Abstract

Six species of mysid shrimp are present in the Sacramento-San Joaquin Estuary, but only one of them, *Neomysis* mercedis, is abundant here. It is an important fish food in Suisun Bay and the Delta, especially for young-of-the-year striped bass. *N. mercedis* feeds on phytoplankton, detritus, and zooplankton. Its distribution is apparently determined by estuarine circulation acting on its vertical migration pattern. These factors concentrate it in the zone where fresh and salt water initially mix. Light intensity greater than 10^{-5} lux on the bottom and net flow velocity $<0.12\ m \cdot s^{-1}$ apparently limit its upstream spread. In the San Joaquin River low populations are associated with low dissolved oxygen concentrations in combination with high temperatures. Fecundity appears to be a function of female length, temperature, and food supply (phytoplankton). Seasonal fluctuations in reproduction are usually paralleled by population fluctuations. Population differences between years appear to be a function of food supply and habitat size.

THE ROLE OF MYSID SHRIMP IN THE SACRAMENTO-SAN JOAQUIN ESTUARY AND FACTORS AFFECTING THEIR ABUNDANCE AND DISTRIBUTION

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Six species of mysid shrimp are present in the Sacramento-San Joaquin Estuary, but only one of them, *Neomysis mercedis,* is abundant here. It is an important fish food in Suisun Bay and the Delta, especially for young-of-the-year striped bass. *N. mercedis* feeds on phytoplankton, detritus, and zooplankton. Its distribution is apparently determined by estuarine circulation acting on its vertical migration pattern. These factors concentrate it in the zone where fresh and salt water initially mix. Light intensity greater than 10^{-5} lux on the bottom and net flow velocity $<0.12\ m{\cdot}s^{-1}$ apparently limit its upstream spread. In the San Joaquin River low populations are associated with low dissolved oxygen concentrations in combination with high temperatures. Fecundity appears to be a function of female length, temperature, and food supply (phytoplankton). Seasonal fluctuations in reproduction are usually paralleled by population fluctuations. Population differences between years appear to be a function of food supply and habitat size.

Mysid or opossum shrimp are general names used for small, pelagic, live-bearing crustaceans belonging to several genera. They are cosmopolitan. Some, such as *Neomysis,* are coastal species that also occur in estuaries or lakes that are or were formerly connected to the ocean or an estuary. Lakes Merritt in Oakland and Merced in San Francisco where *N. mercedis* occurs are examples. Other mysids are deep ocean inhabitants. One species, *Mysis relicta,* occupies cold, deep, glacier-formed lakes far from the ocean. It is believed to have been pushed out of arctic marine waters by advancing ice sheets (Ricker 1959).

In the Sacramento-San Joaquin Estuary, adults of the largest species, *Neomysis rayi* (formerly *N. franciscorum*) are only 35 mm long. The young of the most abundant species, *N. mercedis* (*N. awatschensis* in many previous publications) are liberated from the female's brood pouch at 2 or 3 mm and grow to a maximum of 17 mm (Fig. 1).

SPECIES, ABUNDANCE, AND DISTRIBUTION IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

Tattersall (1932) identified five species of mysids taken by the *Albatross* on a survey of San Francisco and San Pablo bays in 1912 and 1913. In addition to *Neomysis mercedis* and *N. rayi,* he identified *N. kadiakensis, N. costata,* and *N. macropsis.* The latter two species are now in the genus *Acanthomysis* (Ii 1936).

According to Tattersall, *N. kadiakensis, N. rayi,* and *A. costata* were most abundant in San Francisco Bay and *N. mercedis* was most abundant in San Pablo Bay. *A. macropsis* was evenly distributed throughout the two bays and was the most abundant species taken. We made short surveys of these bays in July and December 1977 and caught all species except *N. rayi.*

The *Albatross* did not sample upstream from San Pablo Bay. However, California Department of Fish and Game (DFG) surveys in Carquinez Strait, Suisun Bay, and the Delta from 1963 to 1976 have collected only *N. mercedis* and *A. macropsis*, of which *N. mercedis* has been by far the more abundant. In 1977 we discovered a previously unreported species which is still unidentified. It is unusually small. Adults are only 3 to 5 mm long. So far only a few specimens of it have been collected in the lower San Joaquin River from Winter Island to the mouth of the Mokelumne River and in the lower Sacramento River near Sherman Lake.

