorophyll *a* in north delta water samples.

The abundance of *S. doerrii*, unlike most other plankton, reaches greater peaks in the Sacramento than in the San Joaquin River (Figure 33). The upper limits of its range in the Sacramento River correspond with shallow areas in the river channel near Brannan Island. *Sinocalanus doerrii* is more like native copepods than *L. sinensis* in that its peak abundance runs from early June to September.

The increased abundance and range of *Sinocalanus doerrii* has coincided with dramatic changes in the native copepod assemblage (Figure 34). One native species of *Diaptomus*, which previously had been scarce in plankton samples, has almost disappeared (California Department of Fish and Game 1987). Another native copepod, *Eurytemora affinis*, has suffered a restriction of range and abundance since the invasion by *S. doerrii* (California Department of Fish and Game 1987). *Eurytemora affinis* was the dominant calanoid copepod in all years prior to the introduction of *Sinocalanus doerrii*; since its introduction, *S. doerrii* has dominated the copepod assemblage of the delta. Both *Eurytemora* and *Sinocalanus* eat a wide array of phytoplankton, but with an emphasis on the centric diatoms *Coscinodiscus* and *Skeletonema* (Orsi 1987). During *Melosira* blooms, copepod guts are frequently empty, although *Melosira* is found in the guts at other times (Orsi 1987). Identifying the possible contributions of competition and changes in phytoplankton composition to changes in range and abundance of native copepods will be difficult.

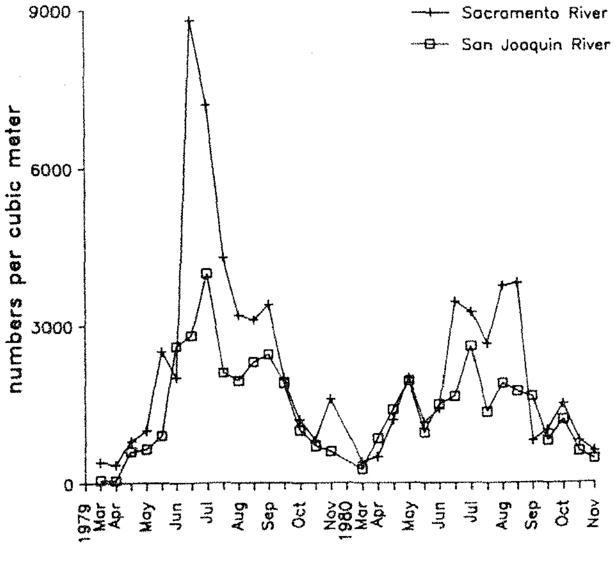

Figure 33. Seasonal abundance of the introduced copepod *Sinocalanus doerrii* in the Sacramento and San Joaquin Rivers. Modified from Orsi et al. (1983).

3.2 OPOSSUM SHRIMP

3.2.1 Distribution and Migration

The opossum shrimp, *Neomysis mercedis* (synonymous with *N. atschwanensis* and *N. intermedia* in earlier discussions of delta mysids; see Simmons et al. 1974 a,b) is found in the diets of almost all fishes of the delta (Heubach et al. 1962; Radtke 1966; Turner 1966 a,b; Turner and Kelley 1966; Moyle 1976; Smith and Kato 1979; Stevens 1979; Moyle et al. 1985). Unlike other elements of the delta zooplankton, the biology of *N. mercedis* has been widely studied and described. Two other mysid shrimp occur in the freshwaters of the delta--*Acanthomysis macropsis* and an unidentified small mysid that was found in the lower San Joaquin River (Orsi and Knutson 1979)--but there are no reports on the biology of either.

Early studies of the distribution of *N. mercedis* found that it was concentrated in areas with higher chloride concentrations, particularly the western delta and, to a lesser extent, the San Joaquin River near Stockton (Turner and Heubach 1966). This observation was initially interpreted as evidence that salinity was a primary factor governing the distribution of the opossum shrimp. Later laboratory studies have shown that the optimal salinity for this species is near 10 ppt, at which it is never found in great numbers while the salinities at which it occurs in its greatest densities (1-4 ppt) are probably osmotically stressful (Sitts 1978).

The upstream limits of *N. mercedis* abundance appear to be set partly by light intensity. Ninety

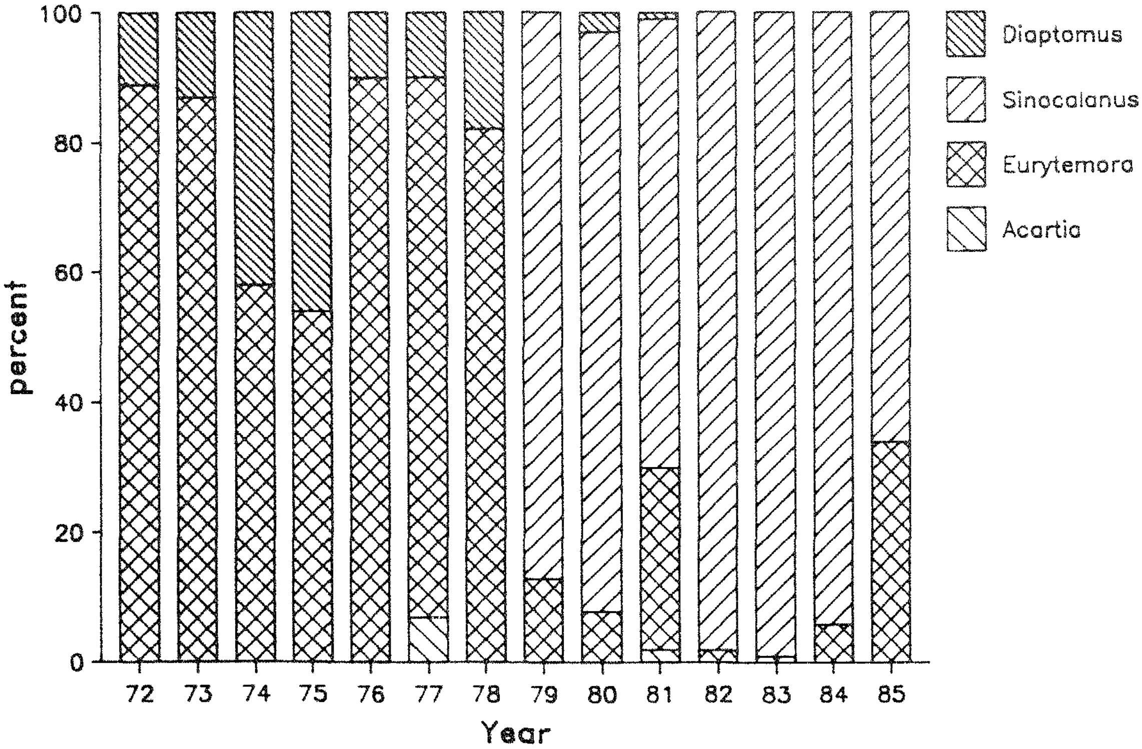

Figure 34. Changes in relative copepod abundances in the western delta following the discovery of *Sinocalanus doerrii* in 1979. Modified from California Department of Fish and Game (1987b).

(percent or more of the adult population is found atdepths where light intensity is less than 10^{-5} lx Heubach 1969). In most delta waters, depths must be greater than 3 m to provide sufficient attenuation of sunlight. In areas where the channels are not at least 3 m deep *N. mercedis* is absent (Heubach 1969). Similarly, in channels with shallow sides, *N. mercedis* is found only in the deeper, central parts of the channel. These conditions are probably what cause the greater abundance of *N. mercedis* in the deeper Sacramento River (Heubach 1969) than in the shallower San Joaquin where most other zooplankton congregate. At night these patterns break down and *N. mercedis* is found uniformly distributed throughout the water column (Heubach 1969; Sitts 1978; Siegfried et al. 1979). In later studies, Siegfried et al. (1979) used a smaller meshed net that permitted them to catch representative numbers of young shrimp. They found that shrimp less than 3 mm long did not seem to respond as strongly to light intensity as larger shrimp, so that the younger shrimp were common in the upper parts of the water column.

Net flow velocities greater than 0.12 m/s appear to prevent *N. mercedis* from maintaining its position in a channel (Turner and Heubach 1966; Orsi and Knutson 1979) and thus are barriers to the upstream migration of *Neomysis*. Operation of the cross-delta channel in 1964 provided evidence of the importance of net flow velocity (Turner and Heubach 1966). Before the gates to the channel were opened, flows in the Sacramento River were over 0.12 m/s, and flows in the cross-channel were less than 0.12 m/s; *N. mercedis* was absent from the river and present in the channel. After the gates to the channel were opened, the flow rates switched between the two sites, as did the distribution of *N. mercedis*. Looking throughout the delta, Turner and Heubach (1966) found that *N. mercedis* was seldom present in sloughs with net flows over 0.12 m/s. During the drought of 1976-77 the barrier effects of net flow were weakened by the greatly reduced outflows and, as a consequence, *Neomysis* was found much farther upstream than usual (Knutson and Orsi 1983).

In addition to their diel vertical migrations in response to light, opossum shrimp also migrate in response to tidal flows. Adults tend to remain on the bottom during ebb tides and rise into the water column during flood tides. Combined with the landward-flowing, density-driven current on the bottom, this behavior tends to move the adult shrimp up into the more freshwater parts of the estuary (Orsi and Knutson 1979; Siegfried et al. 1979). The greater occurrence of young shrimp near the surface of the water column tends to move them downstream from the adults and into the entrapment zone (Orsi and Knutson 1979; Siegfried et al. 1979). The entrapment zone also concentrates nutrients, phytoplankton, and suspended detritus (Arthur 1975; Ball 1975; Arthur and Ball 1979), making it an ideal nursery area for *N. mercedis* (Siegfried et al. 1979).

Studies through several years (Orsi 1986) indicate that there is less of a difference in vertical migration between different ages of *N. mercedis* than reported by Siegfried et al. (1978), whose study encompassed only one year. Smaller individuals are more likely to migrate into the more lighted surface waters on flood tides, when they would be carried upstream. The greater occurrence of smaller *N. mercedis* in landward-flowing flood tides explains their observed scarcity in waters seaward of the entrapment zone where greater water clarity allows deeper light penetrance. Within the entrapment zone, water clarity is low and most of the population moves up into the area of neutral flow between the surface, river outflow regime and the deeper, density-driven currents.

3.2.2 Patterns of Abundance

Regression analysis of the abundance of *Neomysis* from 1968 to 1981 indicates that, in addition to salinity, the abundance of the copepod *Eurytemora affinis* has a significant effect on the density of adult *Neomysis* (Knutson and Orsi 1983). *Eurytemora affinis* is the primary prey item of larger *Neomysis* indicating that the population is, at times, food limited.

Neomysis mercedis shows extremely large seasonal fluctuations in abundance, from mean densities in winter of less than 10/m^3 to almost 1,000/m^3 in spring. Three main bouts of reproduction occur each year, but the high densities of late spring overlap the smaller peaks (Siegfried et al. 1979). The overwintering population consists mostly of large, mature *N. mercedis*, which breed in the early spring. The new generation grows at the same time as the populations of phytoplankton are multiplying. Fecundity is directly related to size, but females in late spring produce more young than females of the same size in early spring (Heubach 1969). Reproduction by the early spring generation produces the large concentrations of *N. mercedis* in late spring. In addition to the changing relationship of length with fecundity, *N. mercedis* matures at smaller sizes in summer than in winter or spring. The summer population produces the overwintering generation.

High temperature (Heubach 1969; Siegfried et al. 1979), low dissolved oxygen (Turner and Heubach 1966; Orsi and Knutson 1979), and predation (Heubach 1969) have all been suggested as the forces behind the fall decline in *N. mercedis* abundance. Hair (1971) found that the upper lethal temperature limit for *N. mercedis* was 22 °C, a common late summer temperature in the delta (Siegfried et al. 1978). In the San Joaquin River at Stockton, near-lethal temperatures are combined with low dissolved oxygen, and it may be the combination, rather than either factor alone, that decimates that population (Orsi and Knutson 1979). Heubach (1969) observed that the greatest numbers of young striped bass, which eat primarily *N. mercedis*, are in the same area as their prey but was unable to quantitatively test the predation hypothesis because he had no measure of bass abundance. This question is still unresolved, but intensive studies on striped bass and *N. mercedis* abundances over the last twenty years are beginning to be evaluated and will probably provide new insights.

Annual variability in abundance of *N. mercedis* can be accurately predicted from knowledge of chlorophyll *a* concentrations and either salinity at Chipp's Island or delta outflows (Orsi and Knutson 1979). Studies during the drought year (Siegfried et al. 1979) demonstrated that the location of the null zone determines the annual fluctuations in *N. mercedis* abundance. If the null zone is in the deep channels of the main rivers, as happens when delta outflows are low, chlorophyll *a* concentrations remain low, because little of the algae is within the photic zone. When outflows are higher, salinity at Chipp's Island is lower, and algal populations of the null zone are in the broad shallows of Suisun Bay. Therefore, more of the algae are in the euphotic zone, and chlorophyll *a* concentrations can attain much higher levels (Siegfried et al. 1978, 1979). Thus, the conditions most favorable for *N. mercedis* are also optimum for its food.

3.2.3 Diet

The diet of *N. mercedis* varies by size, through time, and by location within the estuary. Larger individuals usually eat more copepods, particularly *Eurytemora affinis*, while smaller individuals (<3 mm total length) primarily consume phytoplankton and rotifers. Like most mysids *Neomysis mercedis* is primarily a filter-feeder (Mauchline 1971; Foulds and Mann 1978), taking what passes through its filtering current rather than chasing individual items. However, there is clear selection of the material ingested from what is caught on the filter pads. When rotifers are abundant, the juvenile *Neomysis* take more of them, and the juveniles probably derive most of their energetic gain from that part of their diet (Siegfried and Kopache 1980). There is also strong evidence of selection among phytoplankton species eaten. From March to May 1976, *Skeletonema* was by far the dominant diatom in the western delta, but the guts of *Neomysis* contained mostly *Melosira* or *Coscinodiscus*. Similarly, from June to November the only common diatom in gut samples was *Coscinodiscus* although it was a very small part of the phytoplankton assemblage present. The shift from *Melosira* can probably be partly attributed to the greater size of juvenile *Neomysis* later in the year that makes them better able to ingest the larger species of algae. Other factors also probably affect dietary composition because *Neomysis* from more upstream stations fed on *Melosira* further into the year than their downstream counterparts. Larger individuals fed primarily on zooplankton and also showed strong prey selection. Copepod nauplii were the most abundant component of the zooplankton assemblage but were rarely consumed. *Neomysis* guts contained mostly *Eurytemora affinis*, harpacticoid copepods, and rotifers.

3.3 CAVEATS

The shift to blue-green algae reported by Siegfried et al. (1979) points up a general problem of plankton studies in the delta. Other surveys of phytoplankton use a magnification inadequate for the identification of small blue-greens (Siegfried et al. 1979), making it impossible to estimate the role blue-greens play in the rest of the delta. Even among diatoms, many dominants have probably been misidentified or missed due to their small size. Many of the individuals identified as *Coscinodiscus* were probably *Thalassiosira* and much of the chlorophyll *a* in several blooms may have been contained in *Skeletonema potamos*, which was not collected due to its very small size (J. Arthur and D. Ball, U.S. Geological Survey, Menlo Park, CA; pers. comm.). A similar problem exists for many statements that have been made about zooplankton because most plankton nets have been of 930 micron mesh whereas a mesh of 505 microns is required to accurately describe the abundance and size distribution of *Neomysis* populations (Miller 1977). Striped bass egg and larvae sampling prior to 1977 apparently missed most of the larval bass under 6 mm and resulted in greater biases in estimates of abundance for all larval striped bass under 40 mm (Miller 1977).

CHAPTER 4. ZOOBENTHOS AND SUBSTRATES

4.1 PATTERNS OF ABUNDANCE

The zoobenthos of the delta is better understood than the zooplankton because the benthic community is dominated by only five species, although more than 82 species have been recorded (Table 4). Our understanding of the zoobenthos rests primarily on the monthly samples taken by California Department of Water Resources personnel at four stations within the delta. Two of these stations are in the western delta, in the main channel of the Sacramento River (in the center of the channel and along each bank) and in the center of a nearby flooded island (Sherman Lake). Two are in the

Table 4. Zoobenthos collected by California Department of Water Resources at four stations in the delta during monthly collections through 1984.

- Platyhelminthes
  - Planaridae
    - *Dugesia tigrina*
    - unknown triclad A
    - unknown triclad B
- Nemertea
    - *Paleonermatea* sp.
  - Tetrastemmatidae
    - *Prostoma graecense*
- Nematoda
  - Eudorylaimus
    - *Eudorylaimus*
    - unknown
- Ectoprocta
  - Lophopodidae
    - *Pecinatella magnifica*
- Annelida
  - Oligochaeta
    - Enchytraeidae
      - unknown spp.
    - Lumbricidae
      - *Lumbriculus variabilis*
    - Naididae
      - *Chaetogaster limnaei*
      - *Dero digitata*
      - *Nais pardalis*
      - *Ophidonais serpentina*
      - *Pristina breviseta*
      - *Slavina appendiculata*
      - *Stylaria fossularis*
      - *Vejdovskyella intermedia*
      - *Wapsa mobilis*
    - Tubificidae
      - *Aulodrilus limnodius*
      - *Aulodrilus pluriseta*
      - *Bothrioneurum vejdovskyanum*
      - *Branchiura sowerbyi*
      - *Ilyodrilus frantzi*
      - *Ilyodrilus mastix*
      - *Ilyodrilus templetoni*
      - *Limnodrilus angustipenis*
      - *Limnodrilus hoffmeistri*
      - *Limnodrilus udekemianus*
      - *Peloscolex gabriellae*
      - *Psammoryctides californianus*
      - *Quistadrilus multisetosus*
      - *Spirosperma ferox*
  - Polychaeta
    - Nereidae
      - *Neanthes limnicola*
      - *Neanthes succinea*
    - Sabellidae
      - *Manyunkia speciosa*

(Continued)

Table 5. (Concluded)

- Spionidae
  - *Bocardia ligerica*
- Hirudinea
  - Erpobdillidae
    - *Dina parva*
  - Glossophonidae
    - *Sparganophilus eiseni*
    - *Helobdella triserialis*
- Mollusca
  - Pelecypoda
    - Corbicullidae
      - *Corbicula fluminea*
    - Planorbidae
      - *Gyraulus* spp.
  - Gastropoda
    - Myidae
      - *Mya arenaria*
    - Sphaeriidae
      - *Musculium* spp.
    - Unionidae
      - *Anodonta nuttalliana*
- Arthropoda
  - Arachnida
    - Unionicolidae
      - *Unionicola* sp.
  - Crustacea
    - Cladocera
      - Sididae
        - *Latona setifera*
        - *Sida cristallina*
      - Chydoridae
        - *Eurycercus lamellatus*
      - Daphnidae
        - *Daphnia pulex*
        - *Simocephalus serrulatus*
      - Leptodoridae
        - *Leptodora kindtii*
    - Ostracoda
      - Candonidae
        - *Candona* sp.
      - Cypridae
        - *Stenocypria longicomosa*
    - Copepoda
      - Ameiridae
        - *Nitocra* sp.
      - Temoridae
        - *Epischura nevadensis*
        - *Eurytemora* sp.
      - Centropagidae
        - *Osphranticum labronectum*
      - Cyclopidae
        - *Mesocyclops edax*
    - Isopoda
      - Sphaeromatidae
        - *Gnorimosphaeroma lutea*
    - Amphipoda
      - Asellidae
        - *Asellus occidentalis*
      - Corophidae
        - *Corophium spinicorne*
        - *Corophium stimpsoni*
      - Idoteidae
        - *Synodotia laticauda*
      - Talitridae
        - *Hyallela azteca*
    - Decapoda
      - Palaemonidae
        - *Palaemon macrodactylus*
      - Xanthidae
        - *Rithropanopeus harrisii*
  - Insecta
    - Chironomidae
      - *Ablabesmyia* sp.
      - *Chironomus attenuatus*
      - *Cladotanytarsus* sp.
      - *Cryptochironomus* spp.
      - *Demicryptochironomus* sp.
      - *Harnischia curtilamellata*
      - *Micropsectra* sp.
      - *Monodiamesa* sp.
      - *Nanocladius distinctus*
      - *Paracladopelura* sp.
      - *Paratendipes* spp.
      - *Polypedilum* sp.
      - *Procladius* sp.
    - Coenagrionidae
      - *Zoniagrion exclamationis*
    - Gomphidae
      - *Gomphus olivaceous*
    - Ephemeridae
      - *Hexagenia limbata*
    - Heptageniidae
      - *Heptagenia rosea*

central delta, in the main channel of the San Joaquin River (in the center and along each bank), and in the center of a flooded island (Frank's Tract). These stations cover the range of benthic habitats in the delta, from the most lotic and shallow with generally peaty-muck substrates to the most swiftly flowing riverine with substrates of constantly shifting sand.

