## Benthic Macrofaunal Assemblages of San Francisco Bay and Delta

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### Introduction

Benthic macrofauna are invertebrates, usually larger than 0.5mm, that inhabit sediment. They compose a major component in the estuarine ecosystem that links sediments with the aquatic food web and facilitate nutrient and carbon flux by their burrowing and feeding activities. Benthic monitoring is a standard component of all major monitoring programs in the United States. They are monitored because they are generally not very motile and must respond to a variety of estuarine conditions including salinity changes, sediment flux, and contamination. Thus, benthos are considered to be reliable indicators of sediment conditions within a local area.

Benthos have been well studied in the San Francisco Estuary (Nichols and Pamatmat 1988). An analysis of DWR's benthic monitoring in the northern estuary and delta was reported by Hymanson et al. (1993). This article describes the major benthic assemblages of the entire bay and delta, and their general relationships to key physical factors. "Assemblage" is a term used to describe an association of benthic species that inhabits an area. The geographic scale of an assemblage may vary depending on responses of the organisms to physical factors such as salinity or sediment type, and biological factors such as competition or predation. It is important to recognize that an assemblage is a manifestation of responses by individual organisms.

Information is summarized from four benthic monitoring programs conducted in the bay and delta since 1994: DWR's D1485 Compliance Monitoring Program, SFEI's Regional Monitoring Program for Trace Substances (RMP), the Bay Area Dischargers Association's Local Effects Monitoring Program (LEM), and the State's Bay Protection and Toxic Clean-Up Program (BPTCP) conducted by the San Francisco Bay Regional Water Quality Control Board. A total of 424 benthic samples collected from 44 sites between 1994 and 1996 was analyzed (Figure 1).

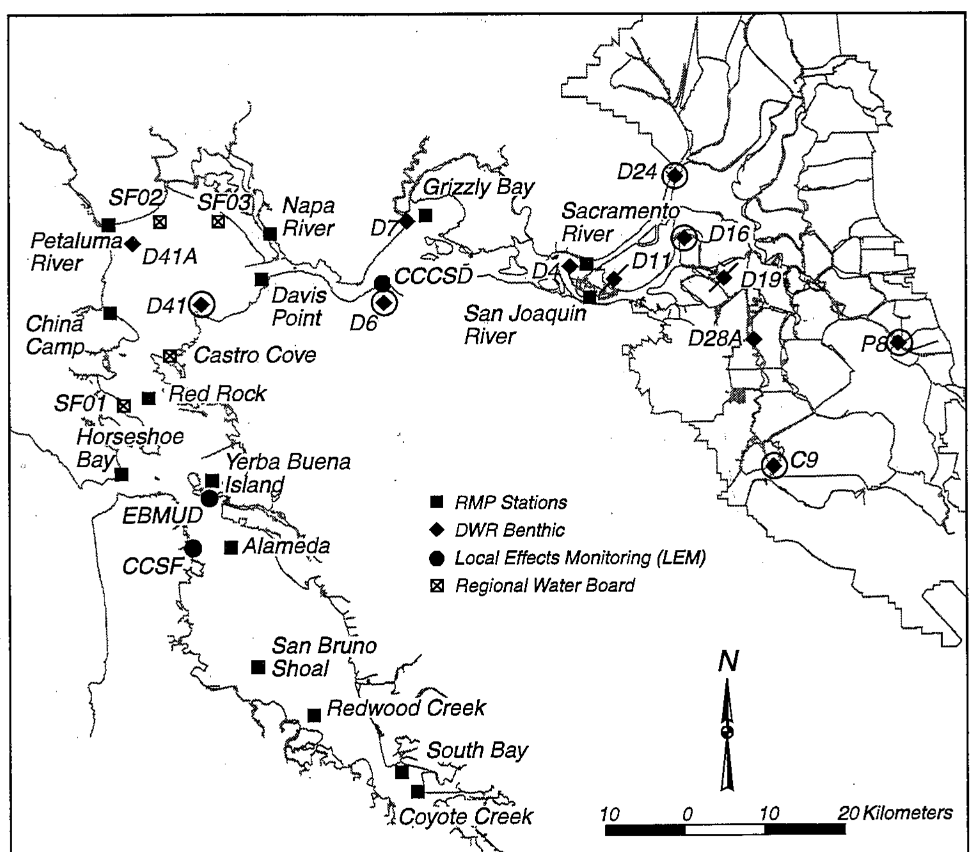


**Figure 1. Benthis Sampling Sites**
*Circled DWR sites were added, slashed DWR sites were dropped in 1996.*
*CCSF=City and County of San Francisco, EBMUD= East Bay Municipal Utility District*
*CCCSD= Central Contra Costa Sanitation District*

