STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF FISH AND GAME

FISH BULLETIN 133

ECOLOGICAL STUDIES OF THE SACRAMENTO–SAN JOAQUIN ESTUARY

PART I

Zooplankton, Zoobenthos, and Fishes of San Pablo and Suisun Bays, Zooplankton and Zoobenthos of the Delta

Compiled by
D. W. KELLEY

1966

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INTRODUCTION

The Delta Fish and Wildlife Protection Study was organized in 1961 to investigate the effects of future water development on fish and wildlife resources dependent upon the Sacramento-San Joaquin River estuary, and to recommend measures to protect and enhance these resources. The investigations described in this bulletin were designed to answer a number of specific questions relevant to water development plans and also to start us toward an understanding of the estuary's ecology. The bulletin describes the results of about 2 years of collecting and 1 year of analysis on zooplankton, zoobenthos, and fishes of the middle or bay portion of this estuary and on zooplankton and zoobenthos of the upper portion that is known as the Delta.

With one exception, all papers are authored by the individuals who were responsible for the work almost from its inception in 1962. "Fishes Collected in the Carquinez Strait in 1961–1962," is the by-product of a study whose original purpose was to monitor downstream migrating young salmon that had been marked for an experiment of the Marine Resources Branch of the California Department of Fish and Game. Records of the fish collected in the Carquinez Strait during this monitoring program fitted in so well with our description of the estuary that we asked James Messersmith to report on it here.

The investigation of Delta benthos reported upon in the last paper in this bulletin was planned and conducted by Charles Hazel. He had completed most of the data analysis when he left the study. I made some changes in his analysis, revised his original draft extensively, and became his co-author.

Conspicuously absent from this bulletin is a description of our investigation of the fishes of the Delta. Reports of this work are now being completed and will be the subject of a second bulletin to be published in the near future.

The bulletin contains no reference to the practical application of the results of our investigations. To date this practical application has been the development and acceptance of a water plan for the estuary that is compatible with all of its uses, including the protection and enhancement of fish and wildlife.

Acknowledgments

Most of the work reported in this bulletin was done under the terms of a contract between the California Departments of Water Resources and Fish and Game. It was financed with funds made available under the California Water Bond Act. Insofar as I know, it is the first time that those who will eventually profit by water development have paid for the intensive investigations needed to protect fish and wildlife resources dependent upon that water.

Much of the description of physical conditions that will be used in the individual papers of this bulletin were provided by engineers of the Delta Studies Section of the California Department of Water Resources. Especially we thank Gerald Cox, Cyril McRae, John Nelson, and Glenn Twitchell. Langdon Owen was especially helpful in arranging matters so engineers and biologists could effectively cooperate.

The work in the bay could not have been done except for "Duke" Mitchell and the crew of the Department of Fish and Game research vessel *Nautilus*.

Fish and Game Assistants Bob Kerr, Elvn Gunderson, and Don Severns kept the other boats running and spent many unrewarded hours in the field. Vince Catania's superior knowledge of the estuary was of great value to all of us.

Biologist Larry Radtke often made the collections of fish in the shallow waters of the bay.

A number of students from the University of the Pacific and San Joaquin Delta College in Stockton helped in the field and laboratory. Don Steffa and John Pierce were with us throughout most of the field collection and laboratory analysis.

The work on fishes in the bay was begun by biologist Clark Blunt, Jr., and that on benthos in the Delta by biologist Don Lollock.

All of the illustrations are by Don Wolf.

Mrs. Janet Boranian did much of the laboratory analysis of zooplankton. She and Mrs. Marlene Oehler handled the office work during our study and typed the manuscripts of this bulletin.

John Fitch, John McClurg, Gerald Cox, and George Warner read the entire manuscript and made many helpful suggestions.

Robert L. Jones, Leader of the Delta Fish and Wildlife Study since its inception in 1961, time and time again solved seemingly insoluble administrative problems, and provided encouragement and advice.

To these and to many others who helped, we express our thanks.

D. W. KELLEY, *Research Supervisor*
Delta Fish and Wildlife Study
Stockton, California
September, 1965

DESCRIPTION OF THE SACRAMENTO–SAN JOAQUIN ESTUARY

D. W. KELLEY

The Sacramento and San Joaquin Rivers have a common estuary. These two streams meet in the center of California's central valley to form the Delta (Figure 1). A hundred years ago the Delta was an extensive tidal marsh, but it has been almost entirely reclaimed for agriculture. The Delta now includes about 738,000 acres of land and water, 700 miles of navigable channels, and 30 large, below sea level islands. About 39,000 acres are covered by water.

Some Delta channels are edged with narrow stretches of intertidal marsh but most of them have steep banks of mud or are covered with large cobbles to prevent erosion. They vary in width from a few hundred feet to a mile and are seldom more than 30 to 40 feet deep. In some areas there are small "waste" islands that flood during high tides. These waste islands and levees that surround all Delta channels are covered with an assortment of emergent aquatic plants, grasses, forbs, shrubs, and trees.

Water heading toward the sea from the Delta passes through Suisun Bay, which is merely the wide combination of the Sacramento and San Joaquin Rivers below the Delta. Thirty-six percent of Suisun Bay is flooded by less than 3 feet of water at mean lower-low tide, and at this stage about 3,000 acres of intertidal zone is exposed. Richard Painter (see p. 40) has included a map of the 6-foot contour.

From Suisun Bay the water flows through the 6-mile long and up to 100 feet deep Carquinez Strait into San Pablo Bay. Almost 60 percent of San Pablo Bay's 73,000 acres is less than 6 feet deep at mean lower-low tide. San Pablo Bay has a much more extensive intertidal area than Suisun Bay.

San Pablo Bay water flows into San Francisco Bay and then through the narrow Golden Gate into the Pacific Ocean. The investigations reported on in this bulletin were geographically limited to the upper and middle portions of the estuary—from the Delta through San Pablo Bay. We have not investigated below San Pablo Bay. McCarty *et al* (1962) described south San Francisco Bay, and Storrs, Selleck, and Pearson (1964) described north San Francisco Bay. Gillian (1957) wrote an interesting and useful popular account of the entire bay.

CLIMATE

The estuary has a mild, marine climate. The influence of the sea is modified with increasing distance inland so that Delta summers are a good deal warmer and the winters several degrees colder than those of the bay (Table 1). Water temperatures in the estuary reflect this difference in the climate.

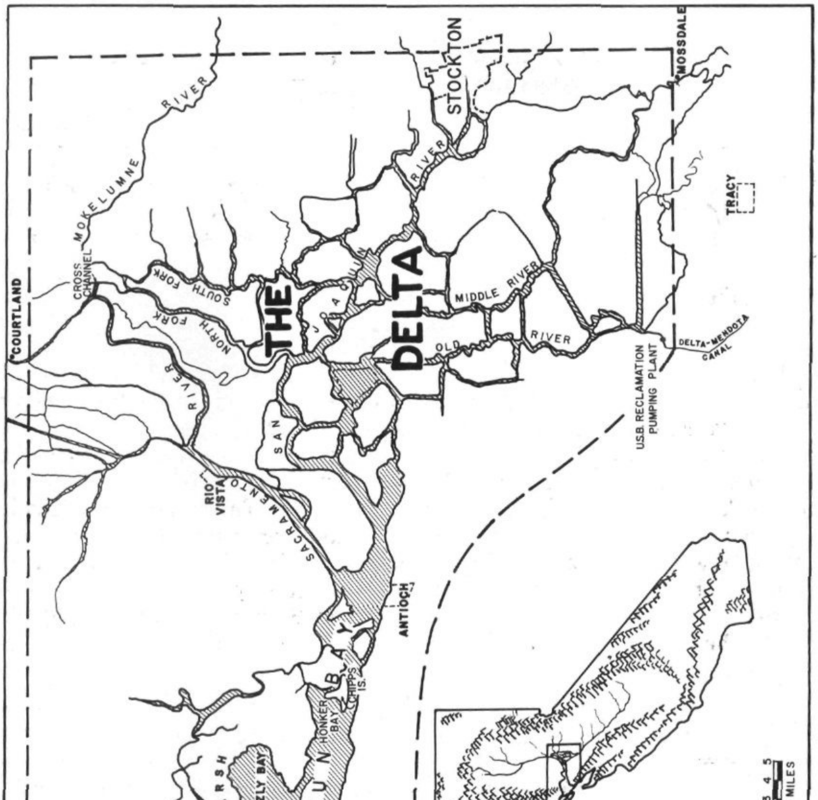

FIGURE 1. Map of the Sacramento-San Joaquin Estuary.

TABLE 1

Comparison of Air Temperature and Rainfall in Bay Area and Delta [1]

	San Francisco on the Bay	Stockton on the Delta
January average temperature	10° C	7° C
July average temperature	15° C	23° C
Maximum temperature on record	38° C	43° C
Minimum temperature on record	−3° C	−8° C
Mean annual precipitation	51 inches	45 inches

[1] Data from U.S. Dept. Agriculture. Yearbook of Agriculture for 1941. Climate and Man, p. 786. U.S. Govt. Printing Office, 1,248 pp.

HYDROLOGY

The runoff from 46,500 square miles of California's land surface drains into the estuary. It enters primarily from three large rivers: the Sacramento, the San Joaquin, and the Mokelumne.

The annual mean amount of fresh water entering the Delta via these streams from 1921 through 1957 was approximately 22 million acre feet (Calif. Dept. of Water Resources, 1962, Table 11). In addition, the estuary receives 14 to 20 inches of rain per year. Most of the river runoff now comes from the Sacramento River and is the result of winter rains in the Sacramento Valley foothill region and the spring melting of the snowpack on the west slope of the Sierra Nevada. The flow in all of these rivers is extremely variable (Table 2).

TABLE 2

Fresh Water Inflow to the Delta During 1963 and 1964 [1]

Month	Mokelumne River		San Joaquin River		Sacramento River	
	1963	*1964*	*1963*	*1964*	*1963*	*1964*
January	826	999	1,754	2,605	18,840	24,400
February	4,195	551	8,185	1,684	55,520	20,500
March	732	152	2,607	795	24,650	13,100
April	0	0	8,616	634	61,710	11,858
May	0	0	9,339	675	43,650	13,940
June	0	0	6,663	602	17,780	10,703
July	0	0	1,822	406	12,320	11,144
August	0	0	1,095	402	11,790	11,806
September	0	0	1,515	832	16,410	13,565
October	96	38	2,588	1,500	13,900	9,919
November	598	108	2,903	2,348	22,206	14,004
December	333	6,928	3,350	6,337	20,410	39,178

[1] Information compiled by Paul L. Skaggs, Delta Studies Section, Calif. Dept. Water Resources. Figures in table are mean monthly flow in cubic feet per second.

Flows are partially controlled with an extensive series of reservoirs throughout the watershed. The summer flows in the Sacramento are increased to repel salinity in the Delta and to furnish water to the U.S. Bureau of Reclamation pumping plant at Tracy. Flows in the San Joaquin and Mokelumne Rivers have been greatly reduced by water diversion for irrigation and municipal uses above the Delta.

Approximately 1.8 million acre feet of fresh water are consumed annually in the Delta by the irrigation of crops and the transpiration of other vegetation (Calif. Dept. Water Resources, 1962, Tables 15 and 19), and about 1.25 million acre feet are pumped out. Most of the latter is taken at the U. S. Bureau of Reclamation pumping plant near Tracy and is limited to the irrigation season.

TIDES

The effect of the tide on water levels throughout the entire estuary has been thoroughly studied (Calif. Division of Water Resources, 1931). The tide here rises and falls twice during a lunar day of about 24.8 hours. Mean tide range is greatest in South San Francisco Bay where it is approximately 6.5 feet, and smallest in the Delta, where it is close to 3 feet (Table 3).

TABLE 3

Surface Area, Volume, and Tidal Ranges in the Sacramento–San Joaquin Estuary[1]

	Surface Area in Acres at Mean Half Tide	Volume in Acre-Feet at Mean Half Tide	Tidal Ranges in Feet	
			Mean High to Mean Low	*Mean High-High to Mean Low-Low*
South San Francisco Bay	72,000	1,300,000	6.5	8.4
North San Francisco Bay	56,960	2,745,000	4.0	5.7
San Pablo Bay	73,100	852,000	4.4	6.1
Carquinez Strait	3,500	186,400	4.4	5.9
Suisun Bay	37,600	408,000	3.9	5.3
Delta	39,300	1,270,000	2.7	3.3

[1] Data for this table were compiled by Gerald Cox and others of the Calif. Dept. Water Resources from a number of the most authentic sources available.

In each lunar day there are two high phases of the tide designated as the high-high and the low-high tides, and two low phases that are called the low-low and the high-low tides. Since the successive tidal phases are only about 6 hours apart, the tide may be rising in the lower part of the estuary and at the same time dropping in the upper part.

The water in Delta channels or in the bay may move 8 miles downstream and back on the ebb and flood of the tide, and as it does, the environment at one location changes markedly. Storrs, Selleck, and Pearson (1964, Appendix B-1) found that a chlorinity change of 6 ‰ was not unusual in San Pablo Bay between the high-high and the low-low tide some 8 hours later. Usually the change is somewhat less in Suisun Bay. Tidal movements of water also subject sessile animals in the Delta to different environmental conditions but, except at the western edge, not to major changes in salinity. Any problems of pollution or dissolved oxygen deficiency move back and forth in a gradually diffusing slug of water in the Delta and can generate puzzling results for those collecting water quality information without reference to the tidal cycle.

CURRENTS

Most of the estuary is subjected to strong currents. Currents in the bay are the result of tides modified largely by wind and to some extent by freshwater outflow. Charts of tidal currents of San Pablo and San Francisco Bay are available from the U. S. Coast and Geodetic Survey in Washington, D. C. These charts show that the currents in the Golden Gate and Carquinez Strait reach 8 feet per second at times. Currents in the main channel of San Pablo Bay sometimes reach 5 feet per second but in the shallow waters of the bay, they seldom exceed more than 1.5 feet per second.

Except for the "dead-end" sloughs, currents in the Delta channels are fairly strong. Velocities of 2.5 feet per second on the ebb flow of the tide are common.

Currents in the Delta are dependent upon tidal movements, river flow, and the operation of the U. S. Bureau of Reclamation's cross channel at Walnut Grove and pumping plant near Tracy (Figure 1). The cross channel diverts Sacramento River water into the channels of the northern Delta. That water flows southward across the San Joaquin, through channels of the south Delta to the pumps on Old River. Beginning in 1955, the U. S. Bureau of Reclamation began to divert large quantities of Sacramento River water into the cross channel, and to pump 3 to 4 thousand cubic feet per second out at Tracy. Each summer this results in a greater than normal net downstream movement of water through the forks of the Mokelumne River and other north Delta channels and a net reversal or upstream movement in Old and Middle Rivers of the south Delta and at times in the main San Joaquin River up to and above Stockton.

Rate and directions of flow and water quality are sometimes changed when the pumps are turned on or off. The changes may have interrupted the normal movements of anadromous fishes (Ganssle and Kelley, 1963), reduced the ability of the north Delta to produce zooplankton (see Turner, p. 97 to 100), and changed the distribution of *Neomysis awatschensis* (see Turner and Heubach, p 106 to 108).

SALINITY

The salinity gradient from fresh to sea water is usually about 50 miles long, extending from the western edge of the Delta to mid-San Francisco Bay. The gradient shortens when the Sacramento and the San Joaquin Rivers are in flood stage and, of course, its location changes as the amount of outflow changes. The mesohaline zone of the "Venice System" of estuarine classification (Reid, 1961; p. 204) moved upstream from San Pablo Bay through Suisun Bay during each of the two summers of our investigations (Figure 2).

Salt water is kept out of the Delta by releases of fresh water from upstream reservoirs in the Sacramento River system during dry summer and fall months.

This is in general a "well-mixed" estuary. Personnel from the Sanitary Engineering Research Laboratory at the University of California, Berkeley, made a large number of measurements relevant to this subject during 1960 through 1963. They found more than 2 to 4 parts per thousand difference in top and bottom salinities only in San Pablo Bay and San Francisco Bay during the late winter and early spring of 1963.

The U.S. Army Corps of Engineers made many measurements of salinity in September 1956 and in February and March 1958 when freshwater inflows from the Delta into the bay were 16,000 and 95,000 cfs respectively. Their measurements show no salinity wedge at the lower flows but a definite one at the higher flows (U.S. Army Corps of Engineers, 1963; Figure 2).

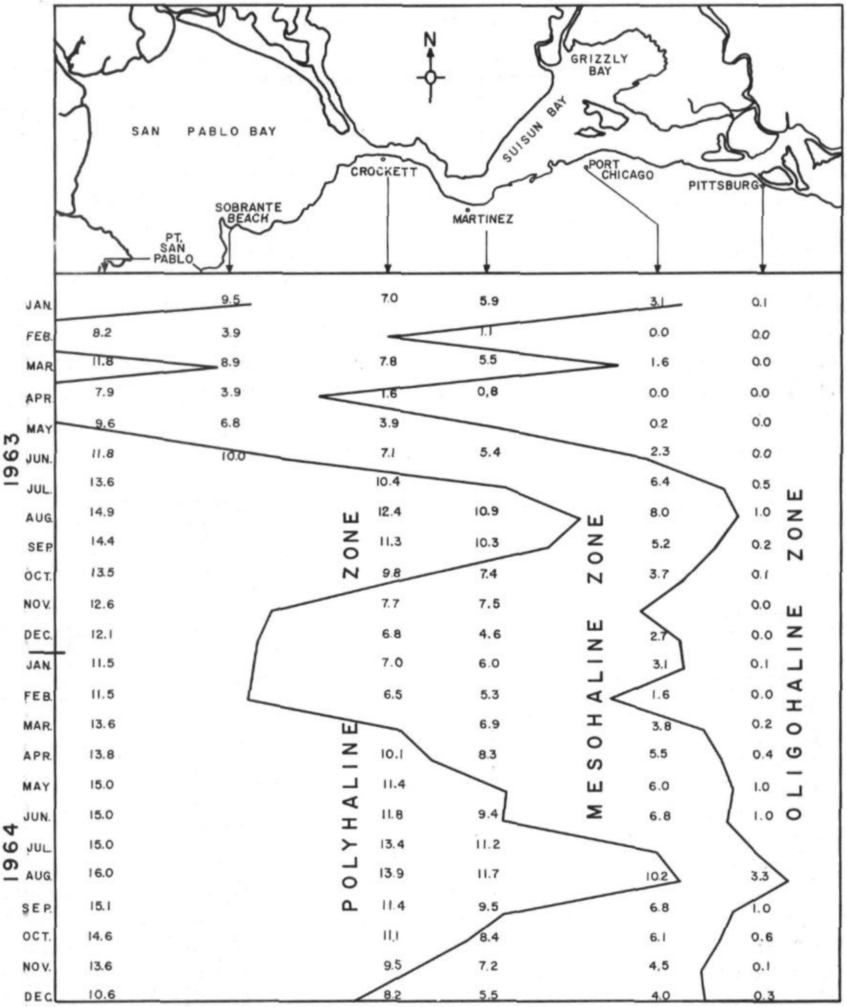

FIGURE 2. Changes in salinity during the study period 1963 and 1964. Figures are parts per million chlorides.

The available evidence is that most of the time the bay is well mixed, but that during periods of flood a tongue of fresh water overlies the saltier water of San Pablo and San Francisco Bays.

There is little vertical stratification in the freshwater channels of the Delta. We have measured water temperature, conductivity and dissolved oxygen concentration of the water column in many channels at many times of the year and rarely found more than slight and temporary differences. Winds, and especially tidal currents, are constantly mixing the waters of each channel and even the so-called ''slack'' water is quiet only on the surface.

WATER QUALITY

Quality of water in this estuary is better than in most estuaries that are surrounded by civilization. Pollution problems do exist in south San Francisco Bay, in the San Joaquin River below Stockton, and in a few other places, but there is no *general* pollution. Dissolved oxygen levels throughout the estuary are usually above 80 percent of saturation. Diurnal fluctuations are seldom large.

Water from the Sacramento and Mokelumne Rivers is soft, with a low dissolved solid content, and water from the San Joaquin River is hard, with a high concentration of total dissolved solids (Table 4). These differences reflect the use that the water from each stream has been put to before it reaches the Delta. The differences are of measurable biological significance.

TABLE 4

Water Quality Characteristics of the Three Main Rivers Entering the Estuary [1]

	Sacramento River at Rio Vista	Mokelumne River at Woodbridge	San Joaquin River at Mossdale
Water temperature in degrees Centigrade	6–26	6–23	7–28
Dissolved oxygen in ppm	5.9–18.8	7.3–13.0	4.4–16.6
pH	6.8– 8.2	6.4– 7.8	6.8– 8.5
Total dissolved solids in ppm	68–204	22–73	58–826
Total hardness as $CaCO_3$ in ppm	40–122	9–32	28–320
Turbidity in ppm	1–600	0–70	0–125
Chlorinity in ppm	3–26	0–7	9–289
Period of sampling	April 1951–Dec. 1961	April 1951–Dec. 1961	Sept. 1952–Dec. 1961

[1] From Quality of Surface Waters in California 1950–61. Calif. Dept. Water Resources, Bulletin No. 65–61, Vol. 1, Part 1, pages 325, 331, 367, August 1963. Ranges shown are maximum and minimum conditions found in grab samples collected monthly for about the last 10 years.

The three kinds of water are mixed by tidal action in the channels of the Delta, and during most of the year the water in a single Delta channel is largely from either the Sacramento or the San Joaquin River. During the summer, the Mokelumne contributes little or nothing. Turner (see p. 100) illustrates the relationship between zooplankton populations and water from the Sacramento, Mokelumne, and San Joaquin River systems as it flows through the Delta channels.

HISTORICAL CHANGES

Extensive reclamation of the Delta tidal marsh began about 1870 and was essentially complete by 1930. Only remnants of the Delta marsh remain today. Some of the tidal marshes adjacent to the bay were also leveed and used for agriculture but as the summer availability of fresh water for irrigation declined, many reverted to marshes and are now used mostly as wintering grounds for waterfowl, and public and private shooting areas. Some intertidal or shallow regions of the bay have been filled for municipal, industrial, or other uses and some of them have been leveed to use as evaporation ponds for salt production.

The inflow of fresh water to the Delta has been considerably altered by the storage of water in many upstream reservoirs and diversion for upstream uses. Flood flows are of less frequency and magnitude in both the Sacramento and San Joaquin River systems. Late summer flows in the Sacramento River have been increased to prevent salinity intrusion into the Delta, but summer flows in the Mokelumne and San Joaquin Rivers have been reduced to insignificant quantities during all but wet years.

Consumptive use of water on lands adjacent to the estuary is probably no greater than that formerly used by the plants of the tidal marsh (Calif. Division Water Resources, 1931), but the mean outflow of fresh water from the Delta to the bay was reduced from 33.6 million acre feet in 1900 to 15.9 million in 1960 (Calif. Dept. Water Resources, 1960).

The position of the salinity gradient in the estuary has been somewhat stabilized by all these changes. Salinities in Suisun Bay are now usually higher than they were under natural conditions, and the invasion of the Delta by salt water during the late summer of dry years is now prevented by the releases of fresh water from upstream storage in the Sacramento River.

In addition to having made many changes in the environment, man has introduced a host of exotic animal and plant species. Most of the fishes that now provide him recreation—striped bass, *Roccus saxatilis*, shad, *Alosa sapidissima*, largemouth bass, *Micropterus salmoides*, and several other centrarchids and the white catfish, *Ictalurus catus*—were introduced years ago and have done very well. The native Sacramento perch, *Archoplites interruptus*, is rare. The tule perch, *Hysterocarpus traski*, is uncommon and the large minnows—the hitch, *Lavinia exilicauda*, the hardhead, *Mylopharodon conocephalus*, the squawfish, *Ptychocheilus grandis*, the Sacramento blackfish, *Orthodon microlepidotus*, and the splittail, *Pogonichthys macrolepidotus*—have been reduced to minority group status.

Skinner (1962) has described the past and present fish and wildlife resources in a review of the historical information.

Two introductions, the carp, *Cyprinus carpio*, and the water hyacinth, *Echornia crassipes*, reported as harmful in other areas have done no extensive damage here.

Recently, the threadfin shad, *Dorosoma petenense*, was introduced. It has become abundant in quiet water of the Delta and is an important food of adult striped bass (Don Stevens, unpublished).

The Asiatic clam, *Corbicula fluminea*, is abundant in some areas. Heavy concentrations of this clam are found in the Delta-Mendota Canal. Tons of these animals are dredged from the canal when it is drained for repairs. A small amount of *C. fluminea* is collected from the Delta and sold as catfish bait.

Over five million people now live around the periphery of the estuary. They use it as a source of municipal, industrial, and irrigation water, a place of recreation, for transportation, and for waste disposal.

Recreational use has increased tremendously in recent years, and although isolated areas are still fairly easy to find, in many places a dozen or more boats are always in sight. Much of the recreational use is sport fishing for striped bass and white catfish. Commercial fishing for salmon, striped bass, shad, and catfish has been outlawed. Only minor commercial fisheries for shrimp, carp, and bait remain.

FUTURE CHANGES

Future changes in the Sacramento-San Joaquin estuary will be the result of increases in human population both here and throughout the state. The population of California is expected to double in 25 years and to quadruple in 50 (U. S. Dept. of Commerce, 1959). The most significant changes for fish and wildlife will be the further reduction of freshwater inflow into the Delta and into the bay, the increase in human waste and agricultural drain water, the changes in hydraulic conditions in the Delta, and the reclamation of the remaining marsh land.

Fortunately the need to protect and improve fish and wildlife resources and the aesthetic qualities of the estuary has clearly been recognized and there can scarcely be any doubt that these uses will be included as part of future plans. The real question is not whether we *want* to protect these resources but whether we *can,* and at the same time make major changes in the environment. There is certainly doubt that this is possible in an old ecosystem whose members have actually evolved to fit the conditions of their environment. Ours is an essentially new ecosystem. The old one has been drastically affected over the last hundred years by major changes in the environment and introductions of exotic animals. Our interest and responsibility lies in learning all we can about the ecology of that system and in using that knowledge for the benefit of man. Fish and wildlife resources of the Sacramento-San Joaquin estuary will depend to a large extent upon how well we do that.

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ZOOPLANKTON OF SAN PABLO AND SUISUN BAYS

RICHARD E. PAINTER

INTRODUCTION

This paper describes the zooplankton of the middle reach of the estuary of the Sacramento and San Joaquin Rivers. The text is based upon 383 plankton samples collected over 12 consecutive months from January through December 1963.

Two copepods, *Acartia clausi* and *Eurytemora affinis,* and the opossum shrimp, *Neomysis awatschensis,* dominated the catch of zooplankton.

The extensive shallow areas of this portion of the estuary were zones of high zooplankton standing crop.

Of the several environmental factors studied, chlorinity was most responsible for species distribution.

METHODS

I collected zooplankton from the main channel of San Pablo and Suisun Bays along the long axis of the estuary, during 1 day each month throughout 1963 (Table 1). A second series of collections over the extensive shallow water "flats" of both bays required several days each month because many of the stations were intertidal and could be sampled only near high tide. Most collections were made close to the middle of each month.

Collection Procedure

In the deep water channel there were no fixed stations. The location of sampling each month depended on the location of the chlorinity gradient from fresh to sea water.

Collections were made with three Clarke-Bumpus samplers fitted with number 10 bolting cloth. One sampler was towed near the surface,

TABLE 1

Plankton Collection Schedule, 1963

Dates on Which Plankton Were Sampled During the Survey

Month	Deep Channel	Shallow Flats: *San Pablo Bay*	*Grizzly Bay*	*Honker Bay*
January	23	22, 23	not sampled	28
February	19	18	21	25
March	20	23	26	26
April	17	22	19	19
May	17	16	20	21
June	16	24	18	17
July	15	18	17	17
August	14	not sampled	16	15
September	11	14	13	12
October	10	19	18	17
November	12	15	14	13
December	10	13	12	11

one at 15 feet from the surface, and another 5 feet from bottom. The procedure was as follows:

1) Sampling from the vessel *Nautilus* started at high-high tide at the western end of San Pablo Bay (Figure 1). The Clarke-Bumpus samplers were fastened to a cable and towed at about 1 knot as the boat moved upstream into the ebbing tide.
2) At the end of 20 minutes, zooplankton sampling ceased and the vessel stopped. Water samples were collected from the surface and 5 feet from the bottom for laboratory analysis of chlorinity and field measurement of temperature.
3) The vessel proceeded up-estuary. The chlorinity of the surface water was measured by hydrometer every 0.5 mile until we reached water with a chloride content of 2 parts per thousand less than that of the previous sample.
4) The three Clarke-Bumpus samplers were again towed upstream for 20 minutes. Surface and deep water samples were again collected.
5) This procedure was repeated as the *Nautilus* moved upstream through the salinity gradient to fresh water. In this way the salinity gradient was thoroughly sampled at seven or more "stations" each month but of course, only the station at the west end of San Pablo Bay was in the same location each month.

To compare the monthly geographic location of plankton concentrations in the tidal estuary, a common tide-stage-reference is needed. Because the vessel *Nautilus* could not travel fast enough between stations to occupy every station at the same tide stage, I corrected the location of all samples from the points where the samples were collected to where that particular mass of water theoretically had been at the last high-high tide. This correction was made by comparing chlorinity gradients supplied by Department of Water Resources engineers and the chlorinities measured from water samples taken during the zooplankton collections.

In contrast with the changing locations of main channel collections, zooplankton collection was done each month at "fixed" stations in the flats of San Pablo Bay and in the Honker and Grizzly Bay portions of

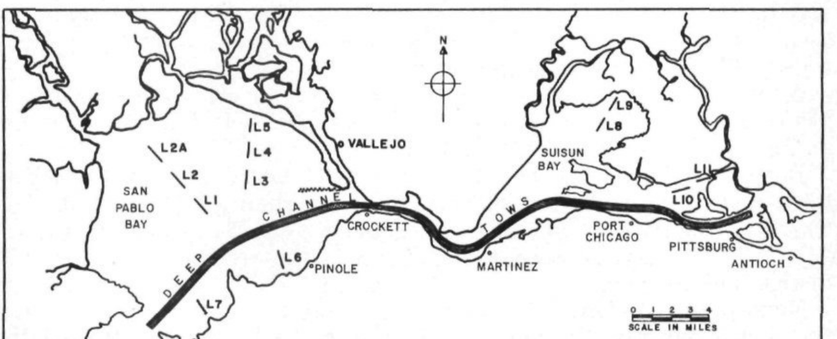

FIGURE 1. San Pablo and Suisun Bay zooplankton collection stations.

Suisun Bay (Figure 1). Each month at every one of these stations I made one, 10-minute surface tow with a Clarke-Bumpus sampler fitted with number 10 bolting cloth.

All zooplankton collections were preserved in 10 percent neutralized (borax) formalin with rose bengal dye added as an organism-coloring agent. To estimate the numbers of net zooplankton per cubic meter of water sampled, a laboratory technician siphoned excess formalin from the quart jar containing field sample, formalin, and rose bengal dye. She poured the remaining contents of the jar into a graduated cylinder and measured the volume of formalin and concentrated organisms. Using a Sedgwick-Rafter counting chamber, she counted the total number of animals in at least 3 cc of this thoroughly mixed concentrate. Numerical abundance was then estimated with the following formula:

$$\text{Number of animals per cubic meter} = \frac{\text{Number of organisms in all cells counted}}{\text{Number of cells counted}} \times \frac{\text{Volume of concentrate in cc}}{\text{Number of cubic meters of water sampled}}$$

The first 100 consecutive organisms counted were identified as specifically as possible, and the percent occurrence of each was applied to the estimate of total numbers to provide an estimate of the number of each species per cubic meter.

CHANNEL ZOOPLANKTON

The concentration of zooplankton in the main channel was high at all times of the year and at all locations sampled (Figure 2). Concentrations ranged from less than 10,000 to more than 500,000 zooplankton per cubic meter. Within this range they were lowest where I began sampling in January, increased to a peak in May, declined some in most areas during June and July, increased again in August, then steadily declined during October, November, and December.

The location of the highest concentration varied during the season with the location of the salinity gradient. It was often centered in that part of the estuary where chlorides ranged from 7 to 10‰.

In the spring when floods and rising temperatures were prevalent, and in the fall and early winter when rapidly falling temperatures occurred, a second center of abundance appeared toward the fresh water end of the chlorinity gradient.

Adult copepods of all species regularly were more abundant in collections made near the bottom of the main channel of both San Pablo and Suisun Bays (Figures 3a and 3d).

Both nauplii and copepodids were usually more abundant in collections made near the bottom of San Pablo Bay channels (Figure 3b, 3c). This was not true of collections from the Suisun Bay channel (Figure 3e, 3f). There was no consistent pattern of these younger stages being distributed according to depth in Suisun Bay.

Two species of Copepoda, *Acartia clausi* and *Eurytemora affinis*, and the mysid shrimp, *Neomysis awatschensis*, made up the bulk of the adult zooplankton. *Cyclops* spp., *Diaptomus novamexicanus*, *Clauso-*

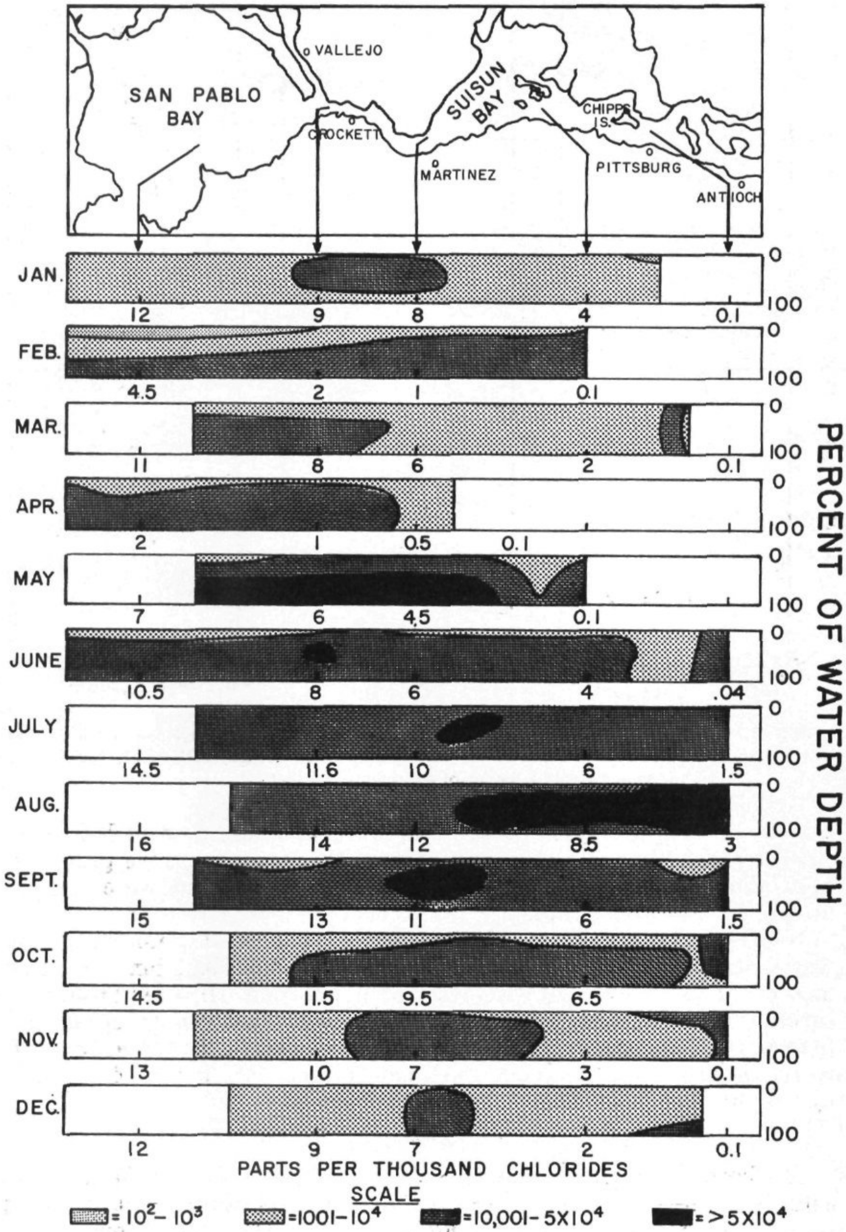

FIGURE 2. Seasonal changes in the distribution and abundance of total net zooplankton in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

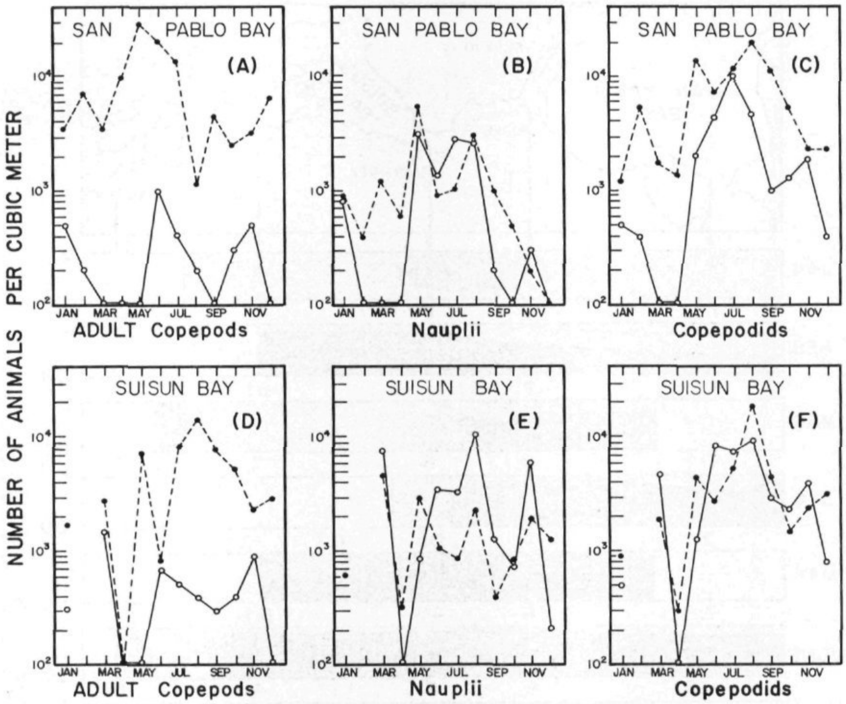

FIGURE 3. Vertical distribution of copepods during the year in the channel of San Pablo and Suisun Bays. Solid lines connect monthly means of all surface collections. Broken lines connect monthly means of collections five feet off bottom.

calanus arcuicornis, *Oithona* sp., and *Euterpina* sp., persisted throughout the survey but were low in numbers. Other species were present or even abundant on occasion, but only the species cited were sampled during most cruises (Table 2).

Monthly changes in population levels, centers of abundance, and distributions by depth and chlorinity of these principal taxa are documented in this paper with isopleths of population densities (Figures 4 through 11). Each isopleth is based on monthly mean numbers of each taxa per cubic meter of water collected from three depths at seven or more stations in the channels. Each monthly isopleth is therefore drawn by graphic interpolation of 21 or more points.

Acartia clausi

The large calanoid copepod, *A. clausi,* was the most abundant species collected in most parts of San Pablo and Suisun Bays. In deep water I took more than 1000 m^3 at most stations and during most months of the year (Figure 4). Highest concentrations appeared in May, June, and July throughout eastern San Pablo Bay, the Carquinez Strait, and western Suisun Bay. During May and June, most of the samples I collected below the surface layer of the study area contained more than 10,000 *A. clausi* per cubic meter of water. The notable

TABLE 2

Zooplankters Collected in the Channel[1]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Annelida												
Polycheata					3			4	3	3	2	2
Arthropoda												
Crustacea												
Branchiopoda												
Alonga gutta				3								
Bosmina sp.		2		3	3					3	2	2
Diphanosoma sp.				2	2	3		3	3	4		
Daphnia pulex				3	2	3			3	3	2	
Leptodora sp.										+		
Cirripeda (nauplii)	4	3	4	3	4	4	5	5	5	5	4	3
Copepoda												
Calanoida												
Acartia clausi	5	5	4	5	5	5	5	5	4	5	4	5
Calanus finmarchicus		3	3	4				3	3			2
Clausocalanus arcuicornis	4	4	3	3			2	2	2	2	3	4
Diaptomus spp.			1	2	3	3	4	4	3	4	3	2
Epilabidocera amphitrites					3		3			3	2	2
Eurytemora affinis	3	5	4	4	5	5	5	5	4	4	4	4
Pseudodiaptomus euryhalinus									3	2		1
Tortanus discaudatus								2				
Cyclopoida												
Corycaeus affinis	3	2		2			3	3	3	3	2	2
Cyclops spp.	3	4	3	4	3	3	4	3	3	3	3	2
Oithona sp.	4	4	3	3	3	3	3		3	2	2	2
Harpacticoida												
Euterpina sp.	3	2	3	3	3	3	3	3	3	3	3	3
Harpacticoid B			3	3	2				2	2	2	
Harpacticoid C			2								1	2
Malacostraca												
Amphipoda												
Corophium spp.		1		1	1	1	+	1	3	1	1	
Photis californica			1	1	+	1	+	+	1	1		
Pontharpinia obtusidens					+							
Isopoda												
Synidotea laticauda		+			+				3	1	+	+
Mysidacea												
Acanthomysis macropsis	+	+	+	+							+	+
Neomysis awatschensis	1	2	2	3	2	3	3	3	3	3	3	3
Cumacea				1								
Decapoda												
Zooea	2	2	3	+	+				3	2	+	2
Crago franciscorum			+	+	+	+	1	+	+	+	+	
Crago nigracauda								+				
Paleomon macrodactylis									+	+	+	
Cheatognatha	1	1	1	1	+	+	+	+	+	1	1	1
Chordata												
Fish larvae/eggs	+	2	2	1	1	2	2	1	1	1	+	1
Acidiacea larvae	4	3	4	3		2			2		3	3
Coelenterata	+	+	+	+	+					+	+	+
Ctenophora		+	+	1	+							
Ectoprocta												
Cyphonautes larvae			3			3	4	3	3	3	3	2
Mollusca												
Gastropoda												
Veliger larvae					2		3	3	3	3	3	2
Lamelibranchia												
Veliger larvae		3			4		3	3	2	3	3	2
Protozoa			3	4	5	5	5	3	5	3	3	
Trochophore larvae	4	3	3	2	3	3	3	4	3	3	3	

[1] Numbers are an index of abundance at the station of greatest occurrence each month. + = present, 1 = 1–10, 2 = 10–100, 3 = 100–1,000, 4 = 1,000–10,000, 5 = >10,000.

exception to otherwise almost universal abundance of *A. clausi* occurred in the Chipps Island reach of Suisun Bay in the winter and spring and in all of Suisun Bay down to the Carquinez Strait in April. This reduction corresponded with the increase in net outflow of fresh water from the Delta and subsequent reduction of chlorinity in the area to less than 2‰.

