NOAA National Status & Trends Bioeffects Program: A Summary of the Magnitude and Effects of Contaminants in the Nation's Coastal Waters

NOAA National Centers for Coastal Ocean Science
Center for Coastal Monitoring and Assessment

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National Oceanic and Atmospheric Administration (NOAA)
National Ocean Service (NOS)
National Centers for Coastal Ocean Science (NCCOS)

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- This document is dedicated to Edward R. Long. (1942-2016) -

Ed was renowned for his many contributions to the field of sediment quality assessment. He developed and applied a variety of empirically based methods for evaluating relationships between sediment chemistry and sediment toxicity. Ed was the first to describe the Sediment Quality Triad, an approach for assessing freshwater, estuarine, and marine sediments that utilizes multiple lines of evidence including results of sediment toxicity tests, benthic invertebrate community surveys, and sediment chemistry. This innovative approach serves as the technical basis for designing and interpreting virtually all of the sediment assessments that have been conducted across the globe over the past 30 years. He was also known for his work on the development of effects-based, empirical Sediment Quality Guidelines (SQGs) for contaminants in marine and estuarine sediments, and systematic evaluations of the predictive ability of these SQGs in marine and estuarine ecosystems. His numerous assessments of sediment quality conditions in marine and estuarine ecosystems on the Atlantic, Gulf, and Pacific coasts represented an essential element of the NOAA National Status and Trends Bioeffects Program, supporting informed decisions on the management of contaminated sediments in the United States. He published over 100 reports and journal articles, with the journal articles alone cited more than 5,000 times. In addition to his scientific work, he was a fearless and successful race-car driver, a sheep farmer, a talented gardener, and avid angler. Ed Long was a great mentor and friend to all he met, with an easy going personality, sharp sense of humor, and a wry grin.

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Introduction

Environmental quality indicators provide resource managers with information to assess coastal habitat condition and make scientifically defensible resource management decisions. The National Oceanic and Atmospheric Administration (NOAA) National Centers for Coastal Ocean Science (NCCOS), through its National Status and Trends (NS&T) Program, provides environmental monitoring and assessment data on chemical, physical, and biological indicators of coastal environments. The NS&T Bioeffects Assessment Program evaluates the health of bays, estuaries, and the coastal zone throughout the nation using the Sediment Quality Triad (SQT) technique (Figure 1). This includes measuring 1) sediment contaminant concentrations, 2) sediment toxicity, and 3) community structure of bottom dwelling organisms. The NS&T Program has conducted sediment bioeffects assessment studies in coastal water bodies since 1991. Results from sediment bioeffects studies in over 20 coastal water bodies and estuaries have been produced and published (Long et al. 1996; Turgeon et al. 1998; Long 2000; Hartwell et al.; 2001, Hartwell and Hameedi 2007; Harmon et al. 2003; Hartwell et al. 2009). NOAA conducts bioeffects studies that are customized to the needs of specific geographical areas of concern.

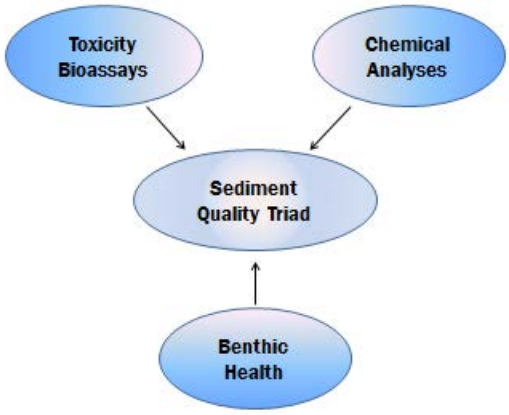

Figure 1. Schematic illustrating the Sediment Quality Triad.

The goal of the NS&T Bioeffects Assessments Program is to quantify the magnitude and extent of contamination that impacts habitat quality. The objectives are to determine the environmental health of coastal and estuarine areas by characterizing incidence and degree of surficial sediment toxicity; determine the spatial patterns or gradients in chemical contamination and toxicity, if any, and determine the association among measures of sediment contamination, toxicity and the benthic macroinvertebrate community structure. Unlike simple trend monitoring, bioeffects assessments address the 'so what' question of whether or not coastal contamination levels are having a deleterious impact on resources important to the public.