Similar methods of sampling and analysis were used by each program. A 0.05 m$^2$ Ponar Grab was used to collect most samples, and they were sieved through a 0.5 mm screen. Each program used different taxonomists (persons who identify organisms, see Acknowledgments), so it was necessary to standardize the species names reported by each program. This required an assessment of taxonomic differences, then resolution through discussions by the taxonomists to produce a standardized species list.

### Results

*Major Benthic Assemblages.* Three major groupings of sites, each containing sub-groupings were identified by classification and ordination (Smith et al. 1988; Table 1). The benthos at the sites in each group had similar species composition and abundances, therefore those groupings are interpreted to represent benthic assemblages. The distribution of the assemblages reflected spatial similarities in species composition among the sites, although temporal differences were shown for some assemblages (explained below).

While it may appear obvious that the assemblages identified were related primarily to the estuarine salinity gradient, no salinity data were included in the ordination and classification analysis. Those analyses only included species names and abundances at each site. The designations used for the benthic assemblages reflect additional analysis (summarized below) which showed that the assemblages represent changes in species composition and abundances related primarily to salinity and sediment type.

***Fresh-Brackish Assemblage.*** This assemblage included all of DWR's sites sampled in the delta, and was composed of three subassemblages that appeared to reflect differences in sediment-type or occasionally higher salinities. Many of the same species inhabited all three subassemblages; the differences between them were mainly due to shifts in numerical dominance or, in the case of the sandy sediment group, decreases in overall abundances.

***Muddy Sediment Subassemblage.*** This subassemblage included 192 samples from 8 sites in the delta (Table 1). Samples from all months sampled were included suggesting generally stable species composition and abundances within the assemblage, both seasonally and in different water years.

The most common and abundant species of this assemblage are listed on (Table 2). The polychaete *Manayunkia speciosa* had the highest average abundances. This species, commonly called the 'feather duster' worm, is native to eastern North America. It was first seen the delta in 1963, and is thought to have been introduced with water used to transport game fish, though it may have been introduced via freshwater ballast (Cohen and Carlton 1995). While this family of worms is commonly found in marine environments, it is one of the few species of this genus that inhabits fresh water. These colonial worms are about 3—5 mm in size and live in tubes constructed of surrounding mud or silt sediments bound together with a mucous secretion. Feathery tentacles protrude from the tube passively collecting organic matter from surrounding water. *M. speciosa* lacks a pelagic larval stage, subsequently it reproduces by budding, releasing young adult worms from the parental tube (W. Fields personal comm.; Cohen and Carlton 1995).

Another common inhabitant is the introduced clam, *Corbicula fluminea*. Native to Asia, they were first col-

**Table 1. Benthic Monitoring Sites That Were Classified in Each Benthic Assemblage**
**Note that some sites were classified in more than one assemblage at differnt times sampled.**

| **Assemblage** / **sub assemblage** | **Sites Name (Code)** | |
|---|---|---|
| Fresh Brackish (oligohaline) | | |
| Muddy sediments | Franks Tract (D19)<br>Old River (D28A)<br>Sherman Is. (D11)<br>Twitchell Is. (D16) | Buckley Cove (P8)<br>Clifton Court (C9)<br>Rio Vista (D24)<br>Collinsville (D4) |
| Sandy sediments | Rio Vista (D24)<br>Collinsville (D4) | Twitchell Is. (D16) |
| Estuarine transition | Grizzly Bay (D7)<br>CCCSD | Pacheco Creek (D6)<br>Collinsville (D4) |
| Estuarine (euryhaline) | | |
| | Pacheco Creek (D6)<br>Petaluma R. (BD15)<br>San Pablo Shoal (D41A)<br>South Bay (Ba21)<br>SFO2 | Davis Point (BD41)<br>Pinole Point (D41)<br>Grizzly Bay (D7)<br>SFO3<br>CCCSD |
| Contaminated sediments | Castro Cove | China Camp |
| Central Bay (stenohaline) | | |
| Muddy sediments | SFO1<br>Alameda (Bb70)<br>EBMUD<br>Redwood Ck. (BA41) | Horseshoe Bay (BC21)<br>Yerba Buena Is. (BC11)<br>San Bruno Sh. (BB15)<br>CCSF |
| | Sandy sediments | Red Rock (BC60) |