Eurytemora affinis

Always most abundant near fresh water, *E. affinis* was distributed along the estuary to 6 to 9‰ chloride concentration (Figure 5). In the Suisun Bay portion of the study area, this calanoid copepod was present in substantial numbers in all seasons. Maximum numbers occurred in February in the Chipps Island reach of Suisun Bay when 16,900 animals per cubic meter were enumerated. The only months 100 or more *E. affinis* per cubic meter occurred in San Pablo Bay were February, April, and May. During these months, increased outflow of fresh water moved the 6 to 9‰ chlorides seaward through the Carquinez Strait into eastern San Pablo Bay. Among the entomostraca, this species is second only to *A. clausi* in numbers of animals caught.

Clausocalanus arcuicornis

This calanoid copepod occurred in greatest numbers in the western portion of San Pablo Bay during the winter months (Figure 6). From a January maximum of 1600 per cubic meter, the population level fell to a minimum in May and June when none was counted. Standing crops were low east of the Carquinez Strait during most cruises. Only during January and December did I find 100 or more *C. arcuicornis* per cubic meter as far east as Point Edith in Suisun Bay.

Neomysis awatschensis

The opossum shrimp, *N. awatschensis,* is the most important invertebrate in the diet of young-of-the-year fish (Heubach, Toth, and McCready, 1963; Ganssle, see p. 92). Population levels of 10 or more *N. awatschensis* per cubic meter were associated with chlorinities of 1 to 7 parts per thousand and were confined to Suisun Bay every month except April, a freshwater flood month (Figure 7). Each month standing crops of *N. awatschensis* increased at all depths toward fresh water. Highest population levels were always found in the bottom samples at the freshest water station where 100 to 500 animals per cubic meter were collected each month from June through December.

Euterpina sp.

This harpacticoid copepod was persistent but never very abundant (Figure 8). Excluding flood months when low chlorinity water was in San Pablo Bay, the 100 organisms-per-cubic-meter contour was associated with a chlorinity range of 7.5 to 11.0‰ or a 10-month average of 8.3‰. Every month *Euterpina* sp. was most abundant toward the seaward end of the study area. August, September, and October, the months of maximum chlorinity intrusion into the estuary, were the only months when 100 or more *Euterpina* per cubic meter were sampled in Suisun Bay.

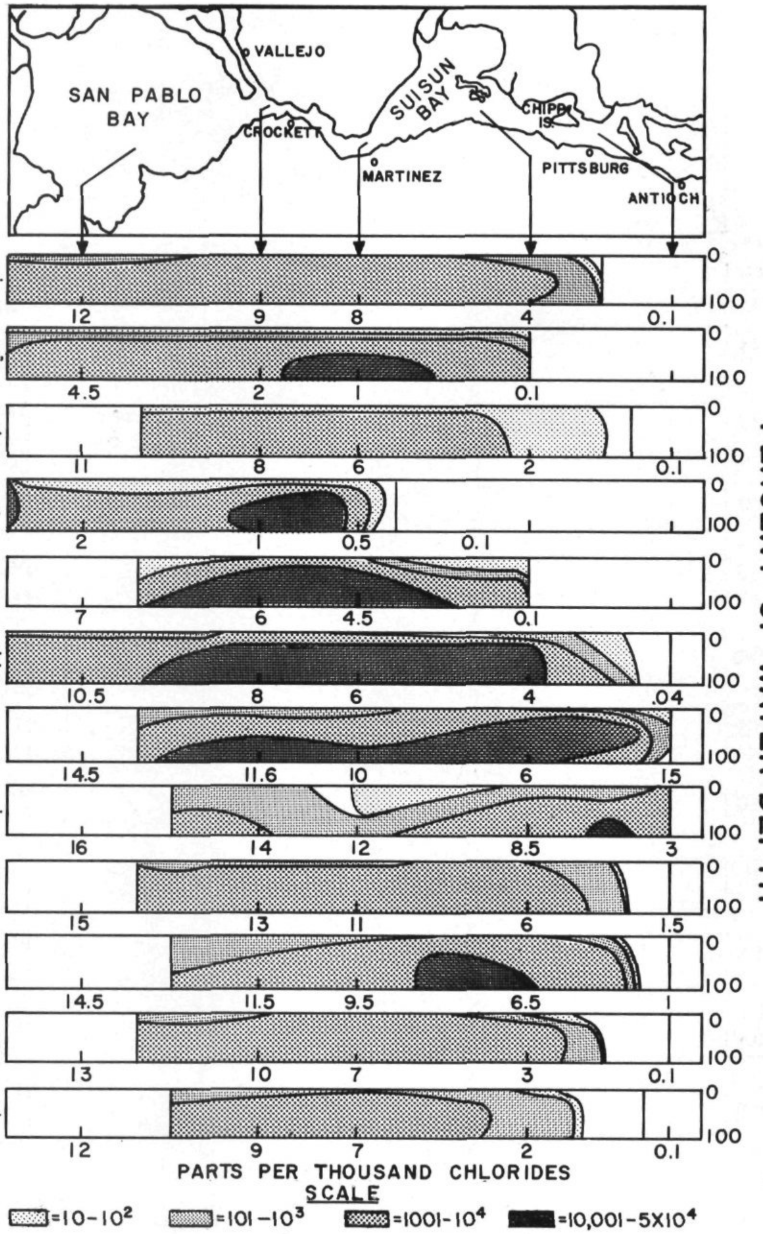

FIGURE 4. Seasonal changes in the distribution and abundance of *Acartia clausi* in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

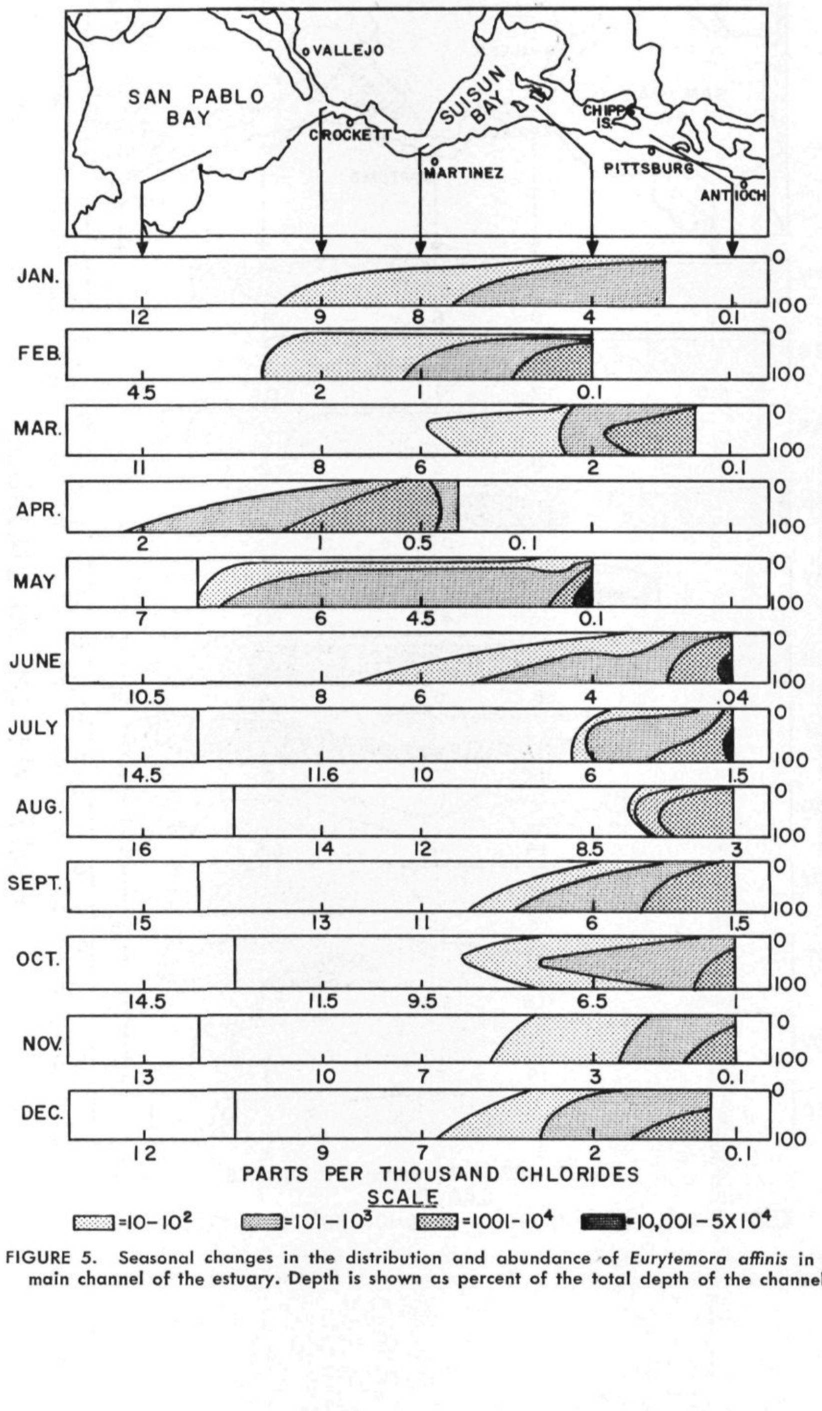

FIGURE 5. Seasonal changes in the distribution and abundance of *Eurytemora affinis* in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

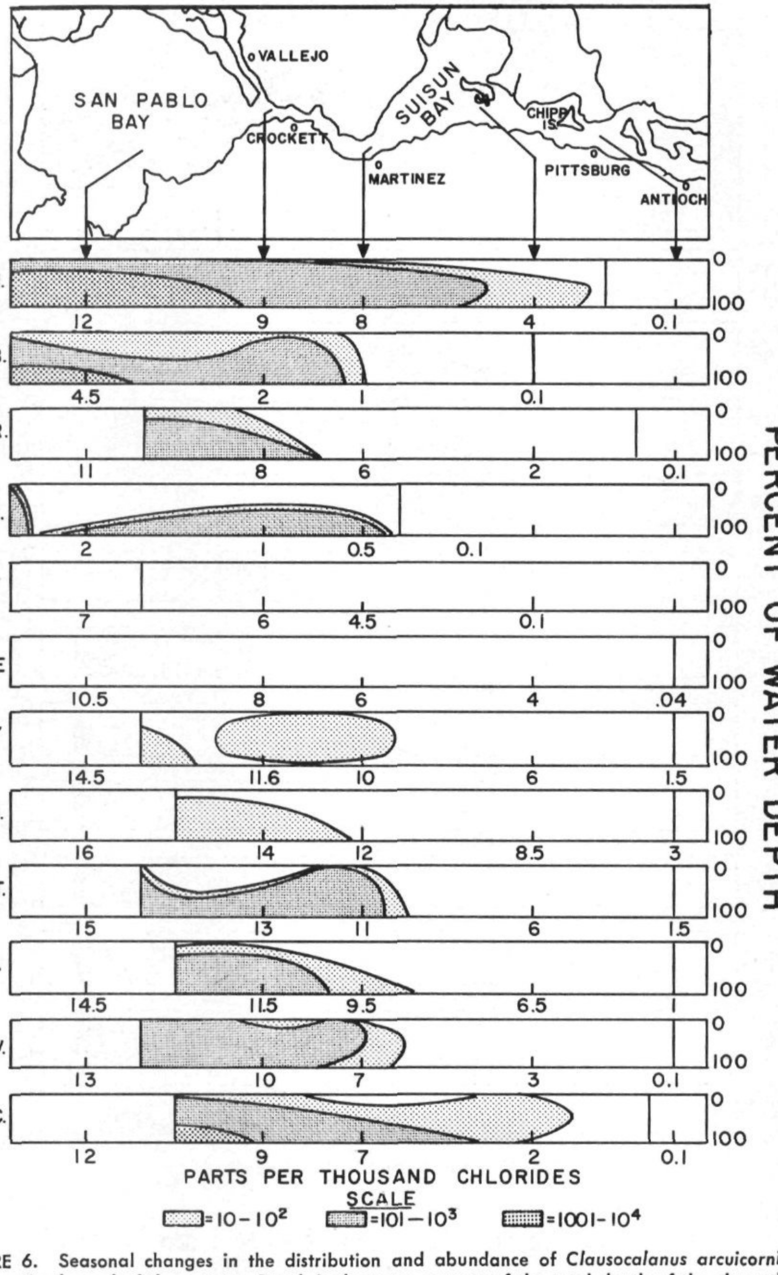

FIGURE 6. Seasonal changes in the distribution and abundance of *Clausocalanus arcuicornis* in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

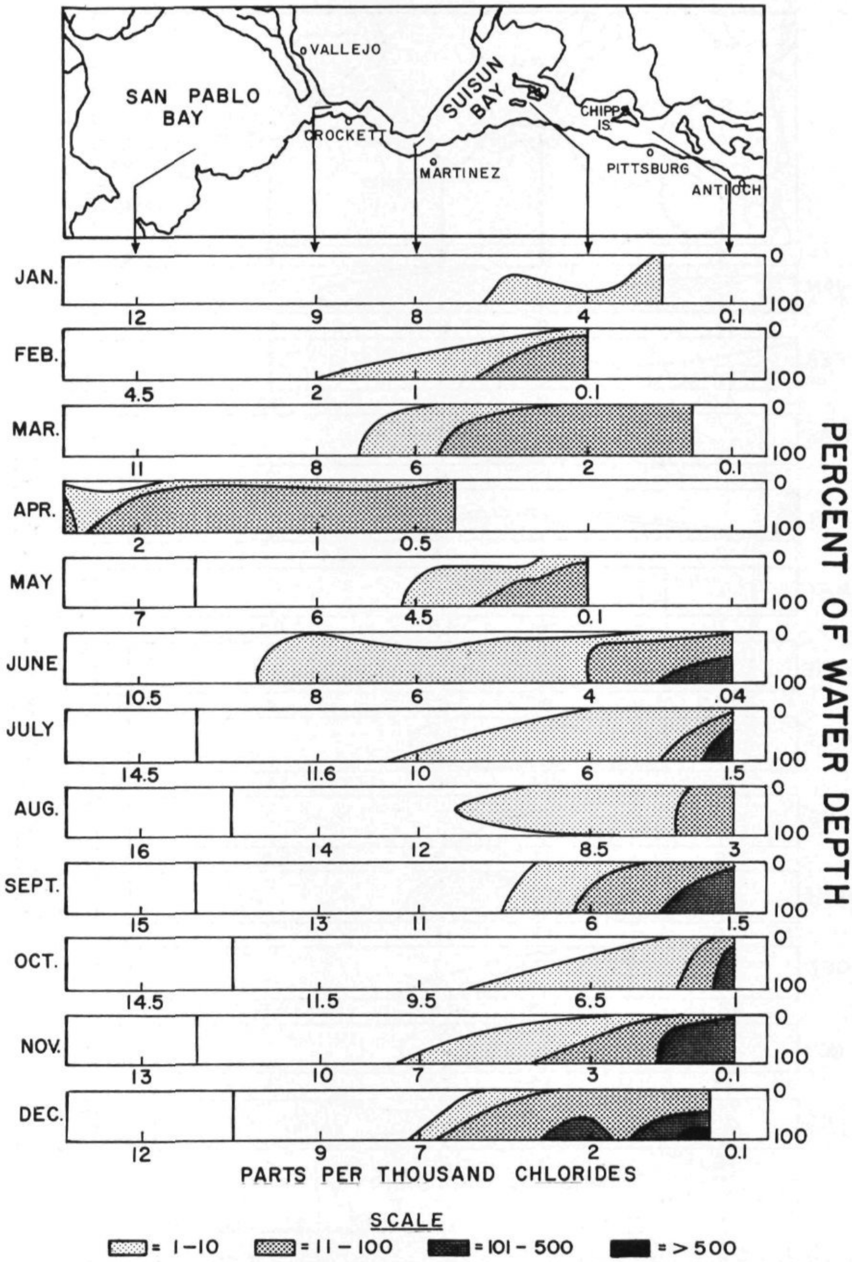

FIGURE 7. Seasonal changes in the distribution and abundance of *Neomysis awatschensis (mercedis)* in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

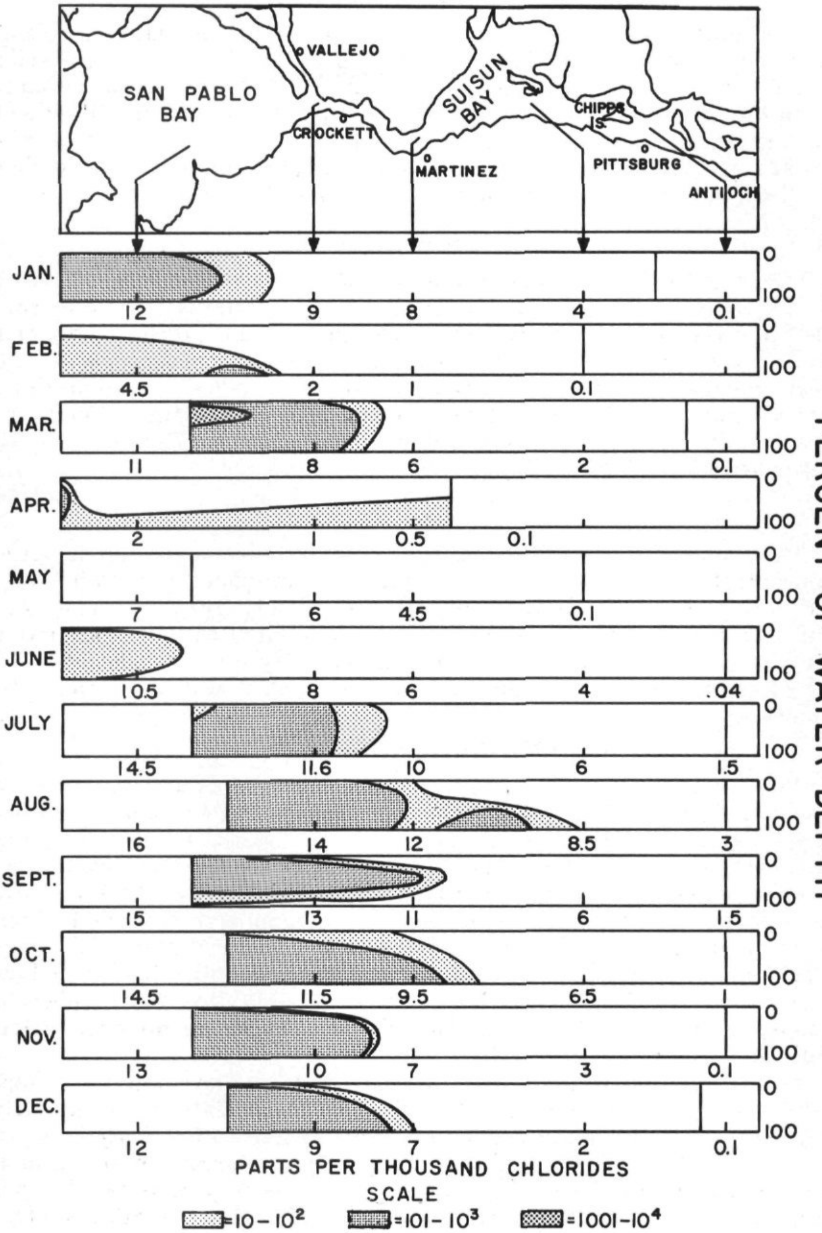

FIGURE 8. Seasonal changes in the distribution and abundance of *Euterpina* sp. in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

Cyclops spp.

I recognized several species of Cyclopoida in regular plankton collections but grouped them together for discussion. Since they were relatively low in numbers in the total zooplankton and are typical animals from the freshwater environment, I made no attempt to identify them beyond genus. As expected, these organisms were most numerous toward the freshwater end of the estuary (Figure 9). Only during flood season were any Cyclopoida found in San Pablo Bay.

Diaptomus spp.

Like the Cyclopoida, the several species of *Diaptomus* encountered during the survey were typical freshwater inhabitants and were carried into the middle estuary from upstream. Pennak (1953) states that the Diaptomidae are confined to fresh water, and that there are no near marine relatives. *D. novamexicanus, D. siciloides,* and a third species not identified were taken during the year. Always found in greatest abundance near fresh water (Figure 10), no *Diaptomus* were taken seaward of Suisun Bay.

Oithona sp.

This copepod was sampled most months but was not present in large concentrations. In winter, it was sampled throughout San Pablo Bay (Figure 11), but it disappeared from the study area in spring and early summer. This species was always most abundant in San Pablo Bay at the seaward-most collection station. Only during February and April, flood months, were any *Oithona* sampled in water less than 7‰ chlorides.

ZOOPLANKTON IN SHALLOW WATERS

The extensive shallow areas of San Pablo and Suisun Bays were zones of high zooplankton standing crop; much higher than in nearby deep water. San Pablo Bay shallows were especially high in total numbers of zooplankton. The average total zooplankton concentration per cubic meter at shallow water stations L1, L2, and L2A (Figure 1) was higher every month of the survey than was the zooplankton concentrations near the surface of the closest channel station (Figure 12a). Also in San Pablo Bay, the average total zooplankton of shallow water stations L3, L4, and L5 (Figure 1) surpassed the number of zooplankton at the nearest surface channel station in all months but July and August (Figure 12b).

Zooplankton collections from Grizzly Bay shallow water stations, while lower in total numbers than the San Pablo flats, were regularly higher than nearby surface channel waters (Figure 13a). Only in April (a flood month), May, and July were shallow areas lower in total zooplankton than the surface waters of the nearby channel. Honker Bay, however, had the reverse situation. For most months, surface samples in the channel stations had greater zooplankton concentrations than did shallow Honker Bay (Figure 13b).

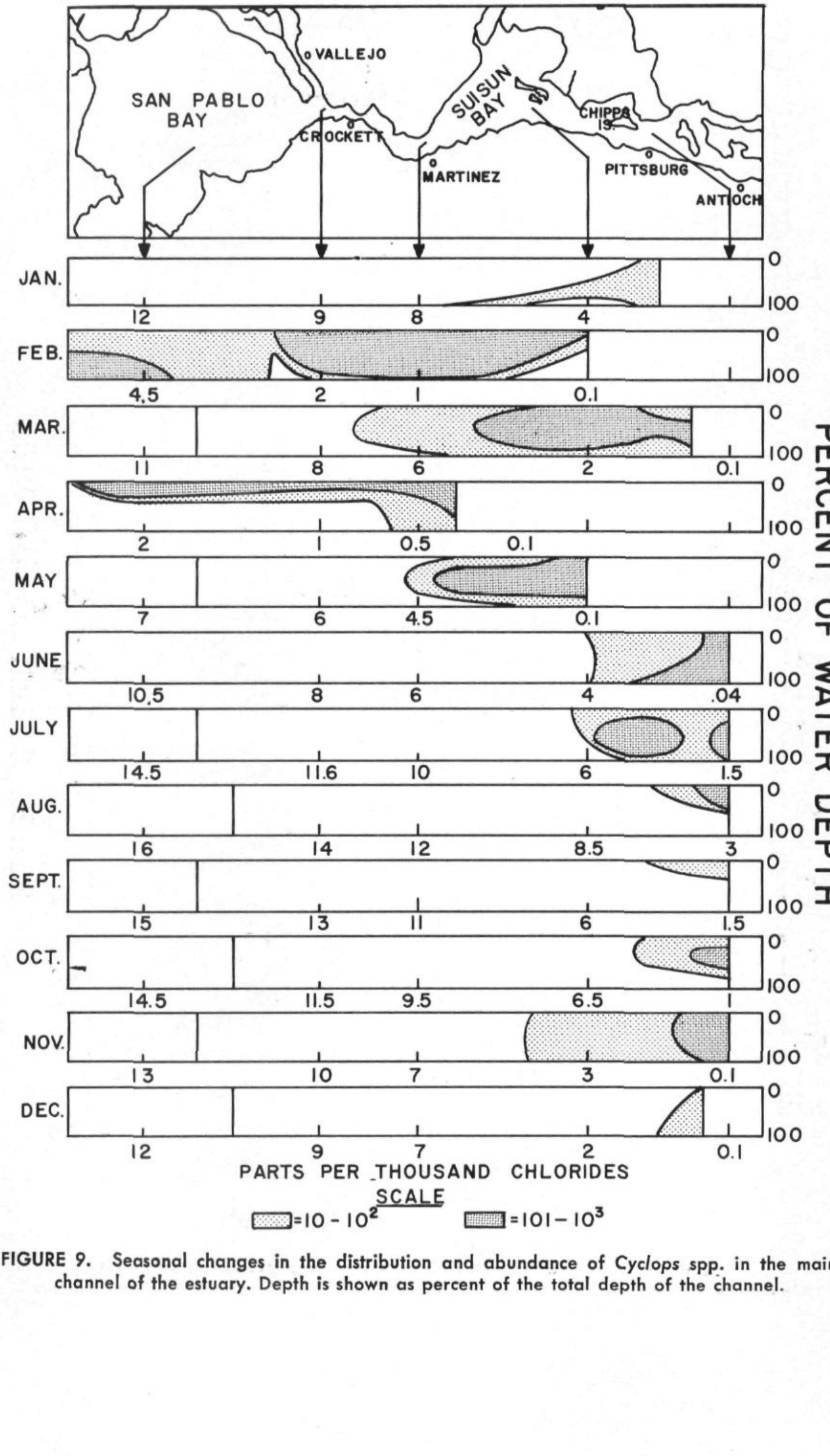

FIGURE 9. Seasonal changes in the distribution and abundance of *Cyclops* spp. in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

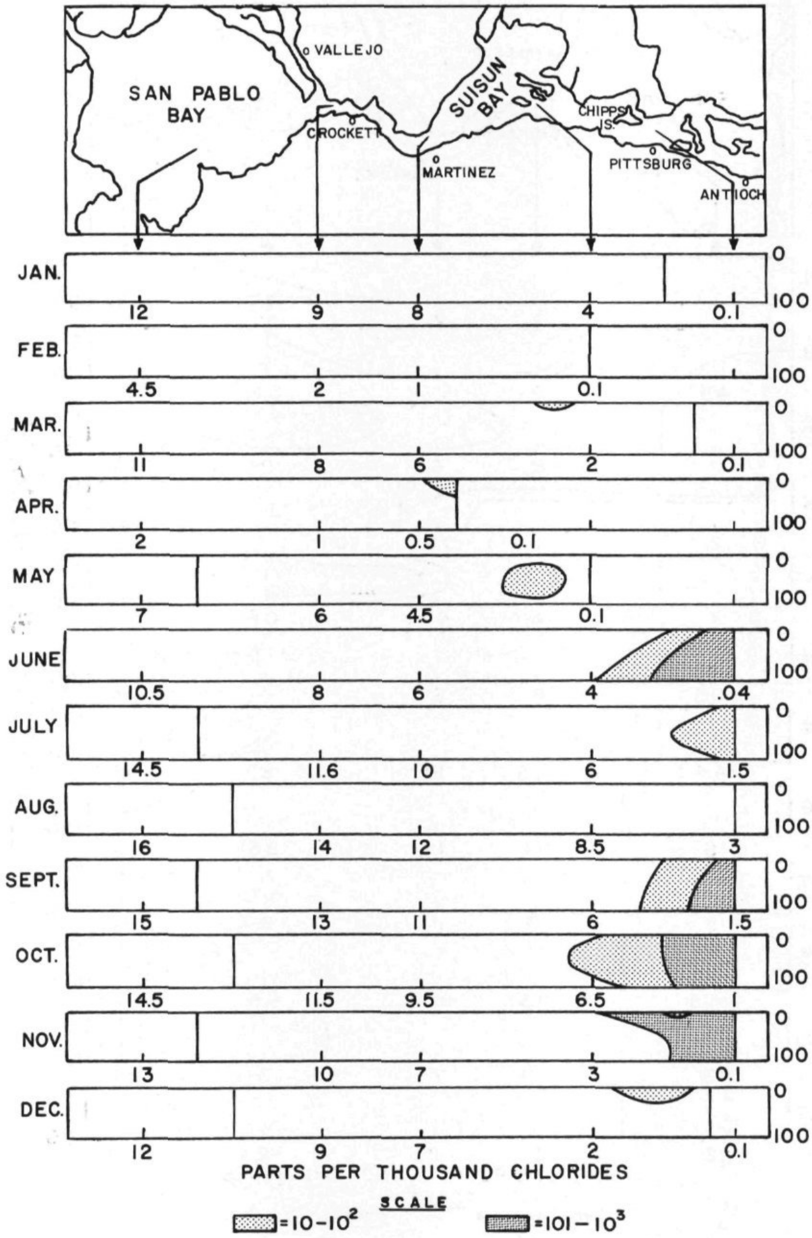

FIGURE 10. Seasonal changes in the distribution and abundance of *Diaptomus* spp. in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

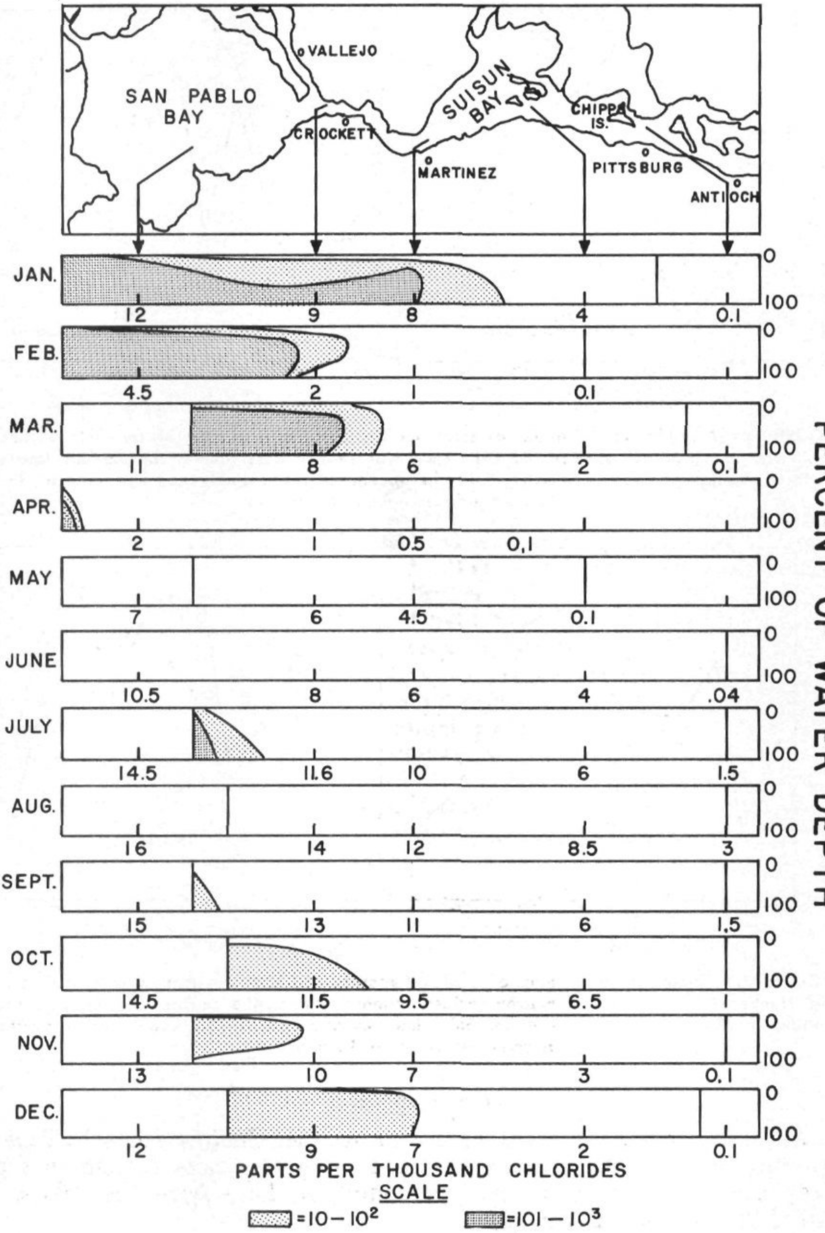

FIGURE 11. Seasonal changes in the distribution and abundance of *Oithona* sp. in the main channel of the estuary. Depth is shown as percent of the total depth of the channel.

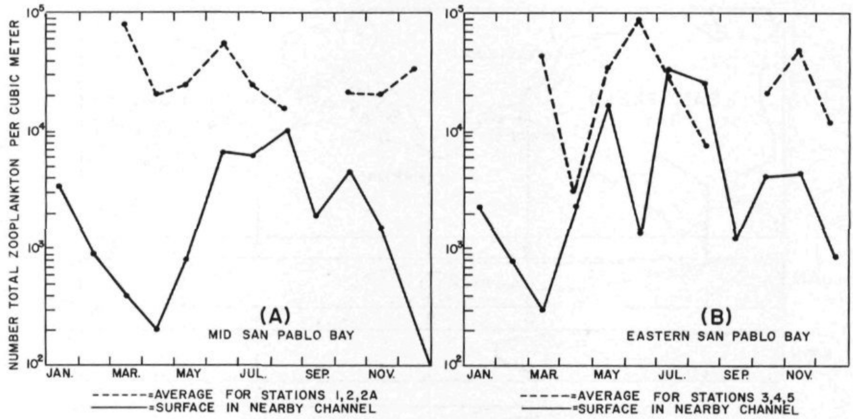

FIGURE 12. Monthly concentrations of total net zooplankton from the shallow flats of San Pablo Bay and a nearby surface channel station. The broken lines connect the monthly means of three contiguous "flats" stations. Solid lines connect the monthly concentration at the nearest surface channel station.

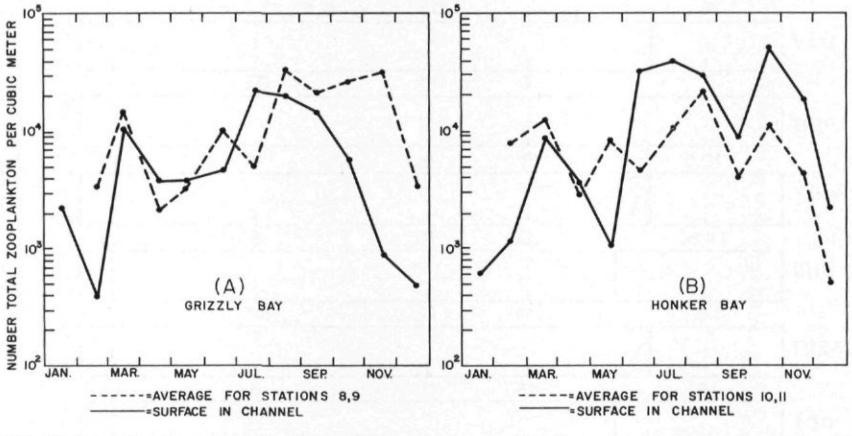

FIGURE 13. Monthly concentrations of total net zooplankton from the shallow flats of Grizzly and Honker Bays and from a nearby surface channel station. The broken lines connect the *monthly means of two "flats" stations. Solid lines connect the monthly concentration at the* nearest surface channel station.

Major Species

All of the 26 species or taxa collected over the shallow "flats" (Table 3) were also collected from the channel. Fourteen taxa present in the deep channel collections were not found in those from the "flats." All of these were of marine origin.

With the exception of *Clausocalanus arcuicornis,* the same species that were dominant in the deep channel plankton collections were also present and abundant over the shallow lateral areas.

Dominant zooplankters again distributed themselves in the estuary according to chlorinity. *Acartia clausi* were found over the more saline water of "flats" in San Pablo Bay. Brackish and freshwater

TABLE 3

Lateral Area Zooplankton Species List [1]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	*Sept.	Oct.	Nov.	Dec.
Annelida												
Polycheata								3			2	
Arthropoda												
Crustacea												
Branchiopoda												
Alonga gutta				3								
Bosmina sp.				3	3						2	2
Diphanosoma sp.				2		2				3	2	
Daphnia pulex		3				2			3			
Leptodora sp.										+		
Cirripeda (nauplii)					2	4	4	4	3	4	4	
Copepoda												
Acartia clausi			5	4	4	5	5	4		4	5	5
Eurytemora affinis		3	4	4	4	4	4	4	3	4	4	4
Diaptomus sp.		2			3	3	3	3	3	4	4	2
Corycaeus affinis											3	
Cyclops spp.		3	3	3	3	3	3	3	3	3	3	3
Euterpina sp.		1	3	3	3	3	2	3	2		3	
Harpacticoid B			3	3	2							
Harpacticoid C											2	
Malacostraca												
Amphipoda												
Corophium spp.		+			1	+	+	1				
Photis californica						1				+	+	
Mysidacea												
Acanthomysis macropsis	1		1									
Neomysis awatschensis	1	1	+	3	2	2	2	2		+	1	1
Decapoda												
Crago franciscorum						+						
Cheatognatha			1			1					+	+
Chordata												
Fish eggs/larvae		3	3	1	1	1	1	1				1
Acidiacea—larvae			3									
Ctenophora			+									
Mollusca												
Gastropoda—veliger larvae								3		4		
Lamellibranchia—veliger larvae									+			
Protozoa			3	4	5	4	4	2		3		
Trochophore larvae			3				4	3		3		

* San Pablo Bay stations not sampled.

[1] Numbers are an index of abundance at the station of greatest occurrence each month. + = present, 1 = 1–10, 2 = 10–100, 3 = 100–1,000, 4 = 1,000–10,000, 5 = >10,000.

species, typically *Eurytemora affinis, Diaptomus novamexicanus, Cyclops* sp., and *Neomysis awatschensis*, were persistent in Grizzly and Honker Bays.

Because distribution and abundance of major species followed the same pattern demonstrated in deep channel sampling, I will discuss only the mysid shrimp separately.

Mysid Shrimp

I sampled two species of mysid shrimp in shallow "flats" zooplankton tows. *Acanthomysis macropsis* was obtained only in small numbers during winter and early spring over the San Pablo flats. *Neomysis awatschensis* was taken someplace in the shallow survey area every month but September.

Neomysis awatschensis was numerous in San Pablo Bay only during the months of June and July (Table 4). In Grizzly and Honker Bays, however, mysids were present from spring through summer but declined abruptly during September.

TABLE 4

Number of *Neomysis* and *Acanthomysis* per Cubic Meter Collected Each Month at Lateral Stations

	San Pablo Bay Stations						Grizzly and Honker Bays			
	L1	L2	L2A	L3	L4	L5	L8	L9	L10	L11
January	(0.1) 0.05	(1.2) 0	**	(1.4) 0.1	(0.4) 0.4	1.0	*	*	1.8	2.5
February	0	0.1	**	0	0.2	0.1	0	4.7	0	0
March	0	(0.2) 0	(1.0) 0.5	0	0	(0.8) 0	0	0.3	0.1	0.1
April	0	2.2	1.2	0	0	0.7	0.1	127.0	1.8	2.2
May	0	0	0	0	0	0.4	35.8	68.1	0.8	6.3
June	1.3	46.7	2.4	3.0	4.6	13.5	22.6	32.8	0	0.3
July	0	1.4	36.0	0.5	3.8	26.3	0.8	0.4	0	0.1
August	0	0	0	0	0	0	56.0	23.0	5.3	4.2
September	*	*	*	*	*	*	0	0	0	0
October	0	0	0	0	0	0.1	0	0	0	0.2
November	0	0	0	0	0	0.7	1.5	0	0.4	0
December	0.3	0	0.2	0.3	0.5	0.8	2.2	0.7	0.9	0

* Too windy to sample.
** Not established as a sample station.
( ) *Acanthomysis*.