Zoobenthos density varies from year to year (Figure 35), with peak densities occurring in early or late summer. In the past, summertime densities have been as high as 100,000/m^2, but mean densities are usually between 10,000 and 40,000/m^2. The wet years from January 1982 to June 1984 led to temporary domination at all stations by freshwater species. The sudden salinity intrusion in July, because of abnormally low snowmelt, caused a sharp decline in zoobenthos density as the freshwater species declined faster than the brackish water species could spread or reproduce (California Department of Water Resources 1978-86a,b; see 1985 data).

4.2 SPECIES COMPOSITION

Species composition is more consistent than species abundance. Although 71 species were

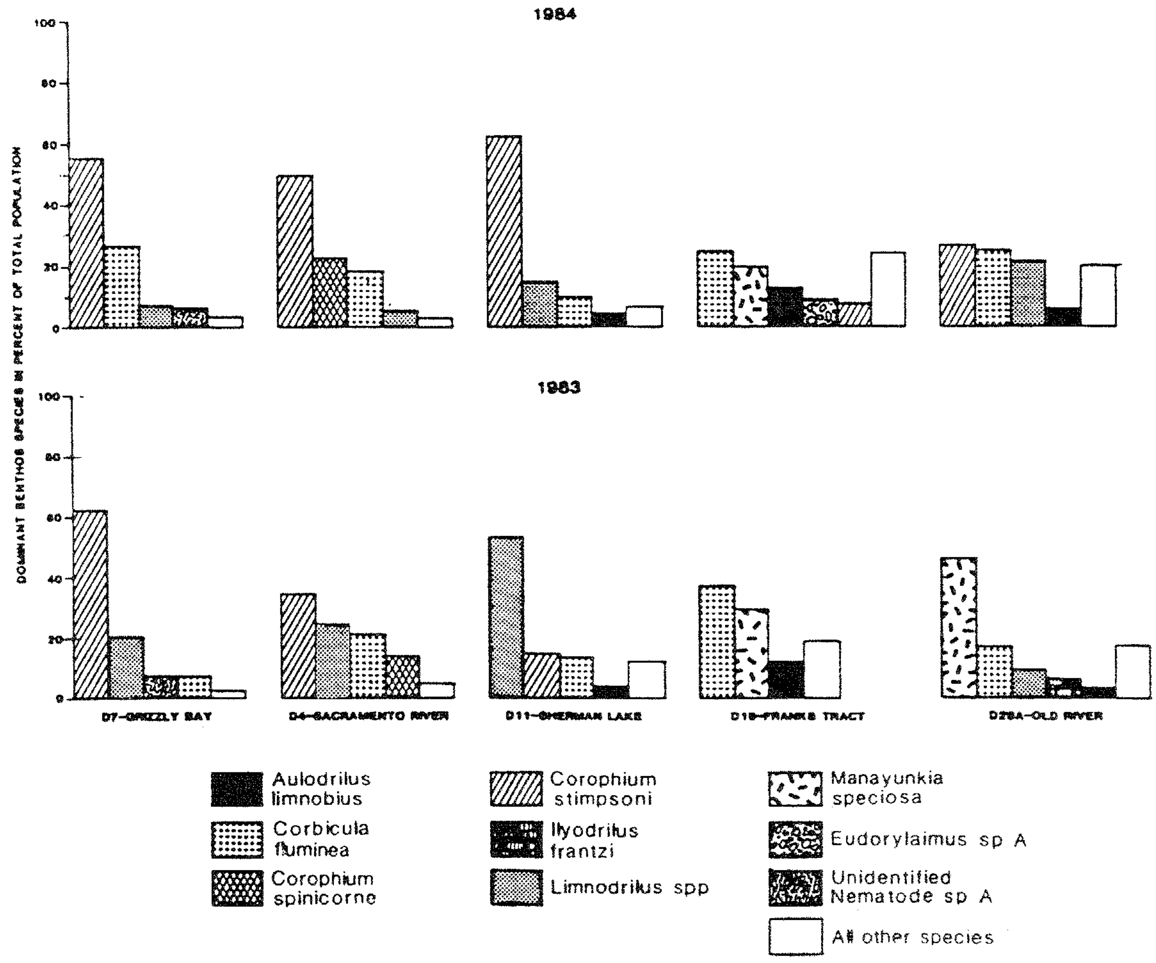

Figure 35. Variation across years in zoobenthos densities in the Sacramento-San Joaquin Delta. From California Department of Water Resources (1978-86a,b; 1985 data).

reported from the 1984 benthos samples, five species (*Corophium stimpsoni, C. spinicorne, Corbicula fluminea, Limnodrilis* spp., and *Manayunkia speciosa*) make up more than 90% of the individuals at most sites in most months of most years (California Department of Water Resources 1978-86a,b; see 1984 data). The domination of the zoobenthos by these five species makes the benthic community one of the most stable aspects of the delta. In addition, the species composition at one site differs from another site but is relatively constant across years (Figures 36, 37, 38, and 39). The distribution of each species seems to be largely determined by patterns of salinity and substrate (Hazel and Kelley 1966). Insects, particularly bloodworms (Chironomidae) are common in the river (Hazel and Kelley 1966), but are seldom found in the central or western delta sites (California Department of Water Resources 1978-86a,b; see 1981, 1982, 1983, 1984, 1985 data).

Members of the genus *Corophium* are filter-feeders on detritus and use some detritus in the construction of tubes. During their summer peaks of abundance *Corophium* densities are regularly 25,000-35,000/m^2.

Corophium stimpsoni is the most abundant benthic animal in the delta (Hazel and Kelley 1966; California Department of Water Resources 1978-86a,b; see 1981, 1982, 1983, 1984 data) and was found in each of 25 samples collected throughout the delta. It was found on all substrates and in all locales, but was most common in the western half and most abundant on substrates of fine sand (Hazel and Kelley 1966). Within a channel *Corophium stimpsoni* shows a marked preference for the deeper, central portions (Hazel and Kelley 1966; Figure 40). *Corophium stimpsoni* appears to undergo a diel vertical migration similar to, but less extensive than that of *Neomysis*. Up to 10% of the population migrates

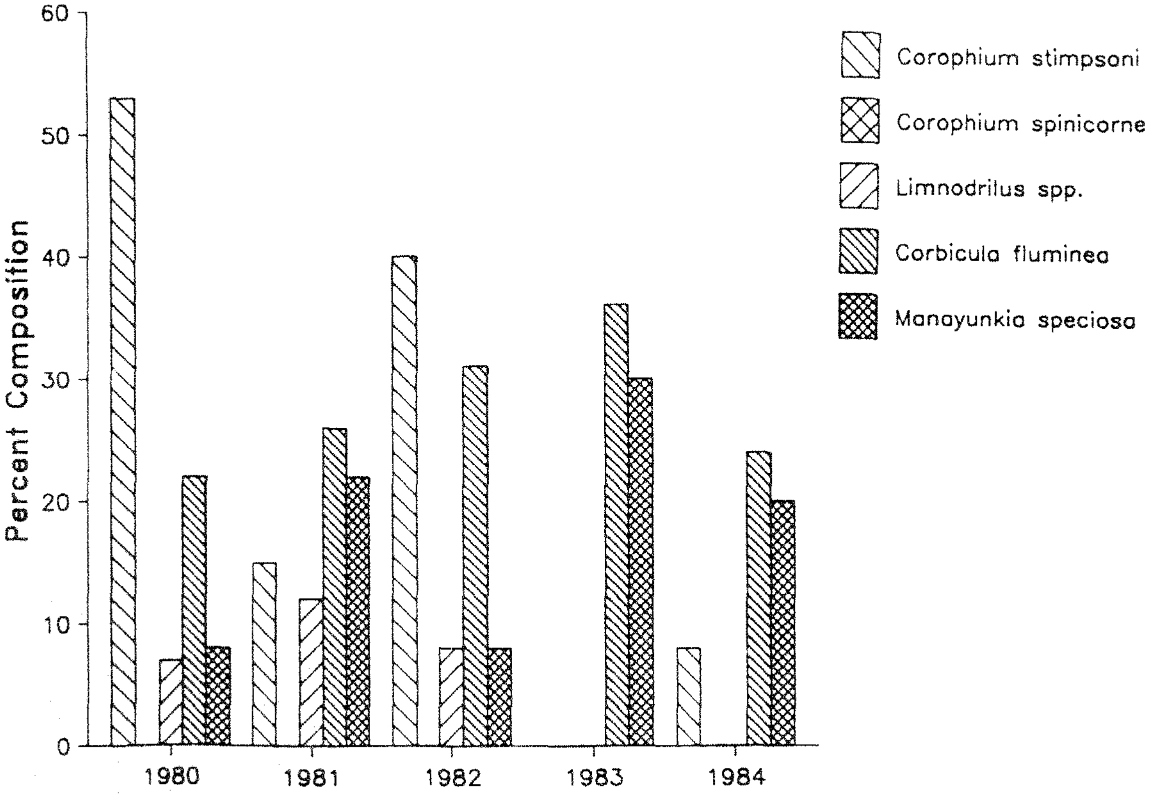

Figure 36. Dominant zoobenthos species across years at sampling sites in a flooded island on the San Joaquin River in the central delta.

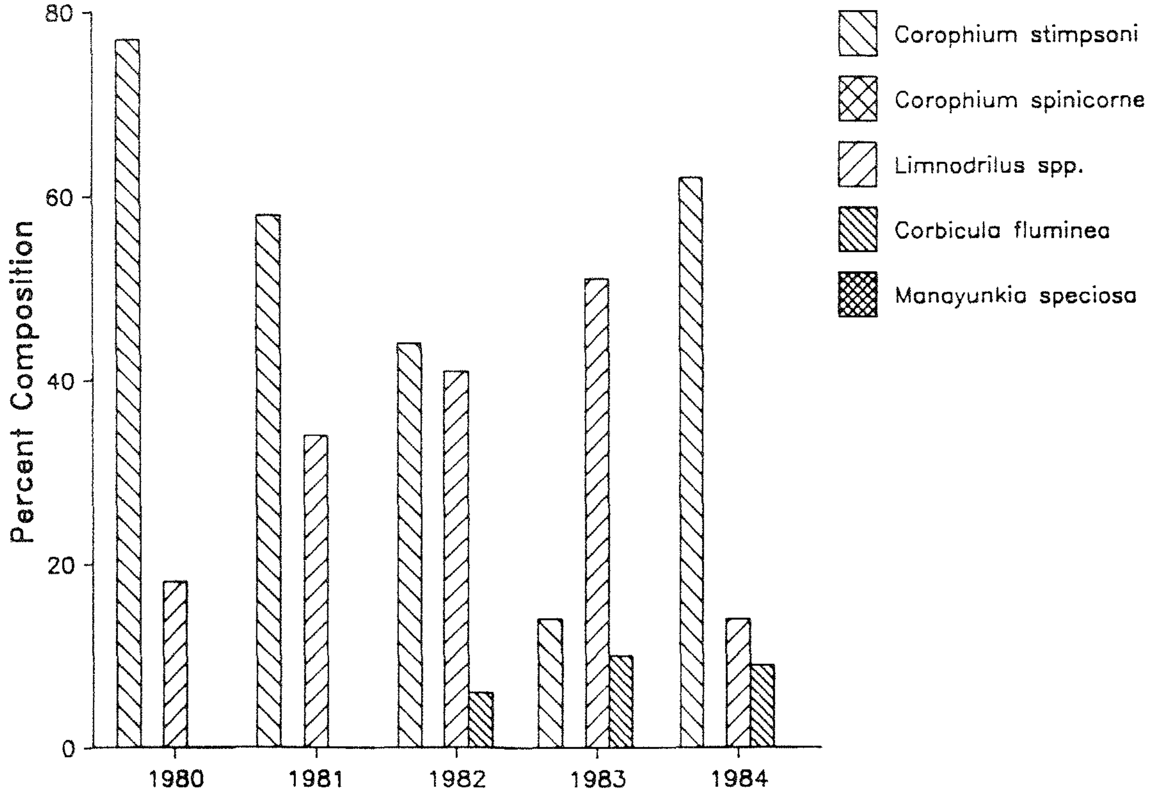

Figure 37. Dominant zoobenthos species across years at sampling sites in a flooded island in the western delta.

into the water column at midnight (Siegfried et al. 1978). Vertical migrations may serve in distributing young *Corophium* downstream. In samples taken from 1980 to 1984 (California Department of Water Resources 1978-86a,b; See 1983, 1984 data), *Corophium stimpsoni* was found regularly at each site but dominated the western sites (Figures 37 and 38).

Corophium spinicorne is a tube dwelling amphipod whose distribution in the delta is almost the complement to that of its congener; it is most frequently found on substrates of peat, cobble, or larger objects while *C. stimpsoni* is usually found on sandy substrates. Like *C. stimpsoni*, *C. spinicorne* is found at all locales in the delta (Hazel and Kelley 1966), but where one is abundant the other is usually rare. *C. spinicorne* is most common on the shallower edges of channels, frequently attached to pilings or riprap. *C. spinicorne* increases in abundance when conductivities increase, whereas *C. stimpsoni* declines at conductivities greater than 5,000 μsiemens/cm (Markmann 1986). In collections made since 1980 by the California Department of Water Resources, *C. spinicorne* has seldom dominated any site (Figures 36, 37, 38, and 39), but this is partly an artifact of its habit of building tubes on solid objects, which results in low capture rates by the Peterson dredge.

Both species of *Corophium* undergo two generations per year, although only one population peak is apparent. An overwintering population begins reproduction in the early spring. The subsequent generation begins to appear in March, grows rapidly through the summer, and produces the next overwintering generation in late summer (Siegfried et al. 1978). Before reproducing, the overwintering population grows larger than the summer population. Fecundity is a logarithmic function of size in *Corophium*, so the overwintering population can produce more young, in a shorter time, than the summer

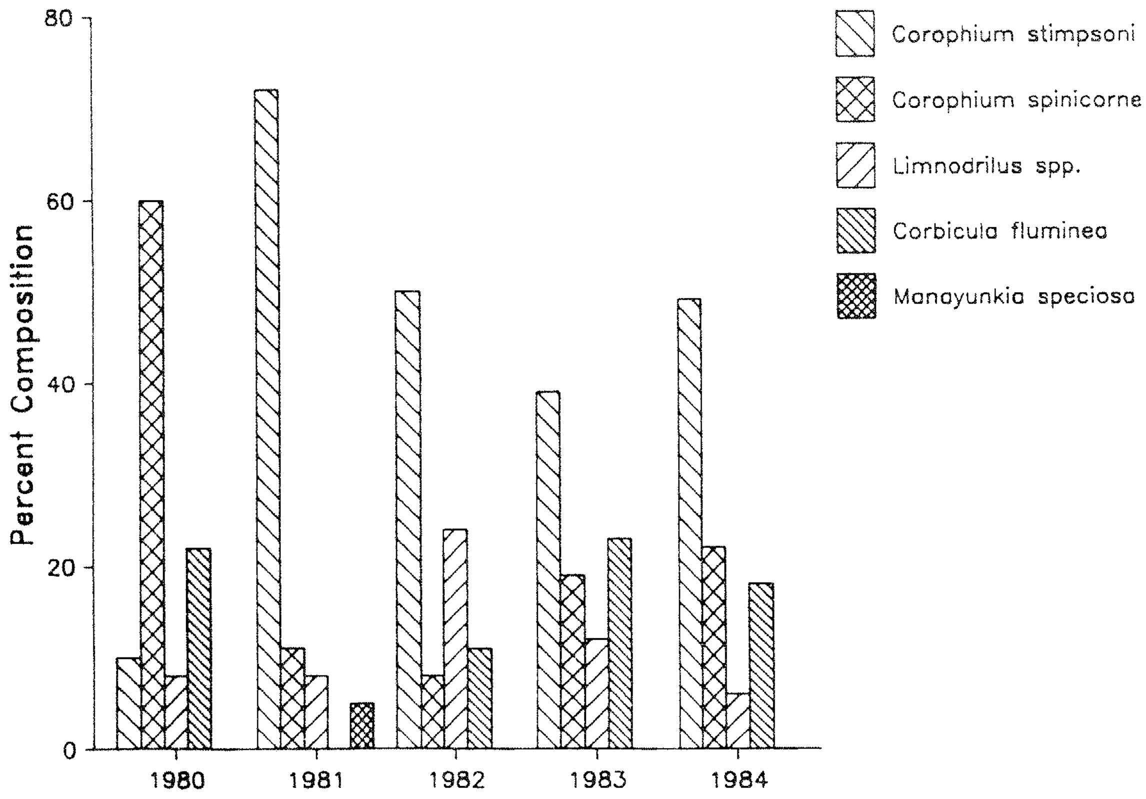

Figure 38. Dominant zoobenthos species across years at sampling sites in the main channel of the Sacramento River in the western delta.

generation (Siegfried et al. 1978). These life history tactics are very similar to those of *Neomysis mercedis*.

Annelid worms of the genus *Limnodrilis* are more euryhaline than other members of the benthic community. They frequently dominate samples from Grizzly Bay, downstream of the delta, as well as freshwater sites in the central delta. Brackish waters of the western delta support the greatest densities (California Department of Water Resources 1982) and appear optimal for their growth and reproduction. The densities and reproductive output of *Limnodrilis* spp. are lower at times of higher salinity (California Department of Water Resources 1982). On the other hand, during the wet year of 1983 when conductivity in the delta never exceeded 200 μsiemens/cm, *Limnodrilis* declined in relative abundance (California Department of Water Resources 1978-86a,b; see 1984 data). *Limnodrilis* lives in burrows as deep as 18 cm, and the lower reaches of these burrows may serve as a refuge for the worm when sudden salinity changes occur at the surface. The ability of these worms to survive low oxygen conditions within their burrows and to use the burrows as buffers against environmental change may explain their greater abundance in Suisun Bay where salinities change frequently and in parts of the southeastern delta where anoxic conditions may regularly occur. Thus, these worms tend to be most abundant in areas which support few other species. If high flows remove *Limnodrilis* from channels they seem to readily recolonize from nearby populations, but they do not appear to use river currents or tidal flow to distribute their young.

The Asian clam *Corbicula fluminea* (perhaps synonymous with *C. manilensis*), introduced into the Columbia River in 1938, had invaded the Sacramento River by 1945 (Gleason 1984). It is now the most widespread and abundant freshwater clam in the

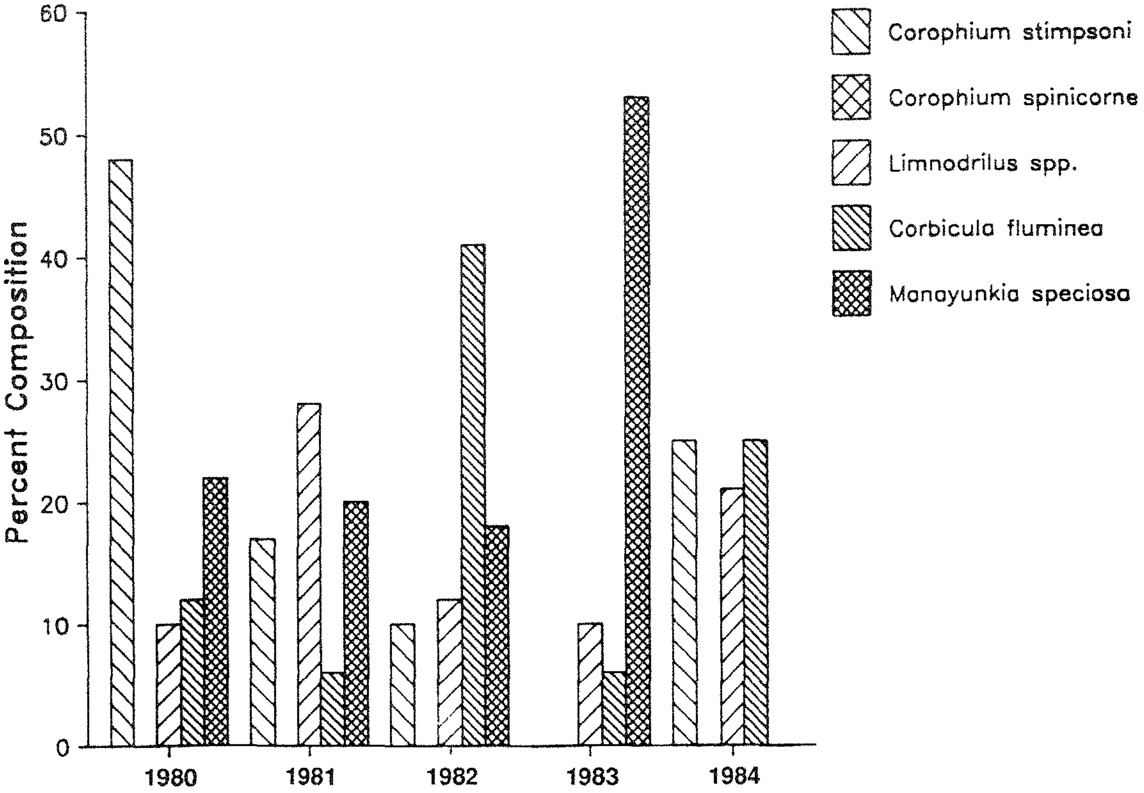

Figure 39. Dominant zoobenthos species across years at sampling sites in the main channel of the San Joaquin River in the central delta.

state. Reproduction is tied to temperature: eggs only develop when water temperature is between 16 and 24 °C. These temperatures typically occur only in the spring and fall, and *Corbicula* reproduction is, correspondingly, bimodal. Fecundity can be as great as 8,000 young/yr. Young leave the parent's mantle cavity in a relatively well-developed state, attaching themselves to the bottom soon after emergence. Colonies of *Corophium* frequently harbor high densities of young clams (Eng 1979). Two thousand clams/m^2 is a common density estimate, but densities of up to 20,000/m^2 have been recorded (Gleason 1984).

