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Factors Regulating Abundance and Distribution of the Shrimp *Neomysis mercedis* in the Sacramento–San Joaquin Estuary

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Abstract

The mysid shrimp *Neomysis mercedis* is a major prey of striped bass *Morone saxatilis* in the inland delta and estuary of the Sacramento and San Joaquin rivers, California. Its abundance during 1968–1981 was highest between 1.2 and 4.6‰ surface salinity. Cross-delta flow of water to large pumping plants and shallow river channels with high current velocities limited the upstream extent of the shrimp. The population shifted spatially in response to salinity changes caused by variations in river outflow. Annual July to October abundance indexes were highest from 1968 to 1975, and lowest during the drought years 1976 and 1977. Regression analysis showed that population size was negatively related to salinity intrusion and positively related to the abundance of the copepod *Eurytemora affinis*, an important food item of the shrimp. High *N. mercedis* populations appear dependent on adequate food supply and minimal salinity intrusion into the western delta.

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Neomysis mercedis is a small (2 to 17 mm total length) mysidacean shrimp that forms an important link in the food web of the Sacramento–San Joaquin estuary, California. It feeds on phytoplankton, zooplankton, and detritus (Kost and Knight 1975; Siegfried and Kopache 1980), and in turn is fed upon by larger shrimps and fish, especially young striped bass *Morone saxatilis* (Heubach et al. 1963; Stevens 1966), the most economically important sport fish in the estuary.

From 1968 to 1981, the California Department of Fish and Game sampled *N. mercedis* to define the environmental factors affecting its abundance and distribution. Sampling for such a length of time made it possible to investigate annual changes in estimated population size in response to changes in environmental variables. A more complete understanding of these factors is necessary because dams and diversions already have altered freshwater flows to the estuary and the effects of planned future water development on *N. mercedis* must be known in order to prevent the possible depletion of this invaluable part of the food web.

Study Area

The Sacramento and San Joaquin rivers, rising in the Cascade and Sierra Nevada mountains, drain 40% of California and empty into the Pacific Ocean at San Francisco. The two rivers form a delta of 300 km² at the eastern edge of Suisun Bay, which is connected to the ocean by Carquinez Strait and San Pablo and San Francisco bays (Fig. 1). Eighty percent of the inflow to the delta comes from the Sacramento River.

During summer and fall, river flow is low and saltwater intrusion creates a salinity gradient, about 80 km long, from the ocean to the western edge of the delta at Sherman Island. High river flows in winter and spring push the gradient downstream into Carquinez Strait and San Pablo Bay. Salinity in western Suisun Bay may reach 13‰ during summer, and may drop below 1‰ during spring. Western delta salinities commonly peak around 2‰ during summer but a drought during 1976 and 1977 raised summer salinities at Antioch to 4‰. The delta is always fresh water (<0.5‰ salinity) upstream