DISCUSSION

Species Composition

The only publications on zooplankton from San Francisco Bay are reports of collections from the steamer *Albatross*' 1912-14 expedition. Esterly (1924) described the copepods taken in that survey and Tattersall (1932) wrote of the Mysidacea collected.

Esterly (1924) reported 11 copepod species from San Francisco Bay and he found 8 of these in San Pablo Bay. I collected seven of the eight species reported by Esterly from San Pablo Bay and 4 additional species that he did not describe anywhere in the San Francisco Bay area.

Besides an increase in number of species from that noted in 1912-13, there has been a significant shift in relative abundance of the various species present. *Epilabidocera amphitrites* was the dominant copepod 50 years ago in San Pablo Bay. *Acartia clausi* was second in total numbers and frequency of occurrence in hauls. My collections were almost devoid of *Epilabidocera amphitrites,* and *Acartia clausi* was the most abundant species present throughout the year.

Tattersall (1932) recorded five species of mysid shrimp from San Pablo Bay. *Acanthomysis macropsis* was the most abundant followed by *Neomysis awatschensis* and *Neomysis franciscorum. Neomysis kadiakensis* and *Neomysis costata* were rarely taken. Only two of these species were collected during the course of this investigation—*Neomysis awatschensis* and *Acanthomysis macropsis*—and *Neomysis awatschensis* was the most abundant species.

Depth

The importance of depth in the distribution of zooplankton is well documented. Diurnal migrations have been noted in many species. Phototropism was reported to be the cause of diurnal migration in one case (Loeb, 1894) and phototaxis and geotaxis (Parker, 1902; Dice, 1914; and Esterly, 1917, 1919) in another. Optimum light intensity is cited by Russell (1926) and Cushing (1951) as a cause for vertical migration, while color responses are suggested as factors by Baylor and Smith (1953).

In this investigation, channel zooplankton increased in numbers, with depth. Copepods, the most abundant animals in the zooplankton, exhibited some change in distribution between life history stages and between areas of the estuary. The adults seemed to prefer deeper water while immature forms were more randomly distributed at all depths. Differences in distribution between adults, copepodids, and nauplii may be a reflection of differing abilities to swim, a real change in depth preference, or both. Differences between areas may be caused by changes in turbidity (as a general rule the estuary becomes less turbid toward the ocean).

Surface concentrations of zooplankton in the channel were often less than concentrations over the shallow "flats." The reason for this difference is unknown. Turner (see p. 99) found larger zooplankton concentrations in the Delta to be correlated with longer residence times of water in certain channels. Similar conditions may be operating over the middle bay "flats." Water remains over large portions of the "flats" many days longer than water remains in a given area in the deep channel (U. S. Corps of Engineers, 1963).

Chlorinity

Many authors state that chlorinity is the major factor controlling distribution and abundance of zooplankton in estuaries (Esterly, 1924; Tattersall, 1932; Alexander, Southgate, and Bassindale, 1935; Hulburt, 1957; Reid, 1957; Cronin, Daiber, and Hulburt, 1962).

Chlorinity was the prime factor that determined the longitudinal distribution of zooplankton in the estuary. The common genera can be divided into three groups based on chlorinities: (i) those genera most abundant near the western or seaward end of the study area; (ii) those genera in greatest abundance toward the freshwater end of the chlorinity spectrum; (iii) those genera present over a broad chlorinity range. These three categories fit roughly the chlorinity zones expressed by the "Venice" system of saline water classification (Beadle, 1958). *Clausocalanus arcuicornis, Euterpina* sp., *Calanus finmarchicus* and *Oithona* sp. all were most abundant near the most saline water sampled each month or in the euhaline zone. *Cyclops* spp. and *Diaptomus* spp. occurred in highest numbers consistently toward fresh water or the oligohaline zone. *Acartia clausi* and to some extent *Eurytemora affinis* and *Neomysis awatschensis* were present over a wide chlorinity range. *Acartia* is a polyhaline-mesohaline species while *Eurytemora* and *Neomysis* are mesohaline-oligohaline forms. A strict chlorinity-taxa classification breaks down with euryhaline forms such as *Acartia* and *Eurytemora* because by definition they can occur over a wide chlorinity range.

SUMMARY

1) During 1963, 383 plankton samples were taken in the main channel and over the shallow flats of San Pablo and Suisun Bays. Collections were made once each month with Clarke-Bumpus samplers fitted with number 10 mesh bolting cloth.

2) The concentration of zooplankton ranged from 10,000 to 500,000 animals per cubic meter in the main channel and was high at all seasons of the year and at all locations in the estuary. Highest concentrations were usually associated with 7 to 10‰ chlorides and near fresh water.

3) Adult copepods were always most abundant in the deepest water sampled at a station. Immature copepods were more random in distribution with respect to depth.

4) The shallow "flat" areas of San Pablo and Grizzly Bays support more net-zooplankton than comparable depths over deep water.

5) *Acartia clausi, Eurytemora affinis,* and *Neomysis awatschensis* made up the bulk of the net-zooplankton in this portion of the estuary.

6) Chlorinity was the prime factor that determined the longitudinal distribution of zooplankton.

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ZOOBENTHOS OF SAN PABLO AND SUISUN BAYS

RICHARD E. PAINTER

This chapter describes the invertebrate bottom fauna of the middle reach of the Sacramento-San Joaquin River estuary and some of the physical and chemical factors that control faunal distribution there. Emphasis is placed upon those animals that were most persistent and abundant or those that were known to be important in the diets of fish and game species in the area.

Samples were taken each month during 1963. Physical and chemical information from representative stations and 1107 benthic samples were collected and analyzed.

Of the several environmental factors studied, chlorinity was the prime cause of differences in species distribution.

METHODS

Station Location

The sites of monthly collections were along eight transects at right angles to the longitudinal axis of the estuary, from the western edge of the Delta near Antioch to the western end of San Pablo Bay (Figure 1). Most transects were about 5 miles apart and included four stations at different depths. Each transect had one deep station in the main channel, usually on "sandy" bottom, one station on the 15-foot depth contour, and one station in 6 to 8 feet of water with clayey-mud or muddy-clay bottom. Most transects had a fourth station in the intertidal-mud zone. Two transects in Suisun Bay and one in the lower Sacramento River did not have an intertidal station.

Sampling Procedure

From January through June, I collected two, 1-square-foot bottom samples from each station with a Peterson dredge. Each sample was processed in the following manner:

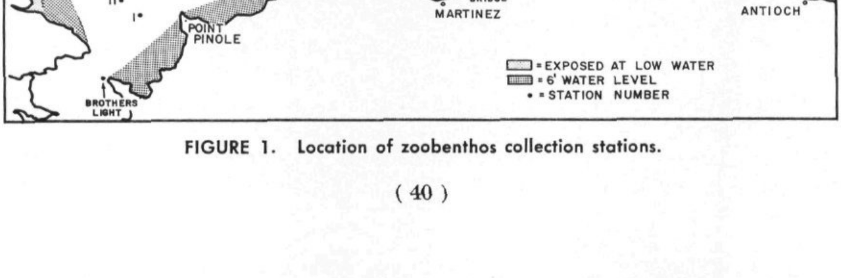

FIGURE 1. Location of zoobenthos collection stations.

1) The sample was washed through an eight meshes per inch screen, which caught the larger invertebrates and debris, and then through a 50 meshes per inch screen, which retained most organisms visible to the naked eye.
2) The organisms and debris left on each screen were washed into a jar (jars).
3) Ten percent formalin containing rose-bengal dye was added to the samples as a preservative and organism-coloring agent.

From July through December, after determining that using an intermediate mesh size decreased field washing time without significant loss of benthic animals, I used only one screen of 30 meshes per inch to separate animals from sediment. This saving in time enabled an additional sample per station to be taken.

Laboratory Procedure

Field samples were rewashed through a 12″ x 12″ screen with 50 meshes/inch until June, and 30 meshes/inch every month thereafter. Large animals were removed by hand and placed in a petri dish. The remaining sample was examined, a tablespoon full at a time, in an enameled pan to which a few cc of water had been added. The animals were removed from these small subsamples and placed in a petri dish for identification and enumeration. Biomass of selected species in each sample was determined by water displacement.

The abundance and distribution of selected species is illustrated in this paper by isopleths of abundance drawn for each of four depths common to most transects. The isopleths of abundance, for every depth except the intertidal zone, were drawn on a grid of 96 points. Each point represented the mean number of animals collected per square foot at each station each month. This mean was based on two, 1-square-foot bottom samples collected each month at each station from January to June and three samples per month collected at each station from July through December. The intertidal zone had a 72 point grid because two transects did not have intertidal stations.

Chlorinity

To describe the bottom chlorinity conditions during most months, I used monthly averages of chlorinity measured near high-high tide, every 4th day, at Department of Water Resources sampling stations close to my transects (Figure 2). These are surface measurements but except for flood periods, the chloride content of near bottom water samples is only 1 or 2‰ greater than those collected on the surface (see Kelley, p. 12). In my opinion they represent a more accurate description of bottom salinity conditions than can be obtained from examining my bottom salinity measurements which were made at different times during the tidal cycle.

During the flood months, however, the high chloride concentrations at the bottom in San Pablo Bay were overridden with a surface layer of relatively fresh water (Figure 3) and a strong bottom chlorinity wedge extended upstream into the Carquinez Strait. The surface and bottom chloride concentrations in Suisun Bay during high fresh water run-off were nearly identical. For the description of chlorinity condi-

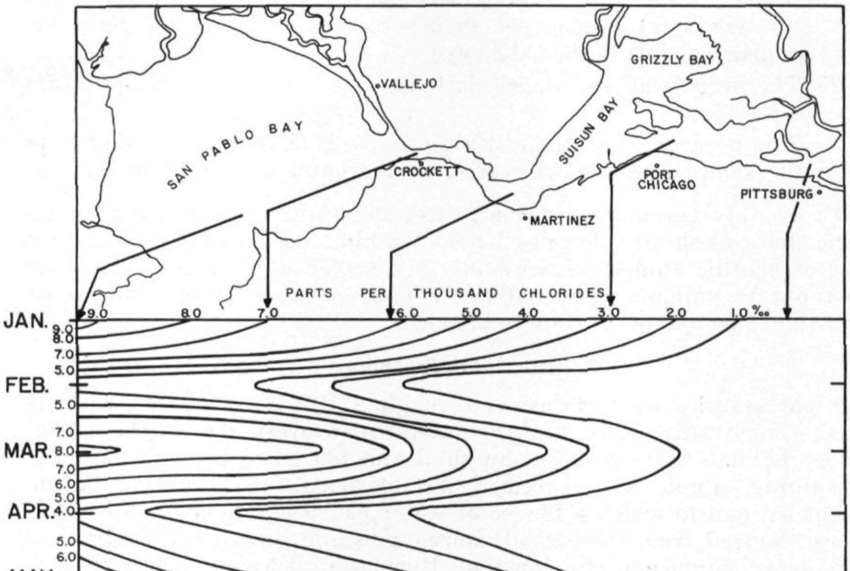

FIGURE 2. Surface isopleths of chlorides drawn from monthly averages of California Department of Water Resources four-day chlorinity observations 1963.

tions on the bottom during the flood months (February through May), I used my own measurements of the bottom chlorinity obtained 1 day each month at various locations in the main channel along the entire length of the study area (Figure 3). These bottom chlorinity values were obtained at different ebb-tide stages and are lower than the concentrations would have been if measurements could have been made at high-high tide.

The same problem arises when trying to describe the bottom chlorinity conditions in the "flats" of the bay. It was impossible to sample at all stations at the same tide stage and during a tidal cycle the chlorinity may change as much as 6‰. Fortunately the bottom chlorinity conditions in the flats were within a few ppt of the concentration on the surface of the adjacent channel (Table 1). I have therefore used monthly averages of the channel surface chloride concentrations at high-high tide as an approximation of chlorinity conditions near the bottom in the "flats."

Monthly averages of surface salinity based on samples collected every 4 days from the channel served then as an approximation of the bottom salinities in the "flats" and in the channels as well during all but the February through March period. Bottom salinities in the channel during these "flood" months were much higher than surface

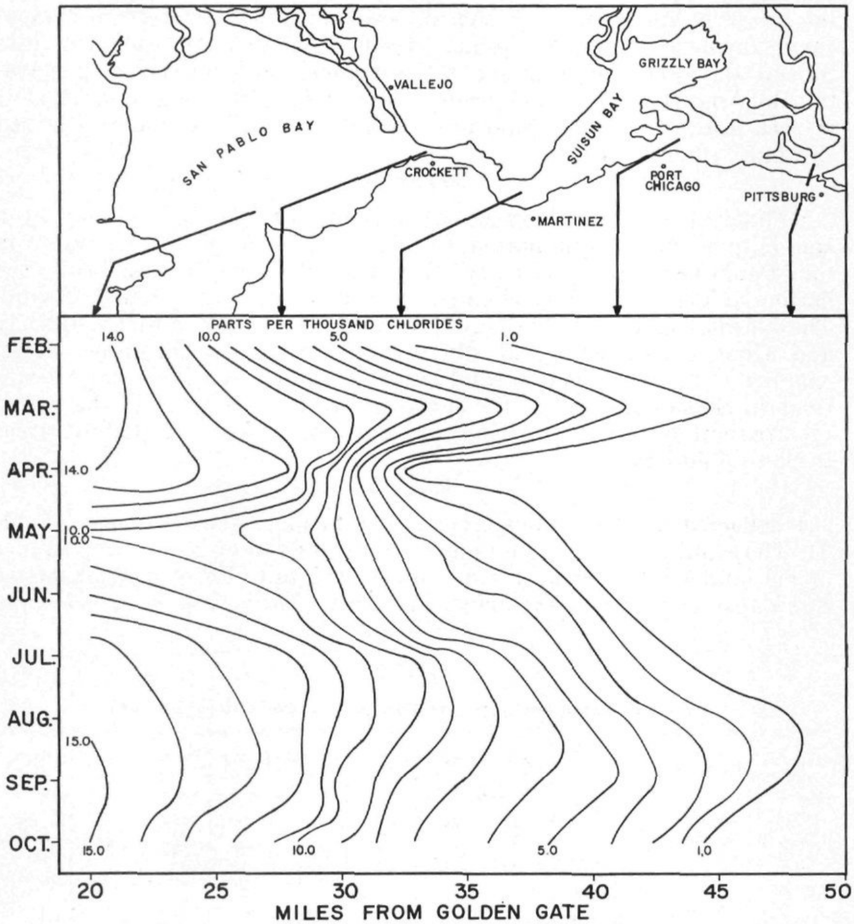

FIGURE 3. Bottom isopleths of chlorides drawn through concentrations measured one day each month, 1963.

TABLE 1

High-High Tide Chlorinity in San Pablo Bay One Day Each Month During 1963 at the Surface Near Point Pinole and Over Shallow Water Near Station 21

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Surface opposite Point Pinole	11.4	4.6	10.6	2.0	6.6	10.5	14.4	16.0	15.2	14.6	13.2	11.8
Surface in six feet of water near Station 21	8.6	2.4	8.6	1.5	5.3	8.6	10.5	12.2	--	10.5	9.6	7.9

salinities, and my description of them is based upon single samples taken at various tide stages.

Based on both surface and bottom chlorinities, the extent of chlorinity encroachment up the estuary varied seasonally (Figure 2). During a winter flood, in late January and early February, and during an early spring flood, in April, water of 1‰ chlorides was temporarily displaced to the Carquinez Strait. Chlorinity encroachment into Suisun Bay went on throughout the summer with maximum penetration in August when 1‰ chlorides reached the Pittsburg area. A slow retreat seaward by the chlorinity gradient in the estuary occurred through fall and winter.

Sediments

Sediments were classified as either sand, silt, silt-clay, or clay by a simple qualitative examination (Table 2). The deep channel water in San Pablo Bay (Stations 1 and 2) had a silt or clay bottom while the bottom of the Suisun Bay channel (Stations 4 through 8) was of sand. The bottoms of San Pablo Bay flats were of clay or silt-clay. Grizzly and Honker Bay flats had silt bottom sediments. Carquinez Strait channel (Station 3) had a sand substrate and resembled channel stations in Suisun Bay while the substrate in flats adjacent to the Strait (Southampton Bay) were clay and resembled those of shallow areas in San Pablo Bay.

RESULTS

I collected benthic animals belonging to more than 40 taxa (Table 3). Those animals that were numerous and/or are of known importance as fish and wildlife food are discussed in detail. *Macoma inconspicua, Synidotea laticauda, Nassarius obsoletus, Tapes semidecussata* and

TABLE 2

Principal Sediment Type at Zoobenthic Collection Stations

Transect number	Location	Station No.	Bottom type	Station No.	Bottom type	Station No.	Bottom type	Station No.	Bottom type
1	San Pablo Bay	1	silt	11	clay	21	clay	31	silt-clay
2	San Pablo Bay	2	clay	12	silt	22	clay	32	silt-clay
3	Carquinez Strait	3	sand	13	clay	23	clay	33	clay
4	Suisun Bay	4	sand	14	clay	24	silt		
5	Suisun Bay-Grizzly Bay	5	sand	15	silt	25	silt	35	silt
6	Suisun Bay	6	sand	16	clay	26	silt		
7	Suisun Bay-Honker Bay	7	sand	17	clay	27	silt	37	silt
8	Suisun Bay-Chipps Island Reach	8	sand	18	silt	28	silt		

TABLE 3

List of Benthic Species Taken During the Survey

Annelida	Arthropoda	Chordata
Asychis amphiglypta	Amphipoda, spp.	*Molgula manhattensis*
Boccardia sp.	*Balanus* sp.	
Eteone lighti	*Callianassa californiensis*	Mollusca
Glycinde armigera	*Cancer magister*	*Corbicula fluminea*
Haploscoloplos elongata	*Corophium acherusicum*	*Gemma gemma*
Hesperonoe complanata	*Corophium spinicorne*	*Macoma inconspicua*
Neanthes lighti	*Corophium stimpsoni*	*Macoma nasuta*
Neanthes succinea	*Crago franciscorum*	*Modiolus senhousei*
Nephtys caecoides	*Crago nigracauda*	*Mya arenaria*
Nereis brandti	*Hemigrapsis oregonensis*	*Nassarius obsoletus*
Notomastus sp.	*Photis californica*	*Tapes semidecussata*
Oligocheata, spp.	*Pontharpinia obtusidens*	
Pectinaria californiensis	*Rhithropanopeus harrisii*	Plathyhelminthes
Polydora uncata	*Synidotea laticauda*	Turbellaria
Streblospio benedicti		
Tharyx parvus		

Gemma gemma are important food of diving ducks (Calif. Dept. Fish and Game, unpublished). Ganssle (see p. ____) lists *Macoma inconspicua, Photis californica* and *Synidotea laticauda* as important fish food in the estuary. *Corophium* spp. and *Nereis (Neanthes)* spp. are a part of the diet of young-of-the-year striped bass (Heubach, Toth, and McCready, 1963).

There was a large difference in zoobenthic biomass from one end of the study area to the other. The total biomass of those animals that were numerous or important as fish and game food was much larger in San Pablo Bay transects than in any Suisun Bay transects (Figure 4). This disparity between the two areas was especially evident in the Mollusca. Mollusca averaged 3.6 cc/ft^2 sample in the most seaward transect in San Pablo Bay and less than 0.1 cc sample in transect four in eastern Suisun Bay.

The biomass of arthropods important in the diets of fish and game species was also highest in San Pablo Bay. Annelid biomass was low in transects at each end of the chlorinity gradient but had no apparent trend in the survey area.

Eleven species were abundant enough to warrant a description of their distribution (Figures 5-15).

Tapes semidecussata

The Japanese littleneck clam was the most numerous pelecypod found in deep water in the study area. I found them only in the main channel through San Pablo Bay and in Carquinez Strait (Figure 5).

Bottom chlorinities in San Pablo Bay where *T. semidecussata* was most abundant ranged from about 7 to 16‰. Maximum numbers occurred in the summer and fall when the highest chlorinities were recorded in the bay. The apparent summer increase in population probably was not due to the summer increase in chlorinity; it may have been the result of sampling errors in the spring, recruitment of young clams into the catch, or both.

I did not take *T. semidecussata* upstream from the Carquinez Strait and only rarely did I find it at stations 6 feet or less in depth. The bay pollution study conducted by the University of California (McCarty *et al.*, 1962) reported *T. semidecussata* in 5 percent of their samples from Suisun Bay. Filice (1958) observed the species from

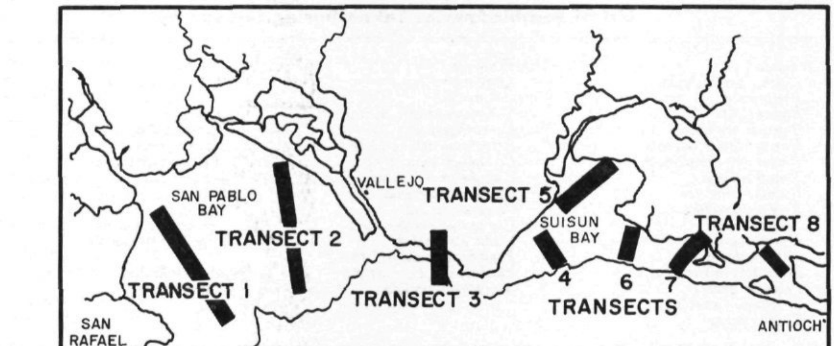

FIGURE 4. Average monthly biomass of fish and wildlife food organisms from eight transects in San Pablo and Suisun Bays.

FIGURE 5. Average numbers of *Tapes semidecussata* per square foot sample each month at four depths along eight transects in the study area.

8.8‰ chlorides seaward. He concluded that they showed a preference for water shallower than 6 feet, but I found it only in my deep water collections.

Gemma gemma

This small pelecypod was the most numerous clam collected in shallow water in San Pablo Bay (Figure 6). It was collected at all four shallow-water stations there from clay and silt-clay bottom types. I found *G. gemma* only on three occasions upstream from the Carquinez Strait.

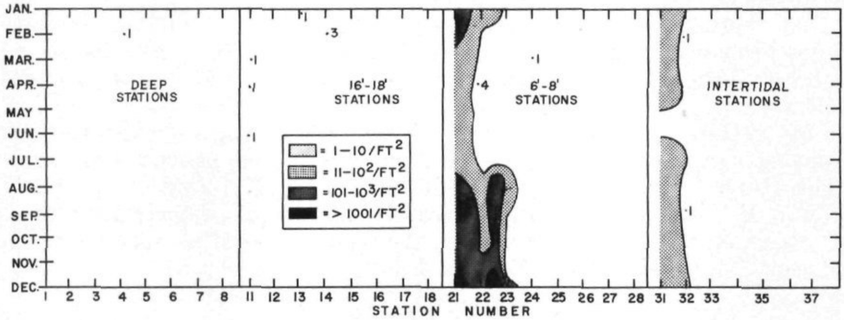

FIGURE 6. Average numbers of *Gemma gemma* per square foot sample each month at four depths along eight transects in the study area.

The chlorinity through which *G. gemma* was found ranged from about 1.5 to 16‰. Except for the two freshwater floods, however, water of low chlorinity did not enter the shallow "flats" of San Pablo Bay where *G. gemma* was abundant. Most of the year, water of 8‰ chlorides or more covered the stations where population levels for *G. gemma* were high.

Macoma inconspicua

This clam was abundant at intertidal stations in San Pablo and Southampton Bays (Figure 7). The seawardmost intertidal station (Station 31) always provided a large sample of *M. inconspicua*. Their numbers ranged from 10 to 46 clams per square foot per sample during

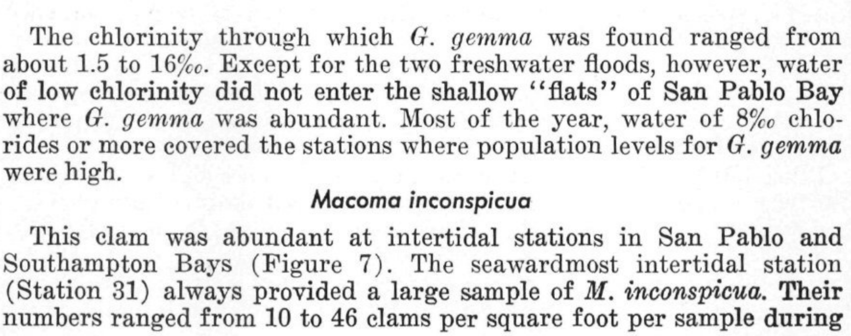

FIGURE 7. Average numbers of *Macoma inconspicua* per square foot sample each month at four depths along eight transects in the study area.

the year. Station 33 in the Southampton Bay flat provided low numbers of *M. inconspicua* in the spring but up to 27 per sample in September.

While the increased numbers of *M. inconspicua* in the fall coincides with maximum chlorinity incursion, increased population levels probably are not caused by the increase in chlorinity. Variance of sampling (sampling error) and recruitment of small clams into the samples probably explain the increase.

M. inconspicua was never taken from the intertidal stations in Grizzly and Honker Bays, but it was collected in small numbers at 6- to 8-foot and 16- to 18-foot stations.

The bottom chlorinity over the area where population levels were high probably ranged from less than 2 to 16‰. For 8 months of the survey, however, the chlorinity was greater than 6.0‰ in these areas (Figure 3).

My results agree with those of Filice (1958) who reported that *M. inconspicua* preferred mud and avoided sand or heavier sediments. The University of California pollution study (McCarty *et al.*, 1962) found *M. inconspicua* in approximately 20 percent of their samples as far east as the Antioch Bridge. In my study I found no specimens upstream from Stake Point (Figure 1).

Mya arenaria

I found the clam *M. arenaria* from the seaward end of the study area to Point Edith in Suisun Bay (Figure 8). Few, however, were collected upstream from the Carquinez Strait. Most were taken from stations at 6 to 18 feet of water in San Pablo Bay and the Carquinez Strait transect. I estimate that the bottom chlorinity where population levels were high ranged from 5 to 16‰. Except for the flood months, when low chlorinity water was present at all depths in the Carquinez Strait, the bottom water was above 8‰.

Filice (1958) found *M. arenaria* in all substrates and at all levels but with a preference for mud substrate between datum (mean-lower-low-water) and 18 feet. He found them in water as low as 5.2‰ chlorides. The University of California study (McCarty *et al.*, 1962) found this species in 27 percent of their samples from San Pablo Bay and in 21 percent from Suisun Bay. Except that I found some

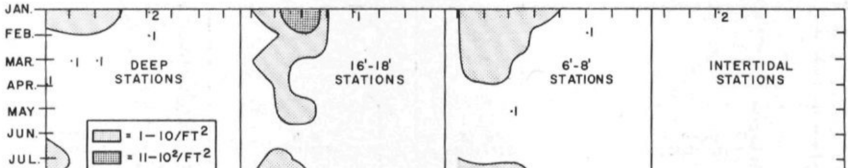

FIGURE 8. Average numbers of *Mya arenaria* per square foot sample each month at four depths along eight transects in the study area.

Mya in lower chlorinity water than did Filice, the results of these two surveys agree with mine.

Photis californica

This small abundant amphipod was present during most months at all depths in San Pablo Bay (Figure 9). It was most abundant at the deep stations. I collected *P. californica* infrequently in Suisun Bay.

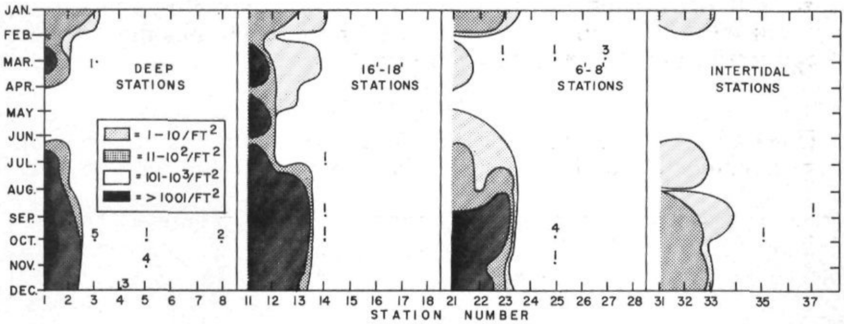

FIGURE 9. Average numbers of *Photis californica* per square foot sample each month at four depths along eight transects in the study area.

In all San Pablo Bay stations, wide fluctuations in concentration or the absence of *Photis* corresponded to the spring flood period. Not until late-summer chlorinity encroachment was well underway did numbers of *Photis* appear at the Carquinez Strait. At this time, an average of 1500 animals per square-foot sample, the maximum number of *P. californica* at any station for the year, was taken at the seawardmost deep station.

Filice (1958) did not report this species from the area. Storrs, Selleck, and Pearson (1963) described distribution similar to the one I found.

Corophium spp.

I sampled three species of these small amphipods during the survey. *Corophium acherusicum* was found throughout San Pablo Bay at all stations and substrates, but the greatest concentrations were at stations 16 feet and deeper (Figure 10). It did not appear in any Suisun Bay

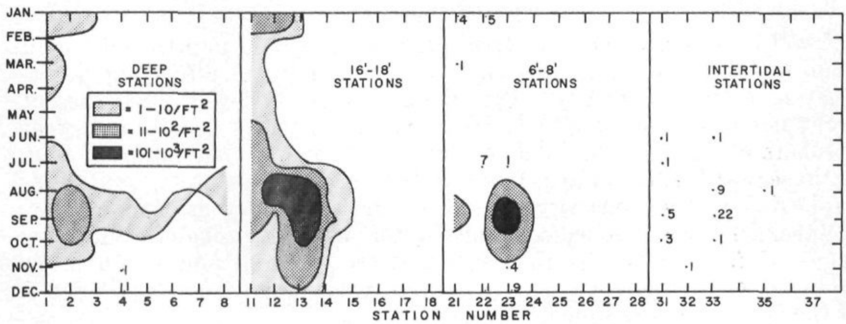

FIGURE 10. Average numbers of *Corophium acherusicum* per square foot sample each month at four depths along eight transects in the study area.

samples until fall when maximum chlorinity encroachment took place. Like *Photis californica,* the appearance of large concentrations of *C. acherusicum* in the Carquinez Strait coincided with the presence of 10‰ chlorides in that area.

C. spinicorne and *C. stimpsoni,* the other two members of the genus taken during my study, are treated fully by Hazel and Kelley (see p. 113 to 133). They analyzed the distributions of these animals from Hazel's and my samples and found a seaward limit for both species centered near Port Chicago. Only during flood conditions did I collect *C. spinicorne* and *C. stimpsoni* in San Pablo Bay.

Synidotea laticauda

This large brown isopod was taken from several stations in San Pablo Bay in January and infrequently thereafter until fall (Figure 11).

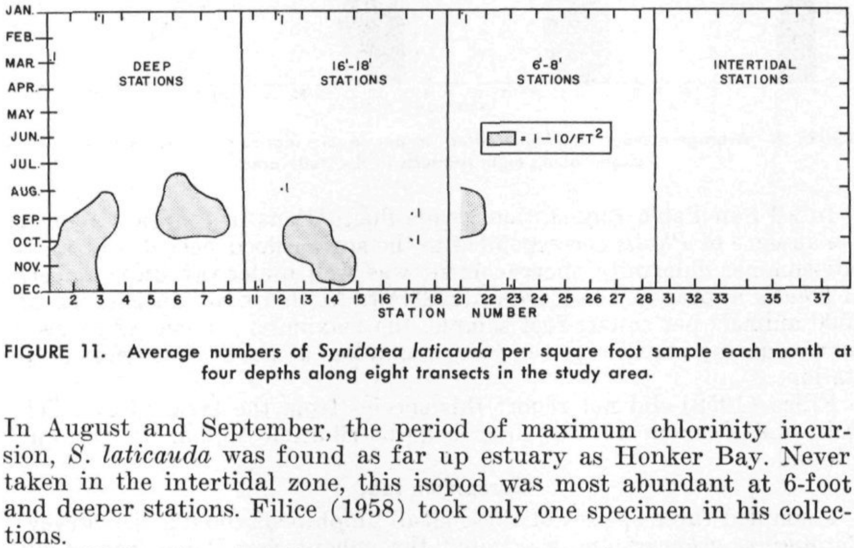

FIGURE 11. Average numbers of *Synidotea laticauda* per square foot sample each month at four depths along eight transects in the study area.

In August and September, the period of maximum chlorinity incursion, *S. laticauda* was found as far up estuary as Honker Bay. Never taken in the intertidal zone, this isopod was most abundant at 6-foot and deeper stations. Filice (1958) took only one specimen in his collections.

The University of California study (Storrs *et al.,* 1963) found them in seven percent of their samples in San Pablo Bay and in only one percent in Suisun Bay.

Neanthes succinea

I collected this polychaete from all substrates and depths but found them in large concentrations most often in the 6- to 8-foot and intertidal zone stations (Figure 12). High population levels were present every month at the Carquinez Strait shallow stations. I collected great numbers of *N. succinea* from the intertidal zone of Southampton Bay. Both seaward and toward fresh water, *N. succinea* were less abundant. A few specimens were found as far up estuary as Honker Bay.

Specimens were collected from water with a probable chlorinity range of from 16 to less than 0.1‰. However, high population levels occurred only where chlorinity concentration was above 6.0‰ for 8 of the 12 months I sampled.

A preference for mud substrates and a chlorinity range of 13.8 to 0.6‰ was demonstrated by Filice (1958) for this species. Storrs *et al.,*

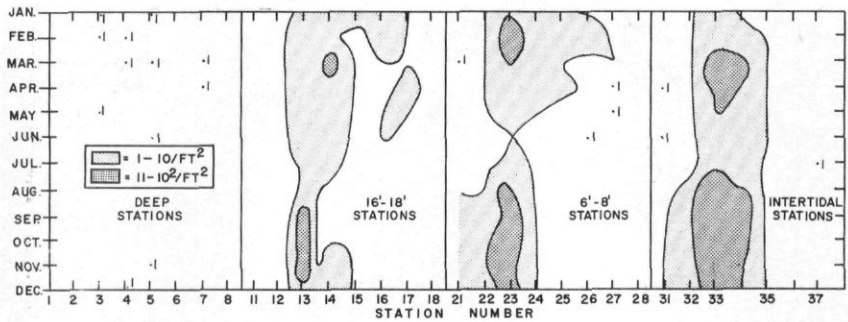

FIGURE 12. Average numbers of *Neanthes succinea* per square foot sample each month at four depths along eight transects in the study area.

(1963) reported them from one end of the study area to the other as far up estuary as the vicinity of the Antioch Bridge.

Glycinde armigera

This polychaete was never very numerous but was persistent in occurrence at the deep San Pablo Bay stations (Figure 13). *G. armigera* was not taken from the intertidal zone stations or up estuary from the Benicia Bridge. Estimated bottom chlorinities in the area where *G. armigera* was collected ranged from 16 to 5‰.

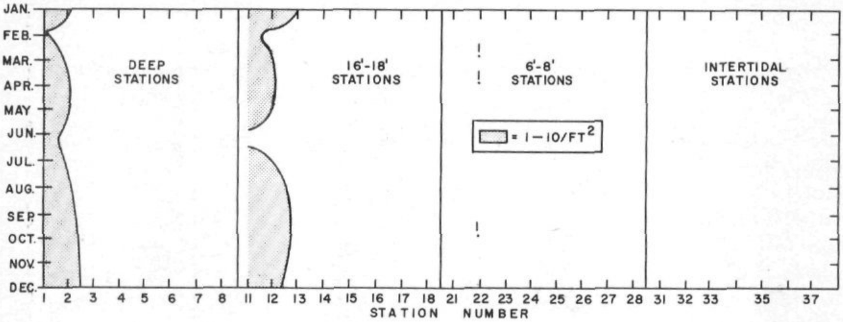

FIGURE 13. Average numbers of *Glycinde armigera* per square foot sample each month at four depths along eight transects in the study area.

Filice (1958) found this species in all substrates. Storrs *et al.*, (1963) reported *G. armigera* as the most common animal in the sediments from San Pablo Bay and abundant to the Carquinez Bridge.

Streblospio benedicti

I found this spionid worm abundant throughout San Pablo Bay at all depths (Figure 14). Few specimens were taken east of the Carquinez Strait. Over the area where *S. benedicti* concentrations were high, I estimate that the chlorinity ranged from 16 to 0.1‰. Most months the chloride concentrations were over 6.0‰.

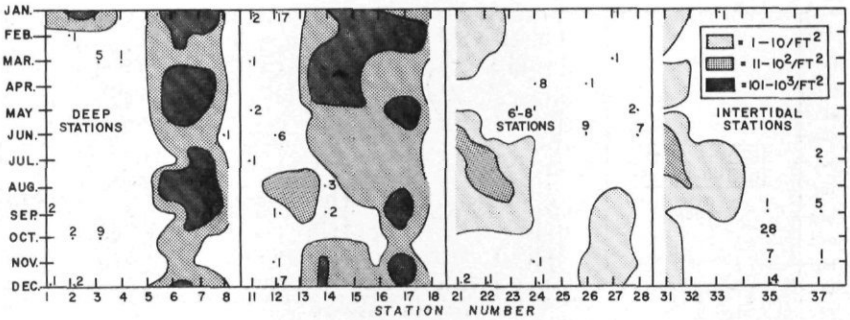

FIGURE 14. Average numbers of *Streblospio benedicti* per square foot sample each month at four depths along eight transects in the study area.

Filice (1958) found *S. benedicti* between datum level and 6 feet below, adverse to the intertidal and sand, and over a chlorinity range of 13.3 to 9.1‰ chlorides. I am unable to determine why Filice did not find *S. benedicti* abundant at other depths. Storrs *et al.*, (1963) found this species in San Pablo and lower Suisun Bays.

Polydora uncata

Another spionid worm, *Polydora uncata,* was distributed throughout the survey area and was found at all stations except Stations 5 and 25 (Figure 1) sometime during the year (Figure 15). Abundance, however, was centered in 16- to 18-foot and deeper stations in Suisun

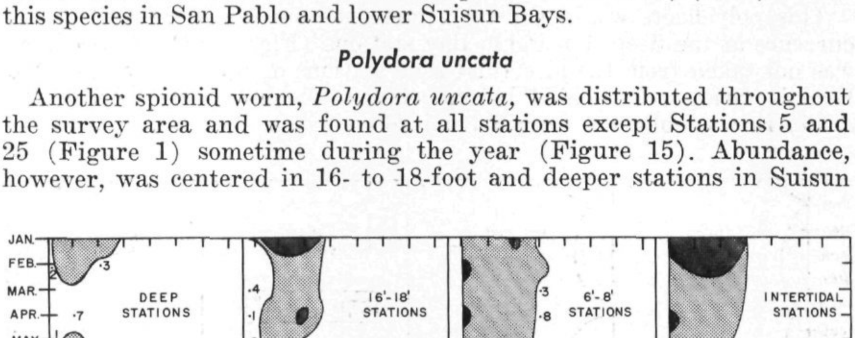

FIGURE 15. Average numbers of *Polydora uncata* per square foot sample each month at four depths along eight transects in the study area.

Bay. Few specimens were taken from deep stations seaward of Port Chicago. Instead, *P. uncata* was found in small concentrations from the 8-foot and shallower stations. *P. uncata* may have avoided deep water in San Pablo Bay because this water typically is 1 of 2 ppt chlorides higher than is shallow water (Table 1). I found *P. uncata* in places where I estimate the bottom salinities ranged from 16 to less than 0.1‰, but most specimens were collected where chlorides were 9‰ or less.

The Peterson dredge is not a good sampler of invertebrates such as crabs and shrimp that are capable of rapid movement. I sampled only two shrimp species, *Crago franciscorum* and *Crago nigracauda*. Both species were taken in San Pablo Bay from deep-water stations. Three crabs, *Rhithropanopeus harrisii* (six specimens), *Cancer magister* (one specimen), and *Pinnixia* sp. (two specimens), were obtained from San Pablo Bay.

Several sedentary species were collected only at one or two stations infrequently during the year. *Pectinaria californiensis,* a polychaete, was taken only at the two most seaward stations of 18 feet and greater depths during five cruises. I found the polychaete *Nereis brandti* only twice, both times at 16- to 18-foot stations in San Pablo Bay. Another polychaete, *Haploscoloplos elongata,* was taken infrequently from deep stations, 30 feet or greater, at the seaward end of San Pablo Bay. The ghost shrimp *Callianassa californiensis* was occasionally taken from the seawardmost stations.

Some species were found at a great number of stations but were never abundant. *Nassarius obsoletus,* the common bay snail, was collected from seven of eight San Pablo stations sometime during the year. Only on three occasions, however, were there more than one snail per square foot sample. The mussel, *Modiolus senhousei,* was collected at least once during the survey from six of eight San Pablo Bay stations. The numbers of *M. senhousei* ranged from 1 to 10 and averaged two per square foot sample when it was present.

DISCUSSION

Substrate-Depth

The influence of depth and substrate on the distribution of any species cannot be separated because these two variables are often functions of each other; i.e., certain depths have certain substrates and no others. The shallow stations in Honker and Grizzly Bays have silt substrates. The deep channel substrates are sand. Thus in Suisun Bay, benthic animals have a choice of bottom types but not at all depths.