Corbicula usually reproduce in the late spring or early summer, but in the central delta there is often another reproductive peak in the late fall. High flows in the spring carry young clams downstream to the upper reaches of Suisun Bay, but high fall salinities and scouring flows of the following spring appear to prevent the establishment of large adult populations in the western delta (Markmann 1986). The fall bout of reproduction in the central delta takes place when flows are lower and young clams probably settle out of the water column near the adults.

Growth is apparently controlled by temperature via its effect on phytoplankton densities. Laboratory studies have shown that *Corbicula* can grow through winter temperatures of the delta if chlorophyll *a* concentrations are sufficiently high (Foe and Knight 1985). However, low temperatures coincide with decreased insolation and residence time to limit algal growth. Thus, in nature, *Corbicula* are not observed to grow at temperatures below 15 °C.

In the Sacramento-San Joaquin Delta *Corbicula fluminea* is usually the third most abundant form of zoobenthos. It is present at all sample sites but is

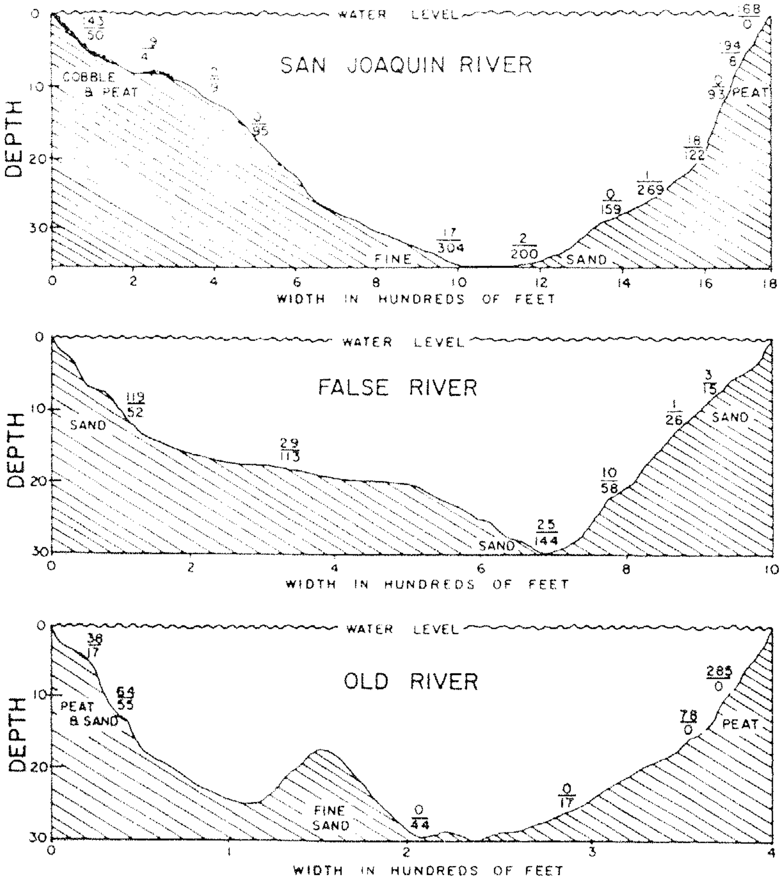

Figure 40. Segregation by depth of two species of *Corophium* in the channel of the Sacramento River. Modified from Hazel and Kelley (1966).

most abundant in the more freshwater, interior sites (California Department of Water Resources 1978-86a,b; see 1985 data). In 1983, an extraordinarily wet year, *Corbicula* rose to be the second most common genus of zoobenthos and increased in relative abundance at the western sampling sites (California Department of Water Resources 1978-86a,b; see 1984 data). Thus, freshwater flows seem to promote the abundance and spread of this species.

The polychaete worm *Manayunkia speciosa* is the most strictly freshwater inhabitant of the five dominant benthic species. Unlike other members of the benthos, *Manayunkia speciosa* is found only in the eastern portions of the delta. The requirement for freshwater makes *Manayunkia* unusual among polychaetes, which are predominantly marine worms. During the exceptionally high outflow conditions of 1983, *Manayunkia speciosa* became extremely abundant. During the 1976-77 drought, the western delta was temporarily invaded by polychaete species typical of the more saline bay waters and *Manayunkia speciosa* abundance in the eastern delta declined (Markmann 1986).

Manayunkia speciosa constructs mucus-and-silt tubes and lives in dense colonies of 2,000/m^2 to 50,000/m^2. Adults are hermaphrodites. Eggs are produced either sexually or asexually and mature within the parental tube. Dispersal appears to be a simple matter of the young crawling out of the parent's tube after hatching and then building their own tube nearby (Markmann 1986). In the

Sacramento-San Joaquin Delta, *Manayunkia speciosa* apparently only breeds in the spring. Its requirements for freshwater and silty substrates restrict *Manayunkia speciosa* to low-velocity waterways of the eastern delta.

CHAPTER 5. EPIFAUNA

Larger, more mobile animals that live on rather than in the substrate are not well sampled by any procedures used to monitor the delta. Although *Corbicula* could often be included in this category, the epibenthos is otherwise composed of arthropods. In the more saline waters of the western delta, the epibenthos consists largely of a native shrimp, *Crangon franciscorum*, an introduced shrimp, *Palaemon macrodactylus*, and an introduced crab, *Rithropaenopeus harrisii*. Further upstream the epibenthos is made up of insects (Markmann 1986): Gomphidae, Ephemeridae, Chironomidae, etc. The most widely distributed and economically important member of the epifauna is the signal crayfish *(Pasifastacus leniusculus)*. The red swamp crayfish (*Procambarus clarki*) is also reported to be widely distributed in the delta (Hazel and Kelley 1966).

Pasifastacus leniusculus var. *leniusculus* was first found in California in San Francisco in 1898 and was apparently introduced from Oregon (Riegel 1959). A commercial harvest of signal crayfish in the delta began in 1970. Today, annual commercial landings in the delta average 500,000 pounds (Kimsey et al. 1982). *P. leniusculus* is tolerant of salinities up to 17 ppt and can be found in the upper reaches of the San Francisco Bay complex.

The two common caridean shrimp of the western delta are ecologically similar (Sitts 1978). *Crangon (=Crago) franciscorum* feeds predominantly on *Neomysis mercedis* and has its densest populations in the same areas in which *N. mercedis* is most abundant (Siegfried 1980). Formerly, *C. franciscorum* supported a large commercial catch in San Francisco Bay (Bonnot 1932), but now it is only taken in small quantities for bait (Siegfried 1980). *Palaemon macrodactylus* was introduced to San Francisco Bay sometime in the 1950's, probably by the dumping of water ballast from ships returning from Korea (Newman 1963; Siegfried 1980). The diet of *P. macrodactylus* also consists largely of *N. mercedis*, but the peak abundance of *P. macrodactylus* is downstream of the overlapping peaks of *C. franciscorum* and *N. mercedis* (Siegfried 1980). Both caridean shrimp show the same sort of vertical migrations as *N. mercedis*. During the season when *N. mercedis* is less abundant, *C. franciscorum* takes more gammarid amphipods and polychaetes while *P. macrodactylum* takes more copepods (Knight et al. 1980).

Crangon franciscorum is more marine and apparently less tolerant of water quality degradation when in freshwater than *Palaemon macrodactylus* (Siegfried 1980). Ovigerous females are never found in the delta, only in San Pablo and Suisun Bays. Increased osmotic stress in freshwater appears to prevent egg development at salinities below 15 ppt (Krygier and Horton 1975). Breeding occurs year round but with a peak from December through June (Israel 1936). During seasons of high river outflow *C. franciscorum* is absent from the western delta but abundant downstream (Siegfried 1980). Temperature and salinity interact in their physiological effects on *C. franciscorum*; low temperatures reduce its tolerance for low salinities (Khorram and Knight 1977). When salinities and temperatures rise in the western delta, *C. franciscorum* occurs in channels of the Sacramento River at much higher abundances than in the San Joaquin River. Salinity tolerances change with the acclimation of individuals, so downstream populations are less tolerant of freshwater than upstream populations (Shaner et al. 1987).

Like *Crangon franciscorum*, *Palaemon macrodactylus* is apparently limited in its upstream distribution by low salinity, but *P. macrodactylus* tolerates lower salinities and can be abundant in the more degraded waters of the San Joaquin River. Even at periods of high river outflow, when salinities are lowest, *P. macrodactylum* is found in the western delta. Reproduction appears to be initiated by increasing photoperiod in April or May and continues until August.

CHAPTER 6. FISH

6.1 HISTORICAL PROCESSES

The abundant species of fish in the delta (Table 5) are almost all introduced from the east coast or from Asia and Europe. The ecology of the native fishes prior to the arrival of European settlers is not well known. The decline of native fishes was presumably the result of habitat alteration combined with the introduction of foreign species, circumstances which continue to bring new changes to the delta. Two species which were formerly abundant in the delta are now extinct there; the thicktail chub (*Gila crassicauda*) was last seen in Cache Slough in 1958 (Moyle 1976), and only a few Sacramento perch (*Archoplites interruptus*) have been observed in the delta over the last 25 years, even though they once supported a commercial harvest. Thicktail chubs and Sacramento perch are the most frequent fish remains found in middens of the Patwin Indians which formerly inhabited the Sacramento-San Joaquin Estuary (Schulz and Simons 1973). Most other native species have undergone shrinkage of their ranges or population sizes (Moyle 1976), with the delta smelt (*Hypomesus transpacificus*) showing a recent and severe decline (L. Miller, California Department of Fish and Game; pers. comm.).

The greatest efforts to introduce fish into the delta were made immediately after the completion of the transcontinental railway. Oysters were the most commonly transported organism, but railway cars of oysters were often a means of bringing in various fish, either accidentally or intentionally. Many species of fish were introduced before 1900, but new arrivals have been reported in most decades since then (Table 5). The history of introductions has

Table 5. Abundance of the fish of the Sacramento-San Joaquin Delta and year of introduction or first capture for non-native species. R=resident, A=anadromous, N=nonresident visitor, M=euryhaline marine.

Common name	Scientific name	Abundance	Year
Pacific lamprey	*Entosphenus tridentatus*	Common (A)	
River lamprey	*Lampetra ayresi*	Uncommon (A)	
White sturgeon	*Acipenser transmontanus*	Common (A)	
Green sturgeon	*Acipenser medirostris*	Uncommon (A)	
American shad	*Alosa sapidissima*	Common (A)	1871
Threadfin shad	*Dorosoma petenense*	Abundant (R)	1953
Brown trout (sea-run)	*Salmo trutta*	Rare (A)	
Steelhead	*Oncorhynchus mykiss*	Common (A)	
Pink salmon	*Oncorhynchus gorbuscha*	Occasional (A)	
Coho salmon	*Oncorhynchus kisutch*	Rare (A)	
Chinook (king) salmon	*Oncorhynchus tshawytscha*	Common (A)	

(Continued)

Table 5. (Concluded)

Common name	Scientific name	Abundance	Year
Chum salmon	*Oncorhynchus keta*	Occasional (A)	
Sockeye salmon	*Oncorhynchus nerka*	Occasional (A)	
Longfin smelt	*Spirinchus thaleichthys*	Common (A-R)	
Delta smelt	*Hypomesus transpacificus*	Common (R)	
Thicktail chub	*Gila crassicauda*	Extinct	
Hitch	*Lavinia exilicauda*	Common (R)	
California roach	*Hesperoleucus symmetricus*	Rare (N)	
Sacramento blackfish	*Orthodon microlepidotus*	Common (R)	
Splittail	*Pogonichthys macrolepidotus*	Common (R)	
Hardhead	*Mylopharodon conocephalus*	Uncommon (N)	
Sacramento squawfish	*Ptychocheilus grandis*	Common (R)	
Fathead minnow	*Pimephales promelas*	Occasional (R)	1950's
Golden shiner	*Notemigonus crysoleucas*	Common (R)	>1891
Goldfish	*Carassius auratus*	Common (R)	>1900
Carp	*Cyprinus carpio*	Abundant (R)	1872
Sacramento sucker	*Catostomus occidentalis*	Common (R)	
Black bullhead	*Ictalurus melas*	Common (R)	1874
Yellow bullhead	*Ictalurus natalis*	Rare (R)	1874
Brown bullhead	*Ictalurus nebulosus*	Common (R)	1874
White catfish	*Ictalurus catus*	Abundant (R)	1874
Channel catfish	*Ictalurus punctatus*	Common (R)	1940's
Blue catfish	*Ictalurus furcatis*	Rare (R)	1979
Inland silversides	*Menidia beryllina*	Abundant (R)	1968
Mosquitofish	*Gambusia affinis*	Common (A-R)	1922
Striped bass	*Morone saxatilis*	Abundant (R)	1879-82
Sacramento perch	*Archoplites interruptus*	Extinct	
Bluegill	*Lepomis macrochirus*	Common (R)	1908
Redear sunfish	*Lepomis microlophus*	Uncommon (R)	>1949
Green sunfish	*Lepomis cyanellus*	Common (R)	1891
Warmouth	*Lepomis gulosus*	Uncommon (R)	>1921
White crappie	*Pomoxis annularis*	Common (R)	1951
Black crappie	*Pomoxis nigromaculatus*	Uncommon (R)	>1908
Largemouth bass	*Micropterus salmoides*	Common (R)	1874
Smallmouth bass	*Micropterus dolomieui*	Uncommon (R)	?
Bigscale logperch	*Percina macrolepida*	Common (R)	1953
Yellow perch	*Perca flavescens*	Extinct	1891-1950's
Tule perch	*Hysterocarpus traski*	Common (R)	
Yellowfin goby	*Acanthogobius flavimanus*	Common (R)	1963
Staghorn sculpin	*Leptocottus armatus*	Common (M)	
Starry flounder	*Platichthys stellatus*	Common (M)	
Rainwater killifish	*Lucania parva*	Rare (R)	?
Prickly sculpin	*Cottus asper*	Common (R)	
Threespine stickleback	*Gasterosteus aculeatus*	Uncommon (R)	
Chameleon goby	*Tridentiger trigoncephalus*	Common (R)	

varied from phenomenal success to complete failure. One species, yellow perch (*Perca flavescens*), was introduced but became extinct 60 years later. Other species, such as pumpkinseed (*Lepomis gibbosus*), never survived, while some, such as channel catfish (*Ictalurus punctatus*), succeeded only after repeated introductions. The most recent successful introductions were of inland silverside (*Menidia beryllina*) (Moyle et al. 1974; Meinz and Mecum 1977) and bigscale logperch (*Percina macrolepidotus*) from the southeastern United States (Moyle et al. 1974), rainwater killifish (*Lucania parva*) from the east coast of North America (Hubbs and Miller 1965), and chameleon goby (*Tridentiger tigonocephalus*) and yellowfin-goby (*Acanthogobius flavimanus*) from Japan (Brittan et al. 1963). The documented explosive spread of yellowfin gobies from their first appearance in 1963 to their extreme abundance in 1967 (Brittan et al. 1970) is apparently typical for most successful introductions. Other species continue to arrive. For instance, blue catfish (*Ictalurus furcatus*) were first brought into California at Lake Jennings in San Diego county on October 23, 1969 (Richardson et al. 1970) and were reported in the Sacramento-San Joaquin Delta less than 10 years later (Taylor 1980). Young of the year were found in Clifton Court Forebay in 1986 (H. Chadwick, pers. comm.). White bass (*Morone chrysops*) have been brought into the drainage and may invade the estuary within the next few years.

6.2 CONTROLS OF DISTRIBUTION

The distribution of fish species within the delta is based on productivity and the degree of impact that human activities have had on water flow. Electrofishing surveys in 1974 (Sazaki 1975) found that the greatest abundances of fish are in the slower and more productive waters of the San Joaquin River in the south delta. However, the less degraded but less productive waters of the Sacramento River in the north delta are the predominant areas in which native fishes were found. Because introduced species are more widely distributed, the northern delta supports the greatest diversity of fish species.

The fishes of the delta, like most other aquatic components of the delta community, are frequently controlled by the amount of delta outflow. Some ways in which moderately high flows benefit fish populations are as follows: (1) more flooded vegetation for species that lay eggs there, (2) more suitable habitat for nest construction in upstream streambeds that are normally dry, (3) easier access to upstream sites, (4) more shallow, flooded areas where small or young fish can avoid predators, (5) more easily followed environmental cues (scents and currents) for fish migrating to their natal streams, (6) dilution of pollutants, and (7) providing optimum conditions for food organisms. Fish whose populations have been documented as being tied to river outflows include chinook salmon, striped bass, splittail, American shad, and longfin smelt (Daniels and Moyle 1983; Stevens and Miller 1983). Water development projects and management strategies can have profound effects on these species (Stevens and Chadwick 1979). Some fish are insulated from the effects of variation in outflow by their use of a habitat type or by having a method of reproduction which is independent of flow effects. Several groups of species (i.e., anadromous species, resident species of riverine habitats, and resident species of lacustrine habitats) can be identified because of their shared responses to outflow or their use of similar habitats. Variation within species and in the nature of the delta across years prohibit any strict grouping of species, but some general patterns are apparent.

6.3 ANADROMOUS SPECIES

Adult anadromous species use the delta as a path to their upstream spawning sites, while juveniles use the path on their way to the sea. The delta is also a nursery area for outmigrating young. For some anadromous species the delta is a spawning site as well as part of the regular adult habitat. Common anadromous species of the delta include Pacific lamprey, river lamprey, American shad, white sturgeon, chinook salmon, steelhead, and striped bass. The latter five are economically the most important fish in the delta.

Lamprey. Pacific lamprey and river lamprey use the delta mainly as a path to and from their spawning sites, although some ammocoetes live in silty habitats in the delta (Moyle 1976; Wang 1986).

Sturgeon. Green and white sturgeon occur in the delta. Little is known of the biology of the comparatively rare green sturgeon (Moyle 1976). It is assumed to be similar to the white sturgeon (Wang

1986), although the adults are more marine. White sturgeon spawn between February and May, mostly in the Sacramento River (from Knights Landing to Colusa) and in its tributaries (Stevens and Miller 1970; Kohlhorst 1976; Moyle 1976; Wang 1986). Some juveniles feed in the delta, (Radtke 1966) but most are found west of Chipp's Island. While in the delta, sturgeon feed mostly on *Corophium* and *Neomysis* (Radtke 1966). The number of young sturgeon caught in the delta appears to be directly related to delta outflow, but this is partly a result of greater washout from upstream spawning sites (Stevens and Miller 1970). There is no apparent minimum flow requirement to initiate spawning activity, but survival of young sturgeon in the delta may be enhanced by high river outflows or low rates of diversion (Kohlhorst 1980).

The abundance of white sturgeon decreased from 1967 to 1974, but mean length of captured fish increased (Kohlhorst 1980). This pattern is best explained by continued growth of adults who have failed to reproduce. White sturgeon become of catchable size at 6-12 years, so adult fish in 1967-74 would have been produced in the late 1950's or early 1960's. Three reasons for impaired reproduction by this age class have been suggested (Kohlhorst 1980). After 1958 the volume of water exported from the delta greatly increased, resulting in the entrainment of young fish and the disruption of spawning migrations. Samples of sturgeon gonads in 1975 indicated concentrations of polychlorinated bipheyls (PCB's) of 24 ppm in the eggs. PCB concentrations of 3-7 ppm in other species have been shown to increase egg and larvae mortality. PCB's were widely used from 1930 to 1940 and concentrations in fish from the 1950's and 1960's may represent simple bioaccumulation. Finally, spawning stock size appears to undergo normal fluctuations that may be partly responsible for a small spawning stock. Since 1974, sturgeon populations in the delta have been increasing. However, although more young are produced, their growth rates are still lower than found for sturgeon in 1954 (Kohlhorst et al. 1980).