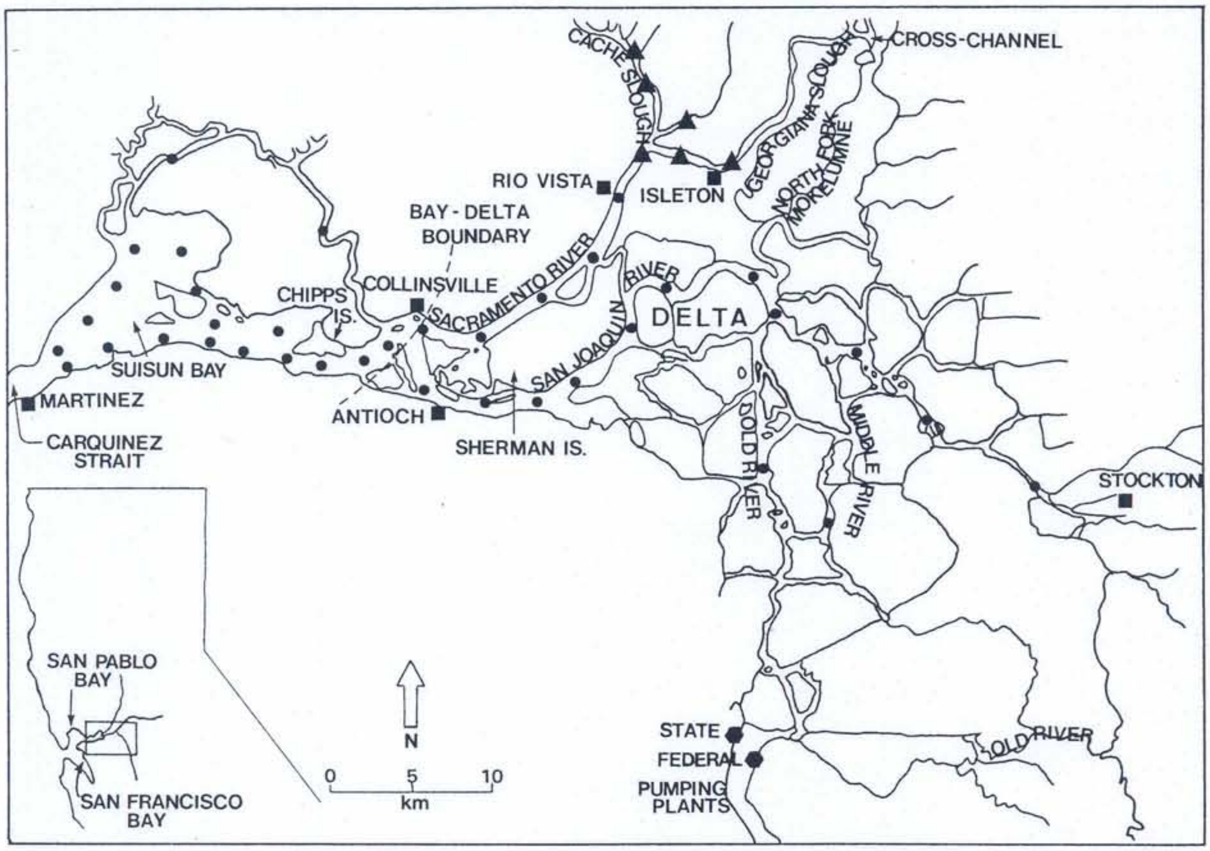

FIGURE 1.—*Stations at which* Neomysis mercedis *was sampled in Suisun Bay and the Sacramento–San Joaquin delta. Dots mark stations sampled in all years, triangles those sampled only in 1977.*

from Rio Vista in the Sacramento River and upstream from the mouth of the Mokelumne River in the San Joaquin River, although salts of terrestrial origin have a minor influence on San Joaquin River salinity at Stockton and farther upstream. Surface salinity is 0.5 to 2.5‰ lower than bottom salinity at surface salinities from 1 to 15‰.

Suisun Bay and the delta are the major habitats for *N. mercedis* (Heubach 1969). These areas are tidal and water masses may oscillate as much as 13 km during a tidal cycle. Water exports from the south delta by state and federal pumping plants also affect flow patterns, primarily during summer and fall. These pumps remove 200 to 300 $m^3 \cdot second^{-1}$ from Old River and create a cross-delta flow from the Sacramento River, down the Mokelumne River and up Old and Middle rivers. The pumping often causes the San Joaquin River to flow upstream from Collinsville to the origin of Old River above Stockton.

The Sacramento and San Joaquin rivers are typically 9 to 11 m deep, with occasional depths to 21 m. Suisun Bay consists mainly of shallow flats less than 2 m deep; a ship channel 11 m deep runs along its southern margin. Kelley (1966) and Conomos (1979) provide more detailed descriptions of the entire estuary.

Methods

Neomysis mercedis was sampled either year-round or from March to November. This paper concentrates on the July–October period because mysid abundance was very low in winter (Heubach 1969), and spring to early summer sampling was incomplete in years when high flows pushed the shrimp into San Pablo Bay. July–October is also the period when *N. mercedis* is the major food of juvenile striped bass. Thirty-eight stations were sampled throughout Suisun Bay and the delta—monthly in 1968–1971 and twice monthly thereafter. In 1977, six additional sampling stations were added upstream from Rio Vista because the mysid population moved unusually far upstream. Each sampling survey took 5–6 days to complete.

Mysids were collected in a conical plankton net located within a rectangular towing frame of 16-mm diameter steel pipe, designed to protect the net from snags. In 1969 and 1970, the net was 1-mm-mesh silk bolting cloth, 1 m long and 30 cm in mouth diameter. From 1971 to 1973, a nylon net, 0.7 m long with 0.93-mm mesh and 30-cm mouth diameter was used. In 1974, Miller (1977) found that 0.505-mm mesh sampled 2- and 3-mm mysids more efficiently than the larger meshes. All three meshes were approximately equally efficient at capturing mysids larger than 3 mm. In 1974, the net was standardized with length 1.48 m, mouth diameter 30 cm, and mesh 0.505 mm. In all years, the net diameter tapered to 7.6 cm at the cod end where a screened polyethylene jar collected the mysids. Pygmy flowmeters measured the volume of water filtered until 1973; thereafter, General Oceanics Mode 2030 digital flowmeters were used.