lected in the delta in 1945 (Cohen and Carlton 1995). They were collected in all but one sample in the delta, and are occasionally found as far downstream as Grizzly Bay. The highest numbers of *C. fluminea* were collected at Frank's Tract and Old River. *C. fluminea* is found mostly in the fresh water of the central delta and is not seen west of Grizzly Bay except in times of very high outflows. This clam contributes the largest proportion to benthic biomass in the fresh-brackish assemblage.

*Sandy Sediment Subassemblage.* This subassemblage included 19 samples from 4 sites in the delta (Table 1). The sediments at those sites were characterized by coarse sand, typical of flowing water. Some sites classified in this subassemblage were sometimes classified in the muddy subassemblage, presumably associated with changes in sediment composition. Most of the same species collected at the sandy sites were also collected at the muddy sites; *C. fluminea* was the most common and abundant species at the sandy sites. However, the sandy sites were generally characterized by greatly reduced numbers of species.

*Estuarine Transition Subassemblage.* This subassemblage included 72 samples from 5 sites, mostly in Suisun Bay (Table 1). Most of those sites are within the range of the mixing zone where salinities fluctuate greatly depending on delta outflow. Some of the sites classified in this subassemblage were sometimes classified with estuarine assemblage sites, presumably associated with changes in salinity. For example, station D7 in Grizzly Bay was classified in this subassemblage 30 of the 33 times sampled, when antecedent salinities were about 4.5 psu. That station was classified in the estuarine assemblage on three occasions when antecedent salinities were above 10 psu.

The most common and abundant species of this subassemblage included both fresh- brackish and estuarine assemblage species (Table 2).

*Estuarine Assemblage.* Sites from the northern estuary and South Bay (approximately equidistant to the Golden Gate) grouped together to represent the estuarine assemblage. In contrast to the other major assemblages, sites with muddy and sandy sediments were not distinguished despite the fact that some sites sampled had quite sandy sediments. This suggests that estuarine sites with a wide range of sediment types are inhabited by similar benthos. Two subassemblages were identified.

*Main estuarine assemblage.* The main estuarine assemblage included 68 samples from 11 sites (Table 1). Samples from all sampling periods were included suggesting rather stable assemblage composition and abundances. The most common and abundant species were the Asian clam *Potamocorbula amurensis* and the amphipod *Ampelisca abdita* (Table 1).

*P. amurensis* has received considerable attention since its introduction to the estuary in 1986 (Carlton et al. 1990), and was by far the most common and abundant species in this assemblage. They were found in almost 99% of the samples collected between 1994 and 1996. They inhabited all benthic assemblages described except for the fresh-brackish assemblage. They contribute the largest portion of benthic biomass, where collected. The presence of this clam since 1986 has changed the ecology of the northern estuary (e.g., Werner and Hollibaugh 1993; Kimmerer et al. 1994).

*A. abdita* was among the most abundant species collected in the estuarine assemblage, as well as in the Central Bay assemblage. Their abundances decreased with decreasing salinity, and they were not collected in samples from the delta or rivers, or from the sandy sediments at Red Rock. Their abundances may be quite variable due to their life history (Weston 1997). It is a tube dwelling amphipod, about 1-4 mm long, native to northwest Atlantic coastal estuaries from Maine to the Gulf of Mexico. It was first collected in San Francisco Bay in 1954, where it may have arrived with shipments of Atlantic oysters around the turn of the century, or could have been introduced to the bay via ballast water. (Cohen and Carlton 1995).