Abundance of *N. mercedis* in Suisun Bay and the Delta is very high compared to abundance of all mysid species combined in San Francisco and San Pablo bays. Using information in Sumner et al. (1914) on net mesh and size, and duration and speed of tows, we estimated the number of mysids per cubic meter in San Francisco and San Pablo bays from the number caught per tow by

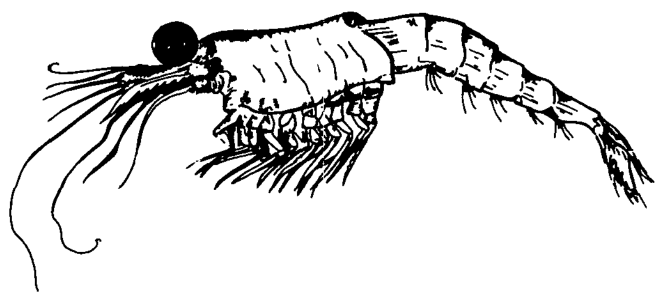

Fig. 1. *Neomysis mercedis,* the opossum shrimp.

the *Albatross.* These estimates ranged to a maximum of 1.6 mysids$\cdot m^{-3}$ for all species combined. We found up to 0.2 mysids$\cdot m^{-3}$ in San Pablo and North San Francisco bays in July and December 1977. But during high spring fresh water outflows the concentration of *N. mercedis* may reach $100 \cdot m^{-3}$ in San Pablo Bay (Painter 1966). In contrast we have found concentrations as high as 1500 *N. mercedis*$\cdot m^{-3}$ in Suisun Bay and the Delta. The abundance of *N. mercedis* makes it the most important species in the estuary.

N. mercedis ranges from Prince William Sound, Alaska to at least the Cañada de la Gaviota, 19 km below Pt. Conception, California (Orsi et al. unpublished ms.). Within the Sacramento-San Joaquin Estuary (Fig. 2) a few specimens of *N. mercedis* have been taken from around Hunter's Point and Angel Island (Tattersall 1932; Orsi and Knutson unpublished) and between Angel Island and San Pablo Strait (Tattersall 1932). It probably occurs in the lower Napa River but no one has sampled there for it. *N. mercedis* is most abundant in Suisun Bay and the western Delta (Heubach 1969; California Fish and Game 1976). *N. mercedis* is also found in Montezuma Slough and other sloughs around the Suisun Marsh and is present throughout the Delta and in the Sacramento Deep Water Channel to Lake Washington at Sacramento (R. Kroger pers. comm.). Water diversions have carried it into the California Aqueduct, the Delta-Mendota Canal, San Luis Reservoir, and possibly other water project reservoirs.

IMPORTANCE

The low abundance of mysids in San Francisco Bay renders them unimportant as a food source for fish there. However, in Suisun Bay and the Delta the great abundance of *N. mercedis* and its size make it an ideal food source for many fishes. It is the most important item in the diet