At each station, a stepwise 10-minute oblique tow was made from the bottom to the surface during daylight hours at or near high slack tide. The vertical distribution of *N. mercedis* varies considerably with light penetration, which varies along the salinity gradient (Heubach 1969, and unpublished). Hence, although mysids are generally most abundant on the bottom during the day, towing only at that level at all stations would have biassed the catches. Stations ranged in depth from 2.5 to 15 m. Boat speed was adjusted to maintain a cable angle of $65° \pm 2°$. After collection, samples were preserved in 10% formalin; addition of Rose Bengal dye aided the sorting of mysids from detritus.

Mysids were counted after being spread out evenly in a tray that was subdivided into 4 to 16 segments for subsampling. The minimum count for a subsample was set at 200. All specimens were counted in samples containing less than 400. The first 100 mysids counted were straightened and measured to the nearest millimeter from the eye to the base of the telson.

Mysid densities (D, m^{-3}) were calculated for each station as

$$D = T \cdot S/V;$$

T = mean number of mysids counted in tray segment(s) subsampled;
S = number of tray segments;
V = volume of water filtered through the net.

To calculate abundance indexes for each July–October period, station densities were multiplied by the water volumes (m^3) represented by respective stations. These products were summed over all stations and surveys for each year and that sum was divided by the number of surveys to obtain mean annual population indexes (Heubach 1969). Only mysids 4 mm and longer were used because smaller ones were inadequately sampled prior to 1974. The California Department of Water Resources calculated station volumes by setting boundaries midway between stations and computing volumes at mean high tide. These indexes are not actual population sizes because station boundaries are arbitrary, water volumes are estimates, and mysid density differs between shallow and deep water (Heubach 1969). They are, however, internally consistent from year to year and thus capable of detecting population fluctuations.

Surface water temperature and electrical conductivity (standardized to 25 C) were measured at the start of each tow. Salinity in ‰ was estimated from a curve of conductivity versus salinity supplied by Martex Instruments, Incorporated. Both measurements are listed in the figures. Because Kelley (1966) reported little salinity stratification, conductivity measurements were made only at the surface for many years. Chlorophyll *a* was measured biweekly at nine stations in the delta and Suisun Bay at a depth of 1 m by the United States Bureau of Reclamation from 1969 to 1971 (USBR 1972, 1974) and the California Department of Water Resources from 1972 to 1981 (CDWR and USBR 1975, 1976; CDWR 1979, 1980, unpublished). Starting in 1972, *Eurytemora affinis* (*E. hirundoides* in synonymy, Heron and Damkaer 1976) was captured in a 154-μm-mesh Clarke–Bumpus net attached to the towing frame above the *N. mercedis* net. This copepod is an important food for *N. mercedis* (Siegfried and Kopache 1980). Abundance indexes for this copepod were calculated in the same way as for *N. mercedis*. Water diversion data from the state and federal pumps were obtained from the California Department of Water Resources.

Simple linear correlation and multiple and partial regressions were used to identify significant environmental variables. The independent variables tested against the *N. mercedis* index were: (1) surface salinity in the Sacramento River at Chipps Island, which is an indicator of the degree of salinity intrusion; (2) and (3) abundance of the major *N. mercedis* food items, *Eurytemora affinis* and phytoplankton (measured by chlorophyll *a*); (4) water diversion rates from the state and federal pumps, which remove mysids from the estuary and reduce river outflow; (5) water temperature, as the mysid's upper lethal temperature in laboratory experiments was 24.2 to 25.5 C (Hair 1971). Temperature in the estuary rarely reaches the lethal level but temperatures that approach it are more common and may have adverse impacts on *N. mercedis*.

The salinity and water-temperature means used in the correlations and regressions were based on data from 38 stations over eight surveys. Chlorophyll-*a* means were derived from nine stations over eight surveys, and diversion rates were means of daily rates.

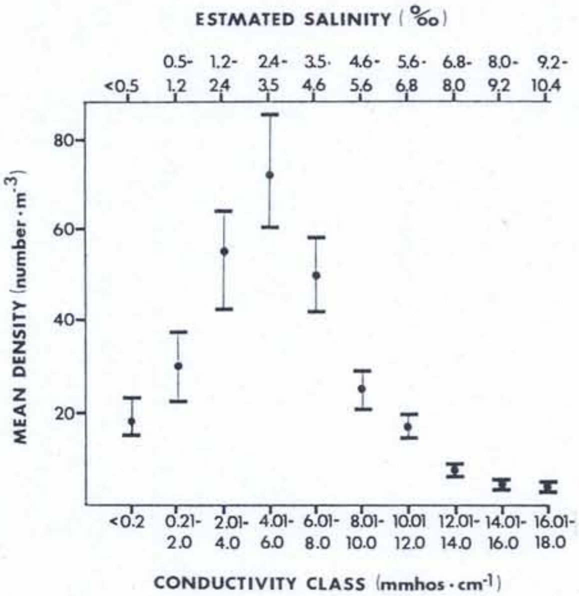

FIGURE 2.—*Densities of* Neomysis mercedis *in Suisun Bay and the Sacramento–San Joaquin delta related to water conductivity class (and salinities estimated therefrom), July–October 1968–1981. Dots are means and bars are standard deviations.*