In contrast, there was little difference in substrate types at San Pablo Bay stations. Shallow water collections were from clay and silt-clays; deep collections were silt and clays. In San Pablo Bay, the few bottom types present were at all depths. Coarse sediments, however, were lacking at all of the San Pablo Bay stations. A few species were abundant only on one bottom type (Table 4). *Gemma gemma* was numerous only in clay sediments while *Tapes semidecussata* was in silt bottom types. All other species had high population levels on two or more substrates. With each species, however, a question remains: Did these species prefer these substrates, or did the animals exist there because chlorinity, depth, or some other factor was more favorable? I cannot answer this question satisfactorily with the results from this investigation.

It was possible from my survey to demonstrate where species had high population levels with respect to depth (Table 4). Three species, *Macoma inconspicua, Neanthes succinea,* and *Gemma gemma,* had large concentrations only in water 8 feet or less in depth. Four species, *Corophium acherusicum, Glycinde armigera, Polydora uncata,* and *Tapes semidecussata,* had concentrations in water greater than 16 feet deep.

TABLE 4

Bottom Type and Depth at Stations Where Selected Species Were Most Abundant

	Tapes semidecussata	*Gemma gemma*	*Macoma inconspicua*	*Mya arenaria*	*Photis californica*	*Corophium acherusicum*	*Synidotea laticauda*	*Neanthes succinea*	*Glycinde armigera*	*Streblospio benedicti*	*Polydora uncata*
Bottom type											
Sand											X
Silt	X			X	X	X			X	X	X
Silt-clay			X		X	X				X	
Clay		X	X	X	X	X		X	X	X	X
Depth											
Intertidal			X					X		X	
6′ to 8′		X	X	X	X			X		X	
16′ to 18′				X	X	X			X	X	X
"Deep"	X				X	X			X	X	X

Three species, *Mya arenaria, Photis californica,* and *Streblospio benedicti,* were ubiquitous in abundance with respect to depth. With each species a question still remains: Were these species found at certain depths because of a preference for that depth or because of the presence of some other favorable environmental factor, e.g., bottom type or chlorinity?

Chlorinity

Of the many environmental and biological factors in combination that determined the distribution of zoobenthic animals in this estuary, chlorinity was the easiest to identify. The influence of chlorinity could to a large degree be separated from the influence of depth and substrate. Most species were collected over a wide chlorinity range but usually there was a chlorinity concentration outside of which members of a given species were reduced or lacking in numbers (Figure 16). Most of the important fish and game food organisms discussed previously had large concentrations in San Pablo Bay where chlorinities at the bottom were higher and fluctuations less severe and of shorter duration than in Suisun Bay.

Filice (1958) described a "faunal break" in eastern Carquinez Strait. My collections illustrate the same change there. Animals that had high population levels seaward from this area were marine and euryhaline species. Toward fresh water, animals with large concentrations were euryhaline and freshwater species.

Limitations

It was difficult to make positive statements about distributions and abundance of all the species encountered in the survey. In some instances the distribution of a particular species was not random, and I could not determine if this non-randomness was the result of a contagious distribution on the bottom or was caused by some micro-environmental fluctuation. It was especially discouraging when one sample at a station would have a hundred animals and consecutive samples con-

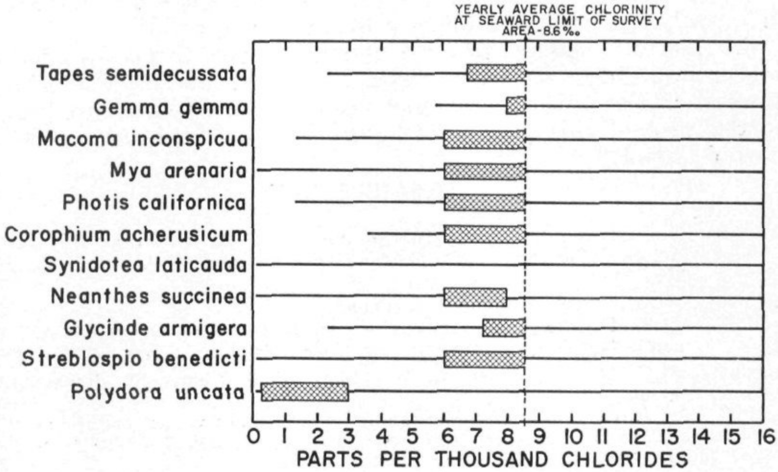

FIGURE 16. Range of chlorinity in which animals were taken (line length) and yearly average range of chlorinity where population levels were highest (bar length).

tained few or none. A lack of time and manpower precluded rigorous sampling procedures to resolve such distributions.

For this reason, only the most obvious of conclusions was made and reported on, and only the most numerous and/or most "important" animals were discussed.

It is obvious that much more study is needed to describe properly the zoobenthos here. More stations, more samples at a station, comprehensive bottom type analyses, frequent chemical information in as well as near the bottom—all these things and more need to be done to achieve a complete understanding of the ecology of the estuary.

SUMMARY

1. Monthly zoobenthic collections at 27 stations were made during 1963. Physical and chemical information and a total of 1107 benthic samples were collected and analyzed.

2. The extent of chlorinity encroachment varied seasonally. Water of 1 ‰ chlorides was displaced to the Carquinez Strait during late winter and early spring floods but 1 ‰ chlorides encroached about 15 miles upestuary to the Pittsburg-Antioch area by August.

3. There is a gross difference in bottom types between San Pablo and Suisun Bays. The deep channel has silt or clay sediments in San Pablo Bay and is primarily sand in Suisun Bay. The extensive shallow flats are clay or silt-clays in San Pablo Bay and are silts in Suisun Bay.

4. More than 40 benthic taxa were recognized of which 11 were of principal importance as fish and game food or were very numerous. The distribution and abundance of these 11 species was discussed in detail.

5. I was not able to separate the effects of substrate and depth on the distribution of zoobenthic species because these two factors were frequently related to each other or to other factors.

6. Chlorinity was the factor contributing most to the distribution of zoobenthos. There was a distinct faunal break, caused by chlorinity, in the eastern Carquinez Strait. Marine and estuarine forms predominated to the west of this area, while estuarine and freshwater species occurred eastward.

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FISHES COLLECTED IN CARQUINEZ STRAIT IN 1961–1962

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INTRODUCTION

During 1961 and 1962, in conjunction with a salmon marking experiment, the Marine Resources Branch of the California Department of Fish and Game conducted periodic midwater trawling in the Carquinez Strait.

Forty-eight species of fish, representing 25 families, were caught (Table 1). The trawl catches serve as a rough index to the concentration of fish residing in the Strait or migrating between Suisun and San Pablo Bay.

METHODS

Trawling was done from the California Department of Fish and Game research vessel *Nautilus* with two square-mouthed midwater trawls. One measured 25 feet on a side and fished with an opening of about 16 by 16 feet. The other was 15 feet on a side and fished with an opening of about 10 by 10 feet. In all, 1,233 20-minute tows were completed (Table 1). Only 233 tows were made with the small trawl, and all but 22 tows were from the surface to the effective fishing depth of the net. During the 22 "deep" tows, the net fished someplace between the surface and 85 feet.

Fishes were identified, counted, and on occasion measured. Numbers were estimated if the catch was extremely large.

Seasonal change in concentration of selected species in the Strait was studied by converting catches to a standard unit of effort—the number of fish per 100 tows. The smaller trawl was used only occasionally except during June when the larger trawl was not available. There were no clear differences in species composition or total catch of the large and small trawls.

RESULTS

The northern anchovy, *Engraulis mordax,* was by far the most abundant species taken. Of the more than 750,000 fish caught, 63 percent were anchovies (Table 1). Anchovies were most densely concentrated in Carquinez Strait from June through August (Figure 1).

The Pacific herring, *Clupea pallasi,* was the second most abundant species, comprising 27 percent of the total (Table 1). Practically all the herring were caught between March and July (Figure 1).

Over 9 percent of the total catch consisted of Sacramento smelt, *Spirinchus thaleichthys,* jacksmelt, *Atherinopsis californiensis,* striped bass, *Roccus saxatilis,* and American shad, *Alosa sapidissima,* in that order (Table 1).

The remaining 42 species of fish made up less than 1 percent of the total catch.

TABLE 1

Monthly Midwater Trawl Catch in Carquinez Strait

Year	1961		1962										
Month	Sept.	Nov.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	
Number of 20-minute tows	64	78	95	94	98	124	210	145	72	101	104	46	
Species	Number of fish												Total
Pacific lamprey *Entosphenus tridentatus*			3	6		3	4	2					18
River lamprey *Lampetra ayresi*				12	3	9	4						28
Gray smoothhound *Mustelus californicus*	1												1
White sturgeon *Acipenser transmontanus*	1									1			2
American shad *Alosa sapidissima*	185	4,699	972	362	520	1,016	507	40	1	161	1,292	1,458	11,213
Pacific herring *Clupea pallasi*	60	77	60	169	5,033	61,262	111,415	17,719	507	1,392	1,085	770	199,715
Threadfin shad *Dorosoma petenense*		1		1		1					5	96	104
Northern anchovy *Engraulis mordax*	27,900	6,450	1,105	1,065	201	10,758	62,333	50,148	122,967	133,645	42,635	11,304	470,518
King salmon *Oncorhynchus tshawytscha*	10	165	41	92	113	296	1,432	1,071	56	19	22	26	3,337
Steelhead rainbow trout *Salmo gairdneri*				4	8	37	33	1		1	12	3	99
Whitebait smelt *Allosmerus elongatus*					2	23	4	1					30
Pond smelt or surf smelt *Hypomesus* sp.			17	1,135	170	47	13	9	3	17	8	1	1,413
Night smelt *Spirinchus starksi*							2	2					4
Sacramento smelt *Spirinchus thaleichthys*			995	2,002	2,830	2,244	13,988	4,138	809	84	290	51	27,931
Goldfish *Carassius auratus*				2	1								3

Carp *Cyprinus carpio*				3	1	7	5	1					17
Sacramento blackfish *Orthodon microlepidotus*						1							1
Splittail *Pogonichthys macrolepidotus*				22	119	89	136	28				1	395
Sacramento squawfish *Ptychocheilus grandis*								1					1
White catfish *Ictalurus catus*				3	2					1			6
Channel catfish *Ictalurus punctatus*			1										1
Pacific saury *Cololabis saira*										1			1
Pacific hake *Merluccius productus*							1						1
Pacific tomcod *Microgadus proximus*		4	56	34	15	7	5	1					122
Threespine stickleback *Gasterosteus aculeatus*		1	11	103	23	33	5	2	1		1		181
Bay pipefish *Syngnathus griseolineatus*		1	1	9	12	69	13				1		106
Striped bass *Roccus saxatilis*	205	1,549	1,346	1,925	1,890	1,576	1,072	3,720	417	348	624	233	15,405
Green sunfish *Lepomis cyanellus*				1	1								2
Bluegill *Lepomis macrochirus*				12	2	2	1						17
Black crappie *Pomoxis nigromaculatus*						1	1						2
White croaker *Genyonemus lineatus*			1		103	31	7			1			143
Shiner perch *Cymatogaster aggregata*		1	2	1	1	13	29	2		1	1		56
Walleye surfperch *Hyperprosopon argenteum*			1			1	3	1			3		10
White seaperch *Phanerodon furcatus*			1										1
Unidentified gobies				2	27	127	13						172
Tidewater goby *Eucyclogobius newberryi*						4	1						5
Bay gobie *Lepidogobius lepidus*						107	71	1					179
Yellowtail rockfish *Sebastodes flavidus*							1						1
Blue rockfish *Sebastodes mystinus*			1										1
Lingcod *Ophiodon elongatus*						1	8						9

TABLE 1—Continued

Monthly Midwater Trawl Catch in Carquinez Strait

Year	1961		1962										
Month	Sept.	Nov.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	
Number of 20-minute tows	64	78	95	94	98	124	210	145	72	101	104	46	
Species	Number of fish												Total
Staghorn sculpin *Leptocottus armatus*		1	1	17	30	146	76	14		5	2	1	295
Cabezon *Scorpaenichthys marmoratus*					1								1
Saddleback gunnel *Pholis ornata*							1						1
Topsmelt *Atherinops affinis*	365	147	5								2		519
Jacksmelt *Atherinopsis californiensis*	21	1		3	35	100	27	15	15,602	2,075	901	135	18,215
Starry flounder *Platichthys stellatus*	1	6	9	3	10	30	81	20	36	4	7	1	208
Sandsole *Psettichthys melanostictus*			2				1						3
Northern midshipman *Porichthys notatus*	3	1		1	1	32	110	48	30	3	57	1	287
													750,780

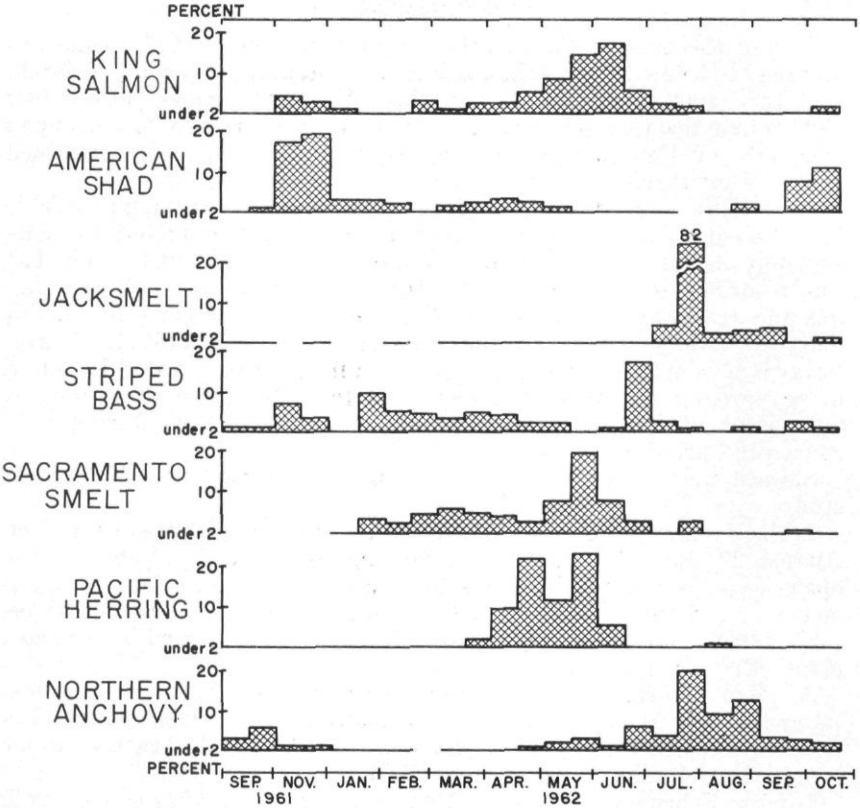

FIGURE 1. Seasonal changes in the Carquinez Strait trawl catch of selected species, September 1961–October 1962. Height of the bars represents percent of total annual catch taken each month.

The Sacramento smelt was common in the Strait from January through July, but rare in our catches during the other months (Figure 1).

Jacksmelt were absent or scarce until midsummer, when they became quite common (Figure 1).

Young striped bass were caught in all months, and although their numbers were highest in June, no apparent seasonal pattern of distribution was evident (Figure 1).

Young American shad were caught at low rates during winter, spring and summer (Figure 1). They were most densely concentrated in Carquinez Strait in the fall of both 1961 and 1962.

Downstream migrant king salmon, *Oncorhynchus tshawytscha,* were caught in all months, but the largest catches were recorded between February and June (Figure 1). A second but smaller group passed through the Strait in the fall.

DISCUSSION

During the survey, the monthly rainfall in central California was average or below average in all but 3 months. In February, March, and April 1962, precipitation was above "normal," river outflow was high, minor flooding occurred, and the chlorinity at Crockett dropped from 11‰ on February 6 to 1‰ on February 18. Chlorinity remained at 5‰ or less through early April.

During these floods, a few freshwater species were caught (Table 1). A smelt, *Hypomesus,* was taken periodically throughout the survey, but in far greater quantities during February 1962. This fish was recorded as the surf smelt, *Hypomesus pretiosus,* but probably was the freshwater pond smelt, *H. transpacificus,* known to inhabit the freshwater end of the estuary (Kimsey and Fisk, 1964). *H. pretiosus* is primarly marine, and it seems unlikely that it would be found in any great numbers in our February 1962 collections. Therefore, I have assumed that the pond smelt was present (at least during February) in Carquinez Strait.

Several unexpected or unusual occurrences were noted during the study.

A Pacific saury, *Cololabis saira,* (29 cm fork length) was caught on August 22, 1962. The saury, a schooling fish normally found in the open ocean, is uncommon in inshore waters and except for one specimen ". . . taken October 18, 1931, in brackish water in the Ain River, . . . Massett Inlet, Queen Charlotte Islands," is unreported in estuarine areas (Pritchard, 1933).

A Pacific hake, *Merluccius productus* (58 cm. fork length), was caught on May 16, 1962. The hake, normally found in ocean waters, has been reported in Puget Sound (Barnhart, 1936) and in brackish water within the Columbia River estuary (Best, 1963).

During February and March 1962, about 100 live king salmon yolk sac fry were collected. By February and March, most king salmon fry have emerged from the gravel of their natal streams and such flows as were experienced during those months in 1962 could sweep them downstream in a very short time. The mouth of the American River, the nearest spawning tributary of the Sacramento River, is about 75 miles above the Carquinez Strait and the mouth of the Molelumne River, the nearest spawning tributary of the San Joaquin River, is 41 miles above the Strait.

Nine lingcod, *Ophiodon elongatus,* were caught during April and May 1962. The lingcod is usually associated with the open coast and rocky bottom, so its presence in the estuary was a little surprising.

ACKNOWLEDGMENTS

I wish to thank the crew of the *Nautilus* for their contributions to the success of the trawling operations, and Aquatic Biologist John L. Thomas who conducted the field operations.

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FISHES AND DECAPODS OF SAN PABLO AND SUISUN BAYS

DAVID GANSSLE

INTRODUCTION

The distribution and abundance of the fishes in the 25-mile section of the Sacramento-San Joaquin River estuary, from San Pablo Bay to the Delta, varies greatly with the changing season and the accompanying changes in freshwater outflow and salinity.

During a 2-year survey of the area, 60 species of fish were recorded. Of these, 31 were typically saltwater forms, 5 were euryhaline but generally associated with the marine environment, 3 were euryhaline but generally associated with the freshwater environment, 13 were freshwater species, and 8 were anadromous.

Freshwater fishes were generally few in number and restricted to the upper end of the estuary. Marine fishes were generally restricted to the lower end of the estuary, and the abundance of several marine species fluctuated widely with season.

The middle portion of the area was characterized by the presence of anadromous and euryhaline species and seasonal immigrations and emigrations of marine and freshwater forms. There appeared to be few resident species.

Ocean salt moved farther upstream during the second year (1964) of the survey and the number of marine species increased. Some species taken in both years moved upstream earlier and farther in 1964 than in 1963.

The food habits of several species were investigated and although many organisms were utilized, one mysid shrimp, *Neomysis awatschensis*, formed an important and probably critical link in their food chain.

METHODS

The survey started in January 1963 and ended in December 1964.

Sampling in 15 to 40 feet of water was conducted from the 50-foot California Department of Fish and Game research vessel *Nautilus*. A 25-foot square-mouthed midwater trawl with a cod-end of ½-inch stretched mesh was towed at the surface, and an otter trawl with a 25-foot cork line and a cod-end of ¾-inch stretched mesh was towed on the bottom. Tows were usually 20 minutes long, and when possible were made alternately with and against the current. Because of variations in weather and tidal or river conditions, it was impossible always to follow the same procedures or sample with equal intensity from month to month (Table 1). During the first 6 months, while sampling and gear handling techniques were perfected, we did not survey the entire area. Routine coverage started in June 1963, and 1 week per month was devoted to the survey until December 1964.

TABLE 1

Number of 10-Minute Trawl Tows and Hours of Gill Net Fishing

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1963						
Pittsburg												
Midwater trawl	1.0	2.0	3.5	1.0	*	4.0	*	7.2	4.3	4.0	4.0	5.0
Otter trawl	*	*	2.0	1.0	*	6.0	*	5.8	4.0	5.0	4.0	4.0
Honker Bay												
Otter trawl	*	*	*	*	*	7.0	*	7.7	6.0	6.0	5.0	*
Gill net	*	*	*	*	*	50.1	*	4.0	4.0	5.0	4.0	3.0
Port Chicago												
Midwater trawl	*	*	*	*	*	4.0	*	3.0	*	2.0	4.0	8.0
Otter trawl	*	*	*	*	*	*	*	3.0	4.0	2.0	1.0	*
Grizzly Bay												
Otter trawl	*	*	*	*	*	2.0	*	8.8	3.0	6.0	*	*
Gill net	*	*	*	*	*	3.0	*	5.5	3.0	4.1	*	*
Martinez												
Midwater trawl	*	*	3.0	2.0	*	2.0	*	3.0	8.0	4.0	4.0	3.0
Otter trawl	*	*	*	2.0	*	2.0	*	10.0	3.0	6.0	6.0	3.4
West Suisun Bay												
Otter trawl	*	*	*	*	*	1.8	*	6.0	7.0	5.6	8.0	*
Gill net	*	*	*	*	*	4.2	*	4.5	3.5	4.8	7.0	3.5
East San Pablo Bay												
Midwater trawl	*	2.0	1.5	3.0	5.0	6.0	*	4.0	2.0	4.0	8.0	4.0
Otter trawl	*	4.5	5.0	2.0	1.0	12.4	*	2.0	1.0	3.0	6.0	2.0
East San Pablo Bay (Shallows)												
Otter trawl	*	7.0	5.0	*	*	*	*	1.0	6.0	8.0	7.0	*
Gill net	*	0.5	4.7	*	*	*	*	4.5	4.0	5.8	4.5	4.5
West San Pablo Bay												
Midwater trawl	*	5.0	6.0	5.0	36.6	12.0	*	11.0	11.0	8.0	3.5	4.0
Otter trawl	*	5.0	5.0	5.0	5.0	*	*	6.0	10.0	4.0	4.0	2.0
						1964						
Pittsburg												
Midwater trawl	*	16.0	12.0	12.0	11.5	10.0	10.0	12.0	12.0	10.0	12.0	10.0
Otter trawl	*	14.2	14.0	12.0	11.0	11.5	11.0	9.5	12.0	12.0	6.0	10.0
Honker Bay												
Otter trawl	8.0	9.8	8.8	8.0	8.0	*	*	*	*	*	*	*
Gill net	5.0	5.0	5.0	5.0	5.0	*	*	*	*	*	*	*
Port Chicago												
Midwater trawl	*	5.5	17.7	12.0	18.5	6.0	6.0	6.0	8.0	6.0	4.0	4.0
Otter trawl	*	*	2.0	*	*	*	*	*	*	*	*	*
Grizzly Bay												
Otter trawl	8.0	10.0	8.0	12.0	10.0	*	*	*	*	*	*	*
Gill net	5.0	5.0	5.5	5.5	4.0	*	*	*	*	*	*	*
Martinez												
Midwater trawl	*	9.0	14.0	11.0	12.0	8.0	6.0	8.0	10.0	4.0	8.0	10.0
Otter trawl	*	5.3	12.0	11.5	7.5	10.0	8.0	6.0	4.0	6.0	6.0	8.0
West Suisun Bay												
Otter trawl	*	4.0	10.0	6.2	10.0	*	*	*	*	*	*	*
Gill net	*	5.0	4.5	4.0	4.0	*	*	*	*	*	*	*
East San Pablo Bay												
Midwater trawl	*	8.0	24.0	15.5	12.0	4.0	4.0	5.5	12.0	10.0	10.0	8.0
Otter trawl	*	8.4	8.0	6.0	16.0	9.0	10.0	14.0	12.0	12.0	8.0	8.0
East San Pablo Bay (Shallows)												
Otter trawl	8.0	10.0	10.0	5.1	12.0	*	*	*	*	*	*	*
Gill net	4.7	5.0	4.2	24.0	5.0	*	*	*	*	*	*	*
West San Pablo Bay												
Midwater trawl	*	4.0	*	*	*	3.1	1.0	*	*	*	*	*
Otter trawl	*	8.0	*	*	*	12.0	3.0	*	*	*	*	*

* Not surveyed.

Data describing the catch of the more important species were combined to show the monthly catch per 10 minutes of trawling with each net in five areas. The areas were 5 to 6 miles long. One area could usually be sampled in a day and each area, with the exception of west San Pablo Bay, contained a California Department of Water Resources chlorinity recording station. They were centered near the towns of Pittsburg, Port Chicago, Martinez, Crockett, and Pinole (Figure 1). Data from the two San Pablo Bay areas were usually combined, as were the data from Port Chicago and Martinez.

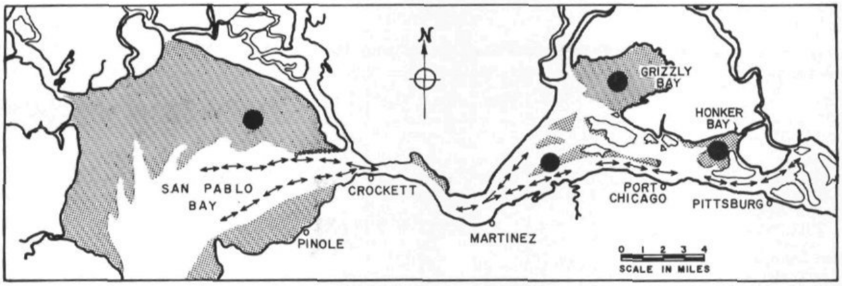

FIGURE 1. Location of sampling areas.

Midwater trawl tows were made outside the ship channel marker buoys. Otter trawl tows were made outside the marker buoys where level, obstruction-free bottom was known to exist. Such bottom conditions were not common in the deep-water portions of Suisun Bay, but it was possible to find favorable otter trawling conditions in most of San Pablo Bay in water 15 to 40 feet deep.

The extensive shallow areas in Honker Bay, Grizzly Bay, western Suisun Bay, and northeastern San Pablo Bay were sampled from a 19-foot launch with an otter trawl and a gill net (Figure 1). The gill net was 450 feet long, 12 feet deep, and had nine, 50-foot sections of different sized ($2\frac{1}{2}$- to 7-inch stretched) mesh. The gill net was usually set in early or midmorning and recovered in early or midafternoon. The otter trawl had a 16-foot cork line, and a $\frac{1}{2}$-inch stretched mesh cod-end and was towed for 10 or 20 minutes. Sampling with the 16-foot otter trawl and gill net started routinely in June 1963 and was stopped in May 1964 (Table 1). Data describing the catch of the more important species were combined to show the monthly catch per 10-minute tow and per 1 hour of gill netting.

In the field, specimens were identified, counted or numbers estimated, and the stomach contents of the more important or abundant species were examined. Stomach samples were not measured volumetrically.

RESULTS

The following discussion of the occurrence and distribution of the animals taken during the survey is, in some cases, based on my impressions and observations. Some of the animals were not vulnerable to our gear and were taken incidentally or in small quantities. Some were quite susceptible to the nets at one size but not at another, so accurate quantitative comparisons were not possible.

The animals are listed in systematic order, and alphabetically by common name within major groups. Following the name of each species, a short summary including the habitat it is usually associated with, total number caught, gear with which the animal was caught, area, date, and size range is given. The more abundant or economically important species are dealt with in more detail, and where appropriate, more data are presented.

Invertebrates

Colonial hydroid, Hydrozoa. Freshwater.

Taken incidentally by otter trawl throughout Suisun Bay, never in San Pablo Bay. Not identified, but presumed to be *Cordylophora lacustris* which is known to be in the lower Delta (Aldrich, 1961).

Small jellyfish, Scyphozoa. Marine.

Incidentally in midwater trawl in San Pablo Bay year-round; a few from Martinez to Pittsburg in spring, summer, and fall.

Comb jelly, Ctenophora. Marine.

About 200. San Pablo Bay, April 1964.

Bay snail, *Nassarius obsoletus*. Marine.

Common, often abundant in San Pablo Bay, but rare east of Carquinez Strait.

Asiatic clam, *Corbicula fluminea*. Freshwater. Introduced.

Occasionally at Pittsburg, Honker Bay, Martinez.

This clam is abundant in the freshwater portion of the Sacramento-San Joaquin Delta, where at times, it forms large beds and becomes a problem in irrigation and drainage works.

Basket cockle, *Clinocardium nuttalli*. Marine.

Occasionally, San Pablo Bay.

Bent-nose clam, *Macoma nasuta*. Marine.

Occasionally, San Pablo Bay.

Mud clam, *Macoma inconspicua*. Marine.

Occasionally, San Pablo Bay.

Japanese littleneck, *Tapes semidecussata*. Marine. Introduced.

Occasionally, San Pablo Bay.

Mussel, *Modiolus* sp. Marine.

Occasionally, San Pablo Bay.

Native oyster, *Ostrea lurida*. Marine.

Occasionally, San Pablo Bay.

Soft-shell clam, *Mya arenaria*. Marine. Introduced.

Occasionally, San Pablo Bay.

Isopod, *Synidotea laticauda*. Marine.

A few at Pittsburg and Crockett, but most abundant at Port Chicago and Martinez in spring and summer of 1964.

Opossum shrimp, *Neomysis awatschensis*. Euryhaline.

This mysid, although too small to be properly sampled by our nets, was at times so abundant that thousands were retained in the webbing or mixed in with the catches of the midwater trawl. Heavy concentrations were observed off Martinez in March 1963 and off Pittsburg, Port Chicago, and Martinez in April and May 1964. Lesser numbers were taken at Crockett during March 1963 and May 1964.

Oriental shrimp, *Paleomon macrodactylus*. Euryhaline. Introduced.

No one knows when or by whom this shrimp was introduced into California. Although never common, it was taken most often in Suisun Bay during April, September, and October and in San Pablo Bay during March and April. Many more were taken in Suisun Bay than in San Pablo Bay. In the spring, small shrimp predominated. In the fall, larger individuals and some egg-carrying females were observed.

Bay shrimp, *Crago*. Marine-Euryhaline.

Bay shrimp, at one time, supported a large commercial fishery in San Francisco Bay. Two species, *Crago franciscorum*, and *Crago nigracauda*, made up almost all of the commercial catch. A third species, *Crago nigromaculata*, was of little importance to the fishery (Bonnot, 1931; Skinner, 1962).

Israel (1936) studied the life histories of the three species from June 1931 to June 1933. He found that *C. franciscorum* was the most tolerant of fresh water and was found 70 miles from the Golden Gate in the San Joaquin River. He also found that both *C. franciscorum* and *C. nigracauda* moved toward the ocean as the spawning season approached and the eggs hatched in water of high salinity. Both species reproduced at the end of their first year, *C. franciscorum* from December to June, and *C. nigracauda* from April to September. Young shrimp were found at some distance from the ocean in water of reduced salinity.

Our nets caught *C. franciscorum* almost exclusively. *C. nigracauda* was caught in small numbers only during May and June 1964 in San Pablo Bay. *C. nigromaculata* was never knowingly taken.

We caught no bay shrimp above Carquinez Strait from February through April 1963, and only relatively small numbers in San Pablo Bay (Figure 2). From August through December 1963, shrimp were present throughout the survey area. Abundance was lowest off Pittsburg.

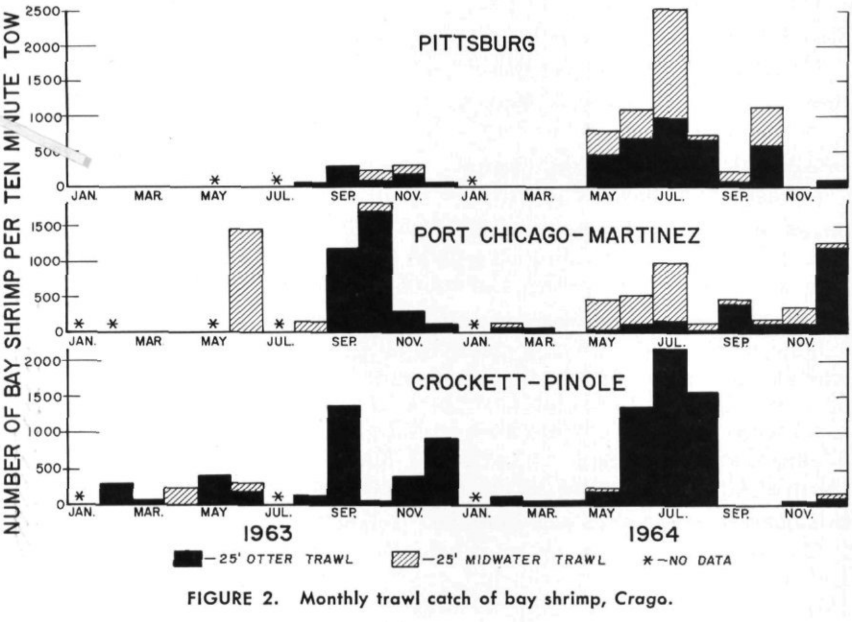

FIGURE 2. Monthly trawl catch of bay shrimp, *Crago*.

A few bay shrimp remained in San Pablo Bay and western Suisun Bay from February to May 1964. We caught none off Pittsburg during that period.

In contrast to the summer of 1963, *C. franciscorum* was abundant off Pittsburg during the summer of 1964. Catches were somewhat smaller than in 1963 at Martinez and Port Chicago.

From September to December 1964, shrimp all but disappeared from San Pablo Bay. Although catches were variable in Suisun Bay, shrimp remained there until the end of the survey.

We kept no record of the size composition of the catch. But it is my opinion that small shrimp were more common in Suisun Bay than in San Pablo Bay.

Market crab, *Cancer magister*. Marine.

From July to December 1963, 33 small (4 to 10 cm) *C. magister* were caught in the San Pablo Bay otter trawl. Between May and December of 1964, over 2,000, in the same size range, were caught in the same area. At times they were taken at a rate of more than 200 per 10-minute tow.

No crabs were taken above Carquinez Strait in 1963 but 56 individuals 4 to 14 cm wide were caught near Martinez from July to December 1964.

Ascidian, *Molgula verrucifera*. Marine.

At times *M. verrucifera* was so abundant in San Pablo Bay bottom tows that it was impossible to haul the trawl aboard by hand. We never found it east of Crockett.

FISHES

Pacific lamprey, *Entosphenus tridentatus*. Anadromous.

Total—3. Midwater trawl. Martinez: April 1964; 66 cm.

San Pablo Bay: May 1963; 59 to 64 cm.

The Pacific lamprey is found in nearly all California streams which enter the ocean, unless blocked by barriers or low flows. Adults often start their spawning migration into fresh water in the fall and in some rivers these migrations continue into the spring, when masses of lampreys are seen ascending obstructions and fish ladders (Kimsey and Fisk, 1964).

After spending 3 or 4 years in their natal stream, young Pacific lampreys, when about 15 cm long, migrate to sea.

The Pacific lamprey parasitizes other fishes, but apparently without the disastrous result attributed to the sea lamprey of the Atlantic.

Unidentified lamprey. Anadromous.

Total—6. Midwater trawl. Suisun Bay: November 1963–May 1964; 11 to 18 cm. San Pablo Bay: October 1963–May 1964; 15 to 18 cm.

These were either downstream migrant Pacific lampreys or river lampreys, *Lampetra ayresi*. Little is known about the habits and behavior of the river lamprey, but it is found in central California streams and is probably responsible for most of the attacks on fish in California streams (Kimsey and Fisk, 1964).

Brown smoothhound, *Triakis henlei*. Marine.

Total—42. Otter trawl. San Pablo Bay.

This shark was taken from late spring to late summer in both years. About 60 percent of those taken were 22 to 35 cm long and 40 percent were 40 to 69 cm long.

One individual containing identifiable food had been eating *Crago franciscorum*.

Dogfish, *Squalus acanthias*. Marine.

Total—4. Gill net. San Pablo Bay: April 1964. Females, 75 to 87 cm long, all containing well developed embryos.

Big skate, *Raja binoculata*. Marine.

Total—47. Otter trawl. San Pablo Bay.

Skates were caught in September and November 1963 and February, March, May, June, October, and December 1964. Over 70 percent were 10 to 20 cm wide, and the rest were from 25 to 60 cm.

Bat ray, *Myliobatis californicus*. Marine.

Total—1. Otter trawl. San Pablo Bay: July 1964; 70 cm wide.

Green sturgeon, *Acipenser medirostris*. Anadromous.

Total—34. Gill net, otter trawl. Suisun Bay, San Pablo Bay.

Almost nothing is known about the life history and behavior of the green sturgeon in California.

The greatest gill net catch was recorded in September, in San Pablo Bay. Otter trawl tows showed no particular pattern of distribution or abundance. However, in Suisun Bay, 67 percent of the green sturgeon were 27 to 35 cm long, and 33 percent were 40 to 48 cm long, while in San Pablo Bay, 1 fish (5 percent) was 25 cm long and 95 percent were between 40 and 74 cm long.

Five sturgeon stomachs collected in Suisun Bay contained identifiable material, which included: *Corophium* sp., annelid worms, *Crago franciscorum*, and *Neomysis awatchensis*.

Eight stomachs from San Pablo Bay contained: *Crago franciscorum*, *Macoma* sp., the amphipod *Photis californica*, *Corophium* sp., *Synidotea laticauda*, unindentified crab, and fish.

White sturgeon, *Acipenser transmontanus*. Anadromous.

Total—146. Gill net, otter trawl. Suisun Bay, San Pablo Bay.

The white sturgeon was once fished commercially in the estuary but has been protected since 1917. A minor but growing sport fishery exists with most catches recorded in late summer and fall in San Pablo Bay (Skinner, 1962). The results of a tagging program conducted in 1954–55 suggest a winter or spring upstream migration and a summer downstream migration of large white sturgeon in the estuary (Pycha, 1956).

We took the greatest number of large white sturgeon in San Pablo Bay in October and November 1963. Sturgeon were common enough at that time that several were taken in the 16-foot otter trawl. Although catches were never large in Suisun Bay, gill netting was most successful there in April, May, and June.

In Suisun Bay, 71 percent of the fish were between 23 and 35 cm long and 29 percent were 40 to 90 cm long. In San Pablo Bay, 3 percent were between 23 and 35 cm, and 97 percent were from 60 to 120 cm long.

Thirty-nine white sturgeon stomachs collected from Suisun Bay contained identifiable food. In order of their frequency of occurrence, the following organisms were found: *Neomysis awatschensis, Corophium* sp., *Crago franciscorum, Paleomon macrodactylus, Synidotea laticauda,* clam remains, and annelid worms.

In San Pablo Bay, 25 stomachs contained identifiable food. It included clams (mostly *Macoma* sp.), annelid worms, *Synidotea laticauda, Crago franciscorum,* fish eggs, *Corophium* sp., *Photis californica* and unidentifiable crab.

American shad, *Alosa sapidissima*. Anadromous. Introduced.

Total—about 6,200. Gill net 188, midwater trawl 5,872, otter trawl 200. Suisun Bay, San Pablo Bay.

American shad were introduced into California in 1871. Within a few years a commercial gill net fishery had developed and the fish were so abundant that they were considered a nuisance. The estuary was closed to commercial fishing in 1957 (Skinner, 1962).

Shad spend most of their life at sea and little is known of their movements there. Adults enter the estuary in early spring and proceed upstream to spawn in fresh water. Skinner (1955) analyzed the commercial shad fishing records for the 9-year period of 1946–1954. He found that 88 percent of the shad caught between Martinez and Pittsburg were landed during the 7-week period from April 10 to May 29.

Ripe or ripening adult shad were taken in our gill nets from February through June. An occasional adult was caught by midwater trawl during the same months. In Grizzly Bay in September 1963, 11 adults with "spent" gonads were caught. No one knows how many (if any) shad in California survive spawning and return to the ocean. This fall catch of spent shad suggests that some do.

We examined 72 adult shad stomachs which contained identifiable food. They held, in order of the frequency of occurrence, *Neomysis awatschensis,* copepods, *Crago franciscorum,* larval fish, and *Corophium* sp. Hatton (1940) found after examining 109 adult shad stomachs from fish taken in Suisun Bay that two-thirds of them contained *Neomysis awatschensis* and one-third copepods.

Shad spawn upstream from our survey area. Hatton (1940) observed spawning shad in the upper Delta and the streams flowing into it. He reported spawning along the entire length of the Sacramento River and far upstream in some of its tributaries. Hatton believed that even though shad did move into the San Joaquin River, it was not used extensively as a spawning area.

The results of studies by the California Department of Fish and Game as well as the consensus among residents of the area indicates that most spawning now takes place in the Sacramento River and its tributaries above the Delta.

In California, shad spawn in the spring and summer. Eggs or small larvae have been found in the Delta as early as April and as late as October Erkkila *et al.,* 1950; Chadwick, 1958). Hatton (1940) first collected young shad at his Martinez station on May 4, 1939. He further reported that the "migration" continued until January 1940.

At Pittsburg, we first took young of the 1963 year-class in August of that year (Figure 3). A peak was reached in November, and following a decline in December, catches of small shad were low until August 1964 when young of the 1964 year-class were caught. While apparently not as abundant at Pittsburg as the 1963 year-class, the 1964 year-class was taken in moderate numbers until the end of our survey.