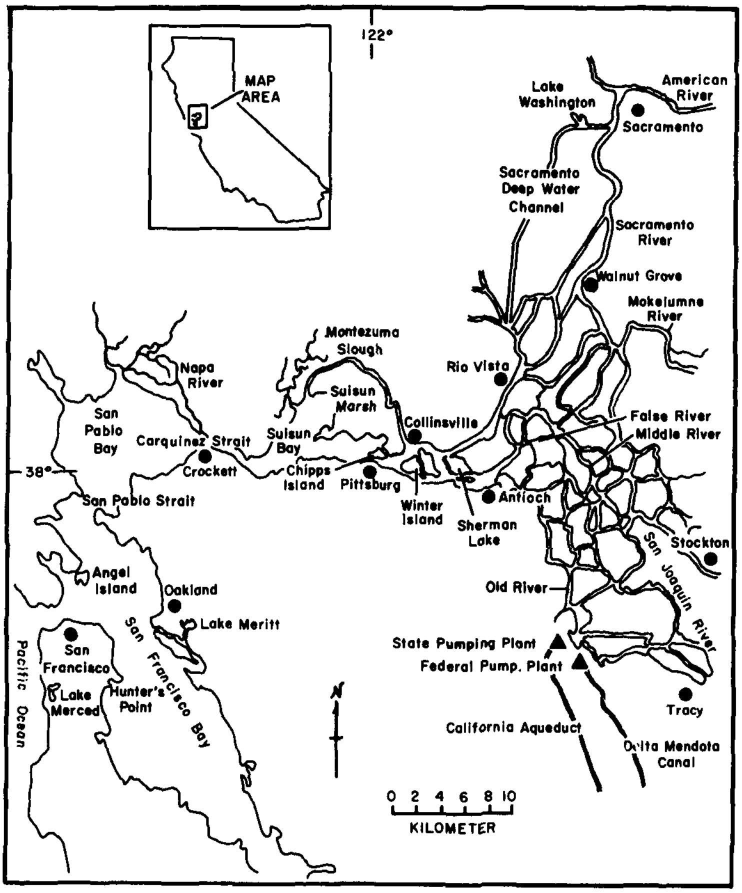

Fig. 2. Sacramento-San Joaquin Estuary.

of young-of-the-year striped bass and it is very important to juvenile striped bass (Heubach et al. 1963; Stevens 1966a; Thomas 1967; Stevens 1979; Smith and Kato 1979). *N. mercedis* is also an important food of juvenile white and green sturgeon (Radtke 1966), adult American shad (Stevens 1966b), black crappie (Turner 1966a), white catfish (Turner 1966b), and young king salmon (Sasaki 1966). Two larger shrimp, *Crangon franciscorum* and *Palaemon macrodactylus* feed on it (Siegfried et al. 1977).

FOOD HABITS

Mysids feed on phytoplankton, detritus, and other zooplankton. The only study of mysid feeding habits from this estuary was done by Kost and Knight (1975) on *N. mercedis* collected in Suisun Bay and the Delta. The most abundant foods were diatoms (phytoplankton) and unidentifiable material classified as detritus. Zooplankton remains were rare. The abundance of detritus relative to diatoms was greater in winter than in summer and increased with shrimp size. However, the actual importance of detritus is difficult to determine. Edmondson (1957) states that the presence of unrecognizable organic material in zooplankton guts cannot be taken as proof that they have been feeding on detritus. Phytoplankton break down after being consumed and the remains can be mistaken for detritus. Even if such feeding occurs, detritus may be nutritionally inferior to phytoplankton, Harris (1974) found that detritus never equaled algae in sustaining egg production in the copepod, *Scottolana canadensis.*

Although Kost and Knight's study suggests that *N. mercedis* does not feed extensively on zooplankton in the estuary, it has been maintained on a diet of brine shrimp nauplii (*Artemia*) in the laboratory (Simmons and Knight 1975). Also, W. T. Edmondson (pers. comm.) has found *N. mercedis* to be an effective predator in feeding experiments; and the guts of mysids he collected from Lake Washington (Washington State) contained large quantities of copepods and cladocerans. In our laboratory large *N. mercedis* have attacked larval striped bass and smaller *N. mercedis.*

EFFECTS OF ENVIRONMENTAL FACTORS

DFG biologists have studied *N. mercedis* since 1963 in an attempt to understand how environmental factors affect its distribution and abundance. Such knowledge is necessary to protect the primary food source of young-of-the-year striped bass in the face of planned water development projects (see for example Gill et al. 1971).

Heubach (1969) found that *N. mercedis* was most abundant in the estuary from fresh water to 7.2 °/oo salinity and least abundant at salinities exceeding 18 °/oo. We have found *N. mercedis* to be most abundant in essentially the same area, although we would prefer to define it as from the upper end of the salinity gradient to the downstream end of the entrapment zone (as defined by Arthur and Ball 1979). Heubach also found reproduction to be greatest from fresh water to 3.6 °/oo salinity and thought reproduction was the principal factor affecting seasonal and geographical abundance. Heubach presented some evidence that salinity might lower reproduction and thus explain the low abundance at high salinities. Our data do not demonstrate such effects of salinity on reproduction. Our present conception is that reproduction is indeed the principal factor affecting seasonal abundance but geographical abundance is the result of tidal currents and estuarine circulation interacting with the tidally influenced vertical migration of *N. mercedis.* During all tidal stages more than half of the shrimp are closer to the bottom than to the surface (Heubach 1969). However, on flood tides a larger percentage of the shrimp are in the upper half of the water column than on the ebb tides. Since surface water velocities are higher than bottom velocities (see for example Conomos 1979), Heubach hypothesized that flood tides carried the shrimp farther upstream than ebb tides moved them back downstream. In addition, we hypothesize that the landward flowing bottom density current in and below the entrapment zone (Arthur and Ball 1979) hampers the downstream movement of mysids on the ebb tides.