Results

Abundance, Distribution, and Salinity

Averaged over the 14-year study, the highest July–October *N. mercedis* densities occurred between 1.2 and 4.6‰ salinity (Fig. 2). There was a progressive decrease in mysid density at salinities outside this range, both in fresh water and in more saline water. Salinities in which *N. mer-*

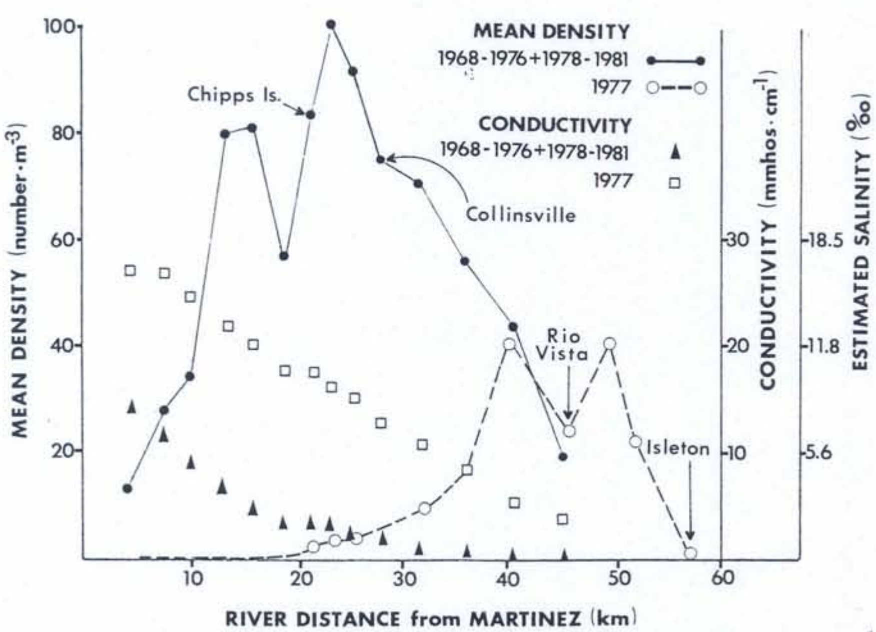

FIGURE 3.—*Mean density of* Neomysis mercedis, *July to October, and electrical conductivity (and estimated salinity) at each channel station from Martinez on Suisun Bay to Isleton on the Sacramento River. The drought year 1977 is isolated from other years.*

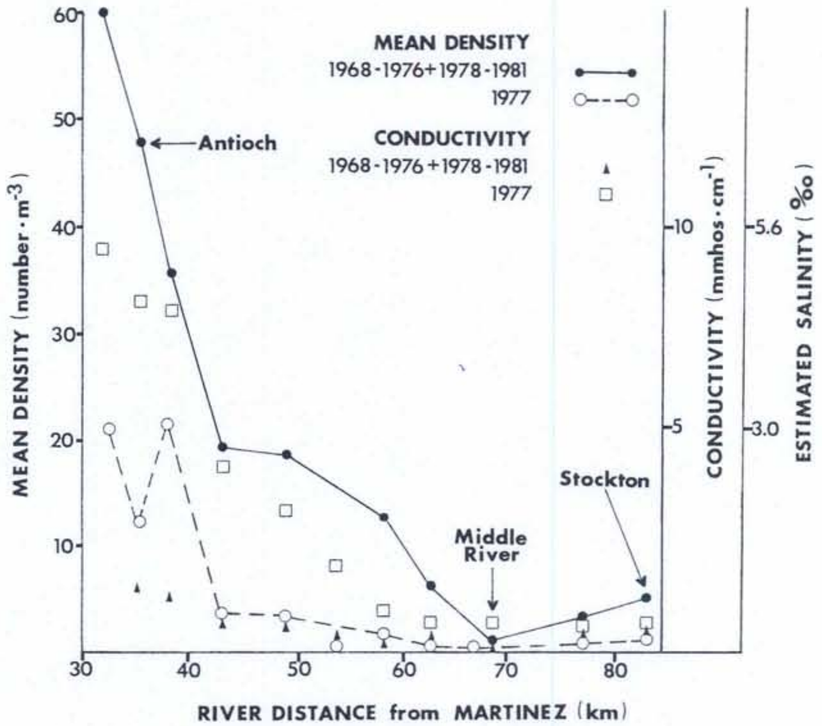

FIGURE 4.—*Mean density of* Neomysis mercedis *and electrical conductivity (and estimated salinity) at each channel station from Antioch to Stockton in the San Joaquin River. The drought year 1977 is isolated from other years.*