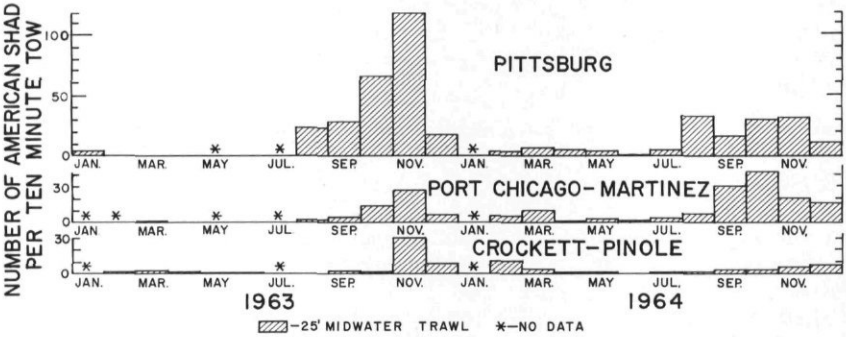

FIGURE 3. Monthly trawl catch of young-of-the-year American shad, *Alosa sapidissima*.

At Port Chicago and Martinez almost no small shad were caught until August and September 1963. The 1963 year-class reached a low peak of abundance in November. After that, catches were generally low until July 1964, when the 1964 year-class appeared. That year-class reached a peak in November and was commonly taken in December.

In San Pablo Bay, low numbers of the 1962 year-class (6 to 12 months old) were taken from February through June 1963 (Figure 3). In September, a few 1963 year-class shad appeared and a low peak was reached in November. Some small shad were caught in San Pablo Bay until the end of the survey, but only a few 1964 year-class fish were found.

Identifiable food was found in 59 young-of-the-year shad. Food items, in the order of their occurrence, were: *Neomysis awatschensis*, copepods, larval fish, and *Corophium* sp.

Many of the trawl tows, in addition to young-of-the-year shad, yielded a few larger fish that were in their second year of life. Although no accurate record of the occurrence of these yearlings was kept, they were recorded from all areas and at times made up as much as 10 percent of the catch.

Nine yearlings contained identifiable food which consisted of *Neomysis awatschensis* and copepods.

Pacific herring, *Clupea pallasi*. Marine.

Total—about 100,000. Midwater trawl, Suisun Bay, San Pablo Bay.

Adult herring enter San Francisco Bay in the winter and spring, spawn, and return to the sea immediately. Most spawning takes place in San Francisco Bay near Tiburon and Sausalito. However, during past dry periods spawning has been reported in San Pablo Bay and Carquinez Strait. It is generally believed that reduced salinity limits upstream spawning (Miller and Schmidtke, 1956).

In San Pablo Bay, we caught small numbers (less than one fish per tow) of ripe or ripening adult herring in February 1963. No adults were found at Pittsburg that year but occasionally they were taken near Martinez. Newly-hatched herring appeared in San Pablo Bay in February and March 1963 (Figure 4). They increased in number to a peak of several hundred per tow in May and June. A few were caught in August and young-of-the-year were almost totally absent from September 1963 on. A few (less than one per tow) young of the 1963 year-class were taken near Martinez and Port Chicago in June and August 1963.

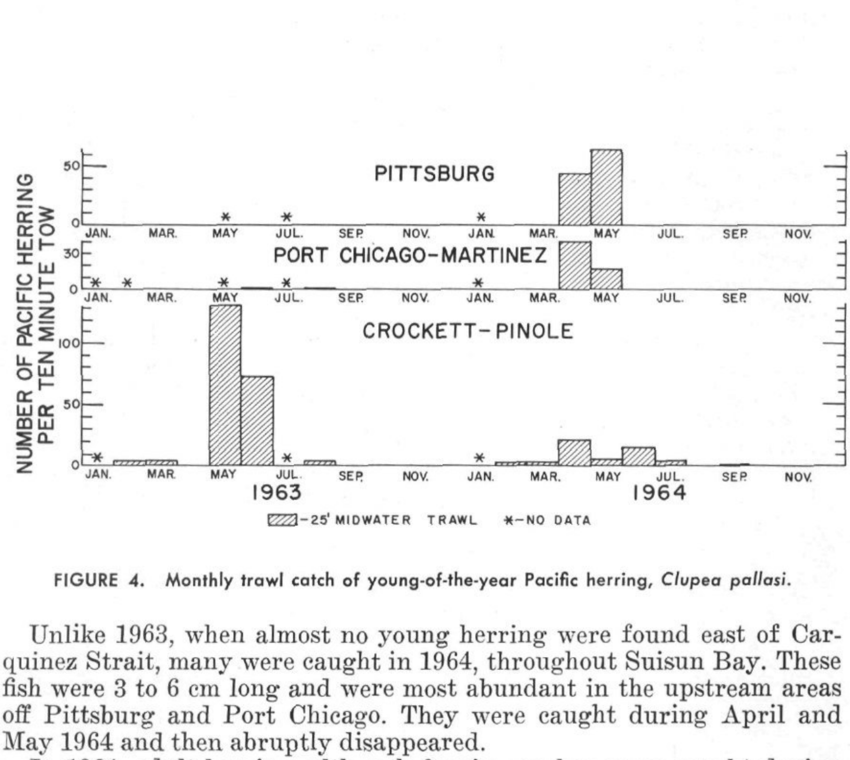

FIGURE 4. Monthly trawl catch of young-of-the-year Pacific herring, *Clupea pallasi*.

Unlike 1963, when almost no young herring were found east of Carquinez Strait, many were caught in 1964, throughout Suisun Bay. These fish were 3 to 6 cm long and were most abundant in the upstream areas off Pittsburg and Port Chicago. They were caught during April and May 1964 and then abruptly disappeared.

In 1964, adult herring, although few in number, were caught during January, February, and March in San Pablo Bay. Young of the 1964 spawning appeared in San Pablo Bay in April, May, and June but were not as plentiful as the 1963 year-class (Figure 4).

Threadfin shad, *Dorosoma petenense*. Fresh water—Euryhaline. Introduced.

Total—2,050. Midwater trawl. Suisun Bay, San Pablo Bay.

The threadfin shad was introduced into California, from Tennessee, in 1953. It is present in many central California reservoirs and has, in recent years, become established in the Sacramento-San Joaquin Delta. It has become an important food of larger fishes in many areas. The threadfin shad spawns at intervals after the water temperature reaches about 21° C. and ceases in the fall when the temperature drops below this (Kimsey and Fisk, 1964).

During September, October, and November of 1963 and 1964, threadfin shad were commonly caught off Pittsburg and Port Chicago. Peak catches of from 50 to 80 fish per tow were reached in November. Smaller catches were made off Martinez during the same months.

No threadfin shad were found in San Pablo Bay until November and December of 1963, when 3 to 5 fish per tow were caught. In November and December of 1964, threadfin shad were again caught at low rates.

Northern anchovy, *Engraulis mordax*. Marine.

Total—about 120,000. Midwater trawl.

Anchovies enter San Francisco Bay in spring and summer, but little is known about the amount of spawning that takes place in the bay. World wide, anchovies spawn over a broad range of conditions from oceanic to estuarine.

A smaller "brackish water" subspecies of *E. mordax* was reported in San Francisco Bay (Roedel, 1953), but we made no attempt to identify or separate it.

In late spring and summer of both 1963 and 1964, many anchovies entered San Pablo Bay (Figure 5). All ages, including many ripe and ripening adults up to 17 cm in length, were caught. As summer progressed, the proportion of large fish decreased until, in the fall and early winter, only recently-born and some 1- or 2-year-old fish were found.

Fewer anchovies were caught above Carquinez Strait but the proportion of young to adults was about the same as in San Pablo Bay. No anchovies were taken in the Pittsburg area until August 1964.

Only seven anchovies containing identifiable food were examined. All had been feeding on the copepod *Acartia clausi*.

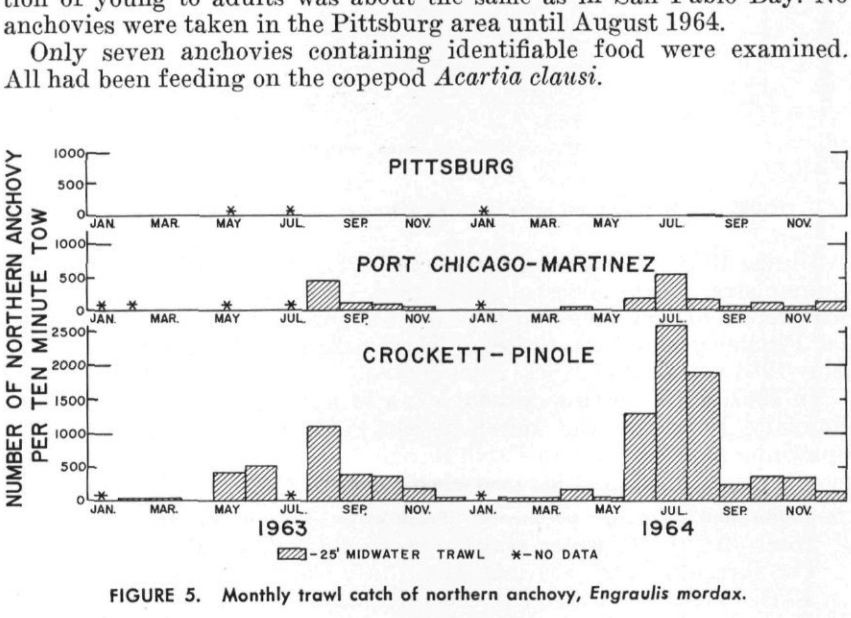

FIGURE 5. Monthly trawl catch of northern anchovy, *Engraulis mordax*.

King salmon, *Oncorhynchus tshawytscha*. Anadromous.

Total—682. Gill net, midwater trawl. Suisun Bay, San Pablo Bay.

The Sacramento-San Joaquin River run of king salmon is one of the largest on the Pacific Coast. In the past 15 years, estimates of spawning adults have ranged from 100,000 to 500,000 annually. Most mature fish move upstream in the fall, but there is a smaller spring run and a still smaller winter run (Fry, 1961; Skinner, 1962). Some mature king salmon are probably in the estuary during all months of the year.

The general movement of upstream migrant salmon in the estuary is well understood. We made no special effort to catch them and our nets were not designed or set to do so. During the survey, we caught only 20 adult or precocious male king salmon, all in Suisun Bay. Most (18) were fall-run fish and were taken between August and November. One was caught in May and one in June.

It is generally accepted that mature salmon do not feed while in fresh water. The stomachs of all those we caught were empty.

Young salmon move downstream soon after they emerge from the gravel. In the past, the peak of the downstream migration has been observed from February to April (Rutter, 1903; Hatton, 1940; Erkkila *et al.*, 1950).

Downstream migrants were present in almost all months and apparent peaks of abundance were reached during April, May, or June and November (Figure 6). In the spring, these young fish were from 6 to 10 cm long while in the fall, they were 10 to 17 cm long.

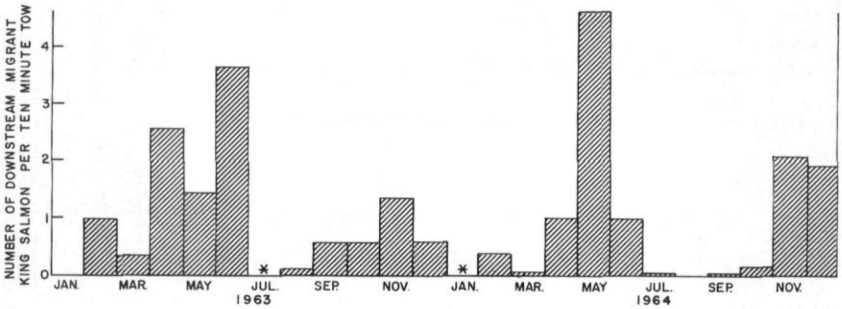

FIGURE 6. Monthly trawl catch of downstream migrant young-of-the-year king salmon, *Oncorhynchus tshawytscha*.

In Suisun Bay, the stomachs of 37 small (7 to 15 cm) salmon held identifiable food. Terrestrial insects and spiders were present in 32, *Neomysis awatschensis* in 14, *Synidotea laticauda* in 1, and *Corophium* sp. in 1.

In San Pablo Bay, 25 downstream migrants contained identifiable food. Of these, 17 had been eating terrestrial insects or spiders. *Neomysis awatschensis* was found in 5, "fish" in 4, and *Crago franciscorum* in 1.

Rutter (1903) and N. B. Scofield (1913) found insects to be the most important food item in the diet of downstream migrant king salmon.

Steelhead rainbow trout, *Salmo gairdneri*. Andromous.

Total—26. Gill net, midwater trawl. Suisun Bay.

After hatching, steelhead trout remain in fresh water for 2 or more years. Little is known of their habits in the ocean. In a large river such as the Sacramento, upstream and downstream migrants are present at all times but the bulk of the spawning fish move upstream in the winter and spring (Shapovalov and Taft, 1954).

We caught steelhead in every month but June, July, November, and December. Their size ranged from 24 to 64 cm.

Only two steelhead containing identifiable food were examined, each had been eating insects and *Synidotea laticauda*.

Night smelt, *Spirinchus starksi*. Marine.

Total—7. Midwater trawl. San Pablo Bay. February–March 1963.

Pond smelt, *Hypomesus transpacificus*. Fresh water—Euryhaline.

Total—about 7,100. Midwater trawl. Suisun Bay, San Pablo Bay.

Almost all pond smelt were found in Suisun Bay (Figure 7). Highest catches were made in summer and fall at Pittsburg. Small fish, 2 to 5 cm long, appeared in June and July and very few individuals greater than 8 or 9 cm were ever caught.

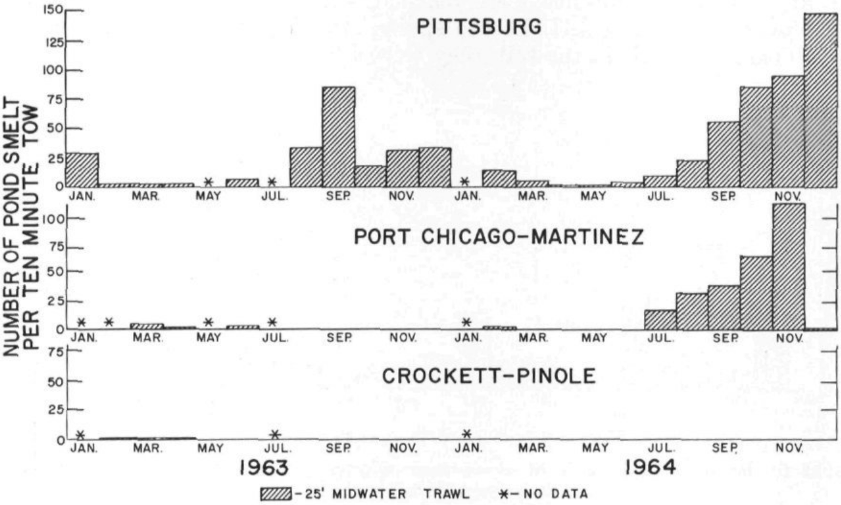

FIGURE 7. Monthly trawl catch of pond smelt, Hypomesus transpacificus.

Sacramento smelt, *Spirinchus thaleichthys*. Marine-Euryhaline.

Total—at least 20,000. Midwater trawl, otter trawl. Suisun Bay, San Pablo Bay.

Ripening adults (8–10 cm) were found in San Pablo Bay and western Suisun Bay in March and April 1963 (Figure 8). In May, a large number of 2 to 6 cm smelt appeared in the Crockett-Pinole area. It was not possible to count or estimate the catch reliably at this time because many of the small fish were not retained in our nets.

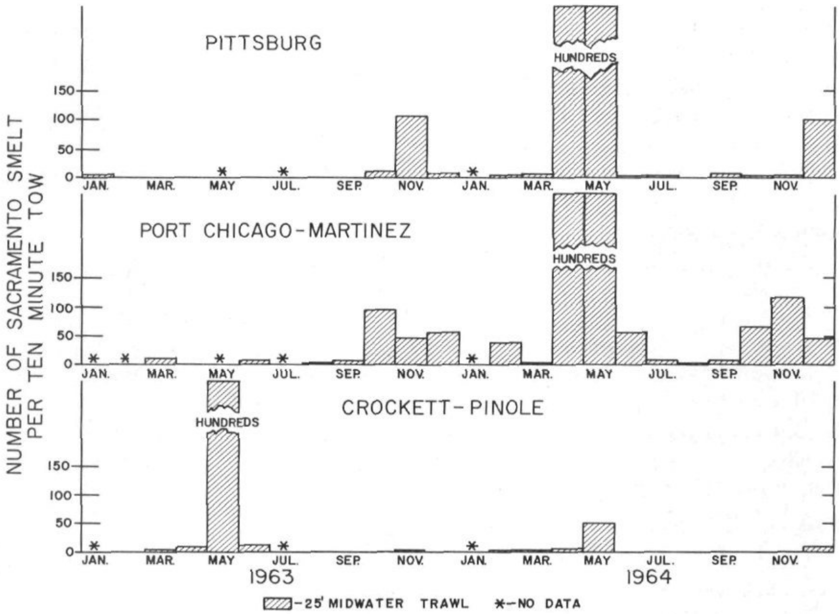

FIGURE 8. Monthly trawl catch of Sacramento smelt, *Spirinchus thaleichthys.*

By August 1963 almost all Sacramento smelt had disappeared from San Pablo Bay. They were caught in Suisun Bay where they remained through the winter.

Small *S. thaleichthys*, 2 to 6 cm long, were abundant off Pittsburg, Port Chicago, and Martinez during April and May 1964, but were relatively uncommon in San Pablo Bay. Again, many of the fish passed through our nets and reliable counts were not possible. After a summer decrease, catches increased in October, November, and December. At that time, two sizes of smelt were in evidence; one group at 6 to 8 cm, and another of ripening adults at 10 to 13 cm.

Surf smelt, *Hypomesus pretiosus*. Marine.

Total—8. Midwater trawl. Suisun Bay: March–April 1964, 12 to 19 cm. San Pablo Bay: March 1963, 8 cm; February–March 1964, 8 to 12 cm.

Whitebait, *Allosmerus elongatus*. Marine.

Total—2. Midwater trawl. San Pablo Bay: May 1963, 12 cm; February 1964, 7 cm.

Carp, *Cyprinus carpio*. Fresh water. Introduced.

Total—458. Gill net, midwater trawl, otter trawl. Suisun Bay.

The largest catches of carp were made in the shallows of Honker and Grizzly Bays during spring months. However, one otter trawl tow off Port Chicago in September 1963 yielded 25 large carp.

Goldfish, *Carassius auratus*. Fresh water. Introduced.

Total—1. Gill net. Honker Bay: November 1963, 20 cm.

Sacramento blackfish, *Orthodon microlepidotus*. Fresh water.

Total—4. Gill net, otter trawl. Honker Bay, Grizzly Bay, Martinez: March, April 1963 and 1964, 25 to 42 cm.

Sacramento squawfish, *Ptychocheilus grandis*. Fresh water.

Total—6. Gill net, midwater trawl. Pittsburg, Honker Bay, Grizzly Bay: June, September 1963, February 1964, 39 to 52 cm.

One squawfish with identifiable food had been eating small striped bass.

Splittail, *Pogonichthys macrolepidotus*. Fresh water.

Total—291. Gill net, midwater trawl, otter trawl. Suisun Bay, San Pablo Bay.

Splittail were distributed much the same as carp. Highest catches were made in Honker and Grizzly Bays, but two fish were caught in San Pablo Bay. Two size groups, one between 10 and 15 cm and one with a mean length of 25 cm, were about equally represented.

Sacramento western sucker, *Catostomus occidentalis*. Fresh water.

Total—3. Gill net, otter trawl. Honker Bay: June, October 1963, February 1964, 39 to 47 cm.

Black bullhead, *Ictalurus melas*. Fresh water. Introduced.

Total—1. Gill net. Honker Bay: February 1964, 29 cm.

Brown bullhead, *Ictalurus nebulosus*. Fresh water. Introduced.

Total—1. Otter trawl. Grizzly Bay: March 1964, 15 cm.

White catfish, *Ictalurus catus*. Fresh water. Introduced.

Total—53. Gill net, midwater trawl, otter trawl. Suisun Bay.

White catfish were found all over Suisun Bay, with the best catches recorded in Honker Bay. Most were between 20 and 40 cm long but a few as small as 15 cm long were taken.

We examined the stomachs of 28 white catfish containing identifiable food. *Neomysis awatschensis* was found in 24, *Corophium* sp. in 14, *Crago franciscorum* in 6, and *Paleomon macrodactylus*, annelid, clam and fish in each.

Pacific tomcod, *Microgadus proximus*. Marine.

Total—259. Midwater trawl, otter trawl. Suisun Bay, San Pablo Bay.

Over 80 percent of the tomcod were taken in San Pablo Bay. All but one (caught at Port Chicago) of the remainder were found near Martinez. The fish ranged from 7 to 23 cm in length. No particular pattern of seasonal distribution or abundance was apparent.

Only one specimen containing food was examined; it had been feeding on *Crago franciscorum*.

Threespine stickleback, *Gasterosteus aculeatus*. Fresh water—Euryhaline.

Total—11. Midwater trawl, otter trawl. Suisun Bay, San Pablo Bay: March, May, August 1963, April, May, July 1964, 2 to 3 cm.

Bay pipefish, *Syngnathus griseolineatus*. Marine.

Total—2. Midwater trawl. San Pablo Bay: March 1963, February 1964, 20 to 23 cm.

Striped Bass, *Roccus saxatilis*. Anadromous. Introduced.

Total—About 16,000. Gill net, midwater trawl, otter trawl. Suisun Bay, San Pablo Bay.

Striped bass were introduced into California in 1879. They soon became established in the Sacramento-San Joaquin River system, and in a few years supported large commercial and sport fisheries (Skinner, 1962). Commercial fishing was outlawed in 1935, but the sport fishery is still the most important in the area.

Striped bass are migratory fish. As they pass through various stages of their life history, they travel to different areas within the Sacramento-San Joaquin River system.

Calhoun (1952), after analyzing the results of tagging studies conducted in 1947, 1950, and 1951, felt that in the summer months, adult bass are distributed mainly in San Francisco Bay and the ocean. In the fall and winter most of them move upstream to San Pablo Bay, Suisun Bay, and the Delta. In the spring the spawning population moves farther upstream where they spawn, mostly during May and June, in fresh water of 15°C or higher. After spawning, most large fish return to the lower bays and the ocean (Calhoun, 1952).

We did not feel that our gear sampled the adult population adequately. However, our limited catches did indicate that large bass were generally most abundant in Suisun Bay in the summer and fall and in San Pablo Bay in the fall and winter (Figure 9). The large catch of February 1963 was based on a $\frac{1}{2}$-hour experimental gill net set.

Striped bass eggs are free-floating and hatch in 2 or 3 days. The larvae are feeble swimmers and for 1 or 2 weeks are at the mercy of the current. In the Sacramento-San Joaquin River system they are carried downstream to the Delta and upper bays at a rate depending on the magnitude of river outflow (Calhoun and Woodhull, 1948; Erkkila *et al.*, 1950). Scofield and Bryant (1926) reported that young bass were plentiful in San Francisco Bay and the upper bays until the cold of winter set in. They believed that at this time a seaward migration took place.

Our survey started when the 1962 year-class of striped bass was 7 to 9 months old. That year-class was rare in Suisun Bay but relatively common in the San Pablo Bay channel in the winter and spring of 1963 (Figure 10).

Young of the 1963 year-class were first caught off Pittsburg and in Honker and Grizzly Bays during August 1963. Catches reached a peak in Honker and Grizzly Bays in September and started to decline in Ocotber. Only a few fish were caught in January 1964. In deeper water off Pittsburg, concentrations were high from September, when most fish were caught in the otter trawl, to November, when most fish were caught in the midwater trawl. A decline took place in December. Concentrations in all three areas were generally low from January through May 1964. But, a slight spring increase in catch occurred in all three areas. This increase could have reflected the entrance into Suisun Bay of young-of-the-year that had remaind upstream and were moving downstream with the increased spring flows.

Off Port Chicago and Martinez, the concentration of 1963 year-class fish, compared to the upstream area, was generally uniform and low.

No 1963 year-class fish were taken in San Pablo Bay until September 1963 (Figure 10). Abundance was high in October, and although de-

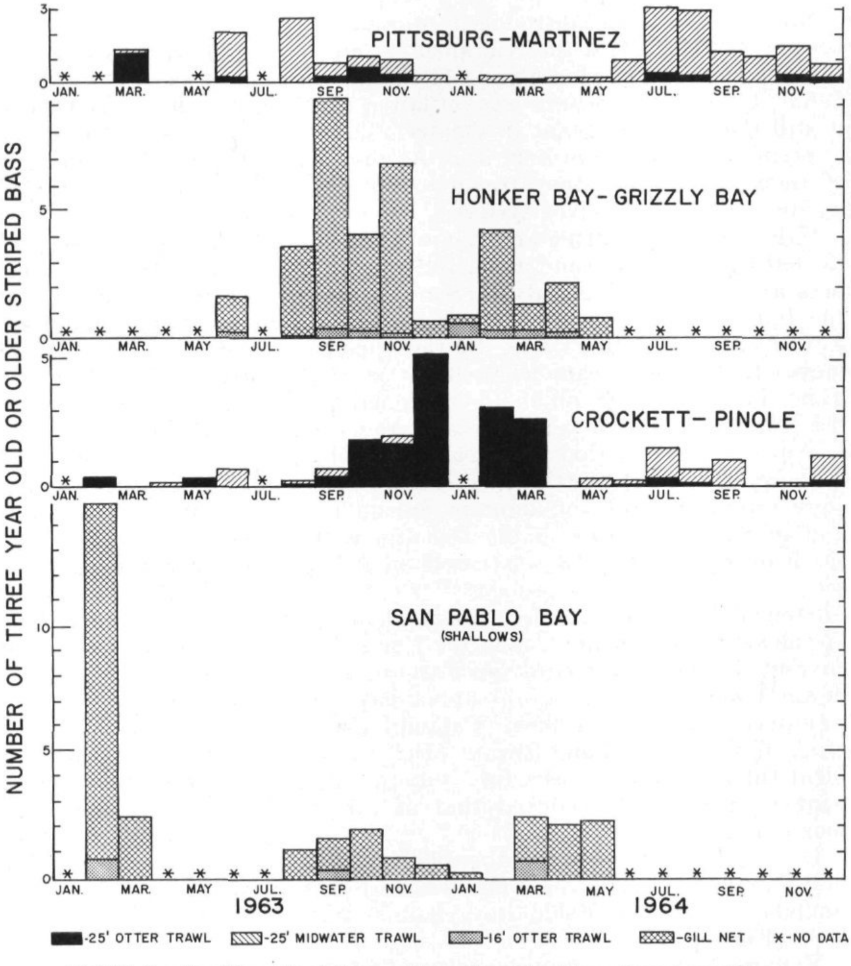

FIGURE 9. Monthly catch of 3-year-old or older striped bass, *Roccus saxatilis.*

clining during November and December, remained relatively high during those months. Young bass were still present in February, March, and April 1964, but were absent in May.

The 1964 year-class started to appear off Pittsburg in June 1964. High abundance was reached in July and from August on the catch fluctuated to a low in December (Figure 10).

At Port Chicago and Martinez, young bass seemed to be present in about the same small quantities as the preceding year.

Few 1964 year-class fish were caught in San Pablo Bay (Figure 10).

At times, the highest catches of young striped bass were made with the 16-foot otter trawl in Honker and Grizzly Bays (Figure 10). The high catches of young-of-the-year fish with this small trawl in the shallows of Suisun Bay led me to believe that such areas are preferred by young bass in their first few months of life.

The migration and distribution of juvenile striped bass (1 to 3 years old) is not well documented. Scofield and Bryant (1926) felt that juveniles as well as young-of-the-year left San Francisco Bay in the winter and spread up and down the coast. Tagging studies by G. H. Clark (1936) did not indicate a migratory pattern, but simply a diffusion from the point of tagging. Calhoun (1949) showed a distribution of 2- to 3-pound bass throughout the Sacramento-San Joaquin system, except for upper and lower San Francisco Bay. Especially heavy catches were made in Suisun Bay during summer and fall.

We took yearling bass during most months in most places where we collected (Figure 11). They were especially concentrated in the Crockett-Pinole area during the winter months. There did not seem to be any particular pattern of distribution in Suisun Bay.

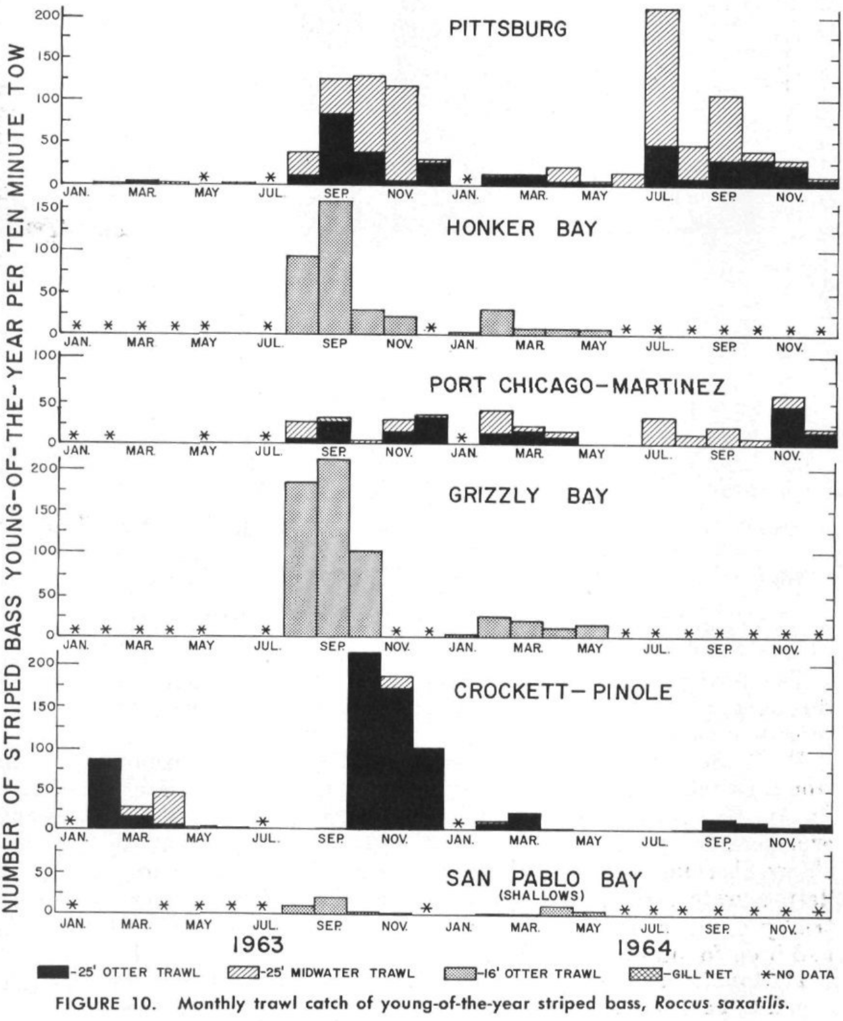

FIGURE 10. **Monthly trawl catch of young-of-the-year striped bass, *Roccus saxatilis*.**

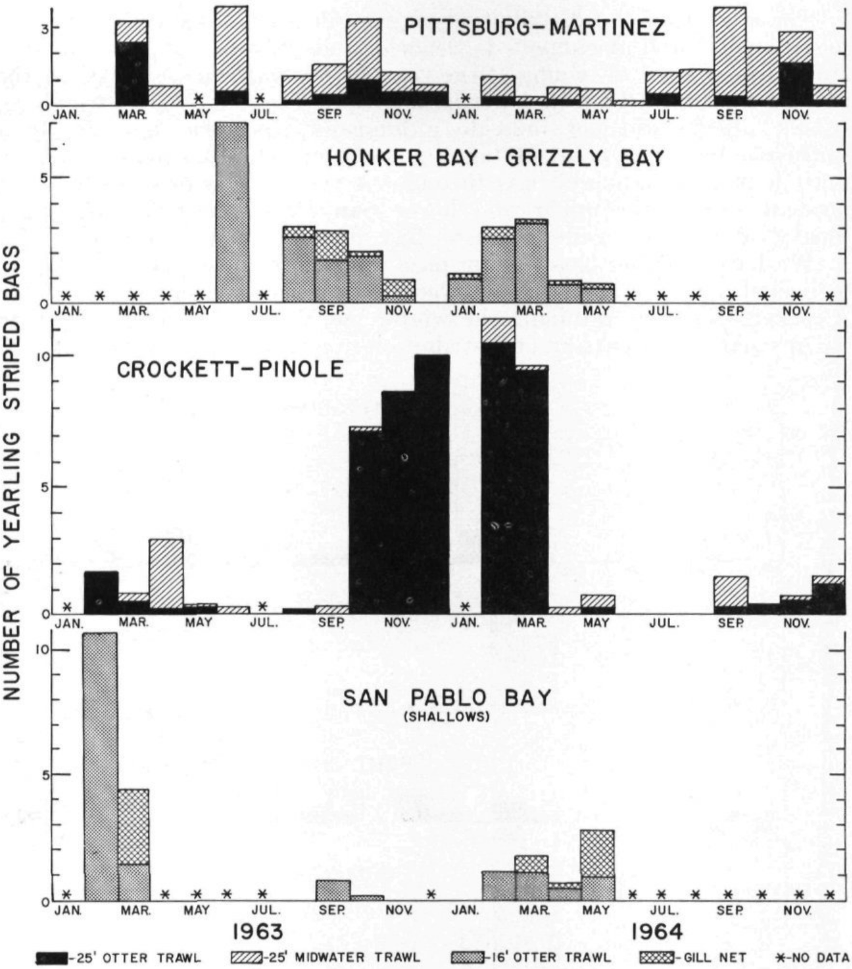

FIGURE 11. Monthly catch of yearling striped bass, *Roccus saxatilis*.

The food habits of striped bass have been investigated on and off throughout the years, but no detailed study has been conducted in Suisun or San Pablo Bays.

E. C. Scofield (1928, 1931) reported on random examinations of stomachs taken throughout the year in San Francisco, San Pablo, and Suisun Bays. He found that striped bass fed on periwinkles and "small crustaceans" when in the flats at high tide and on bay shrimp, anchovy, herring, "smelt," splittail, and their own young when in deeper water. He summed up his observations by saying that practically every marine form common to the San Francisco Bay region had been found in striped bass stomachs.

Hatton (1940) found that the stomachs of 57 young-of-the-year and yearling bass taken at Martinez in September and November 1939 contained, in order of the frequency of occurrence, "amphipods," *Synidotea laticauda*, "fish," and *Crago* sp. He found, after the water had freshened considerably, that 100 percent of the identifiable organisms in the stomachs of 45 young-of-the-year bass taken at Martinez in February and March 1940 were *Neomysis awatschensis*. Hatton also examined the stomachs of approximately 100 adult striped bass taken in Suisun Bay between March and May 1939. About 75 percent contained: "unidentified fish," "clupeoids," "osmerids," "split-tails," "lampreys," "atherinids," and "catfish or sculpins." "Shrimp or crab" were found in 25 percent of the stomachs.

Johnson and Calhoun (1952) found that the food of 229 adult and juvenile striped bass, caught during the summer in San Pablo Bay, consisted primarily of bay shrimp and northern anchovy.

Heubach, Toth, and McCready (1963) examined the stomachs of 355 young-of-the-year striped bass caught in the years 1956–1961 between Carquinez Strait and Pittsburg. They found that in the summer, 85 percent contained *Neomysis awatschensis*. Copepods and *Corophium* sp. were present in 19 and 18 percent. In the fall, 77 percent ate *Neomysis awatschensis* and 45 and 19 percent ate copepods and *Corophium* sp.

In the course of our 2-year survey, we examined the stomachs of 739 young-of-the-year striped bass, 602 yearlings, and 492 fish over 2 years of age, that contained identifiable food.

In eastern Suisun Bay, young-of-the-year striped bass fed almost entirely on *Neomysis awatschensis* and *Corophium* sp. (Figure 12). At times, the rate of occurrence of *Corophium* was fairly high but numbers were low and we considered their volumetric contribution to be negligible.

Young-of-the-year bass in middle and western Suisun Bay, although eating *Neomysis awatschensis* and *Corophium* sp. at about the same rate as fish upstream, began feeding on small *Crago franciscorum*, small fish and *Synidotea laticauda* (Figure 12). Unlike *Corophium* sp., these organisms, because of their size, did contribute significantly to the volume of food ingested, but *Neomysis awatschensis* was still dominant.

Neomysis awatschensis became less important in the diet of small bass in San Pablo Bay, and *Corophium* sp. although still present was augmented by its marine counterpart *Photis californica* (Figure 12). Small fish, annelid worms, bay shrimp, and *Synidotea laticauda* began to play an increasingly important role.

In the Pittsburg area, *Neomysis awatschensis* continued to be the predominant food organism utilized by yearling bass, being present in 77 to 100 percent of the stomachs. Small fish, shrimp, and isopods made up the remainder. Yearling bass at Port Chicago, Martinez, and in San Pablo Bay began to depend more on fish, shrimp, and isopods.

Neomysis awatschensis were frequently found in the stomachs of 3-year-old or older bass, but contributed little to the total food consumed. These adults depended almost entirely on *Crago franciscorum* and fish.

The fish diet of the striped bass varied with the size of the individual and the season. The occurrence of a given species of fish in the diet generally reflected the abundance of that species in the trawl tows.

All the common species, including young striped bass and king salmon were utilized at one time or another.

I am indebted to John Thomas, of the Inland Fisheries Branch of the California Department of Fish and Game, who analyzed the stomach contents of most of the large bass during 1964.

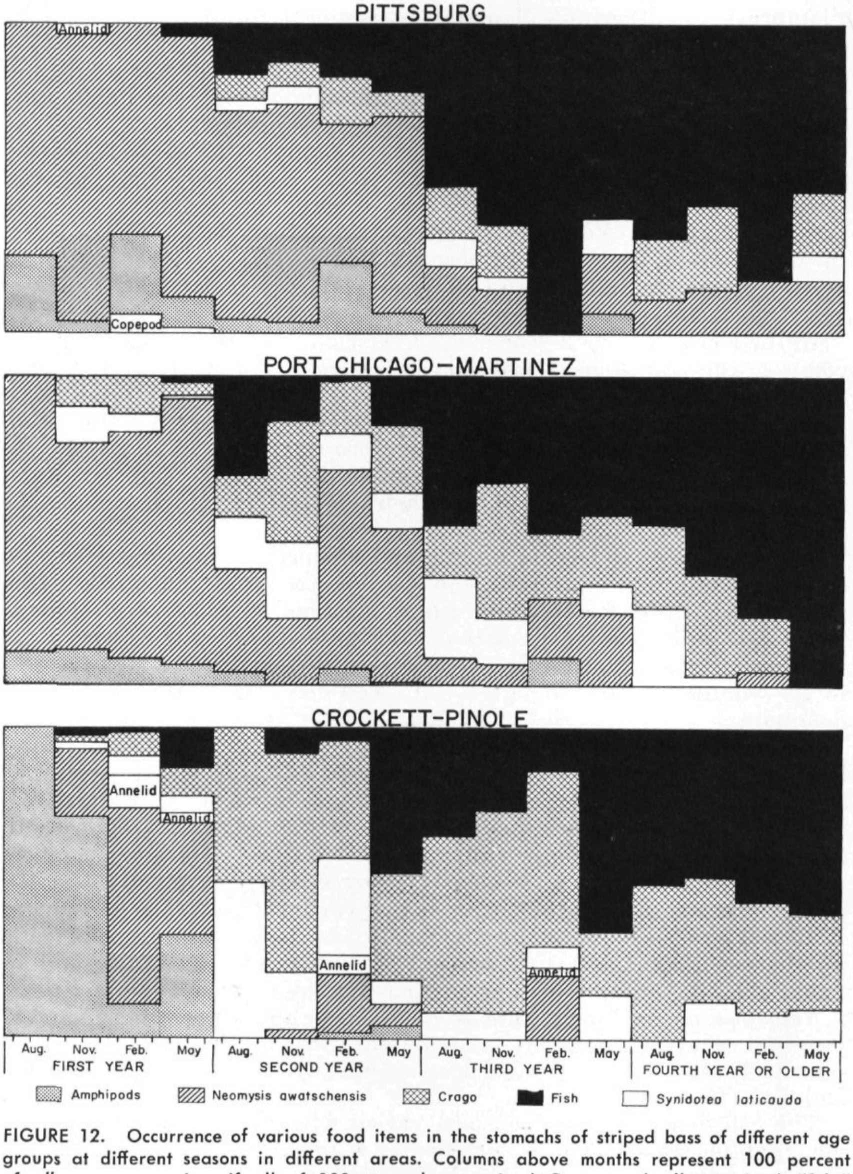

FIGURE 12. Occurrence of various food items in the stomachs of striped bass of different age groups at different seasons in different areas. Columns above months represent 100 percent of *all* occurrences; i.e., if all of 100 stomachs contained *Crago* and all contained "fish," column would show; *Crago*—50 percent, "fish"—50 percent.