Salmon. All five species of Pacific west coast salmon have been recorded from the Sacramento-San Joaquin Estuary; in order of abundance these are chinook, chum, pink, sockeye, and coho salmon (*Oncorhynchus tshawytscha, O. keta, O. gorbuscha, O. nerka,* and *O. kisutch*) (Hallock and Fry 1967). Only the chinook, or king, salmon occurs regularly. Four races of chinook salmon spawn in the Sacramento-San Joaquin river system: a fall run from July to December begins spawning in October, a late-fall run from October to April begins spawning in January, a winter run from December to July begins spawning in April, and a spring run from April to October begins spawning in August. Thus, runs can occur in all months and, although no spawning takes place in the delta, the large adults migrating through have been dramatic features of the aquatic environment. Because the adults rarely feed once they enter freshwater, their impact on the ecosystem is slight. Fry are abundant in the delta from February to April (U.S. Fish and Wildlife Service 1987). Out-migrating smolts appear in the delta mostly from April to June (Sasaki 1966c; Wang 1986). In their natal streams the juveniles are drift feeders, while in the delta their diets consist of *Neomysis*, amphipods, and shrimp (Wang 1986).

Formerly, the spring run of chinook salmon contained a large population that oversummered in cool, deep pools of upper Sacramento River tributaries, such as the McCloud or Pit Rivers, before spawning in the fall. Shasta Dam and other water developments have eliminated access to most of these habitats, and this run has declined sharply. The summertime releases from Shasta Dam are from the bottom of the dam, making the summertime flows of the Sacramento River greater, more constant, and cooler. This situation has apparently favored the fall run, which spawns in the main Sacramento River (Moyle 1976). Most of the $44 million derived from this fishery (Meyer Resources Inc. 1985) is based on this run. The winter and spring runs are now very low, and efforts are being made to place them on the State and Federal lists of threatened species.

Variations in river flow affect salmon in several ways. High flows permit adults to spawn in small tributaries or to pass dams, but the young produced may be stranded after water levels decline. Nonetheless, this feature may permit rehabilitated streams to recover their salmon runs. High volumes of water prevent the reverse flows characterizing the lower San Joaquin River, thereby allowing San Joaquin fish to avoid swimming "upstream" to the export pumps (Sasaki 1966c). Finally, high runoff permits down-migrating juveniles to escape predation more effectively by hiding in emergent vegetation (Stevens and Miller 1983). Cross delta flows, increased water temperatures, and entrainment into water diversions are probably the features responsible for the loss of many fry and smolts from the delta (U.S. Fish and Wildlife Service 1987). Particularly for San Joaquin River smolts, survival is highly correlated with river flow (Stevens and Miller 1983; U.S. Fish and Wildlife Service 1987).

Steelhead, which are anadromous races of rainbow trout, are ecologically similar to salmon and have little impact on the delta community. Juveniles stay in their natal stream for 1, 2, or occasionally, 3 years prior to entering the ocean (Moyle 1976). As they pass through the estuary the juveniles feed on *Corophium*, various small crustaceans, and small fish (Sasaki 1966c). They are found in all habitats of the delta, but the length of time individuals stay in the delta and the delta's importance as a nursery area are unknown. Construction of Shasta Dam blocked access to about half of the suitable steelhead spawning sites in the Sacramento River drainage. Much of the salmon and steelhead production is now conducted at the Nimbus and Coleman fish hatcheries.

Shad. American shad were introduced in the 1870's and 1880's, at the height of silt deposition in the estuary from hydraulic mining (Hedgepeth 1979). Their semi-demersal eggs are kept in the water column when current velocities exceed 1 m/s. American shad eggs have wide perivitelline spaces, presumably to protect them as they bounce along the bottom; the chorion of the shad eggs is also particularly tough and thick (Wang 1986). One requirement for successful reproduction of striped bass, and probably American shad, is sufficient water velocities to keep the eggs and larvae suspended (Meinz and Heubach 1978). The explosive spread of American shad in the Sacramento-San Joaquin estuary was probably enhanced by having eggs that could not be smothered by silt. The semi-demersal eggs also serve to concentrate the young in the null zone where their zooplankton food is also concentrated--at least for striped bass (Stevens 1979). Both species spawn within the delta and avoid much of the habitat alteration and dewatering that have affected native anadromous species (Stevens and Miller 1983).

As with salmon, American shad spawn mostly in waters of the Sacramento River. American shad begin their spring spawning runs as early as September (Stevens 1972), but they do not become abundant until April and May. Shad spawn in May and June, and by July the adults are nearly absent from the delta (Stevens 1966). Males begin spawning at the age of 3 or 4 and females generally at the age of 4 or 5, although spawning individuals of either sex have been found at 2 years of age (Wixom 1981). Once an individual begins spawning, it spawns annually until death. California populations of American shad apparently differ from the native populations on the east coast in that they feed as they swim upstream (Stevens 1966). Stevens (1966) reported many stomachs filled with *Neomysis* (as many as 4,000 shrimp/stomach) with smaller quantities of copepods and cladocerans. Number and identity of food items in adult shad stomachs closely reflect the available zooplankton populations. Young shad begin their downstream migration as early as July, and by December they are almost completely gone (Stevens 1972). Food of young shad seems to be mostly copepods and cladocerans (Stevens 1966). River flows apparently affect shad populations primarily through their effects on habitat availability (Stevens and Miller 1983).

American shad populations expanded very rapidly following their introduction in 1871. A commercial shad fishery existed by 1879. From 1900 until 1945, the commercial catch was frequently 1 million pounds and rose in 1917 to 5.6 million pounds. After 1945, shad populations declined, and in 1957 commercial fishing in the delta was banned (Skinner 1962). Formerly, American shad spawned throughout the estuary (Nidever 1916; Hatton 1940), but now only the upper reaches of the north delta are used (Stevens 1966; Painter et al. 1977). The decline in shad populations seems to be most closely tied to water diversions. Upstream reservoirs reduce the amount of spring outflows and so may fail to attract adults upstream and fail to transport young fish to appropriate nursing areas downstream. Diversions within the delta entrain many shad and may reduce zooplankton abundance by decreasing residence times of water in the delta. The decline of shad populations coincides with the construction of Shasta Dam. Operation of Shasta Dam has changed the delta from an estuarine to a freshwater system, so the simultaneous declines in anadromous species, like shad, and increases of freshwater species, like channel catfish, are not surprising.

Striped Bass. The breeding biology of striped bass is very similar to that of American shad and their successful introduction into California may, perhaps, be attributed to their silt tolerant eggs. This may have been particularly important since chinook salmon (the native, anadromous, predatory fish) were probably decimated by hydraulic mining at the same time striped bass were introduced. As with American shad, most reproduction of striped bass takes place in the waters of the Sacramento River. In most years the high concentrations of total dissolved solids in the lower San Joaquin River block the upstream migration of most striped bass (Farley 1966; Radtke 1966). Timing of spawning in striped bass appears to be set by temperatures near 15 °C; in cooler, wetter years many bass migrate as far upstream as Red Bluff, while in warmer, drier years most spawning occurs before the fish have moved past Sacramento (Farley 1966). Similarly, striped bass that spawn in the San Joaquin River do so as much as 1 month earlier than those in the Sacramento River, and this has been attributed to the higher temperature of that water (Chadwick 1958; Wang 1986).

Male striped bass begin their spawning runs in late March or early April and are followed by the females, which arrive in late April and early May (Radtke 1966). Differences in temperature between years and in direction of migration, as already noted, can affect the timing of these runs. Spawning is usually completed by May (Farley 1966) but has been reported as early as April and as late as June (Scofield 1931; Calhoun et al. 1950; Erkkila et al. 1950; Chadwick 1958; Moyle 1976; Wang 1986). Adult striped bass are almost strictly piscivorous (Thomas 1967), taking a wide variety of prey but particularly young striped bass and threadfin shad. However, they do not feed heavily during their spawning migration and so have little effect on fish populations within the delta (Stevens 1966). Some adult striped bass remain within the delta all year, often in the expanse of open water in Frank's Tract (Radtke 1966).

Young striped bass commonly stay within the delta for up to 3 years. When fish are smallest, copepods constitute their most common prey (Heubach et al. 1962; Eldridge et al. 1981), but by the time the bass are 3 months old, *Neomysis* is the dominant dietary item (Stevens 1966). Seasonal abundances of young threadfin shad and of *Neomysis* appear to control the diet of young striped bass, with larger individuals getting progressively better able to catch shad even at low densities (Figure 41; Stevens 1966). In their first year striped bass eat invertebrates almost exclusively. By their second fall (when shad are abundant and *Neomysis* are scarce) their diet is half fish, but it returns to almost 90% *Neomysis* when that prey is abundant. This pattern continues through the next two falls but with a general increase in the use of fish at all seasons. Within the delta *Corophium* are sometimes a significant portion of the diet (Stevens 1966).

For many years there was a close relationship between spring outflows and reproductive success of striped bass (Turner and Chadwick 1972) and

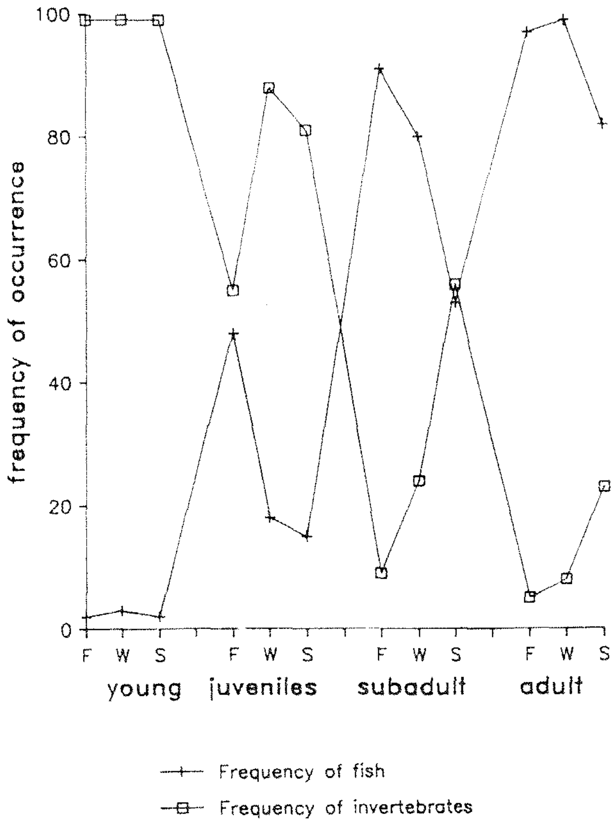

Figure 41. Contributions of vertebrate and invertebrate prey to the diets of four size classes of striped bass across seasons of differing abundances of *Neomysis mercedis*, the most common invertebrate prey. *Neomysis mercedis* is least abundant during the fall season (F) and most abundant during the spring season (S). Modified from Stevens (1966).

between spring outflows and the survival of young (Stevens 1977a). Since the drought of 1976-77, these relationships have broken down, with the abundance of young striped bass always lower than expected. Many reasons have been proposed for the lowered production but those now seriously considered (Stevens et al. 1985) are as follows:

(1) Adult populations have declined to levels insufficient to produce enough eggs to permit population growth. The principal objection to this theory rests on the observation that average fecundities of individual fish are 0.5 million eggs and can be as high as 2 million (Moyle 1976). Inherent in this objection is the assumption that young striped bass are controlled by density-dependent processes, so that fewer young imply greater survival rates. Entrainment in water diversions and toxic effects of chemicals on the environment are two density-independent factors that may kill many young striped bass in the delta. An additional objection to the role of limiting adult population size is the observation that the initial introduction consisted of a much smaller population than currently available. This overlooks the substantial changes in the delta since 1871.

(2) Plankton food supplies were particularly depressed following the drought and this may limit growth of young striped bass. Phytoplankton blooms in the central delta have coincided with shutdowns of the Tracy pumping plants, implicating lower residence times in the decline of productivity. Alternatively, much of the variability in striped bass abundance can be associated with variance in biological oxygen demand within the delta, and it has been suggested that better sewage treatment has reduced delta productivity. The average densities of zooplankton in the delta have not changed greatly, but calculations of densities where the striped bass begin feeding show a very marked decline. In any case, it seems evident from laboratory determinations of the food requirements of young striped bass (Daniel 1976; Eldridge et al. 1981) and recorded densities of zooplankton in the field (Daniel 1976) that the only young striped bass apt to survive are those that find themselves in unusually dense patches of prey. The size and density of such patches seem to have declined since the 1976-77 drought.

(3) Many young striped bass are lost through entrainment into water diversions. The pumping plants at Tracy, coolant intakes at power plants, and agricultural uses are the principal sites of such entrainment. On average the three main diversions take up to 300 m^3/s, 90 m^3/s, and 110 m^3/s, respectively (Chadwick et al. 1977). The concentration of young bass and bass eggs, at least in the agricultural diversions, are equal to the concentrations in the sloughs (Allen 1975). Striped bass losses were estimated to be 869 million in 1978 and 910 million in 1979.

(4) Toxic chemicals have been found in the delta at concentrations sufficient to kill striped bass (Finlayson and Lew 1983), but the occurrence of such high concentrations is probably rare.

These factors may all interact, and their effects may be exacerbated by effects of temperature and dissolved oxygen fluctuations that may limit the distribution of striped bass within the delta (Coutant 1985).

6.4 RESIDENT SPECIES

Species that do not migrate from the delta must be able to survive there year-round. The delta's conditions were formerly much more variable and harsh than the present, highly managed situation. Most native resident species are characterized by breeding biologies which minimize the impact of annual variations in delta outflows, but many are apparently sensitive to the drastic habitat changes that characterize most of the delta. Most current resident fishes in the delta are not native; most of the endemic fauna have declined in abundance or range. Native resident fishes occur primarily in the more saline habitats of the western delta or in the less productive waters of the Sacramento River, which are avoided by most of the introduced fish species.

Feeding. Unlike the introduced species, each native species has a distinctive diet or foraging mode. Splittail (*Pogonichthys macrolepidotus*) are exceptionally euryhaline compared to other cyprinids. They are distributed widely through the delta, but are particularly abundant in the western delta and Suisun Bay. Splittail are the only resident species that have been shown to be controlled by patterns of delta outflow; they spawn on flooded vegetation and presumably years of high water provide more suitable habitat (Daniels and Moyle 1983). Their barbels, large upper caudal fin lobe, and downward oriented eyes indicate that splittail are bottom browsers (Moyle 1976). Gut-content analyses show that they consume invertebrates, particularly *Neomysis* in Suisun Marsh (Herbold 1987) and amphipods or clams within the delta (Caywood 1974). Blackfish (*Orthodon microlepotus*) and hitch (*Lavinia exilicauda*) are most abundant in the lower San Joaquin River near Mossdale where concentrations of dissolved solids are frequently high, and most non-native species are rarely found (Turner 1966c). Both blackfish and hitch feed in midwater, blackfish primarily on phytoplankton or organic detritus and hitch on zooplankton (Moyle 1976). The piscivorous Sacramento squawfish (*Ptychocheilus grandis*) and the bottom-browsing Sacramento sucker (*Catostomus occidentalis*) are found more frequently in upper parts of the rivers than in the delta. Tule perch (*Hysterocarpus traski*) and prickly sculpin (*Cottus asper*) feed on bottom invertebrates, but tule perch are bottom pickers that concentrate on *Corophium* while prickly sculpins are lie-in-wait predators that feed on large invertebrates and small fish. Introduced resident fishes include: yellowfin goby, common carp (*Cyprinus carpio*), and various catfish and sunfish. The diets of these fish in the delta have not been thoroughly described but all are bottom browsers on a wide array of prey, including mysid shrimp, insect larvae, and copepods. Larger catfish are piscivorous.

Breeding. Most of the native resident species appear to breed mostly in tributaries of the delta (Moyle 1976; Wang 1986). Tule perch breed within the delta, but by giving birth to live young they minimize any impact of variations in river outflow. Similarly, prickly sculpins avoid the effects of environmental fluctuations by laying their eggs on the underside of submerged rocks or trees where the males guard the eggs (Wang 1986).

Nest building is a reproductive strategy used by some of the most successfully introduced resident species. Bullheads and catfish (family Ictaluridae) and sunfish, crappies, and largemouth bass (family Centrarchidae) all raise their young in nests. In addition, most of these species are isolated from the effects of outflow variation by living in the still waters of dead-end sloughs in the eastern portion of the delta (Turner 1966c). Two exceptions to this pattern of habitat selection are the white catfish and channel catfish. The white catfish is apparently more tolerant of dissolved solids than any other catfish, since it occurs throughout the delta and down to Suisun Bay in salinities of 8 ppt (Turner 1966c). Perhaps as a consequence of this tolerance it is the most abundant catfish in the delta, accounting for 95% of catfish caught. It also is the most popular warmwater sportfish in California (Turner 1966c). Channel catfish are more stenohaline than white catfish and are found most commonly in the larger channels of the Sacramento River. Repeated efforts were made to introduce this species from 1874 to 1940 when a self-reproducing population was finally established (Moyle 1976). The success of this introduction coincides with the construction of Shasta Dam and the greatly reduced incursion of saline waters into the delta. Yellowfin gobies lay their eggs in a burrow. In Japan this species is catadromous, moving down into more saline mudflats to spawn (Wang 1986). Yellowfin gobies are abundant in the delta, and their ecology needs more research.

Four introduced cyprinids reside in the delta, exhibiting three reproductive strategies that minimize the risks of breeding in a variable environment. Carp and goldfish do little breeding within the delta; instead they appear to migrate up the rivers to more freshwater conditions (Turner 1966c). Breeding in the delta seems to be concentrated in quieter water such as in Frank's Tract or in dead-end sloughs (Wang 1986). Both species are bottom-feeding generalists and are found most commonly in the San Joaquin River where dissolved solids concentrations are high (Turner 1966c). Fathead minnows (*Pimephales promelas*) and golden shiners (*Notemigonius crysolucas*) have probably been distributed throughout the delta as bait releases by fishermen (Wang 1986). Fathead minnows are common only in localized patches, generally in small creeks (Wang 1986). They build nests, guarded by the males, in shallow water (Moyle 1976; Wang 1986). Golden shiners are more widely distributed, usually occurring in still water in association with centrarchids. They exhibit no parental care or migration but frequently safeguard their eggs by laying them within the nests of centrarchids (Wang 1986).

Shad. Threadfin shad breed by broadcasting their eggs and milt. Their high fecundity and rapid growth compensate for the presumed high mortality of eggs. The breeding season in the delta is prolonged (Wang 1986); this may permit the population to reproduce successfully in the face of any variation in flow. Threadfin shad eat copepods and cladocerans (Moyle 1976) and are eaten extensively by striped bass, largemouth bass, and other centrarchids (Kimsey and Fisk 1964). The threadfin shad is one of the most numerous fish species in the delta.

Smelt. Delta smelt and longfin smelt are native planktivores which are similar in their breeding biology but differ greatly in their response to outflow conditions. Between 1967 and 1978 longfin smelt in the delta varied in abundance by a factor of 450, while delta smelt in the same period varied only by a factor of 5.3 (Stevens and Miller 1983). In recent years, however, the delta smelt population has plummeted (Figure 42). Both species migrate into the delta in winter and lay their adhesive eggs between December and May, but delta smelt tend to spawn later than longfin smelt (Radtke 1966).

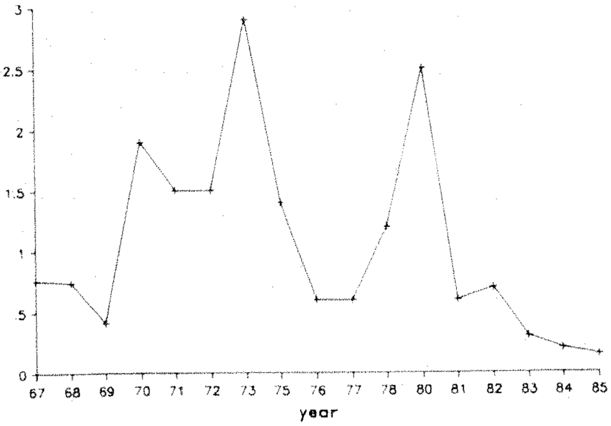

Figure 42. Mean catch of delta smelt per trawl across 17 years. Data are from trawls performed by California Fish and Game in the course of regular sampling of striped bass abundance.

Longfin smelt abundance is closely correlated with outflow for all months from February to September, while delta smelt abundance is not significantly correlated with outflow of any month (Stevens and Miller 1983). Diets of the adults of these two species show little overlap; longfin smelt eat predominantly *Neomysis*, whereas delta smelt eat mostly copepods and cladocerans (Moyle 1976). Delta smelt distribution seems to be tied to the presence of the entrapment zone; there is a significant correlation between the catch of delta smelt in midwater trawls and intermediate conductivities of water in the area where the trawls were made (Herbold 1987).

Centrarchids. A variety of sunfish, crappie, and black bass reside in the delta year round, principally in dead-end sloughs. Bluegill, the most abundant sunfish in the delta, and the less abundant green sunfish are widely distributed. Warmouth are more restricted to dead-end sloughs and the western delta (Turner 1966b; Sazaki 1975). Although 1963-64 surveys reported no redear sunfish, Sazaki found them in the northeastern delta in 1974, while surveys in 1984-85 found them to be more abundant and more widely distributed within the waters of the Sacramento River (California Department of Fish and Game 1987).