cedis was most abundant occurred in eastern Suisun Bay and the western delta, from Chipps Island up to Collinsville in the Sacramento River and to Antioch in the San Joaquin River (Figs. 3, 4). This is an area of deep, broad channels. Density dropped sharply upstream from Collinsville in both rivers. In 1977, the salinity gradient was located much farther upstream than in other years, and density peaked around Rio Vista in the Sacramento River, but in the San Joaquin River the location of maximum density did not move upstream.

Significant reductions took place in the abundance of *N. mercedis* and its food items in the Sacramento and San Joaquin rivers in 1976–1981 compared to prior years (Fig. 5). Mysid densities were greatly reduced in the first 10 km of the Sacramento River in 1976–1981. In the remaining length of the river to Rio Vista, the reduction in density was smaller, due mostly to the upstream shift in the population in 1977. *Eurytemora affinis* also showed an upstream shift in population location in that year, so its average density in 1976–1981 increased from km 10 to Rio Vista while decreasing downstream from km 10. Chlorophyll-*a* concentrations were slightly lower throughout the entire river in 1976–1981.

In the San Joaquin River, *N. mercedis* suffered a large decline in density in the first 30 km. The decline was particularly severe between km 15 and the mouth of Old River. Over this stretch of the river, density dropped below $3 \cdot m^{-3}$. For *E. affinis*, the 1976–1981 decline was mainly restricted to the first 8 km of the river. This copepod also failed to move upstream in the San Joaquin River in 1977. Chlorophyll-*a* concentrations dropped along the entire length of the river to Stockton. The reduction was much greater than occurred in the Sacramento River so that chlorophyll-*a* concentrations were similar throughout most of both rivers in 1976–1981 instead of higher in the San Joaquin as they had been in previous years.

The shifts in *N. mercedis* distribution in response to changes in the location of the salinity gradient caused the percentage of the population (abundance index) found in Suisun Bay to be lower at higher mean July–October salinities at Chipps Island (Fig. 6). Simultaneously, of course, the percentage of the index in the delta increased. In 1977, salinity intrusion was so ex-

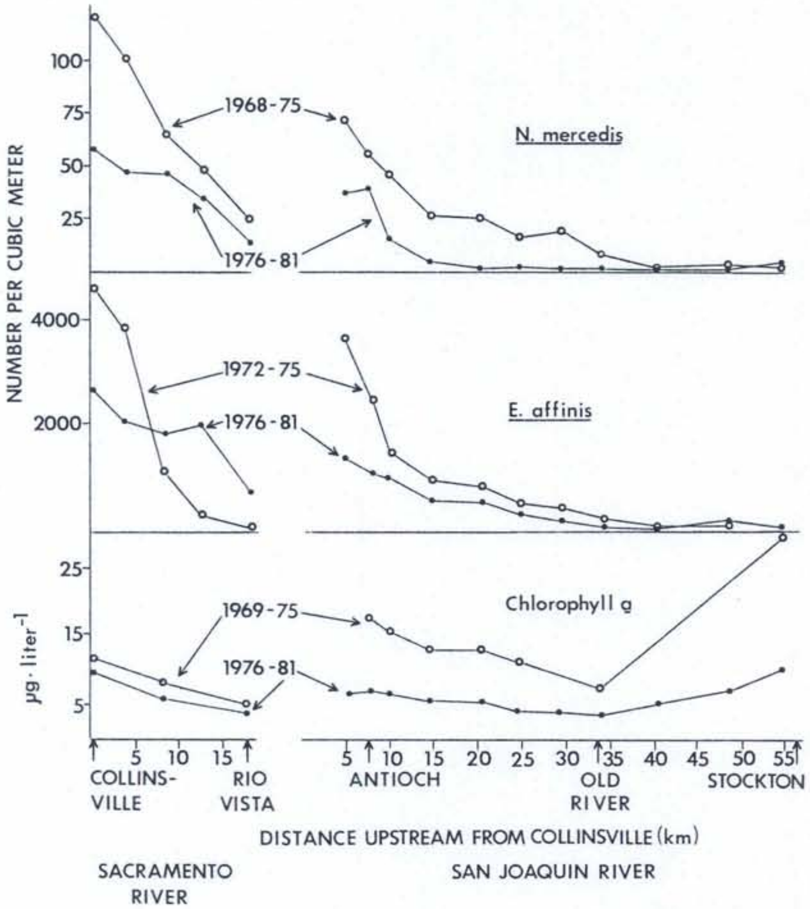

FIGURE 5.—*Mean July–October densities of* Neomysis mercedis *and* Eurytemora affinis *and chlorophyll-*a *concentrations at each Sacramento and San Joaquin River sampling station in 1968–1975 and in 1976–1981.*

