Intro spp Corbicula fluminea 296,301
Macoma balthica 296,301
Boccardia ligerica 296,301
others 301

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The Benthos of a Portion of the Sacramento River (San Francisco Bay Estuary) During a Dry Year

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ABSTRACT: Early in 1976 benthic studies were initiated in a 20 kilometer long portion of the Western Sacramento–San Joaquin River Estuary. Water quality determinations indicated little vertical or horizontal differences in pH, temperature, or dissolved oxygen concentration within the study area. Low river outflows allowed the encroachment of seawater into the study area, an area normally exposed to fresh or slightly brackish water. The sediment composition changed dramatically at most stations during the year, being dominated by sands early in the year but by silts and clays in late summer. The shift in sediment composition was accompanied by an increase in grease and oil and metals content.

The benthic community of the study area was generally dominated by the Asiatic clam (*Corbicula manilensis*), *Macoma balthica*, oligochaetes, the amphipods *Corophium stimpsoni* and *C. spinicorne*, nematodes, and a spionid polychaete, *Boccardia ligerica*. These taxa comprised 98% on average of the total benthic macroinvertebrates collected at each study site. The benthic assemblages of each of the stations were generally very similar to one another. Faunal similarities and changes in benthos composition were related to substrate composition and salinity incursion. In general, the upstream-channel stations had higher abundance of benthos than the other stations in the study area. Total benthic abundance was lowest at the downstream end of the study area. Total standing crop peaked in June and was lowest in November. Our studies indicate that the most important factors controlling the size and species composition of the benthos of the study area are salinity and sediment composition.

Introduction

The San Francisco Bay-Delta Estuary is one of the most important aquatic resources in California. It is a region rich in industrial, agricultural, recreational, and aesthetic resources. Knowledge of the dynamics of the estuarine communities is limited and must be expanded so that ecologists can develop information to provide managers with the best possible information for intelligent resource management.

Early in 1976 a study of the macrobenthic community was initiated in the Sacramento River portion of the Bay-Delta (Fig. 1) to provide a generalized indication of environmental conditions. The study coincided with a period of unusually low river flow (fourth-driest year on record) and, simultaneously, with encroachment of salt water into regions normally exposed only to fresh or slightly brackish water.

Most previous studies of the Bay-Delta benthos were conducted as general surveys of relatively large geographic areas (e.g., Filice 1954a, 1954b, 1958, 1959; Storrs, et al. 1966; Painter 1966; Hazel and Kelley 1966). Although comparisons are difficult to impossible to make because of differences in techniques and taxonomic determinations, it is apparent that several factors, individually or in combination, are important

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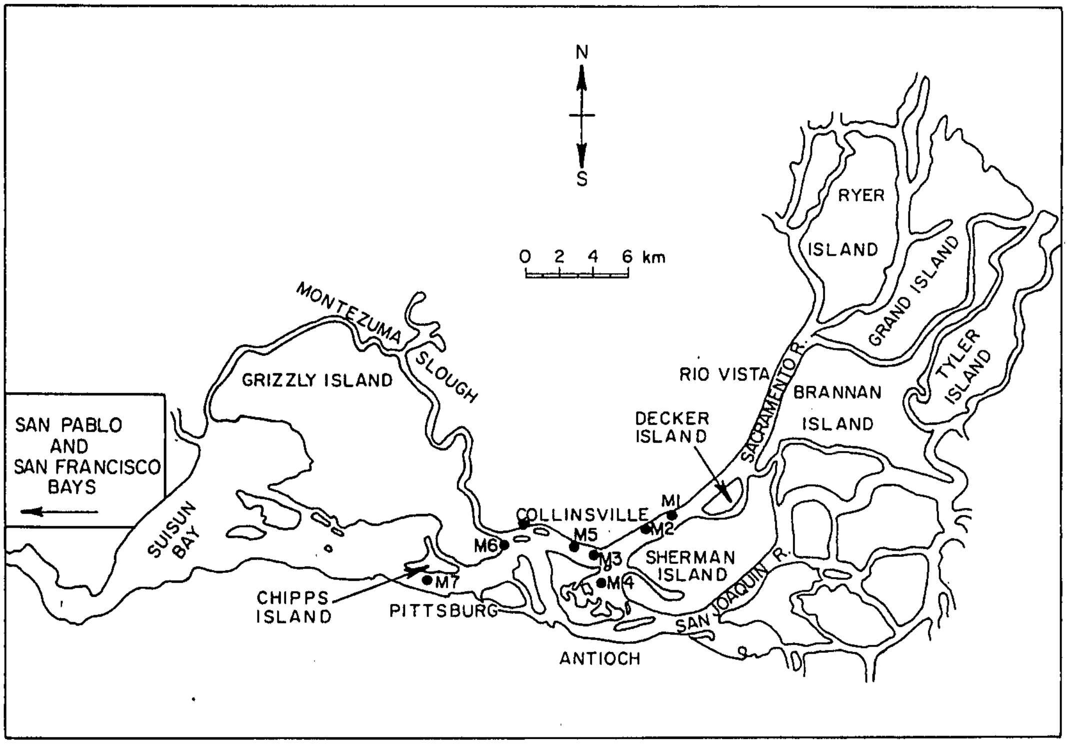


Fig. 1. Location of study sites in Sacramento River Estuary.

in determining the distribution of benthic macroinvertebrates in the Bay-Delta system. Other than perturbations introduced by man, the most important environmental characteristics appear to be salinity, substrate composition, and current (Nichols 1973).