Both black crappie and white crappie occur in the delta but black crappie are much more abundant, particularly in the western delta (Turner 1966b; Sazaki 1975). Largemouth bass are the dominant black bass of the delta with smallmouth bass restricted almost entirely to the easternmost delta waters. As with the other centrarchids, the black basses are most often found in the still, rich waters of dead-end sloughs.

CHAPTER 7. REPTILES AND AMPHIBIANS

All amphibians found in the delta (Table 6) occur predominantly in the marsh or riparian habitats, except for California slender salamanders (*Batrachoceps attenuatus*) and arboreal salamanders (*Aneides lugubris*) which occur in upland habitats. Bullfrogs (*Rana catesbeiana*), an introduced species, are now abundant and widely distributed.

Massive hunting efforts to supply San Francisco restaurants with frog legs in the late 1800's decimated populations of native red-legged frogs (*Rana aurora*), which were formerly abundant in the Central Valley. Only the female red-legged frogs were of sufficient size to interest the froggers, and this may have prompted the introduction of bullfrogs because both sexes are of sufficient size (Jennings and Hayes 1985). The effects on reproduction were much more severe, therefore, on red-legged frogs than on bullfrogs. This disparity in selection pressure may have contributed to the subsequent domination of the valley by bullfrogs (Hayes and Jennings 1986). Predation by introduced fishes probably also played a large role in reducing populations of the red-legged frogs (Moyle 1973).

Table 6. Amphibians of the Sacramento-San Joaquin delta and their distributions within habitat types. Modified from U.S. Army Corps of Engineers (1979) and Rollins (1977). Habitat abbreviations: Aq=Aquatic, Ag=Agricultural, M=Marsh, R=Riparian, Up=Upland, and Ur=Urban.

Common name	Species	Habitat	Abundance
Bullfrog	*Rana catesbeiana*	R,M,Up	Common
Red-legged frog	*Rana aurora*	R,M,Up,Ag	Rare
Foothill-yellow-legged frog	*Rana boylei*	R,M,Up	Uncommon
Pacific tree frog	*Hyla regilla*	R,M,Up,Ag	Common
Western spadefoot toad	*Scaphiopus hammondi*	R,M,Up,Ag,Ur	Common
Western toad	*Bufo boreas*	R,M,Up,Ag,Ur	Common
Tiger salamander	*Ambystoma tigrinum*	R,M,Up	Uncommon
Yellow-eyed salamander	*Ensatina escholtzi xanthoptica*	R,M,Up	Occasional
California slender salamander	*Batrachoceps attenuatus*	Up	Occasional
Pacific giant salamander	*Dicamptodon ensatus*	R,M	Occasional
Arboreal salamander	*Aneides lugubris*	Up	Uncommon
California newt	*Taricha torosa*	R,M,Aq	Common
Rough-skinned newt	*Taricha granulosa*	R,M,Aq	Occasional

Bullfrogs have supported sport and commercial fisheries in the Central Valley, but populations have declined since the 1960's (Treanor 1983). Bullfrogs enter hibernation as late as November and emerge as early as February (Treanor 1983).

Most reptiles of the delta (Table 7) are somewhat restricted to upland or agricultural habitats. The only common aquatic reptiles are western pond turtles (*Clemmys marmorata*, abundant), the western aquatic garter snakes (*Thamnophis couchi*, occasionally found in the delta), and giant garter snakes (*Thamnophis couchi gigas*, listed as threatened by the California Department of Fish and Game). Reptiles are the only animal group in the delta with no successfully introduced species, although occasional red-eared sliders (*Chrysemys picta*) are found as a result of the release of pet turtles.

Table 7. Reptiles of the Sacramento-San Joaquin Delta.

Common name	Scientific name
Pacific pond turtle	*Clemmys marmorata*
Western fence lizard	*Sceloporus occidentalis*
Side-blotched lizard	*Uta stansburiana*
Coast horned lizard	*Phrynosoma coronatum*
Western skink	*Eumeces skiltonianus*
Gilbert's skink	*Eumeces gilberti*
Western whiptail	*Cnemidophorus tigris*
Southern alligator lizard	*Gerrhonotus multicarinatus*
Northern alligator lizard	*Gerrhonotus coeruleus*
California legless lizard	*Anniella pulchra*
Rubber boa	*Charina bottae*
Ringneck snake	*Diadophis punctatus*
Sharp-tailed snake	*Contia tenuis*
Racer	*Coluber constrictor*
Coach whip	*Masticophis flagellum*
Striped racer	*Masticophis lateralis*
Alameda striped racer	*Masticophis lateralis euryxanthus*
Common kingsnake	*Lampropeltis getulus*
Common garter snake	*Thamnophis sirtalis*
Western terrestrial garter snake	*Thamnophis elegans*
Western aquatic garter snake	*Thamnophis couchi*
Giant garter snake	*Thamnophis couchi gigas*
Western rattlesnake	*Crotalis viridis*

CHAPTER 8. MAMMALS

Fifty-two mammal species are reported in the Sacramento-San Joaquin Delta (U.S. Army Corps of Engineers 1979; Table 8) although others in neighboring areas (Trapp et al. 1984) can be expected as rarities.

8.1 FUNCTIONAL ROLES IN DELTA COMMUNITIES

8.1.1 Herbivores

Mammalian herbivores may be of major importance in wetland and riparian habitat because of their consumption of plant material, effects on vegetation structure, and disturbance of the physical environment. The introduced muskrat (*Ondatra zibethicus)* and, to a lesser extent, the beaver (*Castor canadensis)* are particularly important because of their size and abundance.

The muskrat is found in most aquatic habitats, including marshes, ponds, lakes, riparian communities, and ditches (Wilner et al. 1980; Perry 1982). Muskrats are opportunistic herbivores, feeding on a variety of aquatic and terrestrial plants. They use burrows in banks, and if sufficient emergent aquatic vegetation is present, they build nests and feeding platforms of floating vegetation. Like those of the beaver, the entrances of muskrat

Table 8. Mammals of the Sacramento-San Joaquin Delta and their distributions within habitat types. From U.S. Army Corps of Engineers 1979. Asterisks indicate species dependent on riparian or wetland habitats. A # indicates species whose occurrence in the delta is marginal, either because preferred habitat is lacking or the species is at the edge of its range. FE=Fed. Endangered. SE=State Endangered. ST=State Threatened. [1]Federal candidate species. Habitat abbreviations: Aq=Aquatic, Ag=Agricultural, M=Marsh, R=Riparian, Up=Upland, and Ur=Urban.

Common name	Species	Habitat	Abundance
Opossum*	*Didelphis virginianus*	R,Up,Ag	Common
Trowbridge shrew#	*Sorex trowbridgei*	R,Up	Common
Vagrant shrew*	*Sorex vagrans*	R,M,Up,Ag	common
Ornate shrew*	*Sorex ornatus*	R,Up,Ag	Occasional
Suisun shrew*#[1]	*Sorex suisunensis*	R,M,Ag	Occasional
Broad-handed mole#	*Scapanus latimanus*	R,M,Up,Ag	Occasional
Little brown myotis#	*Myotis lucifugis*	R,M,Up,Ag,U	Occasional
Fringed myotis#	*Myotis thysanodes*	R,M,Up,Ag,U	Occasional
Long-eared myotis#	*Myotis evotis*	R,M,Up,Ag,U	Occasional
California myotis	*Myotis californicus*	Up,U	Common
Yuma myotis	*Myotis yumanensis*	R,M,Up,Ag,U	Common

(Continued)

Table 8. (Concluded)

Common name	Species	Habitat	Abundance
Long-legged myotis#	*Myotis volans*	Up,U	Occasional
Silvery-haired bat#	*Lasionycteris noctivagans*	R,M,Up,Ag,U	Occasional
Western pipistrelle	*Pipistrellus hesperis*	R,M,Up,Ag,U	Common
Red bat	*Lasiurus borealis*	R,M,Up	Common
Big brown bat	*Eptesicus fuscus*	R,M,Up,Ag,U	Common
Hoary bat	*Lasiurus cinereus*	R,M,Up	Common
Townsend's big-eared bat	*Plecotus townsendi*	Up,U	Uncommon
Pallid bat	*Antrozous pallidus*	R,M,Up,Ag,U	Occasional
Brazilian free-tailed bat	*Tadardida braziliensis*	Up,U	Occasional
Black-tailed jackrabbit	*Lepus californicus*	R,Up,Ag	Common
Audubon cottontail	*Sylvilagus audoboni*	R,Up,Ag	Common
Brush rabbit	*Sylvilagus bachmani*	Up	Occasional
Calif. ground squirrel	*Spermophilus beecheyi*	R,Up,Ag	Common
Western gray squirrel*	*Sciurus griseus*	R,Up	Occasional
Valley pocket gopher	*Thomomys bottae*	R,Up,Ag,U	Common
Heermann kangaroo rat	*Dipodomys heermanni*	Up, Ag	Uncommon
San Joaquin pocket mouse	*Perognathus inornatus*	Up,Ag	Uncommon
Beaver*	*Castor canadensis*	R,M,Aq	Common
Western harvest mouse	*Reithrodontymus megalotis*	R,M,Aq	Common
Salt marsh harvest mouse*# FE SE	*Reithrodontymus raviventris*	R,M	Uncommon
California mouse	*Peromyscus californicus*	R,Up,Ag,U	Occasional
Deer mouse	*Peromyscus maniculatus*	R,M,Up,Ag,U	Common
Brush mouse	*Peromyscus boylei*	Up	Occasional
Dusky-footed woodrat	*Neotoma fuscipes*	R,M,Up	Common
California vole	*Microtus californicus*	R,M,Up,Ag	Common
Muskrat*	*Ondatra zibethicus*	R,M,Aq	Common
Norway rat (introduced)	*Rattus norvegicus*	R,M,Up,Ag,U	Common
Black rat (introduced)	*Rattus rattus*	Up,Ag,U	Common
House mouse (introduced)	*Mus musculus*	R,Up,Ag,U	Common
Coyote	*Canis latrans*	Up	Occasional
Gray fox*	*Urocyon cinereoargenteus*	Up	Occasional
Red fox	*Vulpes fulva*	Ag, Up	Uncommon
San Joaquin kit fox# FE ST	*Vulpes macrotus*	Up	Uncommon
Bobcat	*Lynx rufus*	R,Up	Occasional
Raccoon*	*Procyon lotor*	R,Up	Common
Ringtail*	*Bassariscus astutus*	R,M,Up	Uncommon
Longtailed weasel	*Mustela frenata*	R,M,Up,Ag	Occasional
Mink*	*Mustela vison*	R,M,Aq,Up,Ag	Common
Badger	*Taxidea taxis*	Up	Occasional
Spotted skunk	*Spilogale putorius*	R,M,Up	Occasional
Striped skunk	*Mephitis mephitis*	R,M,Up,Ag	Common
River otter*	*Lutra canadensis*	R,M,Aq	Common
Black-tailed deer	*Odocoileus hemionus*	R,Up,Ag	Common

burrows may be below water level, making detection of burrow systems difficult. Muskrat feeding and nesting create openings in wetland vegetation which have been shown to attract other wildlife species, including waterfowl, in some areas (Weller and Frederickson 1974; Weller 1981). Muskrats may attain high population densities, and during these times, harvesting of food plants and nesting material may remove a significant fraction of the plant biomass. These "eat-outs" (Lynch et al. 1947; Weller 1981; Perry 1982) may require several years before recovering. Such dramatic effects on vegetation structure appear to be lacking in the delta, perhaps because the delta lacks extensive marsh vegetation, and much of the habitat used by muskrats is discontinuous.

Beavers prefer water with slow-to-moderate flows and access to appropriate foods. They have been described as "choosy generalists" (Jenkins and Busher 1979), since they eat various foods depending on availability, but have definite preferences among the available plant species. They eat a variety of aquatic and woody riparian plants, the latter primarily in winter (Jenkins and Busher 1979; Hill 1982). Leaves, roots, or bulbs of aquatic plants may be eaten. In the delta, beavers eat roots, bulbs, grasses, cattails, tules, and the bark and twigs of woody riparian plants (Grinnell et al. 1937; Tappe 1942). Among the woody plants, beaver prefer (in decreasing order) cottonwood, willow, and alder (Skinner 1972). Grinnell et al. (1937) found that cattail stalks and willow bark were the most common diet items in fall and winter. Beaver denning habits depend on habitat type. In large lowland waterways, such as the delta, flows are extremely variable, and beavers reside in burrows rather than constructing lodges and dams. Tappe (1942) suggested that levee construction allowed beavers to become more abundant in areas subject to inundation. Areas in the delta with suitable food plants are discontinuous and small. Interviews with trappers (Tappe 1942) suggested that beavers are more transient in delta habitats than in other habitats; this may be related to the distribution of suitable habitat or the lack of dam and lodge construction in delta habitats. Beavers are sensitive to habitat loss (Williams and Kilburn 1984). In the delta, the most significant habitat losses are of aquatic vegetation and woody riparian plants.

Muskrats and beavers affect the physical environment by their burrowing and foraging activities. Both dig extensively for roots and rhizomes of aquatic plants. While digging for such foods, muskrats disturb marsh soils and remove plant structures that stabilize such soils. Extensive digging, which can occur during population highs, can result in significant erosion loss of marsh soils (Wilner et al. 1980).

8.1.2 Predators

Several predators in the delta are important consumers. Well-known omnivores, raccoons, opossums, and striped skunks, are common. A wide variety of plant and animal matter, including berries, fruits, insects, small mammals, birds, and carrion are foods for these species. Skunks have been reported as important predators on shoveler and mallard nests (Bellrose 1980). About 20% of cinnamon teal nests in one California study were destroyed, probably by mammalian predators.

Mink *(Mustela vison)* and river otters *(Lutra canadensis)* are carnivores, but are opportunistic in their prey choices. Both are aquatic and feed heavily on aquatic animals. One of the most concentrated river otter populations in the State is just west of the delta in Suisun Marsh. River otters there ate crayfish at all times of the year, with 95% of scats in each month containing crayfish (Grenfell 1978). During the fall and winter, waterfowl became important and were found in 38% of scats. Fish remains were found in 30% of otter scats and were most frequent in winter and spring. There was no evidence of egg predation during waterfowl nesting. Mink also eat a variety of foods, including crayfish and other invertebrates, fish, frogs, small mammals and birds; muskrats are an important food for mink in many areas.

8.2 MAMMALS OF RIPARIAN AND WETLAND HABITATS

About 25% of the mammals found in the delta depend on riparian or wetland habitats (Table 8). They either occur only in this habitat or are rare in other habitats. Suisun shrews (*Sorex suisunensis*) and salt marsh harvest mice were restricted to tidal marsh habitats but may now be found on the managed wetlands of duck clubs. Beavers (*Castor canadensis*), muskrats, mink, and river otters are aquatic, requiring permanent water. Opossums

(*Didelphis virginianus*), raccoons (*Procyon lotor*), and ringtails (*Bassariscus astutus*) use riparian habitats for cover, den sites, and feeding, but also feed in adjacent habitats. Trowbridge, vagrant, and ornate shrews and shrew-moles (*Sorex trowbridgei, S. vagrans, S. ornatus,* and *Neurotrichus gibbsi*) require the moist microhabitats associated with riparian and wetland habitats. The combination of proximity to water, dense vegetation and resulting favorable microhabitats, and variety of available plant foods make riparian and wetland habitats important for many mammals in addition to those dependent on such habitats. Most predators, such as coyotes (*Canis latrans*), skunks (*Spilogale putorius* and *Mephitis mephitis*), and bobcats (*Lynx rufus*) frequent riparian zones for foraging or cover. For the California mammal fauna, a similar proportion, about 25%, depends on riparian habitats (Williams and Kilburn 1984), yet little ecological research has been performed on mammals in California riparian habitats (Trapp et al. 1984).

Little native riparian or marsh habitat remains in the delta, and most native vegetation exists in small, isolated remnants. However, many habitats share enough structural features with riparian habitats that they serve effectively as "riparian surrogates" (Dennis et al. 1984). Levees, ditches, and abandoned land may combine proximity to water with shrubs or trees, providing the vegetation structure favored by many mammals. Riparian surrogates may also serve as important dispersal corridors between true riparian and wetland habitats.

8.3 ECONOMIC VALUES AND COSTS

Damage to levees by burrowing rodents is probably the most significant economic loss caused by delta mammals (Grinnell et al. 1937; California Department of Fish and Game and California Department of Water Resources 1962; Skinner 1972), although they are often blamed for problems arising from the nature of delta soils and levee construction. Muskrats and beavers burrow into the sides of banks and levees, and frequently the entrances to burrow systems are below the water's edge. Such burrows can weaken levees and are a direct source of leaks. California ground squirrels (*Otospermophilus beecheyi*) are also important in terms of their effect on levees (Owings and Borchert 1975; Owings et al. 1977; Daar et al. 1984).

Traditional approaches to levee management involve removal of vegetation in order to inspect the levees. Unfortunately, this practice creates ideal habitat for ground squirrels, which prefer disturbed soils, barren ground, and elevated areas. Daar et al. (1984) suggested that restoration of native riparian vegetation may be an effective means to reduce the impact of burrowing ground squirrels. Pocket gophers (*Thomomys bottae)* avoid frequently flooded areas and peaty soils, but they may be common locally in the delta. Burrows of pocket gophers tend to lie in or close to levees (Miller 1957), making this rodent a source of levee damage. Pocket gophers are active throughout the year, but increase burrowing activity after rainfall (Miller 1948). During hot weather, gophers burrow at greater depths (Howard and Childs 1959).

Several delta mammal species are important furbearers. The most important species are muskrats, beavers, and mink. About 11,000 muskrats, 500 mink, 300 beavers, 200 raccoons, and a few gray fox (*Urocyon cinereoargenteus*) are taken each year in the delta (California Department of Fish and Game and California Department of Water Resources 1962). Although furbearers are economically insignificant at the statewide level, they are important locally in areas like the delta, with its extensive waterways (Scott 1984).

8.4 ENDANGERED OR THREATENED SPECIES

8.4.1 Salt Marsh Harvest Mouse

The salt marsh harvest mouse (*Reithrodontomys raviventris)*, a State and Federal listed endangered species, is found at the extreme western edge of the delta. Chipps, Van Sickle, and Browns Islands and the marshes west of Pittsburg and east of Van Sickle Island provide suitable habitat for this species. Delta harvest mice belong to the race *R.r. halicoetes*. They are usually found in tidal and intertidal salt and brackish marsh habitats, where they prefer areas of dense plant cover, especially *Salicornia*. Recently they have been found in more freshwater marsh habitat, but still in the far west portion of the delta. Harvest mice feed on green vegetation and seeds and are capable of drinking salt water. Shellhammer and Harvey (1982) suggested that ideal habitat conditions include 100% cover, at least 60% of which is

Salicornia about 30-50 cm tall. Harvest mice retreat to higher ground during high water and may inhabit marsh margins if suitable cover is present. Upland marsh edges and peripheral halophytes are thus important habitat components for this species. Pure stands of *Scirpus, Typha, Distichlis*, and *Catula*, often found in disturbed tidal marshes, are poor habitat for harvest mice. The abundance of harvest mice in the delta is unknown. Shellhammer and Harvey (1982) gave capture rates for harvest mice as follows: 77 trap nights/mouse in San Pablo Bay, and 213/mouse in south San Francisco Bay.

8.4.2 San Joaquin Kit Fox

San Joaquin kit foxes (*Vulpes macrotis mutica*) occur marginally in the delta in upland habitats along its southwestern edge. Kit foxes prefer open arid and semi-arid habitats such as alkali scrub and grassland. Loss of such habitat to agriculture has led to the listing of this subspecies as federally endangered and State threatened. Their distribution has contracted, and they now primarily inhabit open foothill habitats. Kit foxes frequently construct their dens by enlarging old ground squirrel burrows.

CHAPTER 9. BIRDS

9.1 HISTORICAL PROCESSES

Birds of the delta (Appendix B) are most commonly either waterfowl or species that normally live in association with human activities. The birds of riparian areas are no longer a significant portion of delta avifauna and have been more extensively studied in upstream areas of the Central Valley.

Before the massive reclamation efforts that began in 1852, when the delta consisted of 600,000-700,000 acres of wetland, the delta was a major nesting area for dabbling ducks (Skinner 1962). For waterfowl generally, it was one of the most significant wintering areas in California (U.S. Fish and Wildlife Service 1978). Reclamation resulted in a decline in waterfowl numbers, due largely to reduction of breeding habitat (Skinner 1962). Now that shallow aquatic habitats are a small part of the delta acreage, other parts of the Central Valley have become more important wintering grounds.