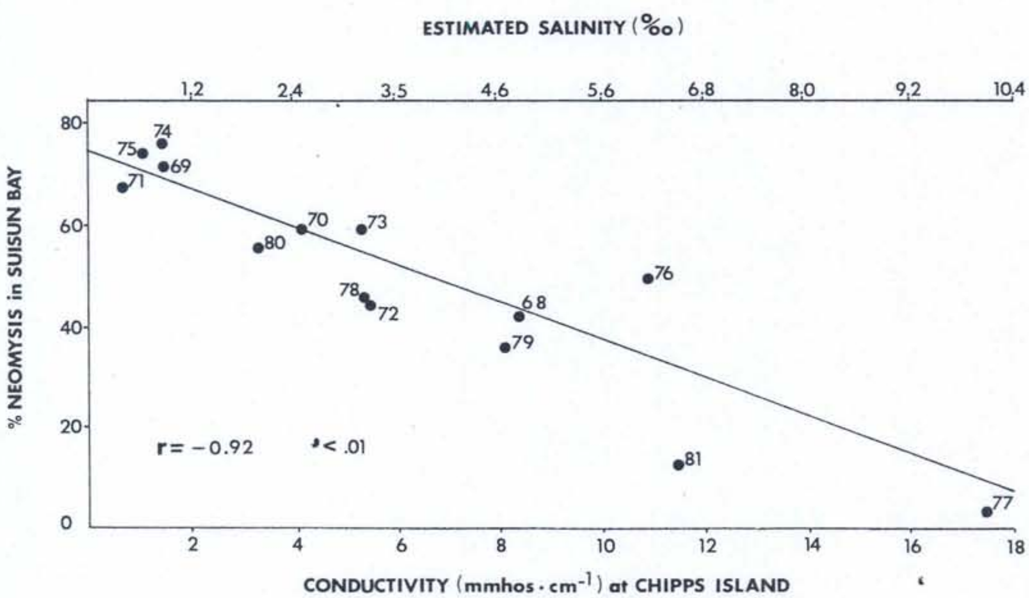

FIGURE 6.—*Fraction of the July–October abundance index for* Neomysis mercedis *contributed by Suisun Bay, related to electrical conductivity (and estimated salinity) at Chipps Island, 1968–1981.*

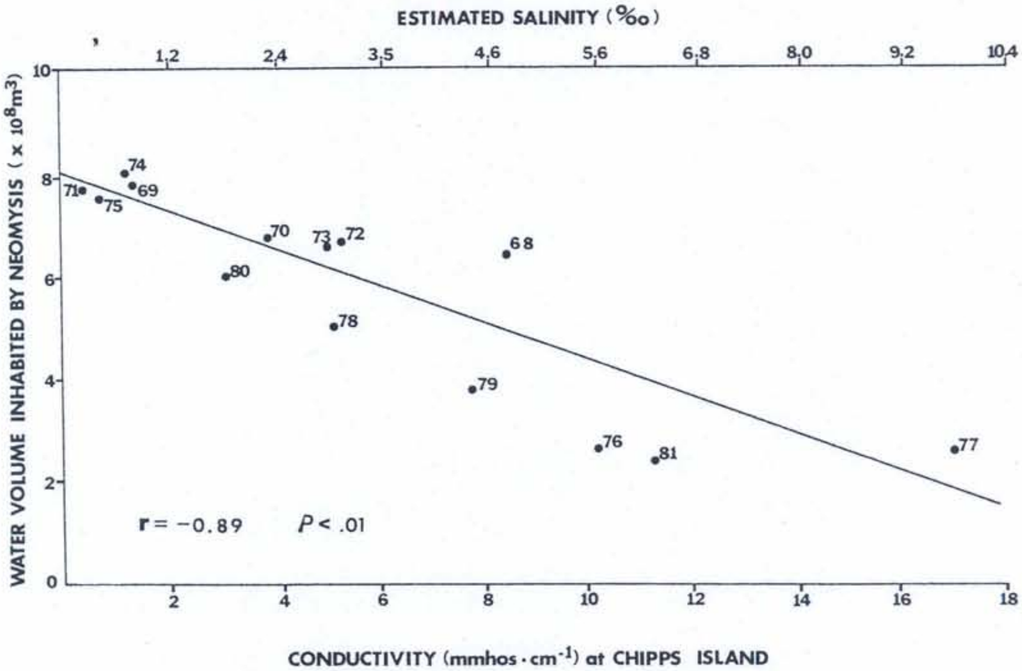

FIGURE 7.—*Mean July–October water volume in Suisun Bay and the delta inhabited by* Neomysis mercedis *in densities greater than* $5 \cdot m^{-3}$ *related to Chipps Island electrical conductivity (and estimated salinity), 1968–1981.*