We are not sure whether mysid populations are high in the entrapment zone merely because they are concentrated there by hydrological forces or because, in addition, conditions there are somehow optimal.

Upstream from the salinity gradient, net flow velocity and light penetration limit distribution and abundance. Heubach (1969) found *N. mercedis* at Isleton on the Sacramento River and at Stockton on the San Joaquin River only when net velocity was less than 0.12 $m \cdot s^{-1}$ and light intensity on the bottom was less than 10^{-5} lux.[1] Apparently net velocity was the limiting factor during the high winter and spring flows and light became limiting during summer and fall. Heubach did not find *N. mercedis* where flows did not reverse on the flood tide, i.e., above tidewater. We found *N. mercedis* to become progressively less abundant in the Sacramento River as net velocities increased from 0.02 to 0.12 $m \cdot s^{-1}$ (California Fish and Game 1976).

High temperature and low dissolved oxygen (DO) appear to reduce mysid abundance in the

[1] 10^{-5} lux $\approx 1.9 \times 10^{-7}$ $\mu E \cdot m^{-2} \cdot s^{-1}$ assuming a mean wave length of light (λ) of 5500 Å. (Ed.)

San Joaquin River between Stockton and the mouth of the Mokelumne River (Heubach 1969). During his investigation at temperatures below 18°C, dissolved oxygen (DO) concentrations as low as 5 mg·liter^{-1} had no apparent effect on abundance. However, above 18°C mean abundance at 9 mg·liter^{-1} DO was 10 to 15 times greater than at 4 to 5 mg·liter^{-1} DO. Mysids were absent when DO was less than 3 mg·liter^{-1} (Table 1).

TABLE 1. MEAN DENSITY OF *NEOMYSIS MERCEDIS* IN RELATION TO WATER TEMPERATURE AND DISSOLVED OXYGEN CONCENTRATION

Temp.	Dissolved Oxygen (mg·liter^{-1})[a]						
(°C)	9	8	7	6	5	4	3
<22	ND	122.5(4)[b]	44.4(7)	13.9(7)	19.4(7)	5.4(3)	0.2(3)
18-22	151.4(2)	56.9(6)	50.1(23)	54.1(6)	15.3(3)	11.4(3)	ND
14-18	13.2(8)	28.7(9)	22.5(7)	21.5(4)	43.0(2)	ND	ND
<14	6.2(19)	9.0(12)	10.5(5)	7.3(2)	ND	ND	ND

[a] Dissolved oxygen conversion factors: 1 mg·liter^{-1} = 1 ppm = 62.5 μg-atoms·liter^{-1}
[b] (n) = number of samples

Heubach (1969 and 1972) suggested that temperatures above 22°C might harm *N. mercedis* and that such high temperatures could have been responsible for the population declines he observed in summer 1966 and fall 1965. Hair (1971) established an upper lethal temperature between 24.2 and 25.5°C for *N. mercedis* in laboratory experiments. Wilson (1951) obtained similar tolerance for the same species. Alternately, Heubach's (1969) results show that the mean density at temperatures in excess of 22°C at 8 mg·liter^{-1} DO was 122.5 individuals·m^{-3}. This density is very high and is twice as great as occured between 18 and 22°C at the same DO (Table 1). It is almost as high as the mean density he reports at 18 to 22°C and 9 mg·liter^{-1} DO (151.4 individuals·m^{-3}. Unfortunately, Heubach did not report how far above 22°C these temperatures rose. Our field collections show that moderate populations sometimes existed where daytime temperatures were as high as 25.6°C (Table 2). Hence, we conclude that if DO remains high (8 or 9 mg·liter^{-1}) *N. mercedis* are not eliminated at temperatures defined as lethal in the laboratory, although those temperatures undoubtedly exceed the optimal temperature range.