Black crappie, *Pomoxis nigromaculatus*. Fresh water. Introduced.

Total—1. Midwater trawl. Martinez: June 1963; 23 cm. Stomach contained one *Neomysis awatschensis*.

Bluegill, *Lepomis macrochirus*. Fresh water. Introduced.

Total—2. Midwater trawl, otter trawl. Pittsburg: February 1963; 4 cm. San Pablo Bay: February 1963; 4 cm.

White croaker, *Genyonemus lineatus*. Marine.

Total—994. Gill net, otter trawl. Martinez, San Pablo Bay.

A few white croakers were caught at Martinez between March and December 1964, but 955 were taken in San Pablo Bay from April to August 1964. Most were 3 to 10 cm long. About 15 fish were 15 to 30 cm long.

Barred surfperch, *Amphisticus argenteus*. Marine.

Total—1. Otter trawl. San Pablo Bay: June 1964; 6 cm.

Black perch, *Embiotoca jacksoni*. Marine.

Total—25. Otter trawl. San Pablo Bay: July 1964; 5 to 7 cm.

Pile perch, *Rhacochilus vacca*. Marine.

Total—33. Otter trawl. San Pablo Bay: June–July 1964; 8 to 33 cm.

Shiner perch, *Cymatogaster aggregata*. Marine.

Total—188. Midwater trawl, otter trawl. San Pablo Bay.

A few shiner perch were caught between February and May 1963, but the majority (177) were taken between May and December 1964. All were from 8 to 14 cm long.

Tule perch, *Hysterocarpus traski*. Fresh water.

Total—2. Midwater trawl, otter trawl. Pittsburg: April 1963; 9 cm. Honker Bay: January 1964; 13 cm.

Walleye surfperch, *Hyperprosopon argenteum*. Marine.

Total—3. Otter trawl. San Pablo Bay: June 1964; 7 to 9 cm.

White seaperch, *Phanerodon furcatus*. Marine.

Total—7. Otter trawl. San Pablo Bay: May–September 1963; 12 to 16 cm. October–December 1964; 27 to 28 cm.

Gobies. Marine—Euryhaline.

Total—72. Midwater trawl, otter trawl.

Although both the arrow goby, *Clevlandia ios,* and the bay goby, *Lepidogobius lepidus* were identified, catches were usually recorded only as "gobies."

Most (61) gobies were caught in San Pablo Bay from May to October 1964. Four were taken off Pittsburg in May and June 1964, and four were caught in San Pablo Bay between May and August 1963. All were 3 to 8 cm long.

Brown rockfish, *Sebastodes auriculatus*. Marine.

Total—41. Otter trawl. San Pablo Bay: June–July 1964; 5 to 7 cm.

Lingcod, *Ophiodon elongatus*. Marine.

Total—31. Midwater trawl, otter trawl. San Pablo Bay: April–July 1964; 8 to 9 cm.

Prickly sculpin, *Cottus asper*. Fresh water.

Total—2. Otter trawl. Martinez: March and December 1964; 14 and 16 cm.

Staghorn sculpin, *Leptocottus armatus*. Marine—Euryhaline.

Total—2,644. Midwater trawl, otter trawl.

Jones (1962) studied the biology of the staghorn sculpin in Tomales Bay and San Francisco Bay, for 2 years. He concluded that spawning takes place between October and March and that small juveniles are most tolerant of low salinity. Small juveniles migrated into fresh water in spring, were confined to highly saline areas in the summer, and, for the most part, had moved into marine water by autumn.

We caught sculpins in all areas in most months. They reached their greatest abundance in San Pablo Bay in June, July, and August, and at Martinez in the fall. Size ranged from 3 to 22 cm. Small fish, up to 7 cm, were common in the winter and spring, particularly in the flats of San Pablo and western Suisun Bay. Ripe adults 20 cm long were taken in San Pablo Bay in April 1964.

About 85 percent of the sculpins were taken in San Pablo Bay, 13 percent at Martinez or in Grizzly Bay and 2 percent at Pittsburg or in Honker Bay.

Jones (1962) found that the principal food items utilized by 87 adult staghorn sculpins taken in San Francisco Bay were: bay shrimp, the blue mud shrimp, *Upogebia pugettensis*, and the northern anchovy. The principal food organisms eaten by 101 juvenile sculpins in Tomales Bay were: *Corophium spinicorne*, *C. stimpsoni*, and the annelid *Neanthes limnicola*.

In Suisun Bay, we examined two sculpin stomachs with identifiable food. One contained bay shrimp, the other, annelid worms. In San Pablo Bay, three specimens contained bay shrimp.

California pompano, *Palometa simillima*. Marine.

Total—11. Midwater trawl. San Pablo Bay: May 1963, May 1964; 10 to 14 cm.

Atherinids. Marine.

Total—1,292. Gill net, midwater trawl. Martinez, San Pablo Bay.

Both the jacksmelt, *Atherinopsis californiensis*, and the topsmelt, *Atherinops affinis*, were in our catches. When small individuals appeared, it was not practical to separate the two species. However, the presence of ripe and ripening jacksmelt in San Pablo Bay led us to believe that most of the small fish were that species.

The jacksmelt reaches a length of more than 50 cm, matures at the age of about 2 years at a length of about 15 cm, and spawns from October to March (F. N. Clark, 1929; Roedel, 1953).

Over 98 percent of the atherinids we caught were in San Pablo Bay. The remainder, eight adults 20 to 36 cm long, and 10 young, 6 to 9 cm long, were caught off Martinez.

Ripening and ripe adults were found from September to April, but the largest catches were composed of fish between 5 and 12 cm and were recorded from July to December in both 1963 and 1964.

California halibut, *Paralichthys californicus*. Marine.

Total—2. Otter trawl. San Pablo Bay: May 1963; 34 cm. May 1964; 80 cm.

Pacific sandab, *Citharichthys sordidus*. Marine.

Total—50. Otter trawl. San Pablo Bay.

More than 90 percent were caught in June and July 1964. All were between 5 and 11 cm long.

Diamond turbot, *Hypsopsetta guttulata*. Marine.

Total—15. Otter trawl. San Pablo Bay.

In 1963, turbots were caught between August and December. In 1964, from May to December. All were 23 to 42 cm long.

English sole, *Parophrys vetulus*. Marine.

Total—1,050. Otter trawl. San Pablo Bay.

In 1963, only one English sole was caught (December; 24 cm). In 1964, small sole were common during some months. From May through July, 1,000 sole 4 to 10 cm long, were taken and from August through December, 49 between 7 and 18 cm, were caught.

Sand sole, *Psettichthys melanosticus*. Marine.

Total—12. Otter trawl. Martinez, San Pablo Bay.

Two sand sole were caught off Martinez (May, December 1964), 10 in San Pablo Bay (no particular seasonal pattern). Sizes ranged from 5 to 28 cm.

Slender sole, *Lyopsetta exilis*. Marine.

Total—2. Otter trawl. San Pablo Bay: April 1964; 15 and 22 cm.

Starry flounder, *Platichthys stellatus*. Marine—Euryhaline.

Total—about 1,000. Gill net, midwater trawl, otter trawl. San Pablo Bay to Pittsburg.

The starry flounder is found in bays and from very shallow water to about 150 fathoms over all types of bottom but rock. In central California, the fish spawn once a year during winter months. Males mature in their 2nd year when about 30 cm long; females in their 3rd year when about 35 cm long (Orcutt, 1950). The starry flounder is a relatively minor component of the commercial flatfish catch but is an important sport fish in central California (Roedel, 1953).

P. stellatus is known to move far upstream into completely fresh water. It has been taken 75 miles up the Columbia River (Gunter, 1942), and during the fish survey of the Delta in 1963, a small starry flounder was caught at Mossdale on the San Joaquin River. Mossdale is about 90 nautical miles from the Golden Gate and is near the limit of tidal effect. Even in periods of drought, ocean salts are absent there.

We caught about 77 percent of our starry flounders in San Pablo Bay, about 14 percent off Martinez or in Grizzly Bay, and about 9 percent off Port Chicago, Pittsburg, or in Honker Bay.

Although one of the largest (44 cm) fish was caught off Pittsburg, size (and age) generally decreased with distance upstream. Small (4 to 15 cm) flounders comprised about 90 percent of the catch off Pittsburg, Port Chicago and in Honker and Grizzly Bays. Off Martinez, about 50 percent were of that size and in San Pablo Bay 20 to 40 percent. Small fish were most abundant in summer and fall but were scattered throughout the estuary year-round.

Larger (20 to 44 cm) fish were common during most months in San Pablo Bay. An increase in numbers was observed in the spring and summer, and the late summer and fall population seemed to be quite high.

In Suisun Bay, we examined 18 stomachs containing identifiable food. Ten had eaten "clam" (mostly *Macoma* sp.), 5 contained *Corophium* sp., 2 *Synidotea laticauda,* and 1 *Neomysis awatschensis.*

In San Pablo Bay, 47 stomachs contained identifiable food: 39 clam (mostly *Macoma* sp.), 8 *Synidotea laticauda,* 4 annelid, 1 *Photis californica,* and 1 unidentified crab.

California tonguefish, *Symphurus atricauda.* Marine.

Total—5. Otter trawl. San Pablo Bay: July, August, October 1964; 9 to 13 cm.

Northern midshipman, *Porichthys notatus.* Marine.

Total—about 700. Midwater trawl, otter trawl. Suisun Bay, San Pablo Bay.

The northern midshipman was most abundant from April to August in both 1963 and 1964. Over 90 percent of the total catch was accounted for during those periods in San Pablo Bay. During the spring and summer months, sizes ranged from 9 to 31 cm, and many of the females contained large, well-developed eggs. From September through the winter months, fish of that size were not common but 3 to 6 cm midshipmen were scattered throughout the bay.

In May and June 1964, three midshipmen were taken near Pittsburg and a few others were scattered throughout Suisun Bay between May and December of both years.

DISCUSSION

The 1962–1963 water year (July to June) was a "wet year" with above-normal precipitation recorded. However, average or below-average rainfall was experienced in the fall and winter and salinity, while steadily decreasing, did not vary widely. In February, March, and April, over 70 percent of the total rainfall was recorded. Heaviest rainfall occurred in February and April, moderate flooding was experienced, and salinity varied abruptly (Figure 13).

The highest average monthly chlorinity recorded at Pittsburg during 1963 was 1‰ in August. For all practical purposes, the water at Pittsburg was fresh during the entire year.

The 1963–1964 water year was a "dry year" with below-normal rainfall recorded. Only in October and November 1963 was above-average precipitation experienced.

At Pittsburg, chlorinity reached 1‰ in May 1964 and a high of more than 3‰ was recorded in August.

Chlorinity at Crockett decreased slowly to 5‰ in January 1964 then slowly rose to a high of 14‰ in August (Figure 13). The fall of 1964 was dry and the chlorinity decreased slowly. The average reading in mid December was between 8 and 9‰. However, 1 week after our survey ended, California was struck by one of the worst storms in its history. On December 22, 1964, the chlorinity at Crockett was 10.7‰; 4 days later the water was completely fresh.

In only 1 of the 24 months of our survey did the average chlorinity at Pittsburg exceed 2.5‰ (Figure 13).

The average chlorinity at Port Chicago was between 0 and 2.5‰ for 7 months, between 2.5 and 9.0‰ for 15 months, and over 9.0‰

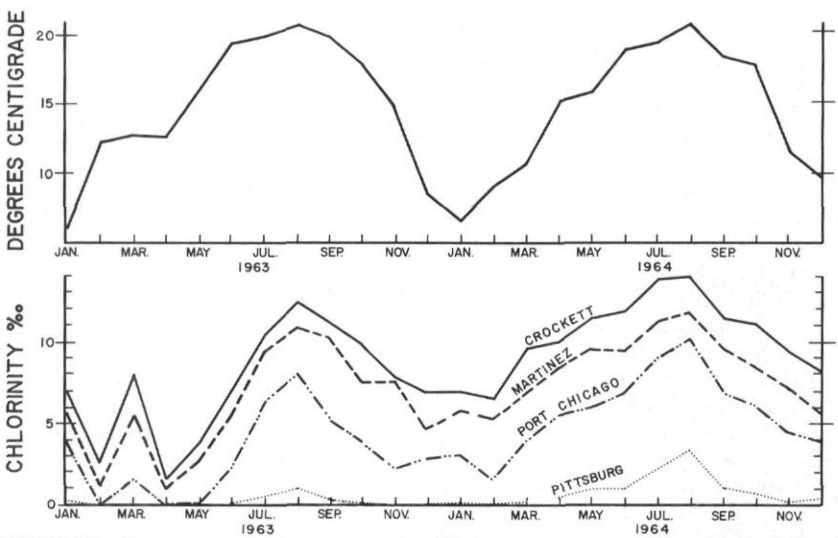

FIGURE 13. Average monthly temperature and chlorinity. Temperature is monthly average of all areas.

for 2 months. At Martinez, chlorinity was 0 to 2.5‰ for 2 months, 2.5 to 9.0‰ for 14 months, and over 9.0‰ for 8 months.

The average monthly chlorinity at Crockett was 9.0‰ or more for 13 months, between 2.5 and 9.0‰ for 9 months and was 2.5‰ or less only during the 2 flood months of February and April 1963.

The estuary is not a static system. The effects of changes (sometimes abrupt) in inflow, two complete tidal cycles of considerable and changing amplitude each day, as well as the effects of wind-driven waves on its large, shallow bays make it a constantly changing dynamic system. Consequently, any classification of an area within the estuary would only be valid for a brief period of time. However, based on the chlorinity readings of 2 years, I feel that it can be divided into three broad zones based on the Venice System of Estuarine Classification (see Kelley, p. 12; Painter, p. 37). They are: an oligohaline or "freshwater" zone centered near Pittsburg, a mesohaline or "brackish" zone centered between Port Chicago and Martinez, and a polyhaline or somewhat less than "marine" zone centered in San Pablo Bay just west of Crockett.

Hedgpeth (1957) stated: "As regions of transition and sharp gradients, estuaries support a fauna recruited principally from the sea, but with a few components from fresh-water environments . . . ."

Of the many species of fish we encountered, most were of marine origin and those decreased in number rapidly or disappeared completely as sampling moved upstream.

Two of the most commonly found so-called euryhaline species of fish, the starry flounder and the staghorn sculpin, though capable of inhabiting waters of a wide salinity range are nevertheless, generally associated with the marine environment. This is also true of the bay shrimp.

Only 3 of the 13 freshwater species, the carp, the splittail, and the white catfish, were taken with any regularity. The others were rarely caught and in some cases only one was recorded during the entire survey.

Only two species of fish, the Sacramento smelt and the pond smelt, appear to be truly "resident" forms. The Sacramento smelt seems to favor the high end of the salinity gradient, and the pond smelt the low. However, little is known about the life history and behavior of these species in central California, and both warrant further investigation.

Gunter (1945), after a survey of the fish fauna of a Texas estuary, concluded that: ". . . the temperature cycle is chiefly responsible for the seasonal movements and other recurrent cyclic activities of the fishes. In a few instances there were indications that either temperature or salinity was clearly more operative than the other factor in influencing the movements or presence of a species in a given environment at a given time, but mass movements coincide with the temperature cycle. Both salinity and temperature have definite limiting and differential effects which are difficult to separate by observation. . . . During the fall most fishes in the bays began to move toward the Gulf of Mexico. The absence of a species was generally first noticed in the upstream areas. In the spring and summer, the fishes return to the bays."

In our study area, the water temperature (which closely follows air temperature) ranged from 6° C. in January 1963 and 1964 to 21° C. in August of both years (Figure 13). Except for changes caused by flood flows, the salinity increased and decreased in much the same pattern (Figure 13). The general abundance of fish also rose and fell in the same way.

It was not possible to separate the effects of temperature and salinity on the obvious seasonal migrations and changes in abundance of such species as the king salmon, American shad, jacksmelt, striped bass, Sacramento smelt, Pacific herring, and northern anchovy, but the general agreement between my data from Crockett and Martinez and those presented by Messersmith (see p. 57) indicates that the seasonal changes in the concentrations of those species are consistent and predictable. However, the effect of salinity on the degree of penetration into the estuary of some of the marine and marine-euryhaline species can be demonstrated.

The average chlorinity at Crockett for the 6-month period from January through June 1963 was 5‰ and for the first 6 months of 1964, 9‰. At Port Chicago, chlorinity was 1.1‰ from January through June 1963 and 4.5‰ in 1964. This means that the estuary was not subjected to abrupt and violent changes in outflow and salinity in the winter and spring of 1964 as it was in 1963, and that a given isohaline was obviously more stable in position and occurred several miles farther upstream in 1964.

In "dry" 1964, the northern anchovy and Pacific herring moved farther up the estuary and the center of abundance of young Sacramento smelt shifted from San Pablo Bay in 1963 to middle Suisun Bay in 1964.

Small bay shrimp appeared in Suisun Bay earlier and in greater numbers, and market crabs, almost totally absent in 1963, were common in San Pablo Bay and present at Martinez.

Several marine forms were caught in San Pablo Bay only in 1964, and some that were not numerous in 1963 were common in 1964.

Since there was no real difference in seasonal temperature between the 2 years, it would seem that variations in outflow and salinity were the dominant factors controlling longitudinal distribution of animals within the estuary.

In the future, with increased upstream development and control of water, extremes of flow will be reduced. Such conditions would allow the transient and seasonal marine and anadromous populations to enter and leave the estuary without being subjected to as many violent and sometimes lethal chemical and physical changes, such as probably occurred in the spring of 1963 and in the winter (after our survey ended) of 1964. Such conditions would probably favor the establishment of more stable and permanent estuarine populations.

SUMMARY

From Janaury 1963 to December 1964, a 25-mile section of the Sacramento-San Joaquin River estuary, from the confluence of the two rivers to San Pablo Bay, was regularly sampled with trawls and gill nets. We were particularly interested in determining the distribution, general abundance, and food habits of the fishes within the salinity gradient.

Sixty species of fish were recorded. Of these, 31 were saltwater forms, 8 were euryhaline, 13 were freshwater species, and 8 were anadromous. Freshwater species were generally few in number and restricted to the upper end of the survey area. Marine forms were generally restricted to the lower end. The abundance of several marine species fluctuated widely with season.

The middle portion of the survey area was characterized by the presence of anadromous and euryhaline species and seasonal immigrations and emigrations of marine and freshwater forms. There appeared to be few resident species.

Ocean salt moved farther upstream during the 2nd year (1964) of the survey and the number of marine species increased. Some species taken in both years moved upstream earlier and farther in 1964 than in 1963.

Bay shrimp, *Crago* spp., were common during the summer and fall, and were important in the diets of large striped bass. Bay shrimp were more heavily concentrated in Suisun Bay and were abundant farther up the estuary in 1964 than in 1963.

Pacific herring, *Clupea pallasi,* entered the estuary each year. They produced millions of young which were abundant in San Pablo Bay during May and June of 1963 and upstream throughout Suisun Bay during April and May of 1964. Except for this short time in the spring, herring were rare in, or absent from, our catches.

The northern anchovy, *Engraulis mordax,* entered the estuary in large numbers during the spring and summer. All sizes from 17 cm adults to newly-hatched larvae were present. Their numbers declined in the fall and winter months and adults were rare or absent. I found

them farther upstream in 1964, and they were more abundant in San Pablo Bay that year.

Young-of-the-year striped bass moved downstream from the Delta and were particularly abundant throughout Suisun Bay from August through November of both years. They were abundant in San Pablo Bay in October, November, and December of 1963 but were scarce there in 1964. Our high catches of young-of-the-year bass with relatively inefficient trawling gear in the "flats" of Suisun Bay suggest that these areas are probably of great importance to the young bass.

King salmon, *Oncorhynchus tshawytscha,* young-of-the-year were most abundant during their downstream migrations in April, May, and November.

Adult American shad were most common in our catches in the spring, during their upstream spawning migration. Some young-of-the-year and yearling shad were always present in the estuary but the numbers of these were greatest in the fall. Eleven adults with "spent" gonads were caught in September 1963, suggesting that some adult shad spawn and return to the sea.

The pond smelt, *Hypomesus transpacificus,* was restricted to the low end of the salinity gradient.

The Sacramento smelt, *Spirinchus thaleichthys,* was found throughout the estuary and seemed to move upstream with increased salinity. Young Sacramento smelt were abundant in April and May.

The food habits of several fishes were investigated, and although many organisms were utilized, the opossum shrimp, *Neomysis awatschensis,* formed an important and probably critical link in their food chain. Striped bass in their 1st and 2nd year of life fed intensively on *Neomysis awatschensis.* Older bass ate a variety of small fish and shrimp. The composition of their food varied with season and location within the estuary. American shad of all sizes fed almost entirely on copepods and opossum shrimp.

Most of the fishes and shrimp that inhabit the Suisun-San Pablo Bay section of this estuary migrate up or downstream as they grow and as the seasons change. The pattern of migration was similar during the two seasons studied but the extent of movement—especially that of marine forms upstream—was different. This is probably because of different salinity conditions during the 2 years.

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SEASONAL DISTRIBUTION OF CRUSTACEAN PLANKTERS IN THE SACRAMENTO-SAN JOAQUIN DELTA

JERRY L. TURNER

INTRODUCTION

Zooplankton collections in the Delta were made over a 12-month period from March 1963 to February 1964. This report describes the standing crop of crustacean plankters and some of the physical and chemical factors that affect their distribution and abundance.

Seasonal variation in concentration of crustacean plankters was correlated with seasonal variation in water temperature. "Residence time" of water in a channel was an important factor influencing abundance in channels containing water of the same river system. Differences in dissolved solids appeared to be the major cause of differences in the zooplankton abundance of the different river systems within the Delta.

Field Methods

Zooplankton samples were collected once a month from 20 Delta stations which had contrasting conditions of flow, water quality, and temperature.

Collections were made with a Clarke-Bumpus sampler fitted with a number 10 net (109 meshes to the linear inch). Ricker (1938) demonstrated that a number 10 net sampled adult crustaceans in proportion to their abundance.

The sampler was towed near the surface behind a power boat moving at approximately 3 feet per second relative to the current speed for 10 to 15 minutes. The sampler metered the volume of water strained through the net. Samples were usually collected from stations in the San Joaquin River and south Delta on one day and from the Sacramento River and Mokelumne River region of the Delta on the following day. They were preserved with formalin. Rose bengal dye was added to facilitate visual separation of animals from detritus.

At the time of sampling, the surface water temperature was recorded and a sample of water was collected so that its electrical conductivity could be measured. Measurements were made with an AC wheatstone bridge and were used to help distinguish the origin of water.

The Department of Water Resources provided estimates of mean net flows and cross-sectional areas of the channel at each station for days samples were collected. These estimates were based upon their daily measurements of inflow to the Delta and past studies of the relationships between these inflows and the net flows and cross-sectional areas of the separate Delta channels (Calif. Dept. Water Resources, 1962a). They were used to compute "mean net velocities"

$$\frac{\text{mean net flow in cubic feet/second}}{\text{area of cross section of channel in square feet}}$$

as an index of the time a given amount of water remains in a channel.

Laboratory Methods

In the laboratory, each zooplankton sample was allowed to settle for several hours so that excess water could be siphoned off without loss of plankters. The volume of the remaining sample was measured, the sample thoroughly mixed, and 1 cc of this concentrate was transferred to a Sedgewick-Rafter counting chamber. A total count was made of the zooplankters on two or three Sedgewick-Rafter cells. Kutkuhn (1958) demonstrated that accurate total counts of macroplankton species could be secured by examining three Sedgewick-Rafter cells per sample of concentrate. A subsample of the first 100 organisms counted in each sample was identified to genus if possible. Total numerical abundance of each genus and/or all copepods and cladocerans per cubic meter of water was then calculated.

DISTRIBUTION AND RELATIVE ABUNDANCE

The concentration of cladocerans and copepods in my samples varied greatly (i) as the seasons changed, (ii) in Delta water from the different river systems, and (iii) at various stations within the same river system (Figure 1). Zooplankton populations were uniformly low in the Delta in the spring; the one exception being a slightly higher concentration in the San Joaquin River below Stockton. The total population of zooplankton increased greatly in the entire Delta during the summer with the highest concentration again being in the San Joaquin River below Stockton. Larger concentrations of zooplankton were found in the central Delta than in the upstream areas of the inflowing rivers. The fall distribution was similar with high concentrations in the San Joaquin River below Stockton, medium concentrations in the central Delta, and low concentrations in the inflowing rivers. A great reduction in zooplankton occurred during the winter. During the winter, concentrations in the central Delta were only slightly greater than those in the inflowing rivers.

Seasonal Differences

The standing crop of both cladocerans and copepods varied with the time of the year (Figure 2). The peak of abundance occurred from August through October; populations were lowest during December and January. A notable dip in the concentration took place during May and June. High flows of more than 10,000 cfs occurred in the San Joaquin River just preceding our sampling during those months.

Copepods were more abundant than cladocerans during most of the months sampled. Very low numbers of cladocerans were present from December through February. The most common cladocerans were *Bosmina longirostris*, *Daphnia* sp., and *Diaphanosoma brachyurum*. The most common forms of copepods were *Cyclops* sp. and *Diaptomus* sp. The population of most genera increased in the late summer and fall and decreased in the winter (Figure 3). *Diaphanosoma brachyurum* disappeared completely from our sampling from December through April.

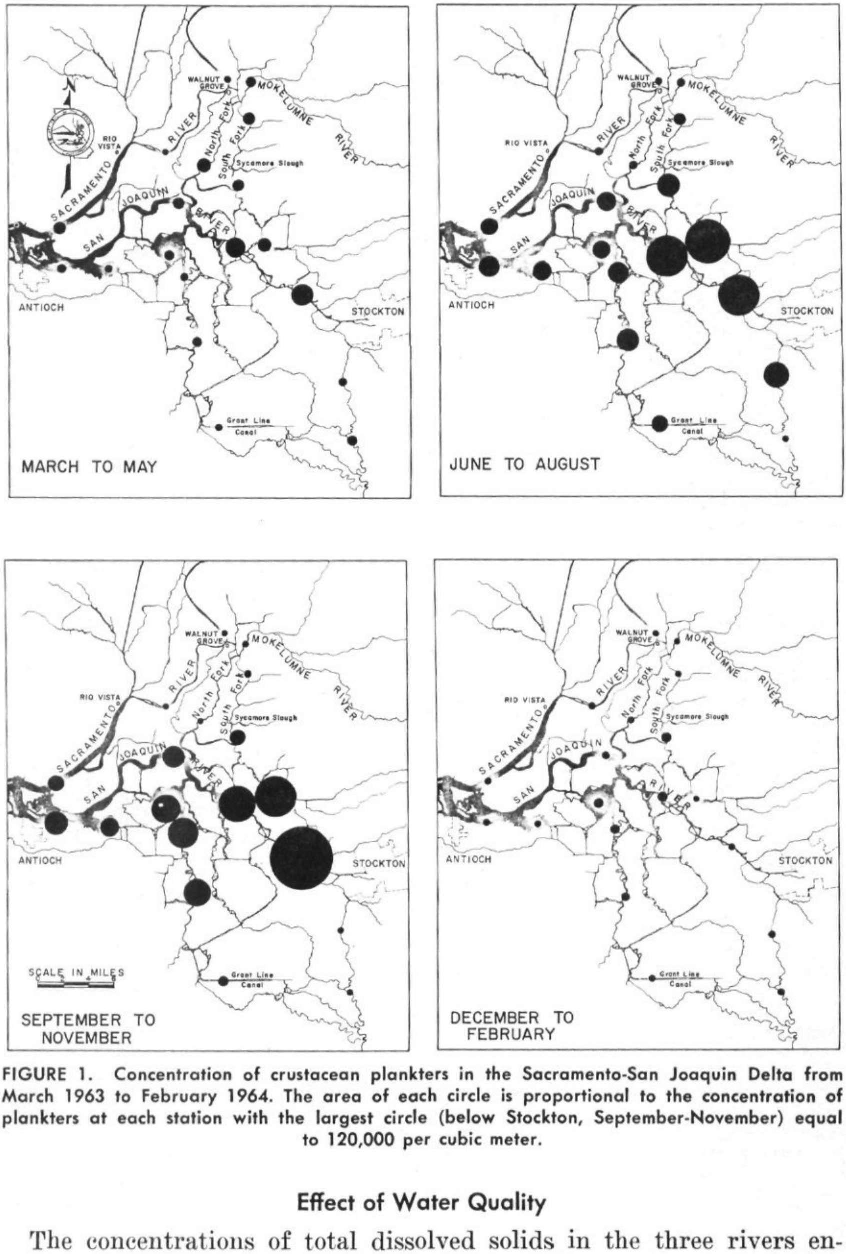

FIGURE 1. Concentration of crustacean plankters in the Sacramento-San Joaquin Delta from March 1963 to February 1964. The area of each circle is proportional to the concentration of plankters at each station with the largest circle (below Stockton, September-November) equal to 120,000 per cubic meter.

Effect of Water Quality

The concentrations of total dissolved solids in the three rivers entering the Delta are very different (Figure 4). For instance, during the 5 years 1960 through 1964, the Mokelumne River had a range of total dissolved solids in parts per million of 24 to 51; the Sacramento River, a range of 37 to 145; and the San Joaquin River, a range of 75 to 826 (Calif. Dept. Water Resources, 1960–1964). In the Delta,

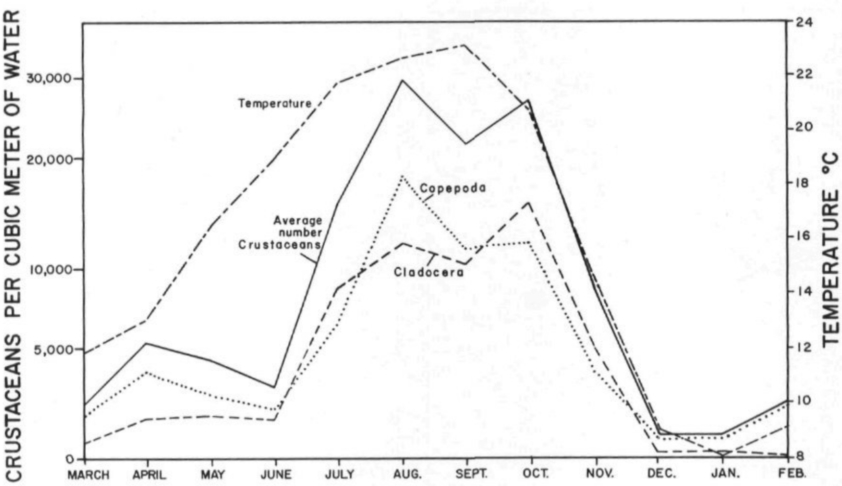

FIGURE 2. Comparison of the average concentration of crustacean plankters with the average temperature for all sampling stations in the Sacramento-San Joaquin Delta from March 1963 to February 1964.

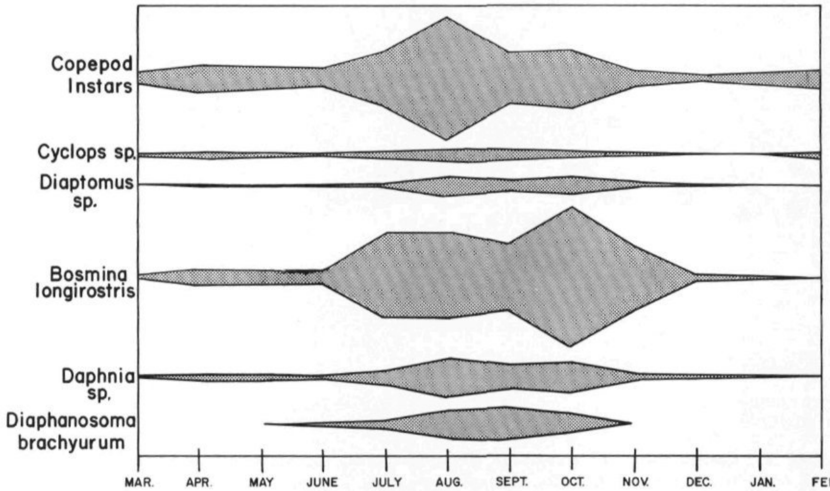

FIGURE 3. The numbers of major crustacean plankters caught each month from March 1963 to February 1964 in the Sacramento-San Joaquin Delta. The width of each line at each sampling period is proportional to the numbers of that species caught.

low mineral content water of the Sacramento River joins the even lower mineral content water of the Mokelumne River by flowing through the man-made Delta cross channel at Walnut Grove. These combined waters flow down the forks of the Mokelumne to join the nutrient-rich water of the San Joaquin. During the irrigation season, great amounts of Sacramento River water released from upstream reservoirs flow southward across the Delta to be pumped at the Tracy pumping plant, mostly for irrigation service from the Delta-Mendota Canal. From early summer to late fall, most Delta channels contain water that originated in the Sacramento River.

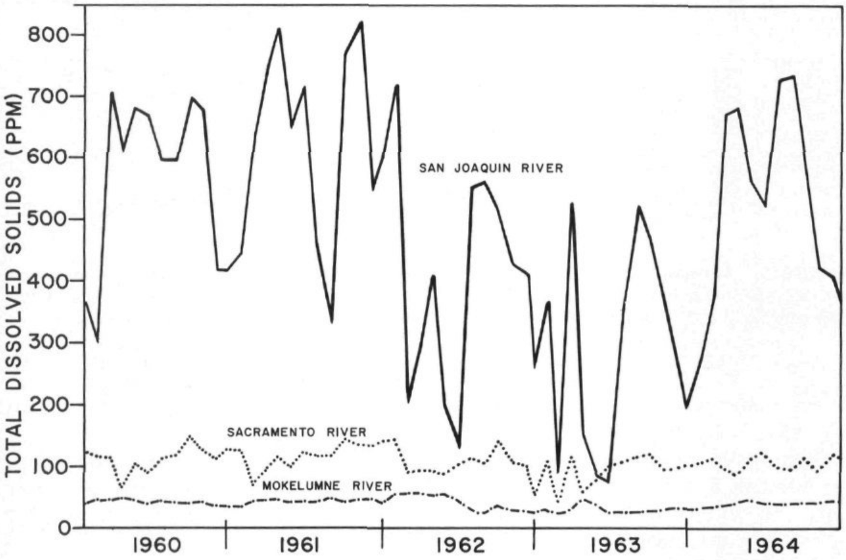

FIGURE 4. Total dissolved solids concentration of water in the Sacramento River at Walnut Grove, the Mokelumne River at Woodbridge, and the San Joaquin River at Mossdale from 1960 to 1964 (data from Calif. Dept. Water Resources, 1960–1964).

I separated the zooplankton data into two parts: one describing collections from the Sacramento-Mokelumne River water, and one describing collections from water of the San Joaquin River. The separation was made on the basis of the electrical conductivity measurements of the water and information about Delta hydraulics supplied by the Department of Water Resources.

During most of the year, and throughout most of the Delta, the collections from San Joaquin River water contained almost twice as many copepods and cladocerans per sample as collections from the Sacramento-Mokelumne River water (Figure 5). This was not true of the collections from the more river-like stations on the edge of the Delta where net velocities were relatively high. Zooplankton concentrations at these stations were uniformly low.

Effect of Rate of Flow

The standing crop of copepods and cladocerans varied among stations with the same river water. Greater concentrations occurred at all stations with low "net velocities of flow" than at stations with high "net velocities of flow" (Figure 5). "Net velocity of flow" is an estimate of the mean rate of downstream (or in a few cases upstream) movement of the water mass in a channel. It really has no relationship to the true velocity of water at any time during a tidal cycle. The

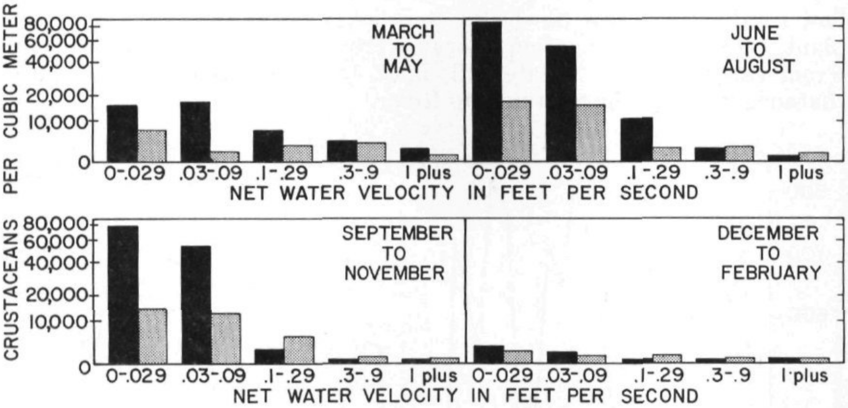

FIGURE 5. Average numbers of crustacean plankters each season in various rivers in the Sacramento-San Joaquin Delta at different net water velocities. Solid columns indicate plankters collected in the San Joaquin River and the stippled columns the plankters collected in the Sacramento-Mokelumne Rivers.

"net velocity" is therefore only an index of resident time of water in the channel.

The influence of "net velocity" or resident time appeared to be much greater in the richer waters of the San Joaquin River than in the lower mineral waters of the Sacramento-Mokelumne River, and much greater in both systems during summer and fall months.

In general, as each channel approaches the bay, there is an increase in its cross-sectional area with a resulting decrease in the "net velocity of flow." There are high "net velocities" in the river areas with narrow channels such as on the Sacramento River above Isleton, on the Mokelumne River above New Hope Landing, and on the San Joaquin River above Stockton. There are low "net velocities" as the rivers divide into numerous channels of larger cross-sectional areas in the central Delta. During our sampling period, the stations with the lowest "net velocities" were always located in the central Delta with the two stations below Stockton having the lowest rate.

DEAD-END SLOUGHS

In addition to the monthly samples collected from the 20 Delta stations, I made six tows to collect zooplankton from the "dead end" Sycamore Slough in June and December 1963. During both sampling periods, the concentrations of cladocerans and copepods were greater toward the closed-end of the slough (Figure 6). This was not true of the uppermost stations in December. The average concentration of cladocerans and copepods at each individual station in June was much higher than at the same station in December.

In a dead-end slough there is a movement of water back and forth due to tidal action but no net flow through the slough except when water is pumped into or out of the channel for irrigation or drainage. An exchange of water does occur between the river and slough during tidal changes. In a dye tracer study of Sycamore Slough, the California Department of Water Resources (yet unpublished) demonstrated an in-

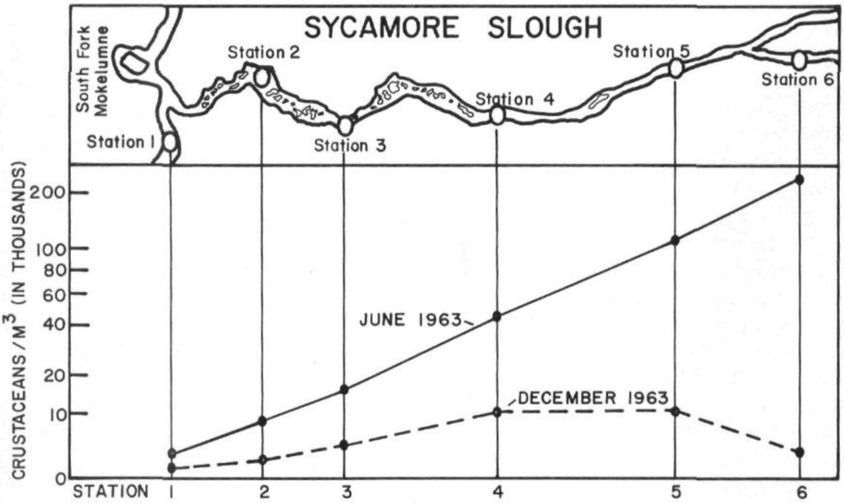

FIGURE 6. Average number of crustacean plankters at various stations in Sycamore Slough in June and December 1963.

crease in retention time of the mass of water with increasing distance into the slough.

During both of my sampling periods, the electrical conductance of the water was progressively higher as I collected toward the upper end of the slough (Table 1). The water temperature was highest in the head of the slough (Station 6) in June, but the opposite was true in December. The amount of dissolved oxygen was lowest in the upper end of the slough in December.

DISCUSSION

In this study I measured only the more obvious factors that others have found to influence zooplankton populations.

Water temperature appeared to be the major factor affecting the seasonal variation in the standing crop of cladocerans and copepods in the Sacramento-San Joaquin Delta. Except during May and June,

TABLE 1

Environmental Characteristics of Sycamore Slough for June 10 and December 17, 1963

		Station number[1]					
		1	2	3	4	5	6
Electrical conductance (micromhos 25°C.)	June Dec.	78 307	86 300	90 262	125 247	170 370	270 680
Temperature (°C.)	June Dec.	18.7 6.7	18.9 6.1	19.5 6.1	20.8 5.6	21.9 5.0	23.2 5.0
Dissolved oxygen (milligrams/liter)	June Dec.	-- --	-- 9.5	(not sa 9.0	mpled) 7.6	-- 5.0	-- 1.5

[1] Refer to Figure 6 for Station Location.

there was a close correlation between average water temperature and concentration of zooplankters. Allen (1920) found that temperature, within certain limits, was the factor determining seasonal trends of plankton in the San Joaquin River. Roach (1932), in the Hocking River in Ohio, found a close correlation between temperature and total plankton abundance, but the zooplankton population showed a rather oscillatory movement. The California Department of Water Resources (1962b), in a study of the Sacramento River, concluded that water temperature was the single most important factor affecting total plankton production.