This study was made possible by a series of gifts to the University of California from Dow Chemical Company, Pittsburg, California. We thank the personnel of Dow Chemical Company, especially D. Bauer, R. Beemer, and K. Otero, for assistance during the study. Additional funding was provided by a grant from the California Water Resources Council. We also thank J. Arthur, M. D. Ball and R. Brown for their interest and assistance during the study and for their review of an early draft of this paper. Special thanks are due W. Lie and the staff of the California Academy of Sciences for providing taxonomic verification of the organisms collected during this study and to F. H. Nichols, V. S. Kennedy, and an anonymous reviewer for their helpful review of the manuscript. The senior author also wishes to thank the Biological Survey, New York State Museum and Science Service, for support during the final phases of manuscript preparation.

Materials and Methods

Seven sites in the Western Delta ranging over ~20 kilometers were selected for study (Fig. 1). Stations M1, M3 and M7 are near midchannel, and all average about 9 m deep (over tidal cycle). Stations M2, M5 and M6 are near shore, respectively averaging about 1, 1 and 5 m deep. Station M4, near the center of Sherman Lake, was about 1 m deep.

Water-quality information, i.e., water temperature, salinity, pH, and dissolved oxygen, was obtained from the California Department of Water Resources (DWR). DWR water-quality determinations in the study area are made on a monthly basis in winter, and biweekly during spring through fall. Details of DWR methodology are presented in their annual water-quality data report (e.g., California Department of Water Resources, 1977). The above characteristics

TABLE 1. Heavy-metal content of sediments at Sacramento River study sites, January–November 1976.

Month	Station No.	Metal Content (mg/kg dry wt.)					
		Hg	Zn	Cu	Cd	Cr	Pb
January	M1	<0.09	98	14	0.5	50	1
	2	<0.09	67	10	0.3	67	8
	3	<0.09	45	5	0.3	40	3
	4	0.02	120	25	0.8	64	29
	5	<0.09	59	12	0.4	65	4
	6	0.09	130	50	1.1	78	—
	7	<0.09	45	3	0.3	48	—
March	M1	<0.09	83	8	0.2	24	4
	2	<0.09	66	5	0.2	24	3
	3	<0.08	69	20	0.5	41	4
	4	0.11	87	14	0.5	42	10
	5	<0.09	66	10	0.2	41	4
	6	0.21	180	35	0.7	48	18
	7	<0.09	27	2	0.1	24	2
June	M1	<0.1	64	2	0.06	40	4
	2	<0.1	52	1	<0.06	44	2
	3	0.2	78	3	<0.1	55	5
	4	0.2	114	5	0.2	61	10
	5	<0.1	56	2	0.1	41	4
	6	0.5	145	7	0.3	70	19
	7	<0.09	32	0.5	0.2	31	3
August	M1	0.2	115	6	0.2	59	9
	2	0.09	78	4	0.06	56	7
	3	0.2	107	9	0.9	82	9
	4	0.3	85	5	0.2	43	12
	5	<0.1	51	2	0.6	47	4
	6	0.4	137	9	0.6	70	23
	7	<0.09	26	0.4	0.06	28	4
September	M1	<0.1	87	8	0.3	46	5
	2	<0.1	69	10	0.3	49	5
	3	<0.1	76	16	0.4	38	6
	4	0.27	110	16	0.4	65	21
	5	0.24	114	1	0.1	93	11
	6	0.37	105	28	0.4	50	25
	7	N.D.*	24	2	0.1	24	<0.5
November	M1	0.12	100	16	0.4	50	11
	2	0.03	44	5	0.1	40	4
	3	0.05	85	14	0.2	50	7
	4	0.29	110	20	0.5	60	18
	5	0.36	100	26	0.5	65	16
	6	0.45	140	19	0.4	80	20
	7	0.04	35	2	0.1	34	3

* N.D. = not detectable.

were also determined at the time benthic samples were collected.

Benthic macroinvertebrates were collected on six dates in 1976 (Table 1) at all stations with a Ponar grab sampler. Of the five Ponar samples of bottom sediment obtained at each station, four were placed immediately in large polyethylene bags and preserved with buffered formalin (10%), and the fifth was divided among three containers provided and prepared by Dow Chemical Company (Pittsburg, California) and placed in an ice chest to maintain temperature at about 4 °C. The iced sediment samples were delivered to Dow Chemical's Laboratory for determination of oil and grease content, concentration of metals (Zn, Pb, Hg, Cd, Cu, Cr), and sediment particle size. Oil and grease content was determined by the modified Soxhlet extraction method for sludge samples (APHA 1971). Metals were determined by atomic-absorption techniques.