*Contaminated Sediments Subassemblage.* Eight sites from Castro Cove and the China Camp wetland tidal channels were classified together. The benthos at those sites included species known to be insensitive to sediment contamination, such as the polychaetes *Capitella "capitata"*, *Polydora lignii*, and *Streblospio benedicti*. Sediment contaminant concentrations were considerably higher at the Castro Cove and China Camp sites than in the main estuarine assemblage sites. Elevated abundances of tubificid oligochaetes (compared to the main estuarine assemblage) are also characteristic of contaminated sites (Canfield et al. 1994). The spionid polychaete *Streblospio benedicti* is assumed to be native due to its wide distribution in the brackish waters of the east and west coasts of North America. If it is truly native to the San Francisco Bay Estuary, it is probably the only native organism that is common and abundant enough to be claimed as a representative of the estuarine assemblage. *S. benedicti* is 515 mm long and sits recumbent on the surface of intertidal mud flats to feed on suspended organic matter.

**Table 2. Most Common and Abundant Species in Each Benthic Assemblage**

| | Num. of Occurrences | Average Abundance |
|---|---|---|
| Fresh Brackish–muddy sediments (n = 192) | | |
| *Manayunkia speciosa* (P) | 103 | 117 |
| *Corophium stimpsoni* (A) | 162 | 56 |
| *Corbicula fluminea* (B) | 191 | 49 |
| *Limnodrilus hoffmeisteri* (O) | 180 | 36 |
| *Gammarus daiberi* (A) | 172 | 36 |
| *Varichaetadrilus angustipenis* (O) | 188 | 29 |
| *Corophium spinicorne* (A) | 120 | 19 |
| *Cyprideis* sp. A (C) | 27 | 15 |
| *Aulodrilus limnobius* (O) | 97 | 13 |
| *Dorylaimus* sp. A (N) | 106 | 13 |
| Fresh Brackish–sandy sediments (n = 19) | | |
| *Corbicula fluminea* (B) | 19 | 18 |
| *Paratendipes* sp. A (C) | 9 | 5 |
| *Gammarus daiberi* (A) | 15 | 3 |
| *Corophium stimpsoni* (A) | 12 | 1 |
| *Marenzelleria viridis* (P) | 11 | 1 |
| *Chaetogaster limnaei* (O) | 2 | 1 |
| *Varichaetadrilus angustipenis* (O) | 12 | 1 |
| *Corophium spinicorne* (A) | 3 | 0. |
| *Potamocorbula amurensis* (B) | 5 | 0.2 |
| *Limnodrilus hoffmeisteri* (O) | 5 | 0.1 |
| Fresh Brackish–estuarine transition (n = 72) | | |
| *Potamocorbula amurensis* (B) | 67 | 28 |
| *Corophium alienense* (A) | 33 | 26 |
| *Marenzelleria viridis* (P) | 57 | 19 |
| *Corophium stimpsoni* (A) | 19 | 3 |
| *Gammarus daiberi* (A) | 32 | 3 |
| *Nippoleucon hinumensis* (Ar) | 26 | 2 |
| *Tubificoides heterochaetus* (O) | 27 | 2 |
| *Limnodrilus hoffmeisteri* (O) | 10 | 1 |
| *Corophium heteroceratum* (A) | 7 | 1 |
| *Tubificoides fraseri* (O) | 8 | 0.4 |
| Estuarine (n = 68) | | |
| *Potamocorbula amurensis* (B) | 67 | 162 |
| *Ampelisca abdita* (A) | 52 | 135 |
| *Nippoleucon hinumensis* (Ar) | 49 | 21 |
| *Corophium heteroceratum* (A) | 42 | 9 |
| *Corophium alienense* (A) | 9 | 4 |
| *Grandidierella japonica* (A) | 29 | 4 |
| *Balanus improvisus* (Ar) | 28 | 3 |
| *Tubificidae* (O) | 13 | 2 |
| *Neanthes succinea* (P) | 54 | 2 |
| *Streblospio benedicti* (P) | 37 | 2 |
| Estuarine–moderately contaminated (n = 8) | | |
| *Tubificidae* (O) | 4 | 404 |
| *Nippoleucon hinumensis* (Ar) | 8 | 144 |
| *Streblospio benedicti* (P) | 8 | 116 |
| *Corophium* spp. (A) | 5 | 92 |
| *Gemma gemma* (B) | 4 | 70 |
| *Ampelisca abdita* (A) | 4 | 54 |
| *Grandidierella japonica* (A) | 6 | 46 |
| *Nematoda* (N) | 4 | 37 |
| *Eusarsiella zostericola* (C) | 4 | 36 |
| *Pseudopolydora kempi* (P) | 4 | 35 |
| Central Bay–muddy sediments (n = 60) | | |
| *Corophium acherusicum* (A) | 34 | 745 |
| *Ampelisca abdita* (A) | 56 | 697 |
| *Corophium heteroceratum* (A) | 55 | 133 |
| *Euchone limnicola* (P) | 26 | 57 |
| *Corophium* spp. (A) | 23 | 52 |
| *Leptochelia dubia* (C) | 37 | 50 |
| *Corophium insidiosum* (A) | 14 | 50 |
| *Photis* spp. (A) | 28 | 42 |
| *Mediomastus* spp. (P) | 52 | 36 |
| *Exogone lourei* (P) | 41 | 26 |
| Central Bay–sandy sediments (n = 6) | | |
| *Heteropodarke heteromorpha* (P) | 4 | 18 |
| *Nematoda* (N) | 3 | 8 |
| *Grandifoxus grandis* (A) | 2 | 3 |
| *Hesionura coineaui difficilis* (Ar) | 3 | 2 |
| *Glycera tenuis* (P) | 4 | 2 |
| *Tellina bodegensis* (B) | 2 | 1 |
| *Tubificidae* (O) | 3 | 1 |
| *Glycera americana* (P) | 2 | 1 |
| *Glycera* spp. (P) | 1 | 1 |
| *Mediomastus* spp. (P) | 1 | 0.3 |