treme that less than 5% of the index was contributed by Suisun Bay, compared to 75% in the high-flow years 1974 and 1975. Upstream shifts in the salinity gradient reduced habitat size by rendering large areas of Suisun Bay too saline to support high *N. mercedis* densities. In 1977, some new habitat was opened up in the Sacramento River above Rio Vista, but this was apparently not enough to compensate for the lost Suisun Bay habitat because during 1976, 1977, and 1981, water volumes containing 5 or more mysids$\cdot m^{-3}$ were less than half as large as in the high-flow years (Fig. 7).

Environmental Variables

Prior to 1976 all of the annual *N. mercedis* abundance indexes were greater than 4.0×10^{10} (Table 1). The indexes dropped dramatically during the drought years, and did not fully recover through 1981. In spite of the high salinity at Chipps Island, 1981 was technically a dry rather than a drought year and had the third lowest index. The 1976–1981 period was characterized by greater salinity intrusion, lower *E. affinis* abundance, and lower chlorophyll-*a* concentrations throughout Suisun Bay and the delta than in 1968–1975.

For 1972–1981 data, significant simple linear correlations existed between *N. mercedis* indexes and salinity, *E. affinis* abundance, and chlorophyll-*a* concentration (Table 2). The correlation with salinity was the highest, and negative; correlations with the two measures of food supply, *E. affinis* and chlorophyll *a*, were positive.

A stepwise multiple regression between the indexes and all of the environmental variables explained 96.1% of the variation in the indexes. The *F* value for temperature was not large enough to enter that variable into the regression equation, which is

$$Y = 5.264 - 0.264X_1 + 0.017X_2 - 0.009X_3 + 1.066X_4;$$

Y = *N. mercedis* index (10^{10});
X_1 = conductivity ($mmhos\cdot cm^{-1}$);
X_2 = chlorophyll *a* ($\mu g\cdot liter^{-1}$);
X_3 = water diversions ($m^3\cdot second^{-1}$);
X_4 = *E. affinis* index (10^{12}).

Partial regressions (Table 2) indicated a significant negative relationship between the index and conductivity and a positive one between the index and *E. affinis* abundance.

Discussion

Neomysis mercedis density was greatest within the area of the estuary known as the "entrapment zone." This is the section of the salinity

TABLE 1.—Neomysis mercedis *abundance indexes and mean environmental variables for the Sacramento–San Joaquin estuary, July–October 1968–1981.*

Year	*Neomysis mercedis* abundance index (units of 10^{10})	Conductivity ($mmhos \cdot cm^{-1}$) (salinity ‰) at Chipps Island	Chlorophyll *a* ($\mu g \cdot liter^{-1}$)	Water temperature (C)	Water diversions ($m^3 \cdot second^{-1}$)	*Eurytemora affinis* abundance index (units of 10^{12})
1968	5.8	8.4 (5.0)	[a]	20.0	157	[a]
1969	5.8	1.4 (0.8)	28.7	19.8	176	[a]
1970	4.3	4.0 (2.4)	30.6	18.7	201	[a]
1971	6.0	0.6 (<0.5)	16.8	20.0	238	[a]
1972	4.8	5.4 (3.2)	24.0	19.7	269	3.08
1973	4.0	5.2 (3.0)	20.0	20.5	281	1.74
1974	4.2	1.4 (0.8)	12.2	20.4	298	1.80
1975	4.2	0.9 (0.5)	9.8	19.3	298	1.34
1976	0.8	10.9 (6.2)	6.6	20.2	258	1.04
1977	0.7	17.5 (10.2)	5.6	20.8	128	0.90
1978	2.6	5.3 (3.1)	18.4	20.7	295	1.28
1979	1.5	8.0 (4.6)	11.2	20.4	261	0.72
1980	3.2	3.3 (2.0)	11.7	20.1	210	0.84
1981	1.0	11.4 (6.4)	6.8	20.5	227	0.54

[a] Not sampled.

gradient with surface salinities of 1.2–6.0‰, where fresh and salt water initially mix, and hydrologic conditions concentrate suspended sediments, particulate nutrients, and plankton (Arthur and Ball 1979). Low densities of *N. mercedis* have been reported downstream from the entrapment zone at salinities as high as 30.1‰ (Orsi and Knutson 1979), and laboratory bioassays showed the mysids to tolerate salinities greater than 25‰ (Sitts 1978). Hence, rather than reflecting salinity tolerance limits, the relation between mysid density and salinity more likely is due to estuarine circulation patterns, light, and tidally influenced vertical migrations (Heubach 1969; Siegfried et al. 1979), which interact to concentrate *N. mercedis* in the entrapment zone.