Sediment particle-size analysis was by a hydrometer method (Day 1965).

The remaining four samples per station were taken to the UCD laboratories and wet-sieved through U.S. #30 (0.59-mm mesh) sieves. The residue retained by the sieves was placed in 1-liter wide-mouthed glass jars, preserved with 70% ethanol, and stained with rose bengal to help differentiate animals from detritus and other sieved materials. Benthic macroinvertebrates were separated from this residue by the sugar flotation technique (Anderson 1959) and by hand-sorting under a powerful scanning lens (to remove bivalves and other organisms remaining after flotation treatment).

The "biological index" developed by Sanders (1960) was used to obtain an objective determination of species (or species group) dominance. The five most abundant organisms in each sample at each station were rated on scale from 5 to 1 with the most abundant organism in each sample receiving a ranking of 5. The rankings for each species were summed to give the "biological index" for that species.

An index of affinity between faunal assemblages at each station was derived by calculating the percentage composition at each station, comparing this with every other station and summing the lower percentages of every species common to both stations. The resulting value is a measure of faunal homogeneity between stations (Sanders 1960). The indices of affinity were then used to cluster stations by the method of unweighted pair-group with simple averages (Sokal and Sneath 1963).

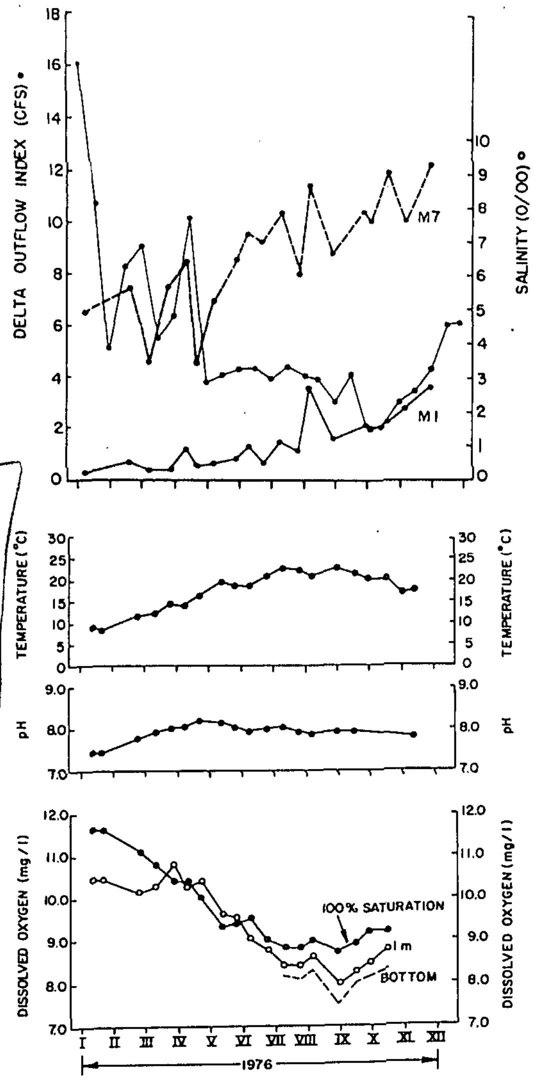


Fig. 2. Discharge (solid line in top fig.), salinity at stations M7 and M1, temperature, pH, and dissolved oxygen concentrations of waters of the Sacramento River, January–November 1976. Temperature and dissolved-oxygen values represent means of all stations; pH is based on measurements at station M3. Roman numerals represent the calendar months from January (I) to November (XI).

Results and Discussion

Physicochemical Characteristics

Water Quality. The Western Delta study area exhibited little vertical stratification in pH, temperature, or dissolved oxygen. Concentrations of dissolved oxygen in 1976 exceeded saturation levels from late March through mid-May but at other times were somewhat below saturation at all stations (Fig. 2). The period of oxygen supersaturation corresponds to the 1976 spring phytoplankton maximum (Siegfried, et al. 1978) and windy weather patterns in this area of the Delta. Dissolved oxygen was generally above 10.0 mg/l in January but declined to below 8.0 mg/l in September. Dissolved oxygen differed little between stations but did decline slightly with depth.

Water temperature and pH also differed little between stations. Water temperature in general varied less than 1.5 °C between stations, ranging from near 8 °C in January to above 22 °C in July and early August, declining with cloudy weather in early August, and increasing again in late August, approaching 23 °C. pH ranged from about 7.3 in January to above 8.0 in summer. The higher pH may reflect, in part, greater primary production rates during spring and summer and the intrusion of more alkaline seawater into the study area.

Salinity in the Western Delta is determined primarily by the volume of net Delta discharge. Low summer discharge allows salt water to move from San Francisco Bay upstream into the Delta. High winter and spring discharges reduce the intrusion of salt water into the Delta. In January (1976), relatively high outflows resulted in fresh water throughout most of the Delta. By May, surface salinities increased to near 7‰ at Chipps Island (high tide) but remained below 1‰ at Station M1 (Fig. 2). These salinity conditions persisted through late September, varying with tidal phases, then increased steadily through November, approaching 3‰ at Station M1. Most water-quality characteristics measured in 1976 are in relatively good agreement with earlier recorded values (Storrs, et al. 1966; California Department of Water Resources 1977).