The State and Federal pumping plants in the south Delta (Fig. 2) remove large volumes of water from the Delta for irrigation and domestic purposes. These plants draw water from the Sacramento River near Walnut Grove, across the Delta, down Old and Middle Rivers, and into the California Aqueduct and the Delta-Mendota Canal. This pumping sometimes causes the lower San Joaquin River to flow upstream toward the pumping plants.

We have been unable to completely evaluate the effects of these water diversions on the abundance of *N. mercedis* because our surveys began in 1968, the same year the Federal Government increased water exports for the San Luis Project, and the State Water Project began operations. This caused water export rates to rise sharply above previous levels. Consequently, our analysis is restricted to the period of high exports, during which we have not found any relation between total population and water diversion rates. However, export pumping does affect salinity intrusion and in turn the location of the entrapment zone.

Export pumping probably also reduces mysid abundance in the central Delta, especially in the region of the cross-Delta water transport channels. Abundance of *N. mercedis* in the San Joaquin River at the mouths of Old and Middle rivers is lower than abundance either up or downstream

TABLE 2. SUMMER ABUNDANCE OF *NEOMYSIS MERCEDIS* (INDIVIDUALS·m^{-3}) AND TEMPERATURE IN THE SAN JOAQUIN RIVER NEAR STOCKTON, 1972-77

Year	May		June		July		August
	I	II	I	II	I	II	I
1972	46(17.8)[a]	70(21.1)	57(25.6)	38(23.6)	9(24.4)	7(26.1)	4(24.4)
1973	42(19.2)	41(22.8)	12(23.9)	34(25.0)	14(25.8)	2(25.0)	2(22.8)
1974	6(20.0)	8(21.1)	44(22.2)	36(23.4)	37(23.4)	8(25.0)	1(25.6)
1975	88(17.0)	8(19.7)	3(22.2)	24(20.8)	0.6(22.5)	26(24.7)	1(25.6)
1976	4(19.4)	12(21.6)	33(20.6)	72(21.4)	12(23.6)	2(26.1)	0.4(23.6)
1977	14(16.6)	20(19.2)	17(23.4)	20(24.4)	4(25.0)	2(25.8)	0.3(25.6)

[a] Water temperature in °C

from these river mouths. This suggests that mysids are drawn up the San Joaquin River from their center of abundance in the western Delta and into Old River, but few manage to reach Middle River. Abundance rises again upstream from the mouth of Middle River as water in the Stockton area of the San Joaquin River tends to remain almost stationary during the summer and early fall, and mysids there propagate until high temperature and low DO affect them.

Reproduction appears to depend upon several factors. From data collected in 1976 we developed a multiple regression equation that predicted seasonal fluctuations in fecundity during 1977 quite well (Orsi unpublished ms.). The equation indicates that fecundity increases as female size and food supply (measured by chlorophyll *a*) increase and water temperature decreases. The fecundity variations contribute to seasonal increases and decreases in abundance of *N. mercedis*, such as Heubach (1969) reported for 1965 and 1966.

The abundance of *N. mercedis* also varies annually. Heubach (1969) noted that the peak abundance in 1965 was about 2.8 times greater than in 1966. Similarly, Hopkins (1965) reported that the peak *N. americana* density in the Delaware River was four times greater in 1958 than in 1957. Neither Heubach nor Hopkins could explain these differences.

To explain annual variations in mean July to October abundance of *N. mercedis* (the period when it is most important to young-of-the-year striped bass) in Suisun Bay and the Delta, we have developed a multiple regression equation which uses mean chlorophyll *a* throughout the area and either Delta outflow or salinity at Chipps Island as independent variables. Mysid abundance was positively correlated with chlorophyll *a* and Delta outflow, and negatively correlated with salinity. During high outflows mysids in concentrations >0.1 individuals·m^3 were distributed throughout a larger area of the estuary than during low outflows. Hence, the regression equation can be interpreted to mean that annual variations in mysid abundance are a function of habitat size and food supply. The unusually low abundance in 1976 and 1977 (Knutson and Orsi unpublished ms.) can be explained by the reduced habitat and low phytoplankton populations in those years. Maintenance of *N. mercedis* populations at 1968-1975 levels appears to require sufficient Delta outflow to keep the habitat large and phytoplankton populations high.

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