The modern delta is still a waterfowl wintering area of national and international significance (California Department of Fish and Game and California Department of Water Resources 1962), supporting 10% of California's wintering waterfowl (Environmental Systems Research Institute 1979a,b). Of all currently unprotected areas in California, the U.S. Fish and Wildlife Service (1978) ranks the delta as the second most biologically important waterfowl wintering area in the Central Valley, after the Butte Sink. The Yolo Bypass, about half of which is within the delta, is ranked fifth among wintering habitat areas in the Central Valley. Both the delta and Yolo Bypass are ranked high in terms of desirability, potential value, and feasibility for inclusion in the National Wildlife Refuge system. The principal value of the delta to waterfowl is as wintering and migratory habitat. Several threatened and endangered waterfowl species as well as other species associated with riparian woodland are found in the delta.

9.2 WINTERING WATERFOWL

At least 26 waterfowl species are found in the delta, mostly in winter. These include 2 swan species, 4 goose species, and 20 duck species (Rollins 1977). The Central Valley is most important in biological and economic terms to tundra swans (*Cygnus columbianus*), snow geese (*Chen caerulescens*), Ross' geese (*Chen rossii*), greater white-fronted geese (*Anser albifrons*), several races of Canada geese (*Branta canadensis*), northern pintails (*Anas acuta*), mallards (*Anas platyrhynchos*), American wigeons (*Anas americana*), green-winged teals (*Anas crecca*), northern shoveler (*Anas clypeata*), gadwalls (*Anas strepera*), and canvasbacks (*Aythya valisineria*) (U.S. Fish and Wildlife Service 1978). The most important waterfowl species in the delta, as illustrated by midwinter Pacific Flyway aerial survey data for the past six years (Table 9) are tundra swans, greater white-fronted geese, snow geese, Ross' geese, and northern pintails.

For most waterfowl, the wintering season in the Central Valley extends from August and September through April and May (McCaskie et al. 1979). Wintering waterfowl begin arriving in the Central Valley in August, with use peaking in December (Gilmer et al. 1982). In the delta, use by wintering waterfowl is limited early in the season, and most use occurs later in the fall and winter (U.S. Fish and Wildlife Service 1978). Delta band recoveries from white-fronted geese begin in October and peak in early January (Timm and Dau 1979), before the end of the hunting season. White-fronted geese remain in the Central Valley through April (McCaskie et al. 1979). Tundra swans arrive in the delta relatively late in the winter. Bellrose (1980) indicated a peak

Table 9. Relative abundance of waterfowl censused in midwinter flyway census. Ranks based on average number counted during midwinter flyover census over the years 1981 to 1986.

	Census area	
Rank	Delta	Delta and Yolo bypass
1	Northern pintail	Northern pintail
2	Tundra swan	Tundra swan
3	Snow/Ross' goose	Mallard
4	Greater white-fronted goose	Snow/Ross' goose
5	Canvasback	Greater white-fronted goose
6	Mallard	Ruddy duck
7	Ruddy duck	Canvasback
8	Northern shoveler	American wigeon
9	Scaup spp.	Northern shoveler
10	American wigeon	Green-winged teal
11	Green-winged teal	Scaup spp.
12	Canada goose	Canada goose
13	Bufflehead	Cackling Canada goose
14	Ring-necked duck	Bufflehead
15	Cackling Canada goose	Ring-necked duck
16	Gadwall	Gadwall
17	Goldeneye spp.	Redhead
18	Cinnamon teal	Goldeneye spp.
19	Wood duck	Cinnamon teal
20	Redhead	Wood duck

season of December through February and McCaskie et al. (1979) give the peak season as November through March.

The wintering waterfowl of the delta can be considered part of the overall Central Valley population, as predictable and regular movement occurs between the delta and other Central Valley waterfowl areas. These patterns are influenced by, and are dependent on, weather changes, water conditions, food availability, and time of season. The patterns only break down during unusually wet years when flooded habitat increases dramatically, such as when the Yolo Bypass floods (U.S. Fish and Wildlife Service 1978).

Interchange between the delta and Suisun Marsh (the easternmost part of San Francisco Bay) is noteworthy. Waterfowl tend to leave Suisun and move to the delta and other areas when winter rains begin, and relatively large numbers of waterfowl remain at Suisun when winter rains are late. Similarly, large numbers of birds move from Suisun to the delta when leaching of agricultural fields begins (U.S. Fish and Wildlife Service 1978). Corn and other cereal grains grown in the delta have been found in the crops of Suisun Marsh ducks late in the season, possibly indicating that these birds forage in the delta (Michny 1979).

9.2.1 Swans

The delta is the most important wintering area in the Pacific Flyway and Central Valley for tundra swans (U.S. Fish and Wildlife Service 1978; Environmental Systems Research Institute 1979a,b,c), and ranks second only to Chesapeake Bay in the entire United States (Bellrose 1980). The Yolo Bypass is ranked second in the Central Valley (U.S. Fish and Wildlife Service 1978). Bellrose (1980) indicated that 85% of the tundra swans wintering in California can be found in the delta. Eighty-six percent of the flyway population winters in the Central Valley (U.S. Fish and Wildlife Service 1978). Estimates of the number of swans wintering in the delta range from 30,000 to 38,000 (U.S. Fish and Wildlife Service 1978; Bellrose 1980). Between 1981 and 1986 Pacific Flyway midwinter aerial surveys have counted averages of 22,553 and 30,438 swans in the delta swans and Yolo Bypass, respectively. Although populations have declined slightly since 1982, the overall trend since the 1940's has been upward, reflecting better management and environmental policies.

9.2.2 Geese

Eighty-two percent of the flyway population of greater white-fronted geese winter in the Central Valley and about one-third of those are found in the delta. Only the San Joaquin Basin approaches the number of white-fronted geese found in the delta (U.S. Fish and Wildlife Service 1978). Timm and Dau (1979) found that 17% of the white-fronted geese banded on the Yukon-Kuskokwim Delta were recovered in the delta. Based on estimates of the Central Valley population (U.S. Fish and Wildlife Service 1978; Bellrose 1980) and the proportion of

Central Valley white-fronted geese using the delta, between 22,000 and 45,000 white-fronted geese winter in the delta. The average numbers of white-fronted geese counted in the delta in the midwinter aerial surveys from 1981 to 1986 were 15,716 in the delta and 18,782 in the delta and Yolo Bypass. The flyway population is declining (U.S. Fish and Wildlife Service 1978); the decline since the 1950's is over 50% (Timm and Dau 1979).

Since snow geese and Ross' geese are similar in appearance, it is difficult to differentiate the status of each species. The delta accounts for 6%-10% of all white geese in the Central Valley, or about 31,500 birds (McLandress 1979). The Central Valley accounts for 93% and nearly 100% of the flyway populations of snow geese and Ross' geese respectively (U.S. Fish and Wildlife Service 1978). In the 1981-86 Pacific flyway midwinter aerial surveys, an average of 16,536 and 20,968 white geese have been counted in the delta and the Yolo Bypass, respectively.

Difficulties in gaining access to the numerous private islands in the delta have prevented determination of the percentage of white geese in each species (McLandress 1979). However, if the proportions found in the Sacramento and San Joaquin Valleys are applied to the numbers of white geese counted in the delta, 22,000 snow geese, or 7.1% of the Central Valley population, are found in the delta. Based on snow goose band returns, the delta and San Francisco Bay region rank third behind Tule Lake and the Sacramento Valley, but the delta accounts for only 5% of the band returns from the Sacramento Valley (Rienecker 1965). The population of snow geese breeding on Wrangle Island (USSR) has declined due to harsh weather conditions over 6 consecutive years, but other breeding populations wintering in the delta have remained stable (U.S. Fish and Wildlife Service 1978).

If the proportions from McLandress (1979) are applied again, Ross' geese in the delta account for 2%-3% of the white geese in the Central Valley, or about 9,400 birds. The population of Ross' geese appears to have increased, possibly doubling since 1965. However, much of the increase may simply reflect more complete surveys because the Sacramento Valley is now included in post-season surveys (McLandress 1979).

9.2.3 Ducks

Northern pintails are the most numerous waterfowl species found in the delta. The delta supports 10% of the Central Valley pintail population of three million birds, which in turn is 75% of the Pacific flyway wintering population (U.S. Fish and Wildlife Service 1978). Estimates of the numbers of pintails wintering in the delta vary widely, probably a result of varying use in different parts of the season and movement of birds between different areas. Bellrose (1980) estimated the delta population at 600,000, which may have included Suisun Marsh. Michny (1979) gave figures of 200,000-1.4 million from November through January. Pintails appear to concentrate in the delta during these months in response to the food provided by flooded agricultural fields (Michny 1979). In addition, when flooded, the Yolo Bypass sometimes attracts large numbers of pintails. Almost 500,000 pintails were counted in the bypass in January 1973 (U.S. Fish and Wildlife Service 1978). Pintail populations in the delta crashed from 132,515 in January 1981 to 25,985 in January 1982 and 3,385 in 1983. Since then, numbers have steadily increased and in 1987 the estimated number of wintering pintails was 55,670.

Although mallards are usually the second most numerous duck species in the delta, the midwinter flyway survey indicates that mallards are, on average, only one-tenth as numerous as northern pintails. Over the past 7 years, mallard numbers in the delta have followed a pattern similar to that of northern pintails. High populations in 1981 (12,135 birds) crashed to only 1,190 in 1982 and 1,175 in 1983. Steady recovery since then has brought numbers up to 5,700 in 1986 and 5,785 in 1987.

9.2.4 Other Waterfowl

Several other waterfowl species make significant use of the delta. Use of the delta by Canada geese is significantly less than that of the other three goose species. The cackling Canada goose (*Branta canadensis minima*) has been the most numerous of the four subspecies wintering in the Central Valley. During the 1970's the wintering population of the valley was estimated at 52,000 birds, which represented 89% of the flyway population, and about 10% of those wintered in the delta (U.S. Fish and Wildlife Service 1978). Band returns indicate that the delta is intermediate in importance, between the Sacramento and San Joaquin Valleys (Nelson and Hansen 1959). Over the past 6 years the overall abundance of cackling Canada geese has declined, the total Pacific flyway population was estimated to be only 23,000 in 1984. Correspondingly, cackling Canada geese in the delta have declined in abundance, both absolutely and relative to the other subspecies. The other subspecies found in the Central Valley are lesser Canada geese (*B. c. parvipes* and *B. c. taverneri*), and Great Basin Canada geese (*B. c. moffetti*), with wintering populations through the 1970's of 13,500 (13% of the flyway population) and 20,500 (14% of the flyway population) respectively. Populations of lesser Canada geese in the Central Valley appear stable, but they are rarely observed within the delta. Numbers of Great Basin Canada geese appear to be increasing (U.S. Fish and Wildlife Service 1978) and have been by far the most abundant species counted during winter surveys.

The Aleutian Canada goose (*B. c. leucopareia*), an endangered species, visits the delta between October and December. The main wintering area of this subspecies is in the San Joaquin Valley, and small numbers regularly winter a short distance west of the delta at Grizzly Island. The Aleutians on Grizzly Island are known to mix occasionally with those in the San Joaquin Valley (Woolington et al. 1979). The subspecies uses fields in the delta as a feeding and resting stop while en route from the Sutter Buttes area in the Sacramento Valley to their early spring grounds in the San Joaquin Valley (Madrone Associates et al. 1980). Small numbers may winter in the Yolo Bypass (U.S. Fish and Wildlife Service 1978) and the delta (Woolington et al. 1979).

American wigeons are usually the second most numerous wintering ducks in the Central Valley (Rienecker 1976), but the midwinter flyway survey indicates that they are less abundant than mallards in the delta. The Central Valley population is estimated to be 472,000, or 58% of the flyway population (U.S. Fish and Wildlife Service 1978), and the average counts over the past 6 winters have been 611 and 8,494 in the delta and Yolo Bypass, respectively. The wigeons in the delta are part of the larger Central Valley population, which mixes somewhat with the Imperial Valley population (Rienecker 1976). Band returns show that the delta (9.1% of returns) ranks slightly behind the San Joaquin Valley (9.6% of returns) and considerably behind the Sacramento Valley (54.9% of returns) in importance to American wigeons. Wigeons appear to be one of the more numerically stable delta waterfowl (U.S. Fish and Wildlife Service 1978).

Gadwalls, green-winged teals, northern shovelers, canvasbacks, and ruddy ducks (*Oxyura jamaicensis*) also make significant use of the delta. Population estimates, flyway proportion in the Central Valley, and survey results for these species are presented in Table 10. Although the U.S. Fish and Wildlife Service (1978) indicated that the delta supports about 10% of the Central Valley canvasback population, or 3,500 birds, the midwinter flyway survey counts average higher. Populations of this species have varied, with a general increase (U.S. Fish and Wildlife Service 1978). Recent survey data from the delta are also highly variable, ranging from 0 in 1982 to 23,320 in 1983, and a similar but less striking range can be seen in data from the Yolo Bypass. Populations of gadwalls, green-winged teals, and ruddy ducks appear stable; and the numbers of northern shovelers appears to be increasing (U.S. Fish and Wildlife Service 1978).

Cinnamon teals (*Anas cyanoptera*) are generally rare in the United States, and only 1,500 have been estimated to winter in the delta (Bellrose 1980). However, these individuals are more important than they seem because they represent 28% of all cinnamon teals that overwinter in the United States (Bellrose 1980). Very few cinnamon teals are counted in the midwinter flyway survey, and the U.S. Fish and Wildlife Service (1978) indicated that they are present only in small numbers.

Several other species regularly winter in the delta, but their status is poorly understood. Ninety percent of the Pacific Flyway wood duck (*Aix sponsa*) population winter in the Central Valley, but aerial survey data are not reliable for wood ducks (U.S. Fish and Wildlife Service 1978), which are not often counted in the midwinter survey within the delta or Yolo Bypass. One-third of the flyway population of ring-necked ducks (*Aythya collaris*) winter in the Central Valley, but aerial survey data are also not reliable for this species (U.S. Fish and Wildlife Service 1978). Greater and lesser scaup (*Aythya marila* and *A. affinis*) together accounted for an average of 838 birds in the delta during the 1981-86 midwinter flyway survey, with much smaller numbers in the Yolo Bypass. Bufflehead (*Bucephala*

Table 10. Comparison of occurrence in the delta and Yolo bypass by several duck species, compared to their estimated abundance in the Central Valley. Delta and Yolo bypass estimates are averages of midwinter censuses of 1981-86. Flyway and Central Valley estimates from U.S. Fish and Wildlife Service (1978).

Species	Estimated Central Valley population	Central Valley proportion of Pacific flyway	1981-86 Midwinter census averages	
			Delta	Delta with bypass
Ruddy duck	23,000	21%	19.3%	48.6%
Canvasback	35,000	44%	17.2%	30.0%
Green-winged teal	157,750	50%	0 .4%	1.6%
Northern shoveler	572,000	80%	0 .4%	1.1%
Gadwall	16,000	65%	0 .3%	0.6%

albeola) numbers counted in the delta during the midwinter surveys from 1981 to 1986 have ranged from 0 to 350, also with much smaller numbers in the Yolo Bypass. Small numbers of common mergansers (*Mergus merganser*) and other mergansers winter in the delta (U.S. Fish and Wildlife Service 1978).

9.2.5 *Migratory Visitors*

Several waterfowl species are present in the delta for short periods during their migration. Some are present only as irregular visitors, such as tule white-fronted geese (*Anser albifrons elgasi*) (Bauer 1979); others are present more regularly, such as blue-winged teals (*Anas discors*).

9.2.6 *Different Habitat Types Used*

Most of the native wetlands of the delta have been converted to agricultural lands that have become important habitat for wintering waterfowl. The smaller numbers of breeding waterfowl found in the delta are less dependent on agricultural habitats.

In the past 25 years, major crops have shifted from potatoes, asparagus, and tomatoes to corn, sorghum, alfalfa, and pasture grasses (U.S. Fish and Wildlife Service 1978). The new forms of agriculture favor waterfowl and the present large concentrations of waterfowl found in the delta were not present in the earlier part of this century (Michny 1979). Some significant areas of agricultural habitat have been at least temporarily converted to deepwater habitat, of lesser value to wintering waterfowl, by levee breaks and resulting floods (Madrone Associates et al. 1980).

Much of the value of agricultural lands in the delta results from the practice of flooding fields in the winter to leach out salts (Rollins 1977; U.S. Fish and Wildlife Service 1978; Michny 1979). The value of the leached fields to waterfowl can be seen by comparing the species richness (for waterfowl only) found by Rollins (1977) and Madrone Associates et al. (1980). Fields in Rollins' study area in the eastern delta were not flooded, and species richness observed by cover type was as follows: 14 species in marsh, 8 in permanent pasture, 2 in riparian woodland, 1 in nonflooded corn, and 0 in nonflooded asparagus. The bird census areas examined by Madrone Associates were located mostly in the central and western delta, where fields are more often flooded. Observed waterfowl species richness in this study was as follows: 18 species in aquatic habitats, 15 in cultivated habitats, 7 in marsh, 1 in riparian woodland, 1 in riparian brushland, and 0 in upland and developed habitats.

The amount of habitat created by leaching varies yearly depending on the crops grown and on the weather. Lack of leaching during the 1975-77 drought adversely affected waterfowl in the delta.

Corn, probably the most valuable crop to waterfowl, is among the most salt-sensitive crops (Madrone Associates et al. 1980), so corn fields require regular leaching (Rollins 1977). In peat soils, corn fields are leached every 1-3 years, and in more mineral soils leaching occurs every 4-6 years (Rollins 1977). Leaching usually occurs in December and January, coinciding with the peak waterfowl use period. In dry years leaching may begin as early as October (U.S. Fish and Wildlife Service 1978). Salt loads in leaching tailwaters may adversely affect other wildlife and fish, especially in the southern part of the delta (Madrone Associates et al. 1980).

In the delta there are several areas of particularly heavy use by wintering waterfowl. The Yolo Bypass as a whole (including the portion outside the delta) supports about 5% of the Central Valley wintering waterfowl populations, although it is not very important during migration. Crops in the bypass include rice, barley, corn, and sorghum. Large areas of irrigated and dry grazing lands are also present, especially where soils are too alkaline for intensive agriculture. Most managed waterfowl habitat in the bypass is on agricultural lands. Land leveling in the bypass has reduced waterfowl habitat, primarily north of the delta. The Stone Lakes basin, in the east part of the delta, receives up to 1 million waterfowl use days per year. Up to 15,000 birds have been observed here, including 4,200 Canada geese and 1,000 tundra swans. Rice and pasture areas near Farmington and Escalon are also significant (U.S. Fish and Wildlife Service 1978).

Migrating waterfowl benefit from an agricultural practice similar to leaching. Some fields are flooded in the late summer and fall to control Johnson grass (*Sorghum halepense*) and centipedes, thus providing key habitat for migrants (Madrone Associates et al. 1980). Duck clubs on "waste" islands in the western delta are used mainly in the early season by migrants and by wintering birds before agricultural areas are flooded (California Department of Fish and Game and California Department of Water Resources 1962).

The relatively few breeding ducks in the delta are associated primarily with freshwater marsh habitats. Riparian woodland in the delta is essential to the breeding population of wood ducks (Madrone Associates et al. 1980).

9.2.7 Feeding

Waterfowl feeding in the delta is closely tied to agricultural practices. Water quality, especially salinity, in the delta is of great concern for this reason (California Department of Fish and Game and California Department of Water Resources 1962; U.S. Fish and Wildlife Service 1978). Although salinity increases could affect croplands, the existing natural marshes at the west edge of the delta are most vulnerable to salinity changes.

Gilmer et al. (1982) discussed the relationship between waterfowl and agriculture. Encroachment by agriculture is the largest single cause of habitat loss. Rice, and cereal crops in general, benefit some species (e.g., northern pintails and mallards) but do not benefit others preferring native wetland habitats (e.g., gadwalls and shovelers). More intensive agricultural practices, such as laser leveling in rice fields, decrease food availability. Studies are underway to determine the effect of rice-stubble burning on waterfowl food. Waterfowl food supplies are also vulnerable to increased harvesting efficiency. Shifts in crops, which are occurring constantly, could significantly alter the waterfowl carrying capacity of the Central Valley.

Within the delta itself, waterfowl now depend on waste crops for food (Madrone Associates et al. 1980). Corn is the most valuable crop to waterfowl (U.S. Fish and Wildlife Service 1978), and the delta corn crop increased fivefold from 1962 to 1976/77 (Michny 1979). Corn stubble, fallow fields, and plowed fields were found to be the most heavily used areas, especially in the central delta (Madrone Associates et al. 1980). In the early 1950's, before corn became a major crop in the delta, damage to crops was light and confined primarily to rice, barley, and wheat on Jersey, Palm, Holland, and Webb Tracts (Biehn 1951).