Substrate. Sediment analyses in the Sacramento River portion of the Western Delta study area indicated that substrate composition at many stations was not stable but changed dramatically during a seasonal cycle (Fig. 3). Sand substrata appear to be characteristic of the San Francisco Bay Estuary east of Carquinez Straits under normal flow conditions (Filice 1954b). Previous benthic studies in this portion of the estuary have characterized the substrate as primarily sand (Filice 1954b; Fisk and Doyle 1962; Painter 1966; Hazel and Kelley 1966). In January 1976, following a year of relatively high Delta outflow, the sediment at all stations was dominated by sand. As Delta discharge decreased during 1976, however, finer sediments began to accumulate, first at the downstream stations and later at the upstream stations as well (Fig. 3). By late summer, silts and clays dominated the sediments of the study area. The accumulation of fine sediments in this portion of the Estuary may result from the tendency for increased flocculation, aggregation, and settling of suspended materials at salinities of ~1‰ (Arthur 1975), and from two-layered flow that characterizes estuarine circulation in the San Francisco Bay Estuary. Nichols (1972) observed that most sediments were deposited in the "entrapment" zone of the James River Estuary in Virginia and that they were generally transitional types, i.e., clayey sand and sand-silt-clay sediments. In 1976, the entrapment zone of the Bay-Delta Estuary was located in our study area from about May on (salinity range ~1–7‰). This presumably led to increased deposition of fine sediments in the study area. Station M7, near Chipps Island, was the only sample site to retain predominantly sand sediments throughout the study period. That was most likely the result of scour by strong currents, preventing fine sediments from accumulating in the area.

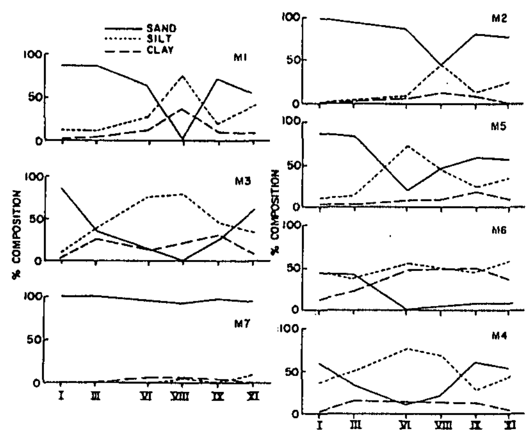
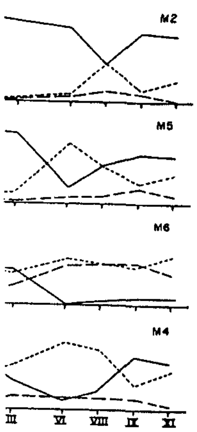


Fig. 3. Sediment particle-size composition of substrate at Sacramento River study sites, January–November 1976. The deep main channel stations are shown on the left and the shallower stations on the right side of the fig. Roman numerals represent the calendar months from January (I) to November (XI).

Changes in sediment composition can influence other sediment characteristics. The grease and oil and organic carbon content of the sediments were significantly correlated ($\alpha = 0.01$) with the silt content of the sediments. Metal concentrations (Hg, Zn, Cu, Cd, Cr, Pb) in the sediments at each station (Table 1) were also significantly correlated ($\alpha = 0.01$) with substrate composition. Sediments dominated by sand, e.g., site M7, were low in metals content, whereas those high in silt and clay or organics were high in metals content. This results



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at least 10 of 18 * introduced species
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TABLE 2. Macroinvertebrates collected from benthos study sites in the Western Sacramento–San Joaquin Delta, January–November 1976.

	Phylum Coelenterata		Phylum Arthropoda (cont.)
	Class Hydrozoa		Class Crustacea (cont.)
*	*Cordylophora lacustris* Allman, 1844 (caspia)	?	*Tanais vanis* Miller, 1940
	Phylum Nematoda	*	*Synidotea laticauda* Benedict, 1897 (laevidorsalis)
	Nematoda spp. (undetermined)	N	*Gnorimosphaeroma insulare* Monzies, 1954
	Phylum Annelida	?	*Asellus* sp.
	Class Polychaeta		Isopoda sp.
N	*Neanthes limnicola* Johnson, 1901 = Hediste limnicola	N	*Corophium stimpsoni* Shoemaker, 1941
*	*Boccardia ligerica*	N	*Corophium spinicorne* Stimpson, 1857
	Polychaeta spp. (undetermined)	*	*Corophium acherusicum* Costa, 1857
	Class Oligochaeta	*	*Grandidierella japonica* Stephenson, 1938
	Tubificidae	?	*Ampelisca* sp. (abdita ?)
	Oligochaeta spp. (undetermined)	?	*Parapoxus millari* Thorsanson, 1941
	Class Hirundinea	N	*Crangon franciscorum* Stimpson, 1859
	Hirundinea sp. (undetermined)	*	*Palaemon macrodactylus* Rathbun, 1902
	Phylum Mollusca	*	*Rhithropanopeus harrisii* Gould, 1941
	Class Bivalvia		Class Insecta
*	*Corbicula manilensis* (Philippi, 1844) (fluminea)		*Chironomus* sp.
*	*Macoma balthica* (Linnaeus, 1758)		Chironomini sp.
	Phylum Arthropoda		*Tribelos* sp.
	Class Crustacea		Orthocladinae sp.
	Ostracoda		*Tanytarsus* sp.
*	*Balanus* sp. (must be B. improvisus)		Ceratopogonidae
N	*Neomysis mercedis* Holmes, 1897		Tabanidae