During my study, there was a widespread decline in the standing crop of zooplankton during May and June. This was probably due to high flow conditions in the inflowing rivers just prior to our sampling. The San Joaquin River was particularly affected at that time as the fresh water inflow reduced both the total dissolved solids and the residence time of water. Blum (1956) summarized several references which showed that flood waters could bring about a sharp decline in total plankton.

Average "net velocity" of flow, an expression of residence time of water, appeared to be the major factor accounting for differences in zooplankton abundance between stations containing water of the same river system. In all three river systems there was an increase in total numbers of cladocerans and copepods at the stations in the central Delta where the river slowed down. A reduction in net velocity of flow apparently creates a more stabilized environment and results in an increased population of plankton.

Residence time of water was one of the first factors considered by many to have a direct effect on plankton production. Kofoid (1903) concluded from his study on the Illinois River that the quantity of plankton, within certain limits, was directly proportional to the "age" of water (length of time for plankton development). The "age" of water is determined by velocity; it decreases with high velocity and increases with low velocity. Eddy (1934) stated that ". . . velocity is one of the important factors controlling the age of water and corresponding conditions of stability necessary for production of plankton." In his study of the San Joaquin River at Stockton, Allen (1920) found that water currents above a moderate rate were inimical to plankton development. Neel (1951) found that both photosynthesis and decomposition exert their greatest effect upon plankton under slow water conditions.

The larger concentrations of copepods and cladocerans in the San Joaquin River could be due to the amount of dissolved solids in the water. Pennak (1946) stated that in a broad sense, there are greater numbers of plankton where there are larger quantities of dissolved nutrients. Northcote and Larkin (1956) found a positive correlation between plankton abundance and total dissolved solids for British Columbia lakes with greatly differing dissolved mineral content. Ward (1957) found a positive correlation between cladoceran and copepod abundance and total dissolved solids at several stations in Shuswap Lake, British Columbia. He believed that the concentration of total dissolved solids was the major factor contributing to station differences, although extreme water temperatures control the upper and lower limits of seasonal zooplankton abundance.

The effect of different residence times, water temperatures, and dissolved solid concentrations on the zooplankton population was demonstrated by the collections and measurements from Sycamore Slough. December zooplankton populations were predictably low in Sycamore Slough as they were throughout the Delta. Within this low range, they were greatest in samples collected from the center and upper-middle reaches of the slough where residence time and dissolved solids were high. In June, water temperature, total dissolved solid concentration, residence time, and zooplankton concentrations were all progressively greater as I sampled toward the upper end of Sycamore Slough. At that time, water temperatures were high enough to allow the other variables of residence time and total dissolved solids to affect the zooplankton population in a more positive way.

In Sycamore Slough, I cannot separate the effects of higher dissolved solid concentration, higher residence time or higher water temperature toward the upper end of the slough. The important point is that these are all influential factors. In Sycamore Slough as in the entire Delta, it is their combined effects that affect the zooplankton population.

Throughout the Delta channels, the wide variations in residence time and dissolved solids combine to create major differences in the standing crops of zooplankton. River-like conditions of high net velocities limit zooplankton populations in the San Joaquin River above Stockton and Grant Line Canal, in the Sacramento River above Rio Vista and the forks of the Mokelumne River. The slower net velocities of the central Delta result in varying concentrations of zooplankton depending on the source and quality of the water. The heaviest concentrations were in the San Joaquin River below Stockton where total dissolved solid concentrations were very high and net flows were very low.

SUMMARY

1) Zooplankton samples were collected from the Sacramento-San Joaquin Delta from March 1963 to February 1964 in order to investigate relationships between crustacean plankters and their environment.

2) The distribution and concentration of cladocerans and copepods varied seasonally, by river system, and within the waters of each river system.

3) The monthly standing crop of zooplankton was closely related to water temperature except for a short period in May and June following flood waters when a reduction in total numbers occurred.

4) The concentrations of each common genera increased in late summer and fall and decreased in the winter except for *Diaphanosoma* which disappeared completely from our sampling from December to April.

5) Besides water temperature, zooplankton concentrations were influenced by "net velocity of flow" (resident time) and total dissolved solid concentrations.

6) "Net velocity of flow" is an index of residence time of water in a channel. Water from the same river produced more zooplankton in

areas where this residence time was greater. "Net velocities" of more than 0.3 feet/second were always associated with low zooplankton populations.

7) Under similar conditions of low "net velocity" and high temperature, zooplankton concentrations in the San Joaquin River waters were about double those in the Sacramento-Mokelumne River waters. Total dissolved solid concentrations were consistently more than three times as great in the San Joaquin waters.

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DISTRIBUTION AND CONCENTRATION OF *NEOMYSIS AWATSCHENSIS* IN THE SACRAMENTO-SAN JOAQUIN DELTA

JERRY L. TURNER and WILLIAM HEUBACH

INTRODUCTION

This report describes our present knowledge of the opossum shrimp, *Neomysis awatschensis* (formerly *Neomysis mercedis*), in the Sacramento-San Joaquin River Delta. *N. awatschensis* is an important fish food in the Delta (Heubach, Toth and McCready, 1963; Ganssle, see p. 92), and major changes in its population could affect the populations of many fishes.

We have found populations of *N. awatschensis* to be highest in the western Delta during the summer but low at most other places and times. Seasonal and geographical variations in the concentration of *N. awatschensis* may be due to changes or differences in salinity and the rates of reproduction. There is also some evidence that depth, rate of water flow, and dissolved oxygen levels influence its distribution in the Delta.

METHODS

The study was conducted as a part of the zooplankton investigation reported in the previous chapter, and collection methods were essentially the same. Twenty-two stations in the Delta were sampled monthly from March 1963 to February 1964. In addition, 15 of the stations were sampled monthly from March to August 1964.

Collections were made with a Clarke-Bumpus sampler fitted with number 000 net (25 meshes to the inch). The sampler was towed behind a power boat traveling against the current for 10 to 15 minutes at a velocity through the water of approximately 3 feet per second. Samples were preserved with formalin. Rose bengal dye was added to stain the animals red and make them easier to separate from detritus.

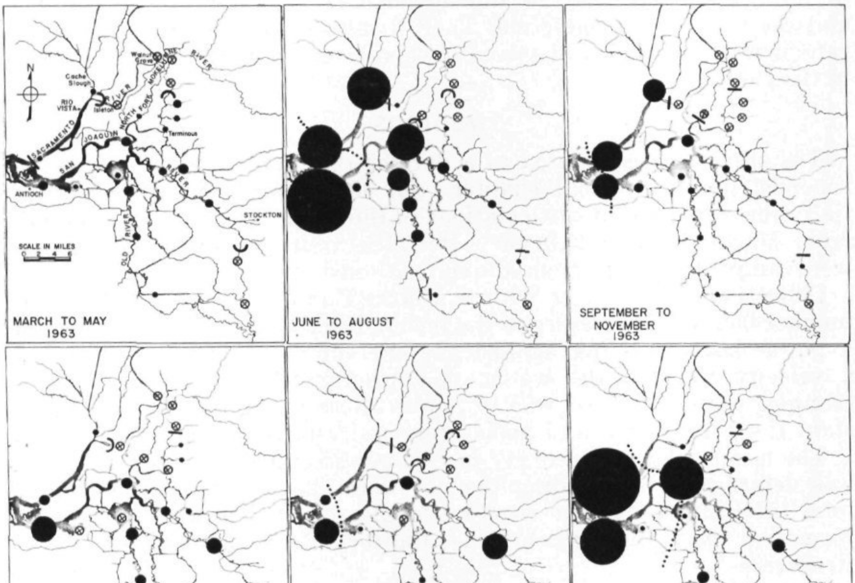
The mean net water velocity in feet per second for the sampling day was determined by dividing the net water flow (total outflow minus total tidal inflow) by the cross-sectional area at each station. This information was supplied by the California Department of Water Resources.

Estimates of locations of the 0.1 ‰ chlorinity concentrations were based on measurements of chlorides taken every 4 days by the California Department of Water Resources.

All *N. awatschensis* in each sample were counted. From July 1963 to February 1964, the juveniles (sex characteristics not developed), males, females, and gravid females from the entire sample or from 100 randomly selected specimens were counted.

GEOGRAPHICAL DISTRIBUTION AND CONCENTRATION

The concentration of *N. awatschensis* was low throughout most of the Delta in the spring of 1963 (Figure 1). The species was not found in the Sacramento River above Isleton, the Mokelumne River above Terminous, or the San Joaquin River above Stockton. In the summer there was a great increase in the concentration of *N. awatschensis* in the western Delta, but few were taken in the Sacramento River above Rio Vista, the Mokelumne River, and the San Joaquin River above the Mokelumne River. In the fall there was a decrease in the high concentrations of the western Delta.



⊗=Neomysis awatschensis NOT PRESENT ....= 0.1 ‰ CHLORIDES
I=NET WATER VELOCITY 0.3 OR MORE ⊃= NET WATER VELOCITY 0.4 OR MORE

FIGURE 1. Seasonal and geographical distribution and concentration of *Neomysis awatschensis* in the Sacramento-San Joaquin Delta, March 1963 to August 1964. The areas of the circles are proportional to the number of mysids per cubic meter. The smallest represents a concentration of 0.1-3.0/M^3 and the largest represents a concentration of 500/M^3.

There was a further decrease in *N. awatschensis* in the Sacramento River and Cache Slough in the winter of 1963–64. The following spring the concentrations were about the same as in the fall, but just below Stockton the population had apparently increased. In the summer of 1964, there were again large concentrations of *N. awatschensis* in the western Delta and comparatively few elsewhere.

Salinity

The largest concentrations of *N. awatschensis* were found in the western Delta during the summer when salinity incursion was the greatest (Figure 1). During the remainder of the year, when the water was only slightly salty or essentially fresh, the density of mysids in the western Delta was relatively low.

Painter (see p. 133) found *N. awatschensis* most abundant at the freshwater end of the salinity gradient, and suggested that salinity was the most important environmental factor affecting its distribution in Suisun and San Pablo Bays. A large concentration of *N. awatschensis* in the low salinity range could explain, in part, the increase in the western Delta as salinity incursion occurred and the decrease when the water was fresh.

Rate of Water Flow

Rate of water flow is an important environmental factor affecting the distribution of *N. awatschensis*. We found very low concentrations of *N. awatchensis* upstream from areas where the net water velocity exceeded 0.3 fps, and never found it where the net water velocity exceeded 0.4 fps (Figure 1).

The apparent influence of net water velocity on *N. awatschensis* was demonstrated in the Sacramento River at Isleton and the North Fork of the Mokelumne River, which are connected by the cross Delta canal at Walnut Grove. The net water flows in the Sacramento River at Isleton and in the North Fork of the Mokelumne River are partly regulated by the opening and closing of the Delta cross canal. When the canal is open, water from the Sacramento River is diverted through it and down the North Fork of the Mokelumne River where the water velocity is thereby increased (Figure 2). At the same time, the net water velocity in the Sacramento River is reduced.

N. awatschensis was present in the North Fork of the Mokelumne River in March and April of 1963 when the canal was closed and net water velocities were below 0.3 fps (Figure 2). At the same time we did not find mysids in the Sacramento River at Isleton where the net velocities were high. During the heavy spring runoff in May 1963, water velocities were high in both the Sacramento River and the North Fork of the Mokelumne River and we did not find *N. awatschensis* in either area.

In June 1963 the canal was opened and high flows were maintained in the North Fork of the Mokelumne River all summer, and we did not find *N. awatschensis*. By August the net water velocity in the Sacramento River at Isleton was approximately 0.25 fps and *N. awatschensis* were present. In October the net water velocity in the Sacramento River was more than 0.4 fps, and again we did not find *N. awatschensis*. In November 1963 the canal was closed. By December the net flow in the North Fork of the Mokelumne River was reduced to 0.1 fps, and we

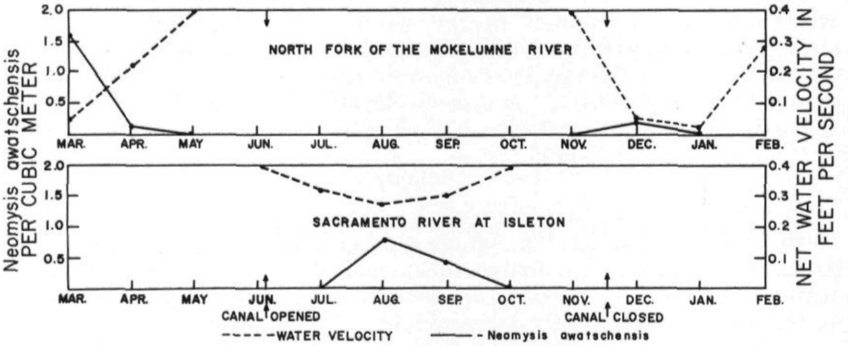


FIGURE 2. *Neomysis awatschensis* per cubic meter and the net water velocity in the Sacramento River at Isleton and the North Fork of the Mokelumne River, March 1963 to February 1964.

collected a few mysids. We did not find them there in January and February even though the net velocity was under 0.3 fps.

In Cache Slough, Old River, and in the San Joaquin River at the mouth of the Mokelumne River, the net water velocity was less than 0.3 fps most of the year (Figure 1). The increase in the density of *N. awatschensis* in these areas of low velocities during the summer may be due to an intrusion from the relatively large concentration of mysids in the western Delta. The changes in the concentration in these areas cannot be attributed to changes in salinity, as the water there was fresh throughout the investigation.

Depth

The depth of the channel also had an important effect on the concentration of *N. awatschensis* (Figure 3). We found greater concentra-

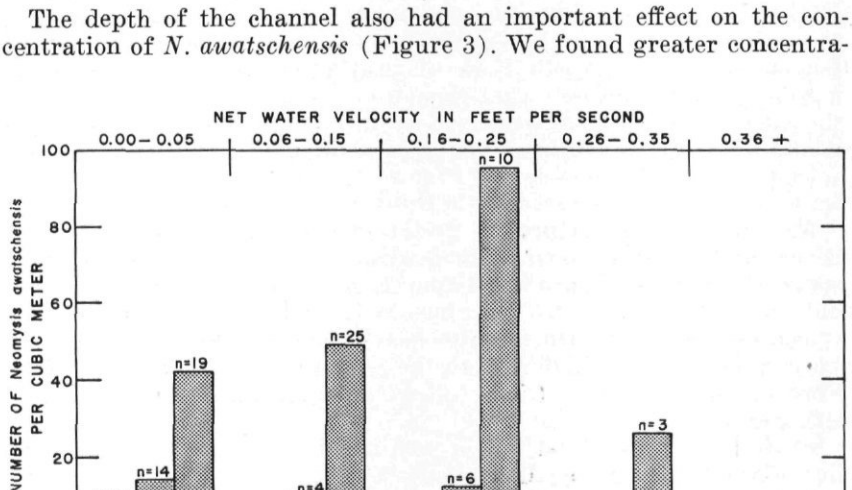


FIGURE 3. *Neomysis awatschensis* per cubic meter in relation to net water velocity and depth, Sacramento-San Joaquin Delta. Number above figure is sample size.

tions in deeper water at all net flows. Low numbers were present at most stations where the channel depth was 15 feet or less.

On August 8, 1963 in mid-afternoon, we made single tows at three different channel depths in the San Joaquin River at Antioch, and at two channel depths at the mouth of the Mokelumne River. At both stations the highest concentration of *N. awatschensis* was in the deepest part of the channel (Table 1).

TABLE 1

Concentration of *Neomysis awatschensis* at Various Channel Depths in the San Joaquin River at Antioch and the Mouth of the Mokelumne River

Antioch		Mouth of Mokelumne River	
Depth in feet	*N. awatschensis* per cubic meter	Depth in feet	*N. awatschensis* per cubic meter
5	4.8	15	0.2
18	35.2		
30	84.5	30	6.3

Oxygen

The low concentration of *N. awatschensis* in the San Joaquin River just below Stockton in the summer may be due to low dissolved oxygen concentrations. In August 1963, two 24-hour surveys of dissolved oxygen concentrations were made at our station just below Stockton. The highest dissolved oxygen level recorded was 5.3 ppm while the lowest was 2.4 ppm. The water temperature was 22°C.

In laboratory experiments, Croft and Turner (unpublished) found that *N. awatschensis* began dying when the dissolved oxygen concentration was reduced to under 5.0 ppm and 100 percent mortality occurred when the dissolved oxygen was lowered to 2 ppm. These experiments were conducted in water temperatures of 10 to 17°C. In other experiments, the temperature was gradually increased while the dissolved oxygen level was held constant. The results indicated that *N. awatschensis* required even higher dissolved oxygen levels at higher temperatures.

Reproduction

From July 1963 to February 1964, there was an increase in the mean length of *N. awatschensis* and a decrease in the percent of gravid females (Figure 4). This probably indicated a higher reproduction rate

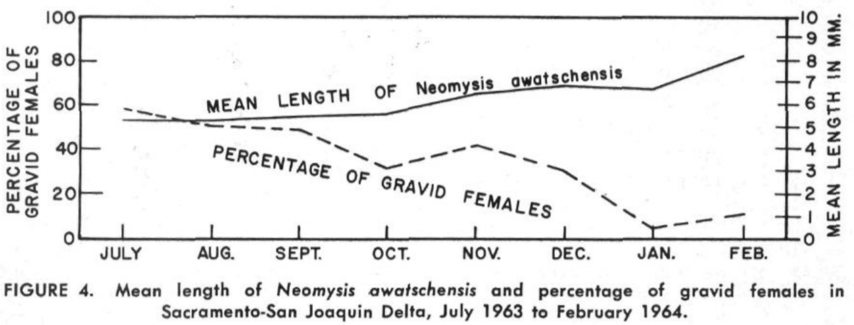


FIGURE 4. Mean length of *Neomysis awatschensis* and percentage of gravid females in Sacramento-San Joaquin Delta, July 1963 to February 1964.

in the summer months. Except in October 1963, we always found a higher percentage of juveniles in the San Joaquin River at Antioch or the mouth of the Mokelumne River than in the San Joaquin River just below Stockton (Figure 5). This may indicate that reproduction was greater in the western Delta.

DISCUSSION

Population studies of mysids in other areas show that salinity, water velocity, depth, dissolved oxygen, and temperature can affect their distribution. The problems of evaluating these influences are compounded in an estuary where tidal action and other water movements occur. While we cannot separate the effects of these variables with our existing data, the results of our investigation indicate that some of them affect the distribution of *N. awatschensis*.

N. awatschensis was most abundant in the western Delta and in the summer. This may have been due to a large concentration of *N. awatschensis* intruding with water of low salinity, or an increased reproduction rate, or both.

Other members of the genus *Neomysis* are affected by salinity. Percival (1929) found *Neomysis vulgaris* in sea water and upstream to a salinity of 0.1‰ in the estuary of the Tamar and Lynher Rivers. The upstream limit of *Neomysis americana* in the estuary of the Delaware River was usually just above the 4‰ isohaline (Hulburt, 1957). He suggested that the principal source of *N. americana* in the estuary was the coastal waters outside the bay.

The consistently higher percentage of juveniles in the San Joaquin River west of the mouth of the Mokelumne River also suggests that the amount of reproduction is greatest in the western Delta, accounting in part for greater numbers in that area.

Based on studies in southern British waters and the English Channel, Tattersall and Tattersall (1951) concluded that mysids in temperate regions reproduce all year, though more slowly in winter than in summer.

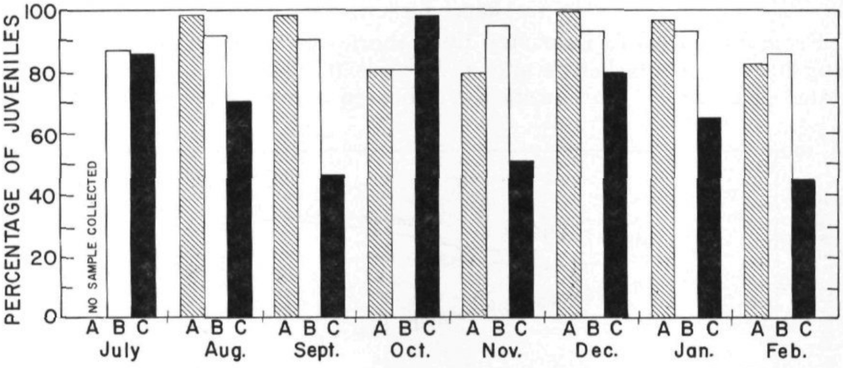


FIGURE 5. Percentage of juvenile *Neomysis awatschensis* in the San Joaquin River at Antioch (A); mouth of the Mokelumne River (B); and just below Stockton (C); July 1963 to February 1964.

N. awatschensis was rarely taken where the net water velocities were high and the channel was shallow. Ricker (1959) states that *Mysis relicta* has never been observed in the field to swim against any considerable current. He states further that Holmquist (1959) found in laboratory experiments that mysids would turn against a gentle current and take refuge in bottom materials. Strong currents washed them away.

Many biologists have found other species of mysids to be negatively phototrophic or positively geotrophic in light. This may explain why *N. awatschensis* is more abundant in relatively deep areas. In laboratory experiments, Foxon (1940) found that normal *Hemimysis lamornae* would always go to the bottom, regardless of the direction of a light source. With their statocyst removed, they would turn their dorsal sides toward the light and move away from it. Herman (1963) found *Neomysis americana* on the surface of Narragansett Bay only at night. In the daytime, it was found on the bottom or immediately above it. He concluded light was the most important single factor governing vertical migration.

The distribution of *N. awatschensis* in the Delta may also be restricted by low dissolved oxygen and high temperatures. According to Tattersall and Tattersall (1951), Jorgensen (1929) found that pollution which resulted in a low dissolved oxygen concentration reduced the number of *Neomysis integer* in the estuary of the Tyne and Coquet Rivers.

Our investigations of *N. awatschensis* in the Sacramento-San Joaquin Delta and estuary showed that the population extends generally from Port Chicago upstream to Rio Vista in the Sacramento River and to Stockton in the San Joaquin River. Downstream it appears to be restricted by high salinities while upstream it seems to be limited by net water velocities over 0.3 fps. Shallow depths and low dissolved oxygen levels also seem to reduce the concentrations of *N. awatschensis*. Annual cycles in the over-all population size are probably due to changes in the reproduction rate.

Further studies are now being conducted to test these hypotheses and to determine how changes in the environment will affect *N. awatschensis* in the estuary.

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ZOOBENTHOS OF THE SACRAMENTO-SAN JOAQUIN DELTA

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INTRODUCTION

Examination of the bottom fauna of the Delta channels revealed that only a few animals are abundant and that their distribution is influenced by substrate types, net flows, and factors we could not identify. High net flows and shifting sand bottoms yielded the poorest samples of fauna.

METHODS

Bottom samples were collected at the same 25 fixed stations used by Turner (see p. 97) to collect zooplankton throughout the Delta. All of these stations were always in fresh water. A few special collections were made in June and December along a transect up the center of dead-end Sycamore Slough.

Samples were collected with a weighted Peterson dredge lowered from a boat. The bite of the dredge on a flat surface covered approximately 1 square foot. During most months, six samples were collected in a transect across the channel at each station.

As each sample was collected, it was classified according to the predominant substrate type by the way it looked and felt. If the sample appeared to have no predominant substrate type, we classed it as "mixed." The accuracy of this field classification was tested by having 12 samples analyzed mechanically (Table 1). It appeared accurate enough for a rough classification, and Hazel's classification of individual samples was used to estimate the percent composition of the substrate in Delta channels (Table 2).

TABLE 1

Comparison of Substrate Classification by Sight and Touch Used During this Study with Conventional Mechanical Analysis[1]

Sample number	Percent composition of individual dredge sample	
	Field classification by C. Hazel	*Mechanical analysis by weight*
M-1	95% fine + medium sand	80% fine sand + 20% medium sand
M-2	95% fine sand	96% fine sand + 4% medium sand
M-3	90% fine sand + 10% silt	10% silt + 86% fine sand + 4% medium sand
M-4	50% silt + 50% fine sand	51% silt + 49% fine sand
M-5	95% fine sand	94% fine sand + 3% silt + 3% medium sand
M-7	90% silt	96% silt + 4% fine sand
M-8	90% silt	48% silt + 50% fine sand + 2% medium sand
M-9	90% silt	91% silt + 8% fine sand + 1% medium sand
M-10	90% medium sand	5% silt + 40% fine sand + 55% medium sand
M-11	75% fine sand + 25% silt	21% silt + 76% fine sand + 3% medium sand
M-12	90% silt	68% silt + 28% fine sand + 4% medium sand
M-13	90% silt	79% silt + 21% fine sand

[1] Mechanical analysis by weight done by Bryte Laboratory of the California Department of Water Resources.

TABLE 2

Percent Composition of Substrates in Delta Channels and Mean Net Velocities June 1963–June 1964[1]

Station	Number of samples analyzed	Rock gravel	Medium sand	Fine-medium sand	Fine sand	Silt sand	Silt	Silt clay	Organic detritus	Peat	Mixed	Net velocity
78—Sacramento river (Walnut Grove)	27	29.6	7.4	14.8	7.4	29.6	0	0	0	0	11.1	1.04
60—San Joaquin River (Mossdale)	64	17.2	9.4	10.9	12.5	32.8	17.2	0	0	0	0	0.95
77—Sacramento River (Isleton)	30	3.3	0	33.3	40.0	20.0	3.3	0	0	0	0	0.50
61—San Joaquin River (Roberts Island)	41	7.3	7.3	12.2	2.4	34.2	36.6	0	0	0	0	0.43
61.5—San Joaquin River (Stockton)	18	33.3	5.6	11.1	5.6	11.1	22.2	0	0	0	11.1	0.43
13—Mokelumne River (North Fork)						no data						0.38
72—Mokelumne River (New Hope Landing)	36	22.2	22.2	2.8	16.7	25.0	5.6	2.8	0	0	2.8	0.36
58—Grant Line Canal	30	3.3	0	6.7	56.7	13.3	10.0	0	3.3	0	6.7	0.24
52—Old River (Quimby Island)	34	0	0	14.7	38.0	2.9	0	0	5.9	29.4	8.8	0.16
82—Sacramento River (Rio Vista)	46	4.3	0	23.9	41.3	4.3	26.1	0	0	0	0	0.16
54—Old River (Woodward Island)	46	6.5	0	4.4	52.2	4.4	10.9	0	11.0	2.2	8.8	0.14
76—Sacramento River (Sherman Island)	54	0	0	20.4	50.0	1.8	25.9	0	0	0	1.8	0.11
56—Victoria Canal	18	0	0	0	0	0	50.0	0	8.3	20.8	20.8	0.10
68—Mokelumne River (Terminous)	36	19.4	0	0	0	2.8	50.0	2.8	11.1	2.8	11.1	0.09
65—*San Joaquin River (Antioch)*	64	3.1	0	15.6	57.8	0	9.4	3.1	0	9.4	1.6	0.08
63—San Joaquin River (Empire Tract)	60	16.7	0	10.0	43.3	0	0	0	1.7	26.7	1.7	0.07
64—San Joaquin River (Bouldin Island)	46	0	0	8.7	52.2	4.4	4.4	8.7	6.5	15.2	0	0.06
62—San Joaquin River (Fourteen Mile Slough)	29	11.5	19.2	7.7	23.1	23.1	3.8	0	0	7.7	3.8	0.06
55—Middle River	8	0	0	0	0	0	37.5	0	37.5	25.0	0	T
67—Disappointment Slough						no data						T
69—Sycamore Slough	18	0	11.1	0	0	0	16.7	0	16.7	33.3	22.2	0
70—Hog Slough	10	0	20.0	0	0	0	33.3	0	10.0	33.3	10.0	0
51—Franks Tract	15	0	0	0	0	0	0	0	0	100.0	0	0

[1]Substrate composition expressed as percent of the samples examined. Net velocity is expressed in feet per second.

Each sample brought aboard the boat was washed through a No. 30 screen with a pore size of 0.59 mm. Small oligochaetes and other small organisms including many *Corophium* less than about 2.6 mm long were washed through this screen and therefore not counted.

To make laboratory sorting easier, 1 gram of rose bengal dye was added to each gallon of formalin used to preserve these samples. Most animals were thereby dyed pink or red.

Whenever an estimate of all species was needed, the preserved and dyed sample was sorted, a tablespoonful at a time, in our laboratory at Stockton. Such total estimates of macrofauna were made on 597 samples. Whenever only *Corophium* were needed, they were floated off by immersing the sample in a sugar solution of 1.11 specific gravity. The method was similar to that used by Anderson (1959). It proved as accurate as hand sorting *Corophium* and took far less time. One hundred and thirty-nine of the samples were counted this way.

When any sample contained more than about 300 organisms, aliquots of $\frac{1}{4}$ or $\frac{1}{2}$ of the sample were counted. Examples of our *Corophium* collections are deposited at the U. S. National Museum and the California Academy of Sciences. The collection of other benthic animals is available for further study at the California Academy of Sciences, San Francisco.

RESULTS

Most of our collecting with the Peterson dredge sampled the bottom of the Delta channels but not the steep intertidal sides, the rare beds of aquatic vegetation, or the communities on piling or posts. These specialized habitats will require further investigation before the fauna of the Delta can be fully described.

Animals belonging to 35 taxa were collected. Only the amphipods, *Corophium spinicorne* and *Corophium stimpsoni*, the Asiatic clam *Corbicula fluminea*, unidentified Tendipedae, and Oligochaeta were in any sense abundant. These were the only animals collected consistently enough to permit analysis of their distribution. Other animals were taken inconsistently and in small quantities. Only their presence in the Delta can be noted.

Sponges of the genus *Spongilla* were collected in the Sacramento River above Walnut Grove. The hydroid, *Cordylophora lacustris*, was taken at most Sacramento and San Joaquin River stations. Unidentified turbellaria, nematodes, and leeches were occasionally found in samples from many areas.

The polychaete worm, *Neanthes limnicola*, was collected in small numbers in most channels except those of the southwestern Delta. *N. limnicola* was often found on substrates of peat and decaying tree limbs and near shore.

A tube-dwelling polychaete, *Manayunkia speciosa*, was collected several times in sand substrate of the lower end of the Mokelumne River. This genus has been previously reported only from the eastern United States (Hartman, 1959; Pennak, 1953). The specimens were identified by Dustin Chivers, California Academy of Sciences, and are deposited in the systematic collections at the Academy in San Francisco.

Most of the amphipods were *Corophium* but occasionally a representative of the genus *Gammarus* appeared in the samples.

The isopods *Asellus tomalensis* and *Exosphaeroma oregonensis* were occasionally found in samples collected from several areas of the Delta. The marine isopods *Synidotea*, the introduced crab *Rhithropanopeus harrisii*, and the barnacle *Balanus*, appeared only in samples from the western edge of the Delta.

Crayfish are common in the Delta but can usually avoid the Peterson dredge. Both the native *Pacifastacus leniusculus* and the introduced *Procambarus clarkii* have been regularly taken with otter trawls in the San Joaquin, Sacramento, and Mokelumne Rivers during the course of our other work.

Neomysis awatschensis was regularly taken with the dredge but was better sampled with nets.

Except for the tendipedids, aquatic insects rarely appeared in the benthic samples. A few specimens of the dragonfly *Gomphus olivaceous,* the mayfly *Hexagenia limbata,* an unidentified caddisfly *Polycentropis* sp., a few simulids, ceratopognoids, and Chaoborinae, were collected only at scattered points.

A few snails of the families Physidae and Lancidae and the clam *Anodonta californiensis* were collected from scattered parts of the Delta. The clam *Gonidea angulata* was collected with an otter trawl fished in the Mokelumne River but none was collected with the Peterson dredge. These clams were identified by John DeMartini, Humboldt State College, and Allyn Smith, California Academy of Sciences.

Casual observations often revealed the isopod *Exosphaeroma oregonensis* and leeches on the undersides of rocks placed along the shore for erosion control.

Corophium

The two most abundant macro-organisms collected from the bottom of Delta channels were two amphipods, *Corophium spinicorne* and *C. stimpsoni.* Their identity was confirmed by Thomas E. Bowman, Associate Curator, Division of Marine Invertebrates, U.S. National Muesum.

Heubach, Toth and McCready (1963) reported the genus *Corophium* as the most important bottom food of young striped bass in the Delta. Stevens (unpublished) has recently examined the stomachs of more than 15,000 fishes from the Delta and has found *Corophium* to be the principal benthic food of fishes there.

During our study, large concentrations of *C. spinicorne* and *C. stimpsoni* were limited to the freshwater, upstream part of the estuary. We did not sample below the Delta but we examined Painter's collections of *Corophium* from the salinity gradient in the bay. We found both species in significant numbers in collections made as far downstream as Honker Bay, but not in those made far below there (Figure 1). Only 10 *C. spinicorne* and 119 *C. stimpsoni* were collected in the 228 Peterson dredge hauls made by Painter in six transects below Honker Bay. The lowest transect where he collected either *C. spinicorne* or *C. stimpsoni* in numbers comparable to the Delta stations was in Honker Bay.

In the fresh water of the Delta we collected both species in every channel sampled. The mean number of each species collected with the Peterson dredge at the 25 stations provides a very rough estimate of their concentrations throughout the Delta (Figure 2). In general *C.*

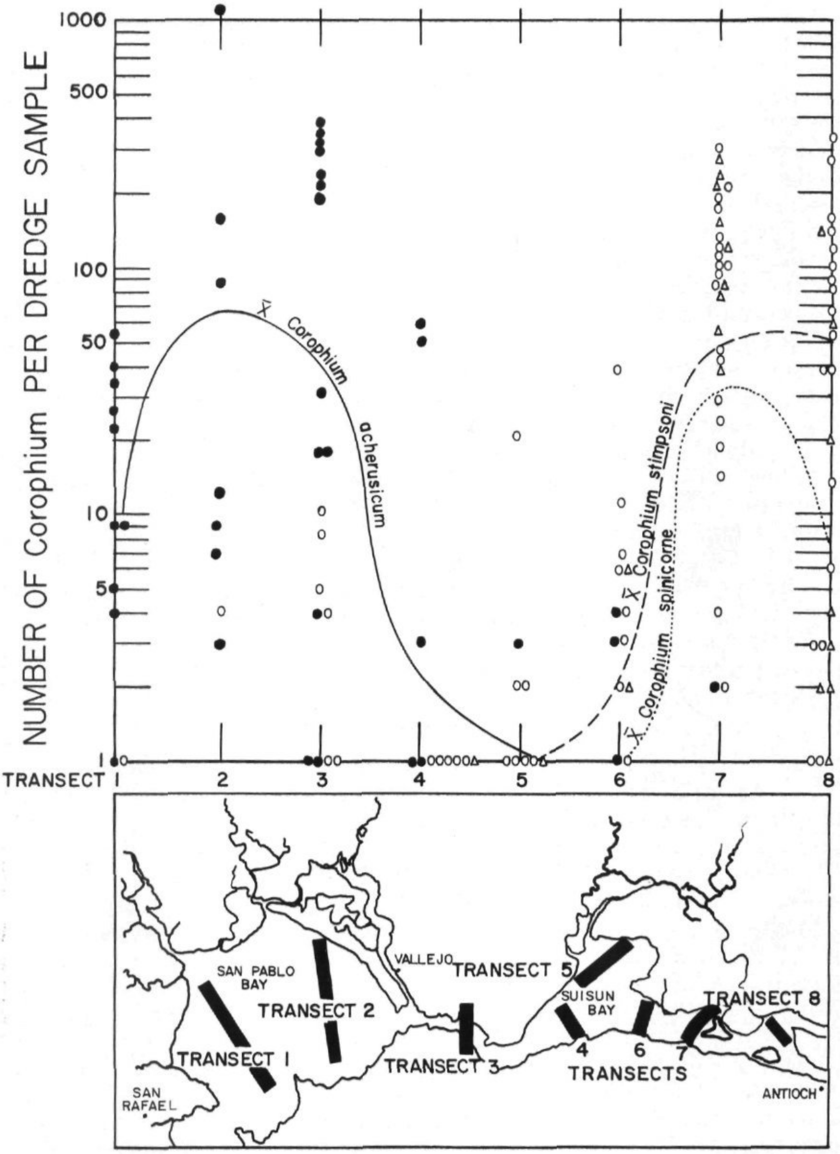

FIGURE 1. Distribution of three species of *Corophium* through the reach of changing salinity. Plotted points represent the numbers in individual Peterson dredge samples collected from the transects shown on the map. Open circles represent *C. stimpsoni;* open triangles, *C. spinicorne;* and blackened circles, *C. atcherusicum.* The curves represent the means of all (281) samples collected on each transect during July-September 1963.

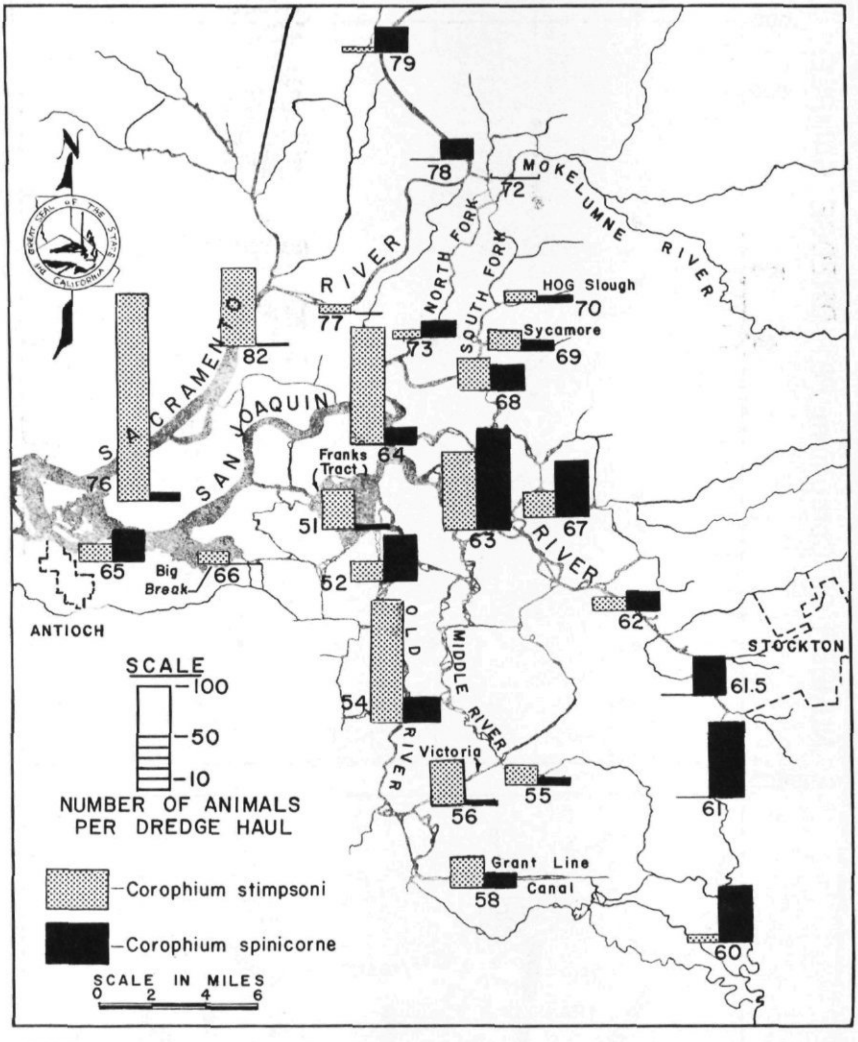

FIGURE 2. Mean numbers of *Corophium spinicorne* and *C. stimpsoni* in Peterson dredge collections at each of 25 Delta stations from August 1963–June 1964.

stimpsoni was most abundant in the broad tidal channels of the Delta. *C. spinicorne* was most abundant along the upstream edge of the Delta, especially in the San Joaquin River. Populations of both species were low in the Mokelumne River region.

Within each channel, we usually found *C. spinicorne* more concentrated near the banks in water between the low tide mark and 10 feet deep (Figure 3). *C. stimpsoni* were usually more abundant in deeper water. Many samples contained both *C. stimpsoni* and *C. spinicorne,* but ordinarily where one species was abundant in a sample, the other was relatively rare. This affinity for different habitats was obvious throughout the Delta. It may be related to the distinct substrate preferences of the two species.

Our conclusions about substrate preferences of *C. spinicorne* and *C. stimpsoni* are based upon a comparison of the concentration of each species in 729 Peterson dredge hauls that were classified according to their predominant sediment type. *C. spinicorne* were usually only abundant in samples that included some solid surface (Figure 4). Such samples were usually classed as cobble, peat, or "mixed."