Oligochaeta = (O), Arthropoda = (Ar), Polychaeta = (P), Amphipoda = (A), Bivalvia = (B), Nematoda = (N), Crustacea = (C)

It was considered to be an indicator of contaminated sediments by Dauer (1993).

## Central Bay Assemblage

Most of the RMP, LEM, and Regional Board reference sites sampled in the Central Bay represented this assemblage. Two subassemblages reflecting different sediment-types were identified.

*Muddy Sediment Subassemblage.* Sixty samples from 8 sites represented this subassemblage (Table 1). Samples from both the wet- and dry-sampling periods were included. This assemblage was characterized by the presence of numerous marine species. The most abundant species were amphipods (6 species) and the polychaete *Euchone limicola* (Table 2). Average abundances of the amphipod *Corophium acherusicum* were inflated due to a large influx in August 1995 at several sites (densities up to 246,880 m-2). They were much less abundant, or absent in previous samples. *A. abdita* was the most commonly collected species (93% of the samples).

Samples from near the EBMUD and CCSF sewage outfalls were classified along with the other Central Bay sites, suggesting very little impact from sewage discharge on the benthos. However, numbers of species and total abundances were elevated at those sites, suggesting moderate impacts (Pearson and Rosenberg 1978).

*Sandy sediment subassemblage.* The 6 samples collected from the RMP site at Red Rock (BC60) represented this subassemblage. That site is a mid-channel location in an area of strong currents and is composed of over 85% sand. That station was inhabited by only four to six species dominated by the polychaete *Heteropodarke heteromorpha* and the amphipod *Grandifoxus grandis*, and characterized by low numbers of species and abundances typical of sandy locations.

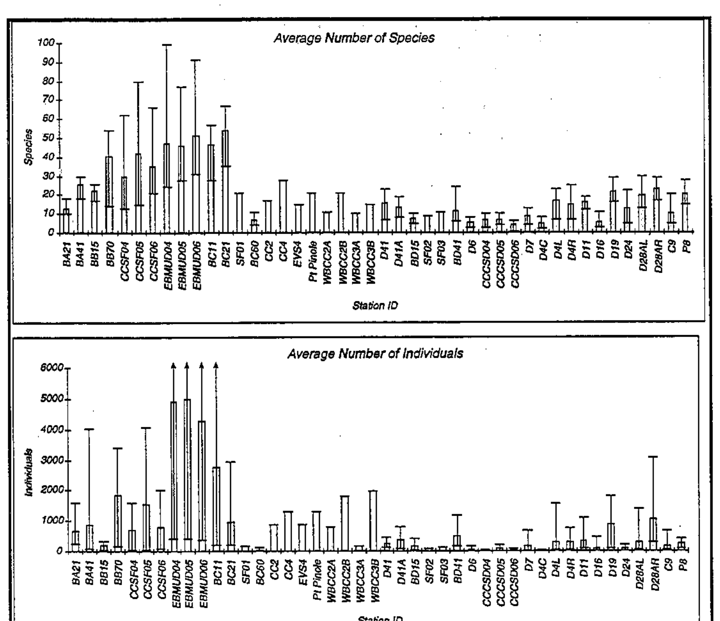


**Figure 2. Average Number of Species and Individuals Sampled from 1994 to 1996**
***Error bars are the range of values.***