from the tendency of silt and clay and organic particles to adsorb metal ions. Thus, when these particles precipitate, the adsorbed metals are also precipitated and become associated with the sediments.

The metals concentrations reported in the present study are lower than concentrations reported from San Francisco Bay (Girvin, et al. 1975; Moyer and Büdinger 1974) and are within the range reported for unpolluted estuaries in England (Bryan and Hummerstone 1971). The concentrations of metals in the sediments of the study sites do not appear to be high enough to create problems within the benthic community but do indicate a potential for future water-quality problems. The entrapment zone appears to be an area critical to the productivity of the Estuary (Arthur and Ball 1978). Increased inputs of metals to this area of the entrapment zone could affect the productivity of the entire Estuary.

Benthos

Community Structure. Macroinvertebrates belonging to more than 30 genera, including representatives of both the epifauna and the infauna, were identified from benthic samples obtained in the study area from January through November 1976 (Table 2). Highly mobile forms such as the shrimps *Crangon franciscorum*, *Palaemon macrodactylus*, and *Neomysis mercedis* are not sampled efficiently with benthic grabs and are not discussed here.

The near-shore stations (M2, M5, M6) generally had the greatest number of macroinvertebrate taxa represented in the benthic samples (Siegfried, et al. 1978). Fewer macroinvertebrate taxa were collected from Stations M4 and M7 than from the other sites, possibly as a result of low habitat diversity (M4) or shifting substrate (M7) (Siegfried, et al. 1978).

The "biological index" for the more common species is presented in Table 3. Oligochaetes, *Corophium stimpsoni*, *Corbicula manilensis*, and nematodes were consistently among the dominant species or species groups at all stations. *Macoma balthica*, *Boccardia ligerica*, and *Corophium spinicorne* were also among the dominant species at some stations. (The two species of *Corophium* were separated on the basis of morphology of the second antennae, the rostrum, and setal patterns and the identification confirmed by J. Chapman of the California Academy of Sciences, San Francisco.)

sum of ranks of 1-5 for five most abundant specimens in each sample, for 5 samples (p 299)

TABLE 3. Biological index for benthic species or species groups found at each station, January–November 1976.

	Biological Index						
	Jan	Mar	Jun	Aug	Sept	Nov	Total
upstream *STATION M1*	(		max = 25			)	(max = 150)
Oligochaetes	14	12	13	15	20	20	94
Corophium stimpsoni	20	20	16	4	4	4	68
Corbicula manilensis	14	16	9	12	10	6	67
Nematoda	3	6	2	8	10	14	43
u *Boccardia ligerica*					16	14	30
Corophium spinicorne			18				18
Ostracoda	6	6					12
STATION M3							
Oligochaetes	19	8	8	18	18	16	89
Corbicula manilensis	17	20	12	12	12	8	81
Corophium stimpsoni	12	12	16	10			50
Corophium spinicorne	2	16	20	8	4		50
u *Boccardia ligerica*				4	18	20	42
Nematoda		4	1	9	1	8	23
downstream *STATION M7*							
Oligochaetes	18	18	20	20	18	4	98
Corbicula manilensis	18	18	16	15	13	18	98
Corophium stimpsoni		8	12	4		4	28
Nematoda		6		10			16
d *Macoma balthica*					4	8	12
Corophium spinicorne	3		4	2			9
STATION M2							
Oligochaetes	14	12	20	20	15	18	99
Corbicula manilensis	17	20	16	16	12	13	94
Corophium stimpsoni	17	16	9	6	8	2	58
Corophium spinicorne	2	1	12	8		2	25
e *Neanthes limnicola*		1	6	3	3	4	17
Nematoda	2	4		6		5	17
u *Boccardia ligerica*						12	12
STATION M5							
Oligochaetes	13	18	20	20	20	20	111
Corbicula manilensis	15	14	16	16	15	12	88
Corophium stimpsoni	19	16	12	6			52
Nematoda	2	6	2	2	3	12	27
Corophium spinicorne	9		5	8		1	23
d *Macoma balthica*				2	7	7	16
e *Neanthes limnicola*	1		6	4	2		13
STATION M6							
Oligochaetes	18	20	19	20	20	20	117
Corbicula manilensis	9	12	17	12	9	13	72
d *Macoma balthica*			9	16	16	15	56
Corophium stimpsoni	18	16	8	1			43
Nematoda	4	5	2	4			15
Corophium spinicorne	2	5	1				8
STATION M4							
Corophium stimpsoni	20	20	20	15	16	17	108
Oligochaetes	16	16	16	17	20	19	104
Corbicula manilensis	11	12	12	12	12	9	68
Nematoda	4	4	4	4	5	6	27
Ostracoda	9	6					15
Corophium spinicorne			5	5			10