In general, geese and swans make the most use of flooded agricultural fields (Madrone Associates et al. 1980). Studies of the food preference of several goose species have shown that geese prefer rice over watergrass (*Echinochloa crusgalli*), but that watergrass is preferred (in order of preference) over milo, alkali bulrush (*Scirpus robustus*), safflower, barley, and lana vetch (*Vicia dasycarpa*). These preferences correlate well with the nutritional value of the grains (McFarland and George 1966). Geese generally feed in early morning and late afternoon, depending in part on weather (Raveling et al. 1972). Geese in the delta may associate in distinct sub-flocks and make continued use of specific feeding areas during the winter (Raveling 1969).

Dabbling ducks also prefer flooded agricultural fields for feeding. Nonflooded agricultural fields are second in importance (Madrone Associates et al. 1980).

Flooded agricultural fields in the delta are considered essential feeding habitat for tundra swans (Madrone Associates et al. 1980). In a study near Stockton, tundra swans were found to feed on waste corn in both flooded and nonflooded fields and on unharvested potatoes (Tate and Tate 1966).

White-fronted geese prefer to feed in open fields (Bauer 1979), especially nonflooded corn fields (Madrone Associates et al. 1980). Flooded fields are also considered to be essential feeding habitat for this species (Madrone Associates et al. 1980). In a natural marsh west of the delta, tule white-fronted geese were found to feed primarily on the tubers of alkali bulrush (Longhurst 1955).

The diet of snow geese shifted from predominantly marsh plants to agricultural plants several decades ago. Most species eat a combination of rice, wheat, and barley grains and young shoots of pasture grasses (Bellrose 1980). In the delta, snow geese have a strong preference for nonflooded corn fields, which are considered essential feeding habitat (Madrone Associates et al. 1980).

Ross' geese share snow geese's preference for nonflooded corn fields, but both flooded and nonflooded corn fields in the delta are considered to be essential feeding habitat for Ross' geese (Madrone Associates et al. 1980).

Northern pintails in the Central Valley feed extensively on barley and rice (Bellrose 1980) and corn and other cereal grains in the delta (Michny 1979). Alkali bulrush may be consumed more readily than corn (California Department of Fish and Game and California Department of Water Resources 1962), but its nutritional value is questionable. In a study of esophageal contents, conducted south of the delta, Connelly and Chesemore (1980) found that the diet of pintails shifted as the season progressed. Early in the season, from September though October, most food eaten was vegetable, predominantly watergrass and swamp timothy (*Heleochloa schoenoides*). Later, from November through February, animal food, mostly adult Chironomids, was eaten the most.

American wigeons have been identified as a key source of crop damage, which has been recorded in lettuce, alfalfa, pasture grasses, and fall-planted barley (Biehn 1951).

9.2.8 Resting

Islands with little hunting pressure are heavily used as resting sites for waterfowl. Several large open-water reservoirs or submerged islands are also heavily used, particularly Frank's Tract, the Clifton Court Forebay, and Bethany Reservoir (U.S. Fish and Wildlife Service 1978). Clifton Court Forebay and Bethany Reservoir appear to have attracted large numbers of waterfowl to the delta since their construction (Michny 1979). Bethany Reservoir, which is not hunted, has been used for resting by up to 250,000 ducks on hunt days. Nonhunting recreational use of Clifton Court Forebay and Frank's Tract reduces use by resting waterfowl (U.S. Fish and Wildlife Service 1978). Resting areas in the delta may be used regularly by subflocks of geese (Raveling 1969).

Flooded agricultural fields are considered essential resting habitat for tundra swans (Figure 43). Small ponds are also used as resting and night roosting areas by this species (Madrone Associates et al. 1980).

During the hunting season, many geese rest in corn fields during the day and feed elsewhere at night (Madrone Associates et al. 1980). White-fronted geese, which prefer open fields for resting (Bauer 1979), prefer to rest in nonflooded corn fields in the delta (Madrone Associates et al. 1980). Both snow and Ross' geese prefer to rest in nonflooded corn fields. In contrast, Canada geese prefer to rest in flooded agricultural fields (Madrone Associates et al. 1980).

Resting northern pintails congregate in large numbers in the Yolo Bypass when it is moderately flooded. These birds move to the bypass from other surrounding waterfowl areas (U.S. Fish and Wildlife

Figure 43. Tundra swans resting in a wintertime agricultural field in Terminous Tract.

Service 1978). In high water years pintails remain on the shallow water of nearby duck clubs and agricultural fields.

9.2.9 Breeding

The relatively few breeding waterfowl in the delta have not yet been studied closely. In Suisun Marsh, a short distance west of the delta, aerial surveys showed mallards, gadwalls, cinnamon teals, ruddy ducks, northern pintails, and northern shovelers to be the most important breeding species (by number of nests). Ground surveys found cinnamon teals, mallards, and gadwalls to be the primary nesting waterfowl (Anderson 1960). Presumably, waterfowl breeding in the delta is also dominated by these species.

9.2.10 Disease and Mortality

Disease and hunting are the major causes of mortality among wintering waterfowl in the delta.

The delta is one of four enzootic foci of avian cholera in California (Titche 1979), and the Central Valley is one of four major enzootic areas of this disease in the United States (Friend 1981, cited by Gilmer et al. 1982). Statewide, waterfowl losses to avian cholera have reached as high as 70,000 birds in one winter (Rosen 1971, cited by Gilmer et al. 1982). Avian cholera among wild waterfowl was first confirmed in California at Bethel Island in the delta. American coots (*Fulica americana*) were affected in this outbreak (Rosen and Bischoff 1949).

In 1948 an avian cholera outbreak that originated at Alviso in the south end of San Francisco Bay spread through the delta where it killed 40,000 waterfowl, including swans (Rosen and Bischoff 1949). In 1965, a small outbreak in the delta near Terminous killed 50 tundra swans. Waterfowl mortality in the delta was estimated at 6,000 birds in the winter of 1977-78 and 3,000 in the 1978-79 winter. During these two seasons, 442 and 68 cholera cases were documented in the delta by necropsy, or 82.6% and 73.9% of the birds necropsied. These percentages were the highest recorded in the State (Titche 1979).

Avian cholera is affected by management decisions (through their effects on habitat conditions), the longevity of the organism, and the presence of carriers. Pond drainage apparently stopped the 1965 outbreak near Terminous (Titche 1979). A rapid flood/drain cycle during the 1976 drought apparently prevented outbreaks (Hunter 1976). A field experiment under marsh conditions in the delta conducted in 1957 showed no residual *Pasturella multocida* (the causative organism) present after 6 months. Known carriers in the delta include muskrats and white-fronted geese (Titche 1979).

Although botulism takes a higher toll on a statewide basis than avian cholera (Hunter et al. 1970), this disease is apparently less prevalent in the delta. During the 1977-78 and 1978-79 seasons, none of the waterfowl from the delta necropsied by Titche (1979) in the first year died of botulism, and only three cases (3% of necropsied birds) were confirmed in the second year.

In the Central Valley, lead poisoning is responsible for 3%-10% of waterfowl deaths. Legislation requiring steel shot was enacted in 1987. The significance of pesticides as a cause of waterfowl mortality in the Central Valley is unknown (Gilmer et al. 1982).

Hunting is a significant cause of waterfowl mortality in the delta. Between 1979 and 1982, an average of 2.5% of the statewide duck harvest, or 52,000 birds, came from the delta. Similarly, the delta accounted for 3.1% of the statewide goose harvest, or an average of 3,650 geese/year between 1979 and 1982 (Bartonek 1983). In the Suisun Marsh, immediately west of the delta, the ducks most commonly harvested are northern pintails, green-winged teals, northern shovelers, American wigeons, mallards, and others (ranked in order of abundance). The geese most commonly harvested in Suisun Marsh are greater white-fronted geese, snow geese, cackling and other Canada geese, and Ross' geese (U.S. Fish and Wildlife Service, unpubl. data). The relative importance of the delta as a waterfowl hunting area is illustrated in Table 11.

Table 11. Waterfowl harvest from delta counties (Contra Costa, Sacramento, San Joaquin, Solano, and Yolo). From Carney (1975).

Species	Percent of statewide harvest
Northern pintail	32%
American wigeon	23%
Northern shoveler	20%
Mallard	18%
Green-winged teal	17%
White-fronted goose	15%
Canada goose	15%
Gadwall	12%
Snow goose	7%
Cinnamon/Blue-winged teal	7%
Wood duck	2%

9.3 OTHER SPECIES OF INTEREST

In addition to Aleutian Canada geese, two other threatened bird species are found in the delta, and a third may also occur there. The black rail (*Laterallus jamaicensis*) is listed as a threatened species by the State of California (California Department of Fish and Game 1980), and is a candidate for Federal listing. This species, more commonly associated with San Francisco Bay wetlands and other coastal wetlands, is known to occur in a marsh near White Slough, San Joaquin County (Manolis 1977; Environmental Systems Research Institute 1979b). Swainson's hawk (*Buteo swainsoni*), also a State-listed threatened species and candidate for Federal listing, nests in the delta (California Department of Fish and Game 1980). The yellow-billed cuckoo (*Coccyzus americanus*), sharing the same status as the previous species (California Department of Fish and Game 1980), is not known to breed in the delta although apparently suitable habitat exists (Madrone Associates et al. 1980).

The California Department of Fish and Game's list of bird species of special concern includes a number of other birds found in the delta (Remsen 1978). These include northern harriers (*Circus cyaneus*), sandhill cranes (*Grus canadensis*), burrowing owls (*Athene cunicularia*), short-eared owls (*Asio flammeus*), yellow warblers (*Dendroica petechia*), and yellow-breasted chats (*Icteria virens*). Sandhill cranes occur in dense flocks near Hog Slough, with 3,000-5,000 birds arriving in the area each fall (Rollins 1977). The patterns of distribution within the delta for the other species have not been described, but may be inferred from their narrow habitat preferences. Northern harriers and yellow-breasted chats are birds of marshes; burrowing owls, short-eared owls, and yellow warblers are found in less disturbed regions of riparian or upland habitat. The restricted occurrence of these habitats within the delta probably mirrors the distributions of these birds.

CHAPTER 10. OVERVIEW

The suitability of the delta for most species varies considerably from year to year. The driving force behind fluctuations in species abundance and reproductive success is primarily meteorological. Winter rainfall and the Sierra snowpack are the main determinants of the quantity of outflow and its duration through the late spring and summer. Dams and reservoirs can decrease flood height and maintain more constant flows through the summer but, especially in the last 10 years, weather has ruled the delta.

Humanity's two greatest impacts on the delta have been the massive alteration of marsh habitats into farmland and the changes in flow pattern within delta channels. Diking, rip-rapping, upstream damming, and pumping are the strongest and most common forms of human disturbance. Dredged, reinforced sloughs decrease residence time of water, reducing phytoplankton productivity and, consequently, zooplankton and fish abundance. Dikes and rip-rapping have removed much of the habitat which would be used by fish for breeding and foraging. Export pumping draws Sacramento River water through the cross-delta channel or up the San Joaquin channel at some times of the year. This influx of cooler, less nutrient-rich water probably reduces productivity of the San Joaquin River, and certainly interferes with the upstream migration of adult anadromous fish and prevents many young fish from reaching more productive areas of the delta. Upstream dams and water diversions have reduced the intrusion of saltwater past Chipps Island for the last 45 years, making the delta more suitable for the many freshwater fishes which have been introduced than for the native species. As more dams permit greater control over waterflow into the delta, there is less flooded vegetation for fish to use for breeding and fewer acres of shallow ponds for wintering waterfowl.

The greatest conflict between natural delta processes and human needs seems to be that human demand on the system is almost independent of the varying amounts of water the system receives. In wet years diversions probably have less impact on most species than in drier years when the continued diversions greatly amplify the effect of meteorological variation. The apparent long term effects of the 1976-77 drought on the timing and pattern of phytoplankton blooms is the most likely candidate for the breakdown of the strong relationship which had existed between striped bass and outflow. The drought may have even coincided with processes which had begun in 1973, or it may have helped shift an unstable system into a new configuration. In any event, unknown factors now limit striped bass reproductive success and make that fishery unpredictable and difficult to manage. Many other species have apparently declined over the same period, but those declines and their effects on the delta community are less known than the changes in striped bass.

At all levels the system is changing, and management's attention will have to focus on the system's future while at the same time addressing long-term studies of its past. Recent declines in delta productivity at all levels from phytoplankton to fish indicate that previous water management policies have been insufficient to protect the delta community. New policies in the determination of outflow through the delta will need to focus on ecological needs in the delta.

Data collected by numerous public agencies are very incompletely described, analyzed, or synthesized in the public literature. Although there is a pressing need to test some of the hypotheses which have been advanced to explain recent changes in the ecosystem; it is even more important to analyze the voluminous data already gathered. Controlling processes may have changed dramatically, but it is futile to pursue answers to new problems when no picture has yet been developed of how the community operated in better times.

The importance of flow regimes on patterns of primary productivity has been only sketchily drawn, and many years of data on flow patterns and algal species abundance and composition need to be analyzed from the records of the U.S. Geological Survey, Bureau of Land Management, and the California Department of Water Resources. Data on zooplankton and fish recruitment are available through the California Department of Fish and Game and the University of California. The connection between primary productivity and productivity at higher levels needs to be demonstrated rather than assumed. Monitoring basic physical, chemical, and biological parameters of delta waters needs to continue, but new research programs are also needed to address such questions as how the ecology of the delta will change as more islands are flooded and what causes mortality in larval fish. Basic questions such as these were raised during the water rights hearings of the California State Water Resources Control Board which began in 1987. The lack of clear answers at that time may have long-term effects on the health of the delta.

Many of the data from State and Federal agencies are now being readied or are regularly entered into STORET, an interagency data base. The widespread availability of these data to the many groups interested in preserving and using the delta bodes well for a blossoming of understanding of all facets of the Sacramento-San Joaquin Delta.

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Appendix A. **Vascular plants of the Sacramento-San Joaquin Delta.**

Common name	Scientific name	Abundance[a]
NON-FLOWERING PLANTS:		
Aspidaceae		
Lady fern	*Athyrium filix-femina*	Common
Equisetaceae		
Horsetail	*Equisetum hyemale*	Undetermined
Pinaceae		
Monterey pine	*Pinus radiata*	Undetermined
Cupressaceae		
Cypress	*Cupressus spp.*	Undetermined
Incense cedar	*Libocedrus decurrens*	Undetermined
DICOTS:		
Aceraceae		
Box elder	*Acer negundo* var. *californicum*	Occasional
Silver maple	*Acer saccharinum*	Uncommon
Aizoaceae		
Hottentot fig	*Mesembryanthemum edule*	Common
Alismataceae		
Broadleaf arrowhead	*Sagittaria latifolia*	Occasional
Amaranthaceae		
Tumbling pigweed	*Amaranthus graecizans*	Common
Anacardiaceae		
Poison oak	*Rhus diversiloba*	Occasional
California pepper	*Schinus molle*	Uncommon
Water hemlock	*Cicuta douglasii*	Occasional
Bolander water hemlock	*Cicuta bolanderi*	Rare
Poison hemlock	*Conium maculatum*	Occasional
Bee thistle	*Eryngium articulatum*	Uncommon
Delta coyote thistle	*Eryngium racemosum*	Uncommon
Fennel	*Foeniculum vulgare*	Common
Cow parsnip	*Heracleum lanatum*	Common
Marsh pennywort	*Hydrocotyle verticillata* var. *triradiata*	Uncommon
Lilaeopsis	*Lilaeopsis masonii*	Rare
Apocynaceae		
Oleander	*Nerium oleander*	Uncommon
Periwinkle	*Vinca major*	Common

(Continued)

Appendix A. (Continued)

Common name	Scientific name	Abundance[a]
Asclepiadacea		
Milkweed	*Asclepius spp.*	Undetermined
Asteraceae		
Yarrow	*Achillea millefolium*	Occasional
Western ragweed	*Ambrosia psilostachya*	Common
Douglas mugwort	*Artemisia douglasiana*	Common
Western mugwort	*Artemisia ludoviciana*	Occasional
Suisun aster	*Aster chilensis* var. *lentus*	Rare
Slender aster	*Aster exilis*	Common
Coyote brush	*Baccharis pilularis* var. *consanguinea*	Common
Mule fat	*Baccharis viminea*	Undetermined
Sunflower	*Balsamorhiza macrolepis*	Rare
Bur marigold	*Bidens laevis*	Common
Yellow star thistle	*Centaurea solstitialis*	Common
Russian knapweed	*Centaura repens*	Undetermined
Needle-leaved rabbit brush	*Chrysothamnus teretifulius*	Uncommon
Slough thistle	*Cirsium crassicaule*	Rare
Bull thistle	*Cirsium vulgare*	Common
Horseweed	*Conyza canadensis*	Undetermined
Common brass buttons	*Cotula coronopifolia*	Uncommon
Cardoon	*Cynara cardunculus*	Undetermined
Eclipta	*Eclipta alba*	Undetermined
Cud weed	*Gnaphalium chilense*	Common
Gum plant	*Grindelia camporum*	Rare
Rosilla	*Helenium puberulum*	Uncommon
Common sunflower	*Helianthus annuus*	Occasional
Spikeweed	*Hemizonia pungens*	Uncommon
Telegraph weed	*Heterotheca grandiflora*	Common
Cat's ear	*Hypochoeris glabra*	Undetermined
Fleshy jaumea	*Jaumea carnosa*	Common
Prickly lettuce	*Lactuca serriola*	Common
Bristly oxtongue	*Picris echioides*	Common
San Francisco lessingia	*Lessingia germanorum*	Occasional
Shrubby butterweed	*Senecio douglasii*	Uncommon
Western goldenrod	*Solidago occidentalis*	Occasional
Sow thistle	*Sonchus sp.*	Occasional

(Continued)

Appendix A. (Continued)

Common name	Scientific name	Abundance[a]
Milk thistle	*Silybum marianum*	Common
Dandelion	*Taraxacum officinale*	Common
Cocklebur	*Xanthium strumarium* var. *canadense*	Occasional
Betulaceae		
White alder	*Alnus rhombifolia*	Occasional
Boraginaceae		
Chinese pusley	*Heliotropium cuassavicum*	Occasional
Bearded allocarya	*Plagiobothrys hystriculus*	Rare
Brassicaceae		
Contra Costa wallflower	*Erysimum capitatum* var. *angustatum*	Rare
Caper-fruited tropidocarpum	*Tropidocarpum capparideum*	Rare
Mustard	*Brassica genicula*	Common
Common yellow mustard	*Brassica campestris*	Common
Perennial peppergrass	*Lepidium latifolium*	Uncommon
Watercress	*Nasturtium officinale*	Undetermined
Wild radish	*Raphanus sativus*	Common
Caprifoliaceae		
Blue elderberry	*Sambucus caerulea*	Occasional
Twinberry	*Lonicera involucrata*	Undetermined
Caryophyllaceae		
Campion	*Silene gallica*	Undetermined
Chenopodiaceae		
Fat-hen	*Atriplex patula*	Occasional
Australian saltbush	*Atriplex semibaccata*	Occasional
Mexican tea	*Chenopodium ambrosioides*	Common
Common pickleweed	*Salicornia pacifica*	Undetermined
Crassulaceae		
Pygmy weed	*Tillaea aquatica*	Undetermined
Euphorbiaceae		
California croton	*Croton californicus*	Occasional
Turkey mullein	*Eremocarpus setigerus*	Occasional
Spotted spurge	*Euphorbia supina*	Occasional
Russian thistle	*Salsola kali*	Common

(Continued)

Appendix A. (Continued)

Common name	Scientific name	Abundance[a]
Convolvulaceae		
Bindweed	*Convolvulus arvensis*	Common
Hedge bindweed	*Convolvulus sepium*	Undetermined
Fabaceae		
Acacia	*Acacia sp.*	Uncommon
Carob	*Ceratonia siligua*	Undetermined
Delta tule pea	*Lathyrus jepsonii* var. *jepsonii*	Rare
Pea	*Lathyrus vestitus*	Undetermined
Lotus	*Lotus corniculatus*	Uncommon
Lotus	*Lotus humistratus*	Uncommon
Spanish clover	*Lotus purshianus*	Common
Deer weed	*Lotus scoparius*	Uncommon
Silver lupine	*Lupinus albifrons*	Uncommon
Lindley's annual lupine	*Lupinus bicolor*	Uncommon
Yellow sweet clover	*Melilotus indica*	Common
White sweet clover	*Melilotus albus*	Common
Black locust	*Robinia pseudoacacia*	Uncommon
Spanish broom	*Spartium junceum*	Uncommon
Winter vetch	*Vicia villosa*	Undetermined
Fagaceae		
Valley oak	*Quercus lobata*	Uncommon
Coast live oak	*Quercus agrifolia*	Common
Alkali heath	*Frankenia grandifolia*	Uncommon
Gentianaceae		
June century	*Centaurium floribundum*	Uncommon
Geraniaceae		
Broad-leaf filaree	*Erodium botrys*	Common
Filaree	*Erodium cicutarium*	Undetermined
Juglandaceae		
Black walnut	*Juglans hindsii*	Rare
English walnut	*Juglans regia*	Occasional
Lamiaceae		
Henbit	*Lamium sp.*	Occasional
Water horehound	*Lycopus americanus*	Uncommon
Mint	*Mentha spp.*	Undetermined
Hedge nettle	*Stachys albens*	Undetermined
Loranthaceae		
Mistletoe	*Phoradendron flavescens*	Undetermined
California loosestrife	*Lythrum californicum*	Uncommon
Horehound	*Marrubium vulgare*	Common