Throughout the Delta we found *C. spinicorne* inhabiting small, mucous-silt tubes fastened onto solid surfaces of submerged logs or rocks. These tubes were especially abundant on the cobble that has been

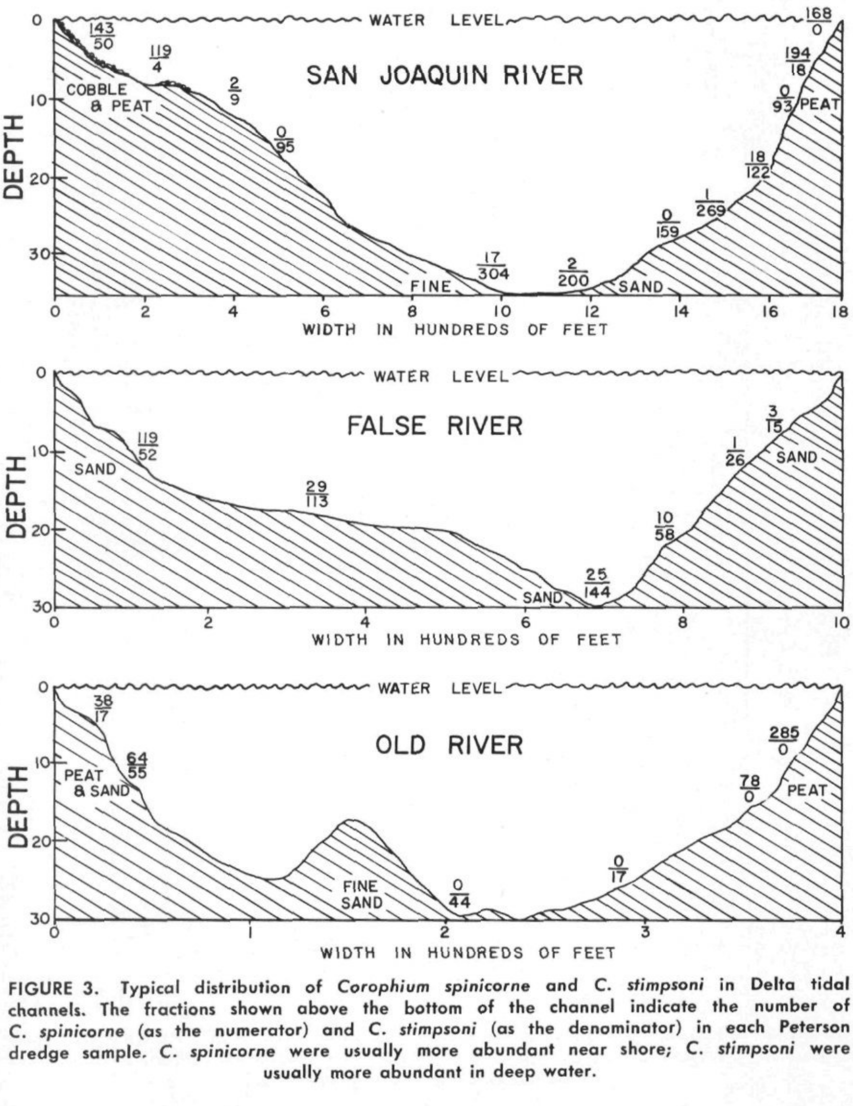

FIGURE 3. Typical distribution of *Corophium spinicorne* and *C. stimpsoni* in Delta tidal channels. The fractions shown above the bottom of the channel indicate the number of *C. spinicorne* (as the numerator) and *C. stimpsoni* (as the denominator) in each Peterson dredge sample. *C. spinicorne* were usually more abundant near shore; *C. stimpsoni* were usually more abundant in deep water.

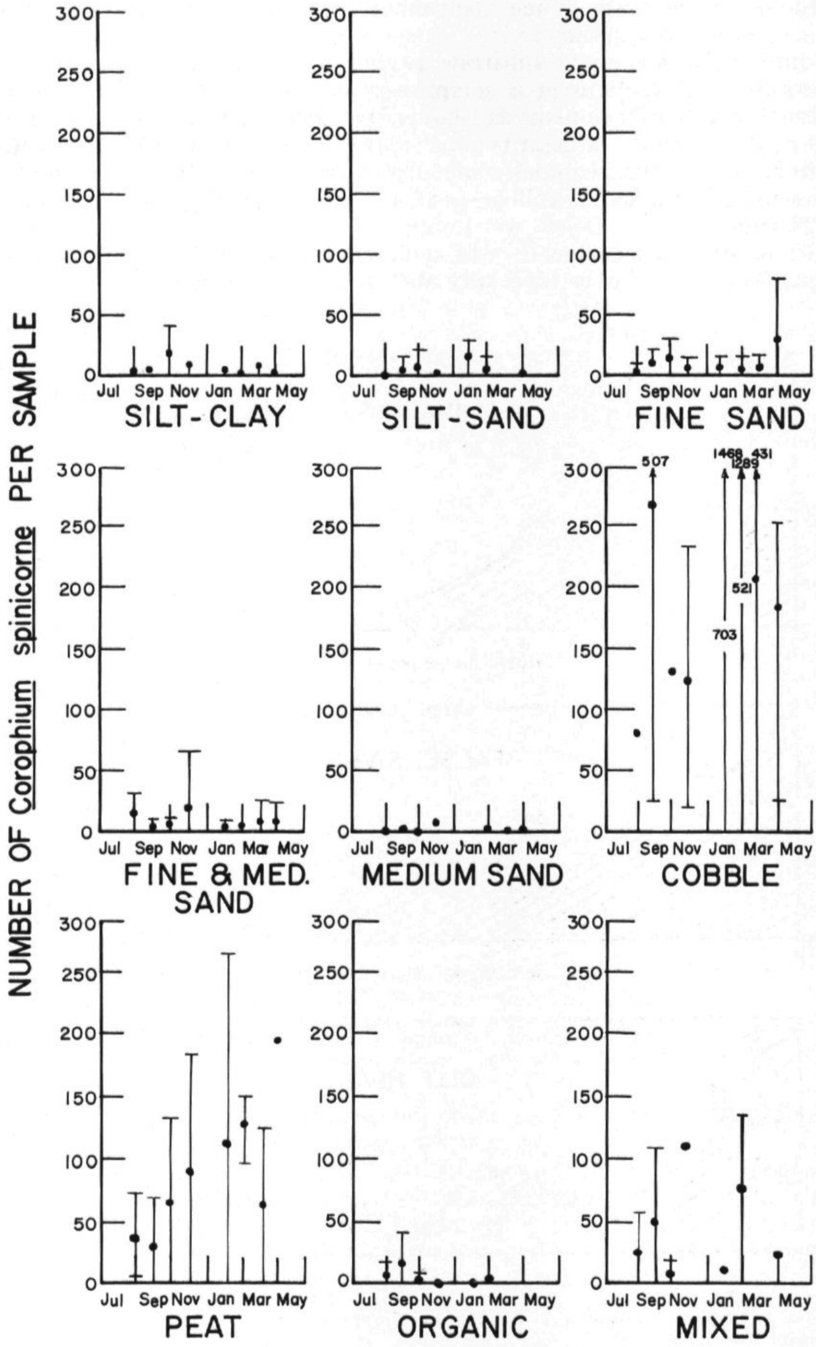

FIGURE 4. Substrate preferences of *Corophium spinicorne*. Each graph illustrates the mean number of *C. spinicorne* collected per dredge sample from a different substrate. Vertical lines illustrate the 95 percent confidence interval.

laid to protect some levees from erosion and on submerged logs and piling that were not sampled with the dredge.

Samples that contained a large proportion of cobble often contained more than 300 *C. spinicorne*. Samples from peat or "mixed" substrates seldom contained more than 100 individuals. Not all samples from these "preferred" substrates held large numbers of *C. spinicorne*. Often, what appeared to be ideal substrate was collected without a single specimen. The confidence limits shown in Figure 4 are therefore very wide.

C. spinicorne had such a well defined "preference" for the cobble, peat, or "mixed" substrates that we expected its concentration at different parts of the Delta to be a function of the concentration of the "preferred" substrates there. To test this we plotted the mean number of *C. spinicorne* per dredge sample at each station against the percent of dredge samples from that station that were classed as the "preferred" substrates (Figure 5). Many of the plotted points lay far outside of any imaginary band that would illustrate a correlation.

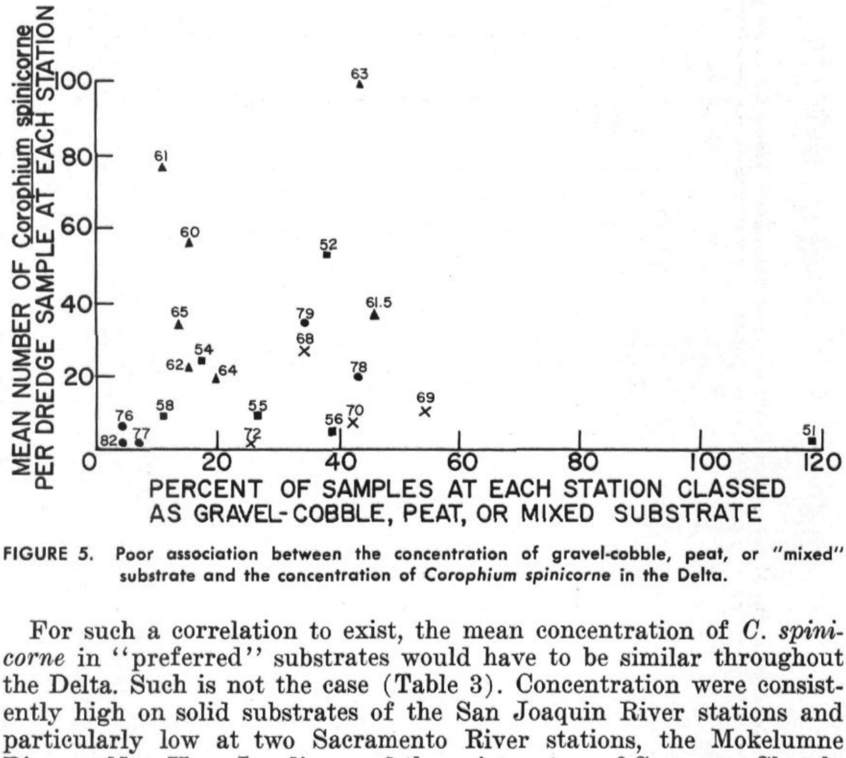

FIGURE 5. Poor association between the concentration of gravel-cobble, peat, or "mixed" substrate and the concentration of *Corophium spinicorne* in the Delta.

For such a correlation to exist, the mean concentration of *C. spinicorne* in "preferred" substrates would have to be similar throughout the Delta. Such is not the case (Table 3). Concentration were consistently high on solid substrates of the San Joaquin River stations and particularly low at two Sacramento River stations, the Mokelumne River at New Hope Landing, and the quiet waters of Sycamore Slough, Hog Slough, Frank's Tract, and Victoria Canal. Probably some conditions other than substrate type have a great influence on the distribution of *C. spinicorne* in the Delta.

C. stimpsoni occurred in samples of every kind of substrate taken from the Delta, but they were most abundant on substrates of fine sand and

TABLE 3

Mean Concentrations of *Corophium spinicorne* and *Corophium stimpsoni* on All Substrates and on "Preferred" Substrates

Number	Station Location	Total samples examined	*C. spinicorne*			*C. stimpsoni*		
			All substrates	"Preferred" substrates		All substrates	"Preferred" substrates	
			Number per sample	Number of samples	Number per sample	Number per sample	Number of samples	Number per sample
	Sacramento River							
79	Courtland	6	36	2	107	Present	0	--
78	Walnut Grove	27	20	11	47	1	6	10
77	Isleton	28	1	2	6	10	18	10
82	Rio Vista	45	2	2	23	80	30	118
76	Sherman Island	52	5	1	6	213	35	280
	Mokelumne River							
72	New Hope Landing	36	1	9	2	1	7	1
70	Hog Slough	10	5	4	2	11	0	--
69	Sycamore Slough	18	10	9	19	20	0	--
68	Terminous	36	27	2	85	33	0	--
73	North Fork	3	16	0	--	8	2	31
	San Joaquin River							
60	Mossdale	60	57	9	371	7	14	17
61	Roberts Island	41	78	3	853	1	6	26
61.5	Stockton	18	38	8	75	1	2	0
62	Fourteen Mile Slough	29	21	5	83	16	8	36
63	Empire Tract	59	98	24	207	83	32	130
67	Disappointment Slough	2	72	2	72	33	0	--
64	Bouldin Island	45	18	9	69	136	28	187
65	Antioch	65	34	8	200	21	46	23
	South Delta							
51	Franks Tract	15	1	15	1	39	0	--
52	Old River at Quimby Island	34	54	13	108	34	18	34
54	Old River at Woodward Island	46	23	7	89	124	26	145
55	Middle River	8	8	2	32	17	0	--
56	Victoria Canal	18	4	7	Present	45	0	--
58	Grant Line Canal	30	8	3	45	29	19	51

a mixture of fine and medium sand (Figure 6). Very few were found in samples classed as medium sand.

The distribution of *C. stimpsoni* like that of *C. spinicorne* was apparently neither a simple function of, nor was it well correlated with the concentration of its "preferred" substrate in different parts of the Delta. A graph of the mean catch of *C. stimpsoni* for each station plotted against the percent of the samples from that station classified as fine and fine-medium sand substrate illustrates no correlation (Figure 7.) The plotted points on that graph do create an interesting pattern of four groups of stations that help to describe the habitat of *C. stimpsoni.*

First, there is a group of four stations from which the highest concentrations of *C. stimpsoni* were collected. This group includes the Empire Tract and Bouldin Island stations on the San Joaquin River; the Orwood Tract station on Old River; and the Rio Vista station on the Sacramento River (Stations 63, 64, 54, and 82). All are wide tidal channels with low net flows. Collections from these stations contained both high numbers of *C. stimpsoni* (greater than 89 per sample) and a high proportion of substrate classed as fine and medium sand (greater than 45 percent).

Dredge samples from the second group of stations contained just as much of the "preferred" substrate as those from the first group but the concentrations of *C. stimpsoni* were always less than half as great. These stations are widespread geographically and do not appear to be at all similar. The group includes the Holland Tract station on Old River; the station in the Grant Line Canal; the station on the San Joaquin River at Antioch; and the station on the Sacramento River at Isleton (Stations 52, 58, 65, and 77).

Stations of the third group provided *no* substrate samples that were classed as the fine sand or the fine and medium sand "preferred" by *C. stimpsoni.* These are the quiet-water stations scattered throughout the Delta. Their bottoms are of peat and silt. Samples from these stations contained moderate numbers of *C. stimpsoni.*

The fourth group of stations are those with relatively small amounts of fine or medium sand and low numbers of *C. stimpsoni.* These are all the more river-like stations on the eastern edge of the Delta. All are subject to tidal flows but are characterized by net flows that are relatively high.

Inspection of the environmental conditions at these four groups of stations suggested that some characteristic associated with water flow had a major influence on the concentration of *C. stimpsoni* in them. Turner (see p. 95) used the "net velocity" as an index of residence time and showed that it had a significant effect on zooplankton populations. To test its relationship to *C. stimpsoni*, we plotted the mean number of *C. stimpsoni* taken at each station against the July 1963–April 1964 average of the mean monthly "net velocities" of each channel at that station (Figure 8). The concentration of *C. stimpsoni* appears related to the net velocity. The highest concentrations were found in stations where the velocities were above 0.05 feet per second and below 0.2 feet per second. Only moderate numbers were found in the stations with net velocities too low to measure or higher than 0.3 feet per second.

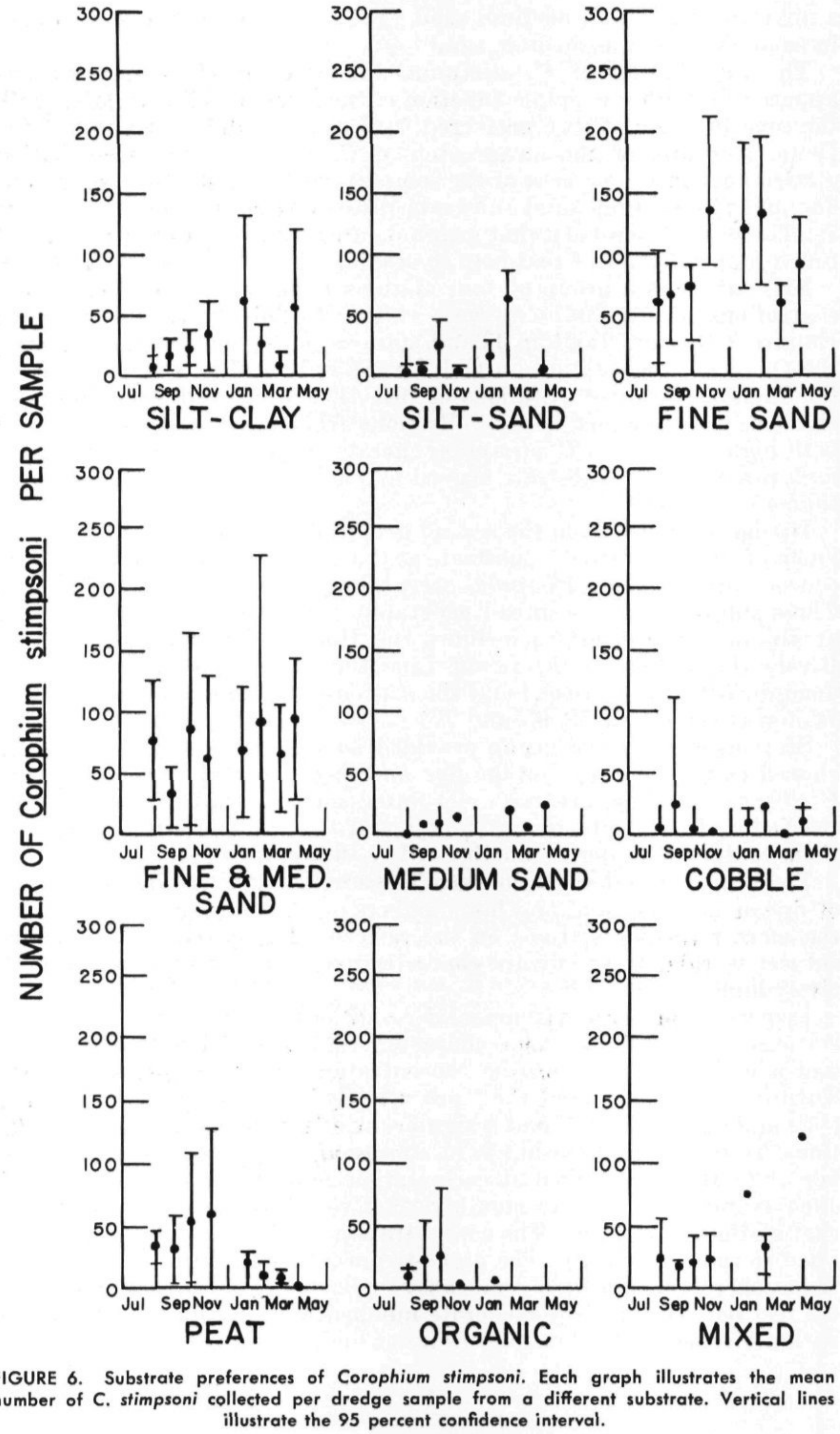

FIGURE 6. Substrate preferences of *Corophium stimpsoni*. Each graph illustrates the mean number of *C. stimpsoni* collected per dredge sample from a different substrate. Vertical lines illustrate the 95 percent confidence interval.

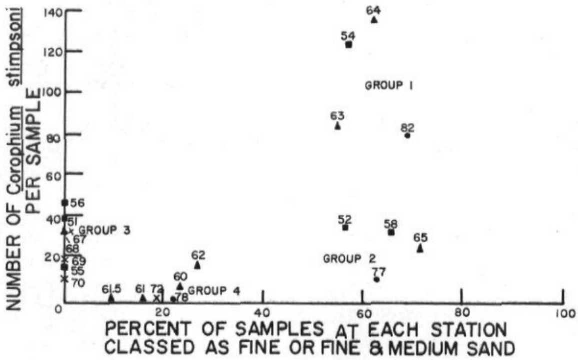

FIGURE 7. Association between the concentrations of fine and fine-medium sand and *Corophium stimpsoni* in the Delta.

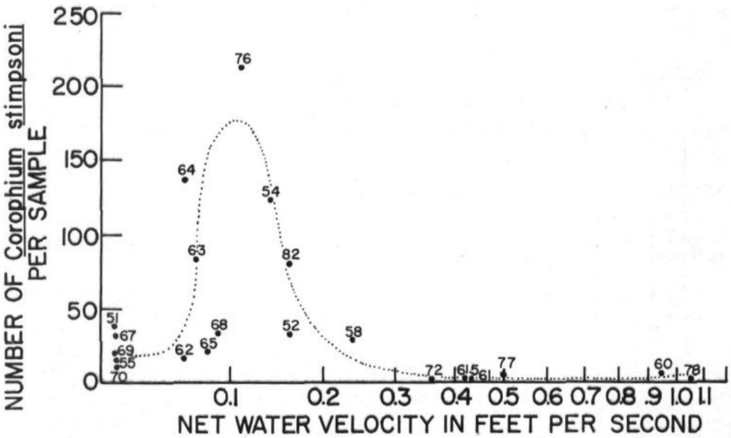

FIGURE 8. The association between net water velocity and the concentration of *Corophium stimpsoni* in Delta channels. "Net water velocity" is the mean *net* downstream flow water expressed in cubic feet per second divided by the area of a typical cross section of the channel. It has little relationship to real velocities of the water but rather is an index of "residence" time.

Not all of the stations in the range between 0.05 and 0.2 feet per second provided samples with large numbers of *C. stimpsoni*. The low numbers in station 62 *may* be the result of low dissolved oxygen conditions that frequently occur in the reach of the San Joaquin River below the City of Stockton, and the low numbers in station 65 may be the result of waste disposal from the industrialized Pittsburg-Antioch area.

Oligochaeta

Oligochaete worms were collected at all of the benthic sampling stations in the Delta. They were more abundant at the upstream stations (Figure 9) where a high percentage of the samples were classed as silt or fine sand (Table 2). Oligochaetes were least abundant at stations of the central Delta where substrates include more peat or coarse organic detritus.

Oligochaetes are usually burrowing deposit feeders. We found them to be more abundant in samples with substrates that were of smaller particle size, rich in organic matter, and not very compact (Figure 10).

Tendipedidae

Tendipedids were not as abundant in the bottom samples as either species of *Corophium* or as oligochaetes. The only stations with more than a few tendipedids were those in the San Joaquin River at or above Stockton (Stations 60, 61, 61.5); one in the Sacramento River at Courtland (Station 79); and one in the Mokelumne River at New Hope Landing (Station 72) (Figure 9).

These include all of the stations on the edge of the tidal basin, and their most distinguishing characteristic is that each has some period in the spring when river currents overwhelm the ebb and flood of the tide.

The substrate at these stations ranges from sand to fine organic silt. There is little to distinguish them from many other stations except that all of these stations did contain some "medium" sand (Table 2). Several other stations (78, 62, 69, 70) had substrates with equal or more amounts of "medium sand" but had few or no tendipedids.

Corbicula fluminea

The Asiatic clam *Corbicula fluminea* is abundant in many parts of the Delta. It is especially abundant on some tule berms and nearshore areas where it is gathered by anglers and on a limited commercial basis for catfish bait. Large populations occur in the Delta Mendota Canal which draws water from the south Delta. Our sampling methods were not designed to measure *C. fluminea* populations and we have not learned much about their distribution. They were present in every Delta channel we sampled. Painter (unpublished) collected young *C. fluminea* regularly throughout Suisun Bay during 1963 but found none in San Pablo Bay. The young are regularly collected in zooplankton nets in the Delta during the spring (Farley, unpublished). Our late fall and winter collections suggest a downstream movement of young (Figure 11).

Sycamore Slough

Some special collecting was done in Sycamore Slough, a short channel tributary to the North Fork of the Mokelumne as it flows through the north Delta. Sycamore Slough is reasonably typical of the Delta's

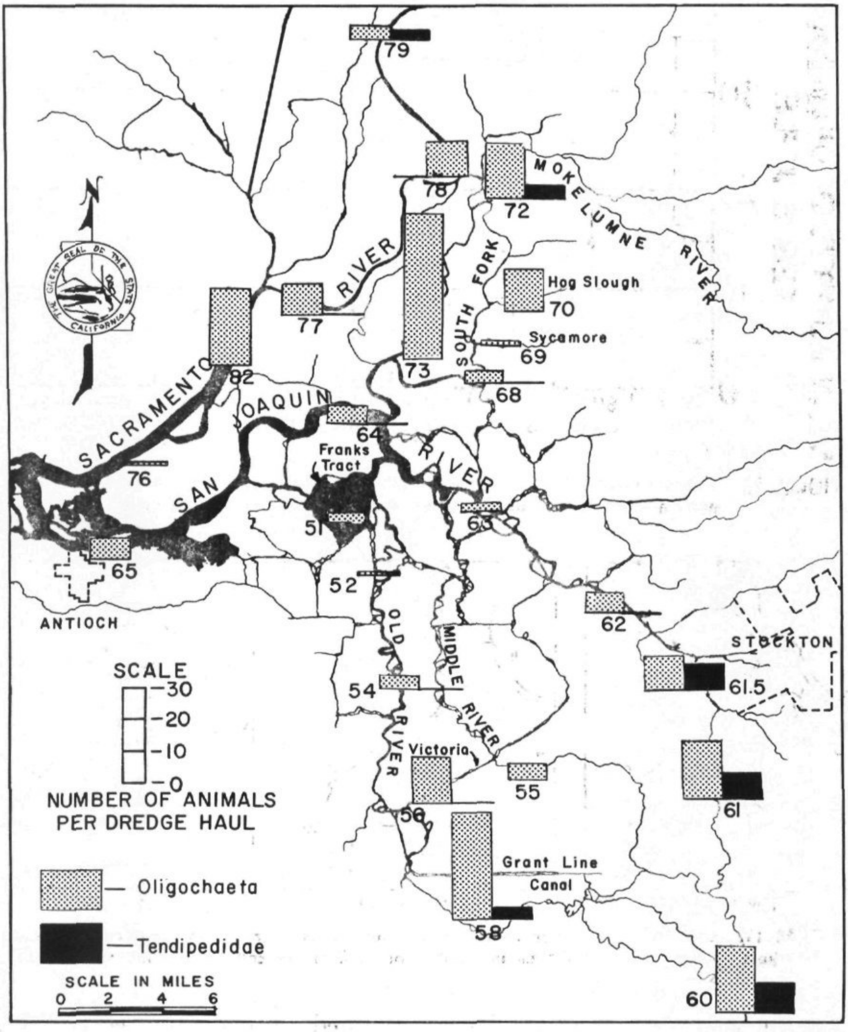

FIGURE 9. Mean concentrations of Oligochaeta and Tendipedidae at 25 Delta sampling stations from July 1963 through November 1963 and in February 1964.

"dead-end" sloughs. It is almost 5 miles long, varies in width from about 700 feet near the mouth to less than 100 near the upper end, and in depth from 18 feet near the mouth to 3 feet and less at the very upper end. Mean tidal range is about 3.6 feet. It has no real inlet or outlet except its mouth which joins with the North Fork of the Mokelumne. Small amounts of water are siphoned from it to irrigate the adjacent islands.

Six stations spaced along the length of Sycamore Slough were sampled with the Peterson dredge on June 10 and again on December 17, 1963. Two samples were collected at each station on each day. These

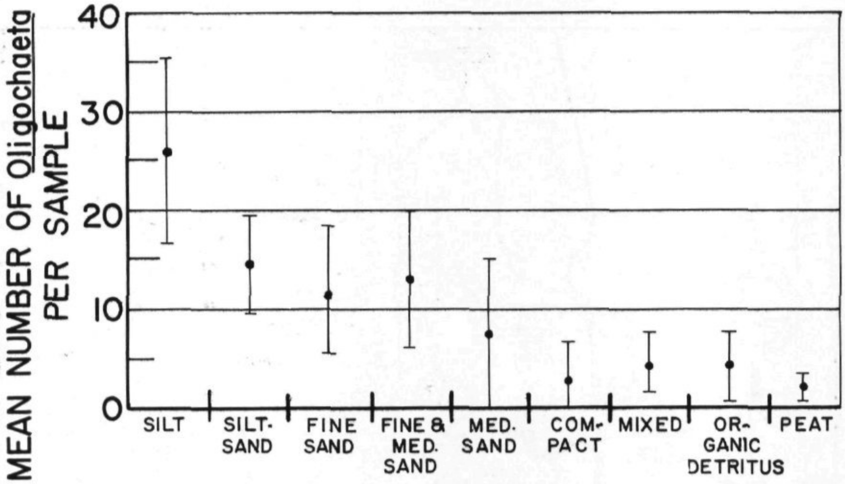

FIGURE 10. Concentrations of Oligochaetes in different substrates of the Delta. Graph shows mean number of animals per sample and 95 percent confidence limits.

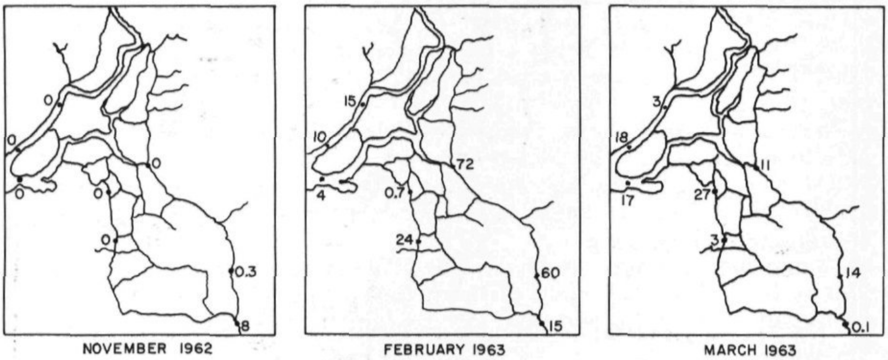

FIGURE 11. Late fall and winter collection of young (less than 5 mm) *Corbicula fluminea*. Numbers on the maps are the mean number of *C. fluminea* collected during the month.

are the same stations where Turner sampled zooplankton (see p. 101).

Tendipedids were the most abundant invertebrates in the dredge samples collected on June 10. They were numerous only from the upper half of the slough (Figure 12).

Oligochaetes were similarly distributed. They were uncommon in the lower end of Sycamore Slough and increasingly abundant in samples collected from the upper end.

On June 10, *Corophium* were reasonably numerous (34 per sample) in the mixed silt and sand bottom about 0.5 mile inside the mouth of Sycamore Slough. They were less than one-third as abundant in similar bottom types upstream 1.5 miles. Only a few were found above there. All *Corophium* were collected within 3.0 miles of the mouth of the slough.

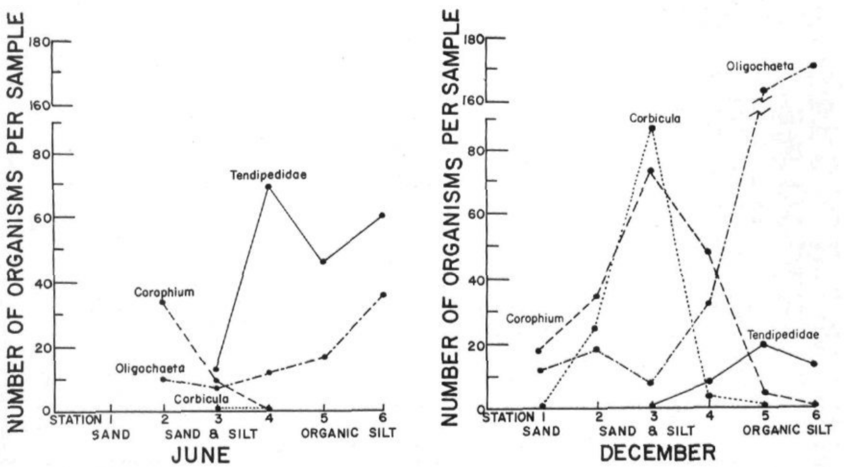

FIGURE 12. Concentrations of benthic macrofauna along the longitudinal axis of Sycamore Slough.

In June 1963 we had not realized that two species of *Corophium* existed in the Delta. Those collected were all labeled *C. spinicorne*. Because they were collected almost entirely from the sand and silt substrate in deep water, we believe that most of them were *C. stimpsoni*.

The June samples from the central part of Sycamore Slough also contained a few young *Corbicula fluminea*.

The collections made the following December 17 contained fewer tendipedids, and many more oligochaetes, *Corophium* sp., and young *Corbicula fluminea*.

During both periods, tendipedids and oligochaetes were most abundant in the soft organic mud of the upper slough. *Corophium* sp. were most abundant on the silt-sand of the central and lower portions of the slough.

DISCUSSION

The distribution and abundance of benthos in the Delta is the result of a combination of a number of environmental conditions some of which we have identified. *Corophium stimpsoni*, for instance, is an animal of fine and fine-medium sand bottoms of the deeper water where the predominant currents are the ebb and flow of tides. Its abundance appeared to be limited downstream by the beginning of the salinity gradient and upstream by high net velocities of the rivers entering the Delta. It does not flourish in quiet water.

The tube builder *Corophium spinicorne* is almost entirely restricted to sediments with some solid substrate like rock, logs, peat, or organic detritus. It is very unevenly distributed and we have been unable to define the factors that affect its distribution on these preferred substrates except that it too appeared limited downstream by salinity.

There are undoubtedly a number of species of oligochaetes in our samples. They prefer the finer and more organic substrates and are not abundant in the central Delta where substrates and are predominantly shifting sand. They are common in the upstream areas.

There are probably several species of tendipedids in our collections and detailed analysis of their distribtuion without identification to species is unwarranted. As a group, they were found in significant numbers only in those stations along the edge of the tidal basin where reverse flows either are not present or are very slight during some period in the spring.

Of all the environments sampled, those with bottoms of "medium" sand were the least productive of macrofauna. Such bottoms are not common in the Delta but were occasionally encountered in the upstream reaches of the San Joaquin River, the Mokelumne River at New Hope Landing, Sacramento River at Walnut Grove and above, and in Hog and Sycamore Slough. The presence of large amounts of this "medium" sand suggests that portions of the substrate may be moving with the current and the finer materials being washed out. This is unlikely to be the case in Sycamore or Hog Slough or in the San Joaquin River below Stockton, but is probably true in the San Joaquin River above Stockton, the Mokelumne at New Hope Landing, and in the Sacramento River at and above Walnut Grove. The bottom fauna of these areas consists largely of *Corophium spinicorne* on cobble laid along the banks to prevent erosion, on tree limbs, logs, and piling.

In general we can say that high net velocities and shifting sand bottoms are detrimental to the macrofauna of the Delta and that the maintenance or addition of some solid substrate, whether it be submerged tree limbs, dock piling, or rock laid along the bank, provides additional and valuable habitat for *Corophium spinicorne* and undoubtedly increases its total population.

Sand has generally been considered to be the least productive of all substrates. Medium or coarse sand of the Delta channels is unproductive but the fine or a mixture of fine and medium sands are the preferred substrates of *Corophium stimpsoni*—one of the two must abundant bottom animals there.

There is some confusion about the distribution of *Corophium spiniicorne* and *C. stimpsoni* in the literature. It may be largely due to misidentification of these two species that look very much alike.

Filice (1954a, 1954b, 1958, 1959) collected 375 samples with an Ekman dredge through most of the salinity gradient from West Island above Antioch, to the lower end of San Pablo Bay, between September 1951 and April 1952. He does not report collecting either *C. stimpsoni* or *C. acherusicum*. He reported taking only a few *C. spinicorne* below Port Chicago. He described collecting *C. spinicorne* at depths below 18 feet more often than was accounted for by chance and concluded that it preferred a sandy substrate. These two criteria correspond well with our definition of the environmental preferences of *C. stimpsoni* but not with those of *C. spinicorne*.

Aldrich (1961) collected about 300 samples with a Peterson dredge from the lower San Joaquin River at West Island (our station 65) and 11 miles upstream. He reported, " . . . that *C. spinicorne* at all times either attained or exceeded expected numbers in sand; in clay when it was available. This was usually true for gravel also. The data definitely indicates an aversion to peaty substrate throughout the area and to mud when mud became a major component of the substrate." These conclusions do not agree with ours that *C. spinicorne* prefers peat and cobble substrates and is seldom found in large numbers elsewhere. Our evidence is that *C. stimpsoni* prefers the fine and fine-medium sand bottoms. Aldrich did not identify any of his *Corophium* as *C. stimpsoni*. Our conclusions about environmental requirements would agree if he merely failed to distinguish *C. stimpsoni* from *C. spinicorne*.

The California Department of Water Resources (1962) collected monthly or bi-monthly zoobenthos samples from April 1960 through June 1961 at 29 stations on the Sacramento River from its junction with the San Joaquin to Shasta Dam. About 50 Peterson dredge samples were collected in that portion of the river flowing through the Delta. The authors report collecting the largest number of *C. spinicorne* in the lower Sacramento River just above its junction with the San Joaquin. They did not mention *C. stimpsoni*. We have examined their preserved collections and found that most of the *Corophium* identified from this region as *C. spinicorne* were actually *C. stimpsoni*. We found no *C. stimpsoni* in their collections from above Walnut Grove. They collected *C. spinicorne* from the Sacramento River 80 miles above tidewater.

Investigators from the Sanitary Engineering Research Laboratory of the University of California have recently collected many benthic samples from the estuary up to and including our station 65 on the San Joaquin River. The SERL Study never collected C. *spinicorne* in San Pablo Bay, but *C. acherusicum* was regularly taken there and in north San Francisco Bay. Their report (Storrs, Selleck, and Pearson, 1964) of the distribution of *C. spinicorne* corresponds with our description of *C. spinicorne* and *C. stimpsoni*. They also report a fourth species, *Corophium insidiosum* from south San Francisco Bay.

The virtual absence of *C. spinicorne* and *C. stimpsoni* from Painter's and the SERL samples collected far below Chipps Island, strongly suggests that both species are either intolerant of salinity or cannot successfully co-exist with other animals that inhabit the salinity gradient. The apparent downstream limit to large populations of both species according to Painter's collections, corresponded to the location of 3‰ chloride concentration at high-high tide in August, the month of maximum salinity intrusion up the estuary. These findings differ from those of Jones (1961) who regularly collected both *C. acherusicum* and *C. stimpsoni* from San Francisco Bay off Point Richmond from January into the fall of 1955.

It should also be noted that Shoemaker (1941) originally described *C. stimpsoni* from specimens collected from the *Albatross* in San Francisco Bay in 1912, from Elkhorn Slough off Monterey Bay and from "very fine specimens taken at Dillon Beach"—all of these are thought to be essentially marine environments. Later Shoemaker (1949), in this comprehensive description of the genus, reported that *C. stimpsoni, C. brevis, C. acherusicum, C. insidiosum,* and *C. oaklandense* had all been collected in San Francisco Bay, and that *C. spinicorne* was collected from the fresh water of Lake Merced and the Sacramento River. We hope to reconcile these apparent differences in future reports.

SUMMARY

1) The collection of substrate samples at monthly intervals from many of the Delta channels revealed that most of the macrofauna on the bottom consisted of two amphipods, *Corophium spinicorne* and *Corophium stimpsoni,* the Asiatic clam *Corbicula fluminea,* a polychaete, *Neanthes limnicola,* and unidentified Tendipedidae and Oligochaetea.

2) *Corophium stimpsoni* and *C. spinicorne* were by far the most abundant animals and were present in every channel we sampled in the Delta. Examination of Painter's collection shows them to be abundant downstream in the estuary to the brackish waters of Honker Bay, but not below there.

3) In the Delta the habitat of *Corophium spinicorne* is on solid surfaces like rock, sticks, logs, or peat. *C. spinicorne* is usually more abundant in shallow water near the shore.

4) The habitat of *Corophium stimpsoni* in the Delta is the fine and fine-medium sand found on the bottom of most Delta tidal channels.

5) The concentrations of *Corophium spinicorne* and *C. stimpsoni* were only partly associated with our measures of the distribution of their preferred substrates. No factor other than substrate preference was identified as influencing the distribution of *C. spinicorne*. The concentrations of *C. stimpsoni* were most abundant in channels with the slow yet distinguishable net flow down stream. *C. stimpsoni* were never abundant in the river-like channels with mean net velocities of more than 0.3 feet per second.

6) Oligochaetes were most abundant in the upstream channels with substrates of silt or fine sand.

7) Tendipedidae were present in significant numbers only in the more river-like environments of the upstream Delta.

8) Collections of bottom samples in a dead-end slough illustrated some of the major influences on the distribution of important macrofauna. *Corophium* sp. (probably *stimpsoni*) were abundant in the lower end of the center of the slough where the bottom was of sand and a mixture of sand and silt. Oligochaetes were abundant in the upper ends of the slough where the currents were less and the bottoms were soft organic mud. Tendipedidae were absent from the lower half of the slough where the tidal currents changed directions but were abundant in the upper end where tidal currents are much reduced.

9) Medium-size sand—its composition probably reflecting a moving bed load—was the poorest producer of macrofauna in the Delta.

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