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, January–November

Nov	Total
20	94
4	68
6	67
14	43
14	30
	18
	12
16	89
8	81
	50
	50
20	42
8	23
4	98
18	98
4	28
	16
8	12
	9
18	99
13	94
2	58
2	25
4	17
5	17
12	12
0	111
2	88
	52
2	27
1	23
7	16
	13
0	117
3	72
5	56
	43
	15
	8
[illegible]	108
[illegible]	104
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The benthos of each station experienced changes in dominance that are thought to be associated with changes in salinity and sediment type (Fig. 4). The benthos at the most downstream site, M7, was dominated by *Corbicula manilensis* and oligochaetes throughout the year (Fig. 4). Amphipods were never abundant at this site, possibly because of heavy scour by strong current. The composition of the benthos at the upstream, deep stations, M1 and M3, changed dramatically during the year (Fig. 4). In January, when the sediments of both sites were dominated by sand (Fig. 3), *C. stimpsoni* dominated the benthos at Station M1, and *Corbicula manilensis* and oligochaetes at Station M3. By March, the sediments at site M3 had become a fairly even mixture of sand, silts and clays, and *C. spinicorne* and *Corbicula manilensis* dominated the benthos. At Station M1 in March, *C. stimpsoni* remained the dominant benthic organism and the sediments were still primarily sandy. By June the sediments at Station M3 were dominated by silts, and *C. spinicorne* accounted for more than 75% of the macroinvertebrates present in the benthic samples from the site (Fig. 4). In June, at station M1 the silt and clay content of the sediments had increased considerably, and *C. spinicorne* became the dominant amphipod (50% total benthos) although *C. stimpsoni* remained a significant portion of the benthos (33%). By August, silts dominated the sediment of both sites and the benthic communities were dominated by oligochaetes. In September and November the polychaete *Boccardia ligerica* dominated the benthos of site M3, while oligochaetes continued to dominate at M1. The virtual elimination of *Corophium* from those sites by September appears to be related, at least in part, to the incursion of saline water into theDelta (Hazel and Kelley 1966).

Both shallow, near-shore stations (M2 and M5) had fairly even representation by *C. stimpsoni*, *C. manilensis*, and oligochaetes in the January benthos, but by June and continuing through November were dominated by oligochaetes (Fig. 4). At station M6 the sediment chiefly comprised silts and clays, and oligochaetes were the dominant benthic forms throughout the year (Fig. 4). In January and March, when salinities were low and the sediments had a significant amount of sand, *C. stimpsoni* was a dominant member of the benthic community at this site. *Macoma balthica* became a significant component of the benthic fauna at Station M6 in June and continued to be a dominant member of the community through November. Prior to June, *M. balthica* was not collected at any of the study sites.

The benthos of Sherman Lake (Station M4) was dominated by *C. stimpsoni* from January through June and by oligochaetes from August through November. Station M4 was the only site at which *C. stimpsoni* was present throughout the year. This persistence throughout the year at Sherman Lake does not appear to be due to unique substrate conditions as *C. stimpsoni* remained abundant throughout the year in spite of changes from sand to silt to sand-dominated substrate. Salinity incursion also occurred in Sherman Lake. However, limited information suggests that salinity fluctuations in Sherman Lake during tidal exchange may be less extensive than the fluctuations occurring in the river channel (Siegfried, et al. 1978). Interactions with other conditions, such as reduced current velocities in Sherman Lake, may enhance the Sherman Lake environment for *C. stimpsoni*.

The results of cluster analysis based on the index of affinity are presented in Fig. 5. In January all stations except M6 clustered above the 70% level of affinity. M6 was the only station at which oligochaetes and *C. stimpsoni* were equally dominant members of the benthic fauna. The January faunal clusters were apparently influenced by sediment composition. Station M6 was the only site at which sand did not compose the major portion of the sediments.

In March the benthos of all stations were fairly similar, being composed chiefly of *C. stimpsoni*, *Corbicula manilensis*, and oligochaetes. In June two distinct clusters were evident. Stations M1 and M3, being the only stations dominated by *C. spinicorne*, thus formed a separate cluster. Oligochaetes composed >70% of the benthos at the remaining stations (except M4) in June, and these stations formed a tight cluster above the 80% level of affinity.