## Patterns in Number Of Species and Abundances

Over 354 taxa have been identified in the bay and delta 1994-1996 samples. In general, the numbers of species and total abundances per sample were highest in the Central Bay assemblage and lowest in the estuarine transition subassemblage in Suisun Bay (Figure 2). Reduced numbers of species and abundances were also characteristic of all the sandy sediment subassemblages.

A gradient of increasing numbers of species and total abundances was evident from South Bay into Central Bay. The highest abundances in the Central Bay were due to the influx of the amphipod *C. acherusicum* described above. From Central Bay, "upstream" numbers of species and total abundances remained low through the northern estuary to the Sacramento River then increased slightly into the delta (Figure 2). The very low numbers of species at the estuarine transition sites in Suisun Bay are also of interest. Those sites are within the range of the "mixing zone" which is characterized by dynamic seasonal changes in salinity and turbidity. An obvious hypothesis is that those factors limit assemblage development, but no specific studies have been conducted. To complicate matters, some sediment contaminant concentrations were also elevated in that portion of the estuary. Further study is needed to understand the relationships between the benthos and physical factors at those sites.

## Influence of Physical Factors on Assemblage Distribution and Composition

In attempting to relate benthic data to ambient water and sediment conditions, one of the biggest problems encountered was that important water and sediment physical measurements were not uniformly sampled by all monitoring programs. For example, DWR measures total organic material in sediments and RMP measures total organic carbon; DWR does not measure contamination at their benthic sites, and salinity was not measured at all LEM sites. With that limitation in mind, correlation analysis showed that salinity was the physical variable most highly associated with the first ordination axis scores (a multivariate measure of Assemblage species composition and abundances; Table 3). However, several other variables were also significantly correlated with axis 1 scores, indicating that salinity was not the only influence along axis 1, or that other variables covaried with salinity. Total suspended solids (TSS) was also significantly correlated with axis 1 scores, but the number of sites where TSS was measured was restricted.

There were few strong correlations with axis 2 scores. Besides TSS again, TOC was most highly correlated with axis 2 scores. Axis 3 scores were most highly associated with sediment type. Percent sand, fines, and depth were each significantly correlated with axis 3 scores. Delta outflow, near-bottom water temperature, and DO were not significantly correlated with any of the axis scores.

The correlations shown on Table 3 were interpreted generally to indicate that salinity had the greatest influence on the distribution of the assemblages, and that sediment type (grain-size and organic content) were also important. Based on those analyses, the bay and delta benthic assemblages may be further described by the ranges salinity, sediment type, and TOC measured when the benthos was sampled (Table 4). Therefore, each assemblage and subassemblage has a characteristic set of salinities and sediment types to which the organisms are adapted. The ranges of salinity for the three major assemblages are very near those reported for other estuaries (Boesch 1977).

**Table 3. Rank Correlation Coefficients for Several Abiotic Variables and Ordination Axis Scores**

| Abiotic Variable | n | Axis 1 | Axis 2 | Axis 3 |
|---|---|---|---|---|
| Salinity | 336 | .808** | -.123* | -.072 |
| Temperature | 306 | -.113* | .061 | .074 |
| Depth | 284 | .176** | .164 | -.544** |
| % Sand | 422 | -.062 | -.121* | -.558** |
| % Fines | 422 | .047 | .122* | .555** |
| % Gravel | 422 | .306** | .002 | -.151** |
| TOC | 419 | -.496** | .346** | .390** |
| TSS | 52 | -.572** | -.538** | .550** |
| mERMq | 113 | .431** | .297* | .266** |
| Dflow | 394 | -.009 | -.031 | -.081 |
| O2 | 58 | .112 | -.126 | -.145 |

* significant at α=0.05
** signigicant at α=0.01
TOC = total organic carbon, TSS = total suspended solids
mERMq = a "contamination index", Dflow = delta outflow index

## Discussion and Conclusions

Species composition and abundances of the major benthic assemblages in the bay and delta have been described. However, since not all areas of the estuary have been sampled, other assemblages may exist (e.g., mudflats, south and central bay shoals, delta sloughs, etc.).