(Continued)

Appendix A. (Continued)

Common name	Scientific name	Abundance[a]
Malvaceae		
Cheeseweed	*Malva parviflora*	Common
California hibiscus	*Hibiscus californicus*	Rare
Alkali mallow	*Sida hederacea*	Undetermined
Moraceae		
Fig	*Ficus carica*	Uncommon
Mulberry	*Morus sp.*	Uncommon
Myrtaceae		
Bottlebrush	*Callistemon sp.*	Uncommon
Eucalyptus	*Eucalyptus sp.*	Occasional
Papaveraceae		
California poppy	*Escholzia californica*	Common
Plantaginaceae		
Plantain	*Plantago hirtella*	Common
English plantain	*Plantago lanceolata*	Common
Platanaceae		
Sycamore	*Platanus racemosa*	Undetermined
Polygonaceae		
Naked-stemmed eriogonum	*Eriogonum nudum*	Uncommon
Water smartweed	*Plantago lanceolata*	Common
Curly dock	*Rumex crispus*	Common
Portulacaceae		
Purslane	*Portulaca oleracea*	Common
Common knotweed	*Polygonum aviculare*	Common
Rosaceae		
Christmas berry	*Heteromeles sp.*	Undetermined
Almond	*Prunus amygdalus*	Uncommon
Pyracantha	*Pyracantha sp.*	Undetermined
California rose	*Rosa californica*	Common
Blackberry	*Rubus vitifolius*	Common
Himalaya berry	*Rubus procerus*	Undetermined
Rubiaceae		
Buttonbush	*Cephalanthus occidentalis*	Occasional
Bedstraw	*Galium trifidum*	Undetermined
Salicaceae		
Silver poplar	*Populus alba*	Undetermined
Fremont's cottonwood	*Populus fremontii* var. *subiflorum*	Occasional
Weeping willow	*Salix babylonica*	Uncommon
Willow	*Salix goodingii*	Common

(Continued)

Appendix A. (Continued)

Common name	Scientific name	Abundance[a]
Sand bar willow	*Salix hindsiana*	Common
Red willow	*Salix laevigata*	Occasional
Arroyo willow	*Salix lasiolepis*	Common
Scrophulariaceae		
Mudwort	*Limosella subulata*	Undetermined
Common monkey-flower	*Mimulus guttatus*	Occasional
Common mullein	*Verbascum thapsus*	Occasional
Speedwell	*Veronica anagallis-aquatica*	Undetermined
Solanaceae		
Tomato	*Lycopersicon esculentum*	Undetermined
Tree tobacco	*Nicotiana glauca*	Uncommon
Small-flowered nightshade	*Solanum nodiflorum*	Undetermined
Tamaricaceae		
Salt cedar	*Tamarix sp.*	Undetermined
Ulmaceae		
Chinese elm	*Ulmus parviflora*	Uncommon
Urticaceae		
Hoary nettle	*Urtica holosericea*	Common
Verbenaceae		
Mat-grass	*Lippia nodiflora*	Uncommon
Vervain	*Verbena bonariensis*	
Vitaceae		
California wild grape	*Vitis californica*	Common
Zygophyllaceae		
Puncture vine	*Tribulus terrestris*	Uncommon
MONOCOTS:		
Cyperaceae		
Sedge	*Cyperus eragrostis*	Common
Sedge	*Cyperus niger* var. *rivularis*	Uncommon
Spike rush	*Heleocharis sp.*	Common
Common tule	*Scirpus acutus*	Common
Southern tule	*Scirpus californicus*	Common
Olney's bulrush	*Scirpus olneyi*	Occasional
Scirpus bulrush	*Scirpus robusta*	Occasional
Hydrocharitaceae		
Brazilian waterweed	*Elodea densa*	Common

(Continued)

Appendix A. (Concluded)

Common name	Scientific name	Abundance[a]
Iridaceae		
Iris	*Iris pseudacorus*	Occasional
Juncaceae		
Baltic rush	*Juncus balticus*	Occasional
Soft rush	*Juncus effusus*	Occasional
Iris-leaved rush	*Juncus xiphiodes*	Occasional
Liliaceae		
Asparagus	*Asparagus officinalis*	Common
Fragrant fritillary	*Fritillaria liliacea*	Rare
Poaceae		
Oats	*Avena sp.*	Common
Ripgut grass	*Bromus rigidus*	Common
Giant reed	*Arundo donax*	Occasional
Bermuda grass	*Cynodon dactylon*	Common
Pampas grass	*Cortaderia selloana*	Common
Salt grass	*Distichlis spicata*	Common
Beardless wild-rye	*Elymus triticoides*	Occasional
Fescue	*Festuca sp.*	Common
Barley	*Hordeum vulgare*	Occasional
Little barley	*Hordeum pusillum*	Occasional
Foxtail	*Hordeum murinum*	Common
Italian wildrye	*Lolium multiflorum*	Common
Colusa grass	*Neostapfia colusana*	Rare
Crampton's orcuttia	*Orcuttia mucronata*	Rare
Knot grass	*Paspalum dilatatum*	Occasional
Canary grass	*Phalaris canariensis*	Common
Common reed	*Phragmites communis*	Common
Rabbitfoot grass	*Polypogon monspeliensis*	Common
Johnson grass	*Sorghum halpense*	Common
Milo	*Sorghum vulgare*	Occasional
Corn	*Zea mays*	Occasional
Pontederiaceae		
Water hyacinth	*Eichornia crassipes*	Common
Typhaceae		
Broad-leaved cat-tail	*Typha latifolia*	Common

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[a] Undetermined abundance indicates that the species presence varies from year to year or reported abundances in the literature disagree with one another or with the experience of local biologists.

Appendix B. Birds of the Sacramento-San Joaquin Delta.

Common name	Scientific name	Abundance	Seasonality[a]
Common loon	*Gavia immer*	Occasional	Migrant
Horned grebe	*Podiceps auritus*	Common	Migrant
Eared grebe	*Podiceps occidentalis*	Common	Migrant
Western grebe	*Aechmophorus nigricollis*	Common	Migrant
Pied-billed grebe	*Podilymbus podiceps*	Common	Resident
White pelican	*Pelecanus erythrorhynchos*	Occasional	Migrant
Double-crested cormorant	*Phalacrocorax auritus*	Common	Migrant
Great blue heron	*Ardea herodias*	Common	Resident
Green-backed heron	*Butorides striatus*	Common	Migrant
Great egret	*Casmerodius albus*	Common	Resident
Snowy egret	*Egretta thula*	Common	Resident
Cattle egret	*Bubulcus ibis*	Uncommon	Migrant
Black-crowned night heron	*Nycticorax nycticorax*	Common	Resident
Least bittern	*Ixobrychus exilis*	Common	Migrant
American bittern	*Botaurus lentiginosus*	Common	Migrant
White-faced ibis	*Plegadis chihi*	Uncommon	Migrant
Whistling swan	*Olor columbianus*	Common	Migrant
Trumpeter swan	*Olor buccinator*	Accidental	Migrant
Canada goose	*Branta canadensis*	Common	Migrant
Greater white-fronted goose	*Anser albifrons*	Common	Migrant
Snow goose	*Chen caerulescens*	Common	Migrant
Ross' goose	*Chen rossii*	Uncommon	Migrant
Mallard	*Anas platyrhynchos*	Common	Resident
Gadwall	*Anas strepera*	Uncommon	Migrant
Pintail	*Anas acuta*	Common	Migrant
Green-winged teal	*Anas crecca*	Common	Migrant
Blue-winged teal	*Anas discors*	Occasional	Migrant
Cinnamon teal	*Anas cyanoptera*	Common	Migrant
American wigeon	*Anas americana*	Common	Migrant
Northern shoveler	*Anas clypeata*	Common	Migrant
Wood duck	*Aix sponsa*	Occasional	Migrant
Redhead	*Aythya americana*	Common	Migrant
Ring-necked duck	*Aythya collaris*	Occasional	Migrant
Canvasback	*Aythya valisineria*	Common	Migrant
Greater scaup	*Aythya marila*	Occasional	Migrant
Lesser scaup	*Aythya affinis*	Occasional	Migrant
Common goldeneye	*Bucephala clangula*	Common	Migrant
Bufflehead	*Bucephala albiola*	Common	Migrant
Ruddy duck	*Oxyura jamaicensis*	Common	Migrant
Hooded merganser	*Lophodytes cucullatus*	Occasional	Migrant
Common merganser	*Mergus merganser*	Common	Migrant
Red-breasted merganser	*Mergus serrator*	Common	Migrant

(Continued)

Appendix B. (Continued)

Common name	Scientific name	Abundance	Seasonality[a]
Turkey vulture	*Cathartes aura*	Common	Resident
White-tailed kite	*Elanus leucurus*	Common	Resident
Sharp-shinned hawk	*Accipiter striatus*	Common	Resident
Cooper's hawk	*Accipiter cooperii*	Occasional	Resident
Red-tailed hawk	*Buteo jamaicensis*	Common	Migrant
Red-shouldered hawk	*Buteo lineatus*	Common	Migrant
Swainson's hawk	*Buteo swainsoni*	Uncommon	Undetermined
Migrant rough-legged hawk	*Buteo lagopus*	Uncommon	Migrant
Ferruginous hawk	*Buteo regalis*	Occasional	Migrant
Golden eagle	*Aquila chrysaetos*	Uncommon	Migrant
Bald eagle	*Haliaetus leucocephalus*	Uncommon	Migrant
Northern harrier	*Circus cyaneus*	Common	Resident
Prairie falcon	*Falco mexicanus*	Uncommon	Resident
Peregrine falcon	*Falco peregrinus*	Uncommon	Migrant
Merlin	*Falco columbarius*	Uncommon	Migrant
American kestrel	*Falco sparverius*	Common	Resident
California quail	*Lophortyx californicus*	Common	Resident
Ring-necked pheasant	*Phasianus colchicus*	Common	Resident
Sandhill crane	*Grus canadensis*	Common	Migrant
Virginia rail	*Rallus lamicola*	Common	Migrant
Sora rail	*Porzana carolina*	Common	Migrant
California black rail	*Laterallus jamaicensis*	Rare	Migrant
Common gallinule	*Gallinula chloropus*	Common	Resident
American coot	*Fulica americana*	Common	Resident
Semipalmated plover	*Charadrius semipalmatus*	Common	Migrant
Killdeer	*Charadrius vociferus*	Common	Resident
Mountain plover	*Charadrius montana*	Occasional	Migrant
Black-bellied plover	*Pluvialis squatarola*	Common	Migrant
Common snipe	*Capella gallinago*	Common	Migrant
Long-billed curlew	*Numenius americanus*	Common	Migrant
Whimbrel	*Numenius phaeopus*	Common	Migrant
Spotted sandpiper	*Actitis macularia*	Common	Migrant
Solitary sandpiper	*Tringa solitaria*	Common	Migrant
Greater yellowlegs	*Tringa melanoleuca*	Common	Migrant
Lesser yellowlegs	*Tringa flavipes*	Occasional	Migrant
Least sandpiper	*Calidris minutilla*	Common	Migrant
Dunlin sandpiper	*Calidris alpina*	Occasional	Migrant
Western sandpiper	*Calidris mauri*	Common	Migrant
American avocet	*Recurvirostra americana*	Common	Migrant
Black-necked stilt	*Himantopus mexicanus*	Common	Resident
Wilson's phalarope	*Steganopus tricolor*	Uncommon	Migrant
Northern phalarope	*Lobipes lobatus*	Uncommon	Migrant
Glaucous-winged gull	*Larus glaucescens*	Common	Migrant
Long-billed dowitcher	*Limnodromus scolopaceus*	Common	Migrant

(Continued)

Appendix B. (Continued)

Common name	Scientific name	Abundance	Seasonality[a]
Western gull	*Larus occidentalis*	Common	Resident
Herring gull	*Larus argentatus*	Common	Migrant
California gull	*Larus californicus*	Common	Migrant
Ring-billed gull	*Larus delawarensis*	Common	Migrant
Bonaparte's gull	*Larus philadelphis*	Common	Migrant
Forster's tern	*Sterna forsteri*	Common	Migrant
Caspian tern	*Sterna caspia*	Common	Migrant
Black tern	*Chlidonias niger*	Common	Migrant
Band-tailed pigeon	*Columba fasciata*	Occasional	Undetermined
Migrant Rock pigeon	*Columba livia*	Common	Resident
Mourning dove	*Zenaida macroura*	Common	Resident
Barn owl	*Tyto alba*	Uncommon	Resident
Screech owl	*Otus asio*	Common	Resident
Great horned owl	*Bubo virginianus*	Common	Resident
Burrowing owl	*Athene cunicularia*	Common	Resident
Long-eared owl	*Asio otus*	Common	Resident
Short-eared owl	*Asio flammeus*	Common	Migrant
Poor-will	*Phalaenoptilus nuttallii*	Common	Migrant
Lesser nighthawk	*Chordeiles acutipennis*	Occasional	Resident
Vaux's swift	*Chaetura vauxi*	Common	Migrant
White-throated swift	*Aeronautes saxatilis*	Common	Migrant
Anna's hummingbird	*Calypte anna*	Common	Resident
Rufous hummingbird	*Selasphorus rufus*	Common	Migrant
Allen's hummingbird	*Selasphorus sasin*	Uncommon	Migrant
Belted kingfisher	*Megaceryle alcyon*	Common	Resident
Common flicker	*Colaptes auratus*	Common	Resident
Acorn woodpecker	*Melanerpes formicivorus*	Common	Resident
Lewis' woodpecker	*Melanerpes lewis*	Common	Resident
Hairy woodpecker	*Picoides villosus*	Common	Resident
Downy woodpecker	*Picoides pubescens*	Common	Resident
Western kingbird	*Tyrannus verticalis*	Common	Migrant
Ash-throated flycatcher	*Myiarchus cinerascens*	Occasional	Migrant
Black phoebe	*Sayornis nigricans*	Common	Resident
Say's phoebe	*Sayornis saya*	Common	Migrant
Willow flycatcher	*Empidonax traillii*	Common	Migrant
Western wood pewee	*Contopus sordidulus*	Common	Migrant
Olive-sided flycatcher	*Nuttallornis borealis*	Occasional	Migrant
Horned lark	*Eremophila alpestris*	Common	Resident
Barn swallow	*Hirundo rustica*	Common	Migrant
Cliff swallow	*Petrochelidon pyrrhonota*	Occasional	Migrant
Violet-green swallow	*Tachycineta thalassina*	Occasional	Migrant
Tree swallow	*Iridoprocne bicolor*	Occasional	Migrant
Bank swallow	*Riparia riparia*	Common	Migrant
Rough-winged swallow	*Stelgidopteryx ruficollis*	Occasional	Migrant

(Continued)

Appendix B. (Continued)

Common name	Scientific name	Abundance	Seasonality[a]
Scrub jay	*Aphelocoma coerulescens*	Common	Resident
Yellow-billed magpie	*Pica nutalli*	Common	Resident
Yellow-bellied sapsucker	*Sphyrapicus varius*	Common	Resident
Common raven	*Corvus corax*	Common	Resident
Common crow	*Corvus brachyrhynchos*	Common	Resident
Plain titmouse	*Parus inornatus*	Occasional	Resident
Bushtit	*Psaltriparus minimus*	Common	Resident
White-breasted nuthatch	*Sitta carolinensis*	Common	Resident
Wrentit	*Chamaea fasciata*	Common	Resident
House wren	*Troglodytes aedon*	Common	Migrant
Winter wren	*Troglodytes troglodytes*	Uncommon	Resident
Bewick's wren	*Thryomanes bewickii*	Common	Resident
Marsh wren	*Cistothorus palustris*	Common	Migrant
Mockingbird	*Mimus polyglottos*	Common	Resident
Sage thrasher	*Oreoscoptes montanus*	Uncommon	Migrant
American robin	*Turdus migratorius*	Common	Resident
Varied thrush	*Ixoreus naevius*	Uncommon	Undetermined
Migrant hermit thrush	*Catharus guttata*	Common	Resident
Swainson's thrush	*Catharus ustulata*	Common	Migrant
Western bluebird	*Sialia mexicana*	Common	Resident
Golden-crowned kinglet	*Regulus satrapa*	Common	Migrant
Ruby-crowned kinglet	*Regulus calendula*	Common	Migrant
Water pipit	*Anthus spinoletta*	Common	Migrant
Cedar waxwing	*Bombycilla cedrorum*	Occasional	Migrant
Loggerhead shrike	*Lanius ludovicianus*	Uncommon	Resident
Starling	*Sturnus vulgaris*	Common	Resident
Hutton's vireo	*Vireo huttoni*	Common	Resident
Solitary vireo	*Vireo solitarius*	Occasional	Migrant
Warbling vireo	*Vireo gilvus*	Occasional	Migrant
Orange-crowned warbler	*Vermivora celata*	Occasional	Migrant
Nashville warbler	*Vermivora ruficapilla*	Common	Migrant
Yellow warbler	*Dendroica petechia*	Common	Migrant
Yellow-rumped warbler	*Dendroica coronata*	Common	Migrant
Black-throated gray warbler	*Dendroica nigriscens*	Common	Migrant
Hermit warbler	*Dendroica occidentalis*	Occasional	Migrant
MacGillivray's warbler	*Opororis tolmiei*	Occasional	Migrant
Common yellowthroat	*Geothlypis trichas*	Common	Migrant
Yellow-breasted chat	*Icteria virens*	Common	Migrant
Wilson's warbler	*Wilsonia pusilla*	Common	Migrant
House sparrow	*Passer domesticus*	Common	Resident
Western meadowlark	*Sturnella neglecta*	Common	Resident
Yellow-headed blackbird	*Xanthocephalus xanthocephalus*	Common	Resident

(Continued)

Appendix B. (Concluded)

Common name	Scientific name	Abundance	Seasonality[a]
Red-winged blackbird	*Agelaius phoeniceus*	Common	Resident
Tricolored blackbird	*Agelaius tricolor*	Common	Resident
Brewer's blackbird	*Euphagus cyanocephalus*	Common	Resident
Hooded oriole	*Icterus cucullatus*	Occasional	Migrant
Northern oriole	*Icterus galbula*	Common	Migrant
Brown-headed cowbird	*Molothrus ater*	Common	Resident
Western tanager	*Piranga ludoviciana*	Occasional	Migrant
Black-headed grosbeak	*Pheucticus melanocephalus*	Common	Migrant
Blue grosbeak	*Guiraca caerula*	Occasional	Migrant
Purple finch	*Carpodacus purpureus*	Common	Resident
House finch	*Carpodacus mexicanus*	Common	Resident
American goldfinch	*Carduelis tristis*	Common	Migrant
Lesser goldfinch	*Carduelis psaltria*	Common	Resident
Rufous-sided towee	*Piplio erythropthalmus*	Common	Resident
Brown towee	*Piplio fuscus*	Common	Resident
Savannah sparrow	*Passerculus sandwichensis*	Common	Resident
Grasshopper sparrow	*Ammodramus savannarum*	Common	Migrant
Dark-eyed junco	*Junco hyemalis*	Common	Resident
Chipping sparrow	*Spizella passerina*	Common	Migrant
White-crowned sparrow	*Zonotrichia leucophrys*	Common	Resident
Golden-crowned sparrow	*Zonotrichia atricapilla*	Common	Migrant
Fox sparrow	*Passerella iliaca*	Common	Migrant
Lincoln's sparrow	*Melospiza lincolnii*	Common	Migrant
Song sparrow	*Melospiza melodia*	Common	Resident
Lark sparrow	*Chondestes grammacus*	Common	Resident

[a] Undetermined seasonality indicates that the species presence varies from year to year or that reported abundances in the literature disagree with one another or with the experience of local biologists.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report describes an ecosystem significantly different from other delta ecosystems in North America. The Sacramento-San Joaquin Delta is one of the 60 largest river deltas in the world and is the largest river delta on the west coast. As the hub of California's water system, the delta is of immense municipal, agricultural, and industrial importance. The amount of freshwater that flows through the delta controls the delta's productivity and regulates the life cycles of many of its organisms. The vast estuary of the Sacramento and San Joaquin Rivers is one of the most highly modified and intensively managed estuaries in the world. Biological processes in the delta are obscured by the temporal dynamics of the system. Many of the most significant alterations, such as leveeing, diking, and agricultural practices, are not now recognized as such by most citizens, making conservation and protection of the delta difficult.

17. Document Analysis a. Descriptors

Estuary	Flora
Delta	Fauna
Ecology	

b. Identifiers/Open-Ended Terms

Sacramento-San Joaquin Delta	Estuary management
Deltaic sediments	Agricultural practices
Water system	Human disturbance

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