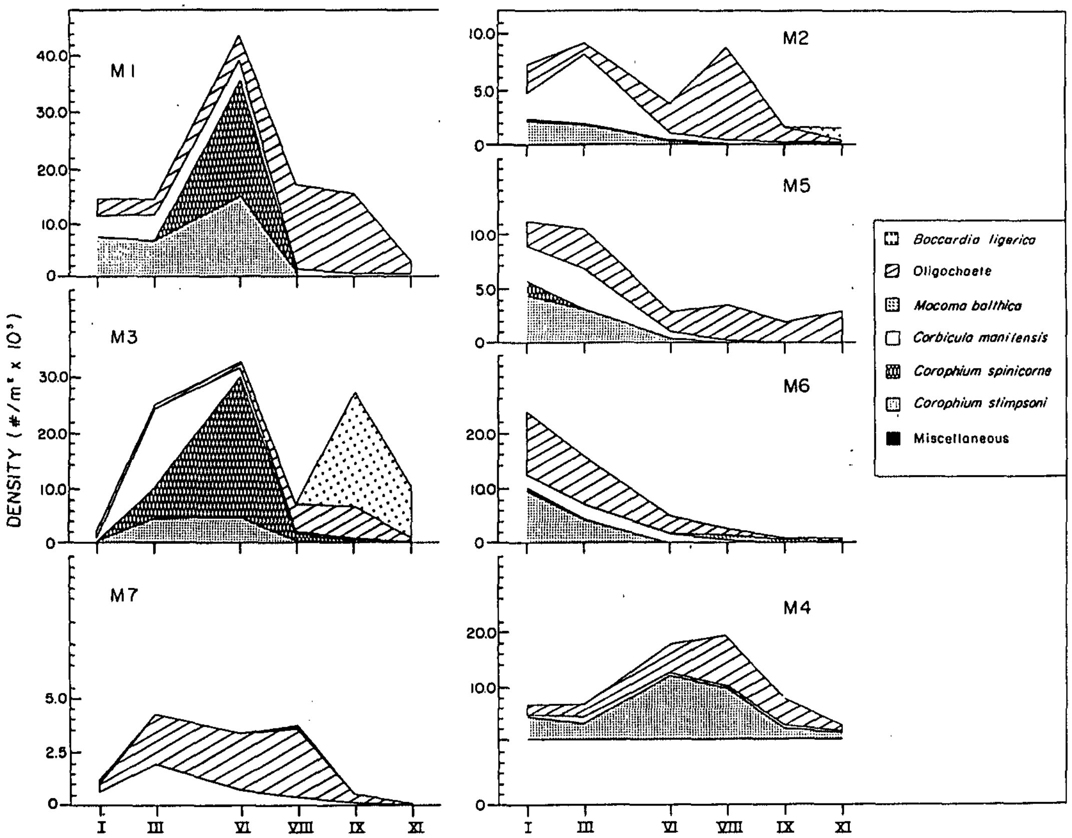
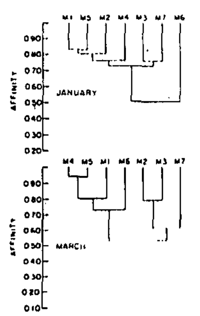


Fig. 4. Composition and abundance of macrobenthos at Sacramento River study sites, January–November 1976. The deep main channel stations are shown on the left and the shallower stations on the right. Roman numerals represent the calendar months from January (I) to November (XI).

In August and September all stations except one were dominated by oligochaetes and formed clusters above the 70% level of affinity. In August, Station M4 was dominated by *C. stimpsoni* (in August *C. stimpsoni* had the greater mean abundance and standing crop although oligochaetes were the dominant form based on the "biological index"). In September, Station M3 was dominated by *Boccardia ligerica*. In November, Stations M2 and M3, dominated by *B. ligerica*, clustered separately, while the remaining stations clustered in order of decreasing oligochaete composition.

Benthic Abundance. Benthic abundance at the near-shore stations (M2 and M5) and at Station M6 generally declined from January to November (Fig. 4). Abundance remained low through the year at Chipps Island (M7), whereas at Sherman Lake (M4) it increased to an August peak before declining. The greatest increase in benthic abundance was at the upstream channel stations, M3 and M1. At Station M3 benthic abundance increased from fewer than 2,300 organisms m^{-2} in January to over 32,000 m^{-2} in June. The increase at Station M1 was similar, from 14,400 to nearly 44,000 m^{-2}, resulting in the highest mean abundance recorded at any station during this study. Abundance at Stations M1 and M3 dropped precipitously in August and continued to decline at M1 in September. Abundance at all stations except M3 was lowest in November. The lowest recorded benthic abundance was from samples collected at Station M7 in November.

Estimates of the precision of benthic abundance determinations suggest that although four benthic samples are generally sufficient for determining benthic abundance at channel stations or other fairly ho-



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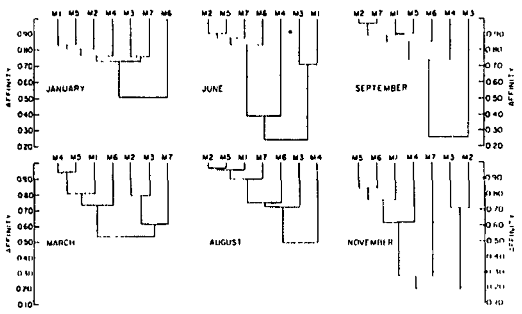

Fig. 5. Dendrograms of the benthos community affinity (Sanders 1960) derived from samples collected in Sacramento River, January–November 1976. Clustering is by the unweighted pair-group method using simple averages.