The spatial distribution of the fresh-brackish subassemblages changes temporally depending on flow, which affects salinity and sediment-types in the rivers and northern estuary. Some sites (e.g., D4L) were classified into different subassemblage depending on the time sampled. When flows were high and salinities low, the sites were inhabited by more fresh-brackish species. During dry periods when salinities were higher, more estuarine species were collected. Only minor temporal changes in species composition within the estuarine and Central Bay assemblages was observed.

**Table 4. Mean (range) of Key Physical Variables for the Benthic Assemblages in the San Francisco Estuary**

| Assemblage | Salinity | Silt-Clay (%) | TOC (%) |
|---|---|---|---|
| Fresh Brackish (oligohaline) | | | |
| Muddy sediments | 0.68 (0—5.1) | 71.8 (1—100) | 3.86 (.3—21.7) |
| Sandy sediments | 0.08 (0—.1) | 15.3 (0—100) | .74 (.20—2.5) |
| Estuarine transition | 4.9 (0—15.9) | 50.9 (0—100) | 2.05 (.10—3.9) |
| Estuarine (euryhaline) | 16.1 (.1—30.7) | 88.2 (13—100) | 2.63 (.10—5.1) |
| Contaminated | 22.8 (22—24) | 91.8 (67.2—99) | 2.0 (1.1—3.3) |
| Central Bay (stenohaline) | | | |
| Muddy sediments | 27.5 (16.3—33.3) | 73.9 (30—97) | 1.00 (.33—2.22) |
| Sandy sediments | 26.6 (15.6—31.9) | 4.7 (2—7) | .40 (01—.96) |

Understanding responses of the benthos to changes in physical factors will require improved coordination in the measurement of water and sediment physical parameters. All programs need to measure similar suites of physical parameters. The focus of the RMP benthic studies is to define "normal" or reference" benthic conditions for the Central Bay and estuarine assemblages against which suspected contaminated sites may be compared (Thompson et al. 1997). Similar comparisons for the fresh-brackish sites will require sediment contamination to be measured at those sites.

The information summarized in this article has demonstrated the ability to combine information from different monitoring programs to provide an estuary-wide picture of the benthos. Although, each program has somewhat different monitoring objectives, similar collaborations will be necessary for other monitoring components as comprehensive Bay-Delta monitoring is developed.

## Acknowledgments

The taxonomists who identified the specimens were Wayne Fields (Hydrozoology, Newcastle, CA) for the DWR material, and Michael Kellogg, Kathy Langan-Cranford, Patricia McGregor, and Brian Sak (City and County of San Francisco) for the remaining samples. Dr. Bob Smith and Laura Riege (EcoAnalysis, Inc., Ojai) conducted the classification and ordination analysis and provided discussions on interpretation. Sarah Lowe and John Haskins (SFEI) assisted with data and reporting.

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# Metal Trends and Effects in *Potamocorbula amurensis* in North San Francisco Bay

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Trace metals can be an influential variable in ecosystem processes, affecting the well-being of organisms, populations, and communities (Luoma 1996). Metal bioaccumulation in macroinvertebrate tissues is an indicator of metal exposures that can either adversely affect the health of the organism, or be transferred up the food web to affect higher organisms. Bioaccumulation in the bivalve *Potamocorbula amurensis* has been used to assess both the fate and effects of trace metals in San Francisco Bay (Brown and Luoma 1995). The present study began in 1990 and consists of monthly sampling at five sites in northern San Francisco Bay (Figure 1). Four of these are deep water sites in the ship channel: near Chipps Island, near Roe Island, in Carquinez Strait near Martinez, and in San Pablo Bay northeast of Pinole Point. One site is in the shallow water of Honker Bay.