Instead of simply moving the population intact from Suisun Bay into the delta, the upstream shift in population associated with salinity intrusion reduces abundance. Reduction in habitat, as suggested by Siegfried et al. (1979), may be responsible for the population decline as the volume of the western delta channels is much less than that of Suisun Bay (34.64×10^7 m^3 versus 44.57×10^7 m^3), and *N. mercedis* is prevented from entering the eastern delta in any significant numbers by cross-delta flows and high water temperatures (Orsi and Knutson 1979). Only the western part of the delta appears to be good habitat for *N. mercedis*—up to Rio Vista in the Sacramento River and Antioch in the San Joaquin. In north delta streams, such as the Sacramento River above Rio Vista, the

TABLE 2.—*Correlation matrix and partial-regression statistics for environmental variables and* Neomysis mercedis *abundance indexes of 1972–1981 (df = 9; *P < 0.05; **P < 0.01).*

Variable or statistic	Water conductivity	Chlorophyll *a*	Water diversions	*Eurytemora affinis* abundance index	*Neomysis mercedis* abundance index	Percent of variance explained
			Correlations			
Conductivity		−0.497	−0.785**	−0.410	−0.844**	71.3
Chlorophyll *a*			0.514	0.797	0.726*	3.4
Water diversions				0.422	0.601	1.5
Eurytemora affinis					0.769**	21.4
		Partial regression (dependent variable:* N. mercedis *index)				
t	−6.012**	0.424	−2.176	3.497**		

Mokelumne River, and Georgiana Slough, net flow velocities are often high. Heubach (1979) found that net velocities greater than 0.12 m$\cdot$second^{-1} formed hydrologic barriers to the upstream movement of mysids. During 1976 and 1977, flow velocities were so low that the barriers were weakened and mysids were found further upstream than usual. During periods of high flows, such as winter and spring of most years, the barriers become stronger and move downstream in the Sacramento River. The *N. mercedis* population thus is sandwiched between the downstream end of the entrapment zone and the hydrologic barriers, both of which shift spatially with river flow.

Because the multiple regression explained a large percentage of the variation in the index, the regression equation could be useful in predicting *N. mercedis* abundance for varying food supplies and salinities. Although Chipps Island salinity can be determined with considerable accuracy from physical and mathematical models of the estuary, the *E. affinis* abundance index also would have to be predictable to use the equation. Further research into the relationship between this copepod and the environment is needed.

Although the partial regression (but not the simple correlation) indicates that chlorophyll *a* is not a significant variable, the importance of phytoplankton should not be underestimated. According to Siegfried and Kopache (1980), it is the primary food of *N. mercedis* neonates (2–3 mm long), and neonates constitute 20 to 45% of the total population from July to October (unpublished California Department of Fish and Game data). Inclusion of neonates in the abundance indexes might have increased the significance of chlorophyll *a* in the partial regression. In addition, *E. affinis* feeds on phytoplankton. The significant simple linear correlation between *E. affinis* abundance and chlorophyll *a* (Table 2) reflects the importance of phytoplankton to this copepod. Phytoplankton is thus important both to small mysids and to the copepods consumed by the large mysids.

An independent consulting company, Ecological Analysts (1981), has concluded that water-export diversions from the delta pumping plants do not remove important numbers of *N. mercedis* from the delta. The conclusion agrees with our multiple regression results. The effect of the diversions is to render the east and south delta and the San Joaquin River at the mouths of Old and Middle rivers unsuitable for *N. mercedis*. This is the area most directly influenced by the cross-delta flow of water to the export pumps.

The low *N. mercedis* abundance indexes since 1976 appear related to high salinity intrusion and reduced food supply, but the sharp decline in mysid density in the San Joaquin River above km 15 is not fully explainable in terms of these factors.

In conclusion, maintenance of a high *N. mercedis* population depends on an adequate food supply for the shrimp and a large habitat in Suisun Bay and the western delta. Arthur and Ball (1979) suggest that high phytoplankton production is likely only when river flows maintain the entrapment zone over the shallows of Suisun Bay during the summer. Keeping the zone in this area by regulating both water releases from upstream dams and water exports from the pumping plants would also ensure a large habitat for *N. mercedis*.

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