TABLE 4. Homogeneous subsets* (HS) of benthic density at each sampling station obtained from Duncan's multiple-range test (α = 0.01), January–November 1976 (HS1 > HS2 > HS3).

Sampling date	Station			
	M1	M3	M7	M4
22 January	No Significant Difference			
26 March	HS2	HS1	HS3	HS3
28 June	HS1	HS2	HS4	HS3
2 August	HS1	HS2	HS2	HS1
21 September	HS1	HS1	HS2	HS1
16 November	HS2	HS1	HS2	HS2

* Subsets of stations no pair of which has mean benthic densities that differ by more than the shortest significant range for a subset of that size.

mogeneous habitats, (M7, M1, M3, M4), more are required at near-shore stations (Siegfried, et al. 1978). Therefore, only mean abundances at Stations M1, M3, M4 and M7 were examined each month by Duncan's multiple-range test (Steele and Torrie 1960) to determine statistically significant differences in abundance (Table 4). In January, differences in abundance were not statistically significant (α = 0.01). In March, benthic abundance was significantly (α = 0.01) greater at Station M3 than at any other station, and in June abundance was greater at Station M1 than at any other station. June abundances were also somewhat higher at M3 and M4 than at other stations. Abundance was highest at Station M4 in August, at M1 in September, and at M3 in November. In general, the upstream channel stations, M1 and M3, had greater abundances of benthos than the other stations in the study area during 1976.

C. stimpsoni population density peaked at site M1 in June of 1976 (~14,500 m^{-2}) but was also relatively high at all stations other than M7 in March but declined precipitously at the most-downstream stations (M5 and M6) by June. After August, significant populations of *C. stimpsoni* were present only at Station M4. The decline of *C. stimpsoni* population within the Sacramento River can be related to salinity intrusion. By June, salinities had reached 5–6‰ as far upstream as Station M3. Previous studies (Hazel and Kelley 1966) had suggested that such salinities would be near the downstream salinity limit for both *C. stimpsoni* and *C. spinicorne*. The annual cycle of *C. stimpsoni* abundance reflected in samples collected at Sherman Lake (M4) may be indicative of its "normal" dynamics (Fig. 4). The population in Sherman Lake was relatively low in spring, peaked in early summer, and remained high before dropping to a wintertime low.

The seasonal abundance of *C. manilensis* at each study site is also indicated in Fig. 4. The population peaked in March at all stations and then declined dramatically. In earlier studies near Station M1, *C. manilensis* density peaked between January and March (Fisk and Doyle 1962; Hazel and Kelley 1966) and was very low from April through November. That is in essential agreement with the present finding, although the population estimates differ by an order of magnitude. *Corbicula* density reached a maximum of 312 m^{-2} in the 1960–61 study (Fisk and Doyle 1962), and in the present study the maxima ranged from ~2,000 m^{-2} at Station M7 to nearly 14,500 m^{-2} at Station M3. March appears to be the peak recruitment period of *Corbicula*, apparently from fresh water, since large numbers of young clams were present both in the water column and in the benthos at that time (Siegfried, et al. 1978). Few clams were present in the water column in January or May, and none were present in August through November.

The marked changes in substrate composition and the incursion of high salinity water in the Sacramento River study area were the most important factors controlling benthos composition and abundance. Salinity and substrate appear to be the controlling factors throughout the San Francisco Bay

Estuary in areas unaffected by waste discharges (Nichols 1973). Studies of European estuaries indicate that the salinity range of 5–7‰ has the fewest species of any area in an estuary (Remane and Schlieper 1971). For much of 1976, salinities in the study area were near this range and the benthic community was of low diversity and abundance. This is consistent with earlier studies of the Bay-Delta which indicated a faunal break at Carquinez Straits. Stations east of Carquinez Straits, particularly river stations, have been found to have generally lower benthic biomass than those west of the Straits (Filice 1956b; Storrs, et al. 1966).

Interestingly, the water column of the upstream end of the mixing zone of the San Francisco Bay-Delta (1–7‰) is one of the most productive areas of the upper estuary. Phytoplankton populations, chlorophyll, zooplankton, and particulate organic and inorganic materials are all higher in this area, the "entrapment zone," than in adjacent upstream or downstream areas (Arthur and Ball 1978). Apparently, physiological stress associated with exposure to this range of salinities and possibly, unfavorable substrates, limits the development of the benthos in spite of the high production in the overlaying waters, and presumably, high food availability to deposit feeding benthos. Regulation of Delta outflow to retard salinity incursion and regulate the location of the entrapment zone in the estuary through controlled upstream reservoir releases is a management tool presently being tested in the Bay-Delta (Arthur, pers. commun.). It may be possible, by regulation of the location of the entrapment zone, to prevent the decimation and/or enhance the production of the benthos populations near the upstream end of the mixing zone.

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