Clams (60-100) are collected at each site and separated into replicate size composites (1mm shell length difference) of 12-15 clams each. Ag, Cd, Cr, Cu, Ni, V, and Zn are measured in the whole soft tissues of the clam. Condition index (mg dry weight for a standard shell length), glycogen content (% tissue dry weight), and reproductive status (Parchaso 1997) are determined monthly to evaluate influences of metals and other environmental factors on the energetics and reproduction in *P. amurensis* as indicators of stress. Surface sediments are collected at the same time and analyzed for metals (Hornberger and Bouse, USGS). Collaborators from UC Davis (Drs. Hinton, Werner, Teh, Clark, Fan, Higashi, Kaufman) are simultaneously studying enzymatic, histopathologic, and biochemical biomarkers in these populations of *P. amurensis* to compare with the trends in contaminants.

Since the beginning of this study, we have observed metal trends over a wide variety of hydrographic regimes. These include three very low flow years (1991, 1992, and 1994) where annual calculated mean delta outflow was less than 220 $m^3sec^{-1}$, and years of moderate to high delta outflow (1993, 1995, 1996, and 1997) where annual mean delta outflow was between 760 - 1710 $m^3sec^{-1}$ (DAYFLOW data). Each of the metals showed slightly different accumulation patterns in *P. amurensis* and thus indicated the variety of factors that control bioaccumulation. Three basic patterns were detected. One pattern indicates that biological regulation of Cu and Zn is an important control on tissue concentrations. The pattern in Cr, Ni, and V tissue concentrations is related to the combined influences of riverine inputs and local industrial inputs. The third pattern in Cd and Ag tissue concentrations is not clearly related to any obvious source, but is linked to patterns in biomarker indicators of metal stress.

Earlier studies (Luoma et al. 1990, Hornberger et al. 1998) showed that Cu contamination increases substantially in the industrialized regions of the Bay-Delta. However, there is no distinct spatial or temporal trend in the tissue concentrations of Cu (or Zn) in *P. amurensis* in the North Bay. Variability in Cu (and Zn) appears to be dominantly controlled by biological processes. Figure 2 shows that, among all times at all sites, the amount of Cu in a 15mm shell length clam is strongly correlated ($r^2$ = 0.53) with the weight of tissue. The same relationship occurs within each site. As animals add (or lose) tissue mass, they add (or lose) Cu. Changes in weight, which occur seasonally and site-to-site, control 53% of the Cu variability in *P. amurensis*. It is known that the bioaccumulation response to environmental Cu and Zn contamination differs among species (Phillips and Rainbow

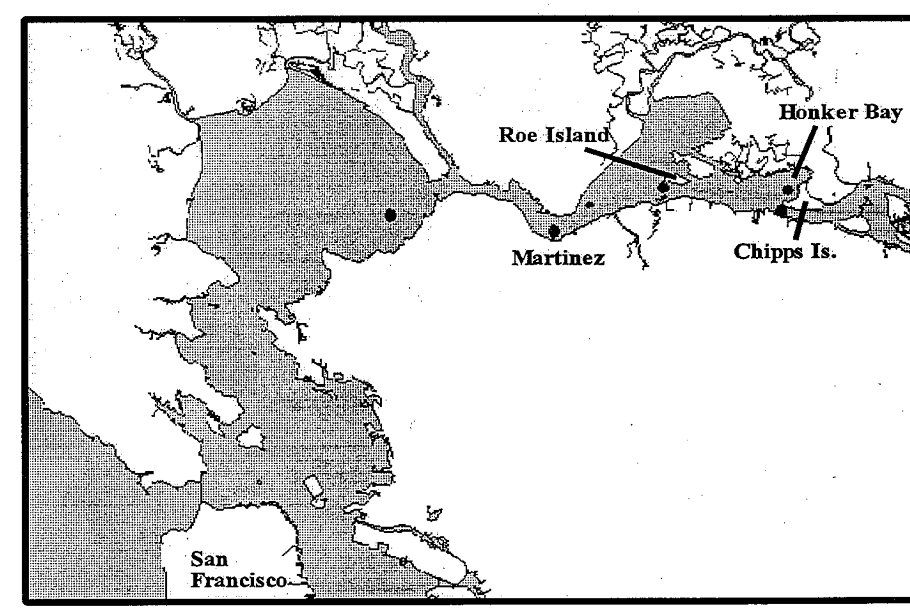


Figure 1. Map of Sampling Sites