Study Design

Bioeffects studies are generally a one-time, intensive sampling effort that may include both stratified random and/or targeted site selection. The study area is first subdivided into strata established in consultation with regional scientists and resource managers, and are based on bathymetric, hydrographic and regional environmental considerations, and previous studies detailing geochemical composition, sediment grain size distribution, organic carbon content, etc. At least three sampling sites within each stratum are established based on stratified-random design, which statistically allows equating sites to determine the spatial extent of sediment toxicity and/or chemical contamination in the study location. This can be done on a stratum-by-stratum basis or over the entire study area. The approach combines the strengths of a stratified design with the random-probabilistic selection of sampling locations, allowing calculation of the percentage of the area that exceed

guidelines. All sites are sampled for chemical analyses, bioassays, and benthic community assessment in as short a time as possible, so the data reflect a snapshot of the condition of the entire system at a point in time.

In brief, field procedures (Apeti et al. 2012) include sampling sediment and the overlying water column. Two sediment samples are taken at each site with a Kynar-coated 0.1 m^2 Young-modified Van Veen grab sampler (Figure 2) and/or a 0.04 m^2 PONAR sampler. Only the upper 2-3 cm of the sediment is retained in order to assure collection of recently deposited materials. The sediment samples are thoroughly homogenized in the field and are subdivided for distribution to various testing laboratories. A second sample is taken for benthic community analysis. The entire contents of the second sample that must be at least 5 cm deep, are sieved on site through 0.5 mm mesh. All organisms are retained and preserved in buffered formalin containing Rose Bengal stain. In instances where the primary site cannot be sampled due to non-accessibility or an unsuitable substratum, a predetermined alternate site(s) is sampled.

Figure 2. A Young-modified Van Veen sediment grab sampler being cleaned between stations.

In addition to the sediment samples, a profile of water quality in the water column is measured to include standard variables such as temperature, depth, salinity, dissolved oxygen, etc. These are important to understanding the distribution of benthic organisms in addition to sediment characteristics. In the oldest studies, only samples for chemical analyses and toxicity were collected. Evaluation of the benthic community began in 1995. Resident organism tissue body burdens analyses began in 2005. In addition, the Bioeffects Program has initiated the collection of larger and more mobile organisms to assess contaminant exposures and impacts relevant to higher trophic levels and sea food safety.

Contaminants

A large variety of contaminants from industrial, agricultural, urban, and marine activities are associated with bottom sediments, including synthetic organic chemicals, polycyclic aromatic hydrocarbons (PAHs), and trace elements. A broad suite of sediment contaminants are analyzed at each station. The list of chemicals analyzed has expanded over time and now includes 58 PAHs, 15 chlorinated pesticides including DDT and its metabolites, 53 polychlorinated biphenyls (PCBs), 14 major and trace elements, and four butyl-tins (Table 1). Other parameters include grain size analysis, total organic/inorganic carbon (TOC/TIC), and percent solids which are important drivers with respect to the distribution of benthic organisms. Trace and major elements are present everywhere because they are naturally occurring elements derived from surface soil and rock. Elevated concentrations may be the result of natural weathering of mineral-rich source rock, volcanic eruptions, or anthropogenic sources such as industrial activity or mining. Many metals are essential micronutrients

at low levels, even some metals that are considered to be toxic at higher exposures. Organisms will absorb metallic elements and attain equilibrium concentrations in their tissues in proportion to their exposure and their depuration processes. Exposure may be by direct contact with environmental media such as sediment or water, ingestion of sediment, or via the food chain. In marine water, many of the metals are chelated by salts or adsorbed by particulates in the water, and free sulfates bind many of the others, all of which will accumulate in local sediment deposits. These sediments may accumulate and become a source of heavy metal contamination in resident organisms, may be dispersed by tidal currents to settle elsewhere, or be diluted to insignificant concentrations.

The organic contaminants assessed in these studies are synthetic chlorinated compounds and PAHs. Most of the chlorinated compounds are synthetic chemicals banned or severely restricted in the U.S. They are of interest due to their persistence, toxicity and tendency to bioaccumulate. PCBs were used in a variety of industrial applications and may have local sources from previous uses and old machinery. Mixtures of PCBs released to the environment proceed through several transformations. The individual congeners will fractionate into different media. Each has a distinct environmental fate and they will accumulate more or less strongly at different sediment depths, in sediments with differing organic content, in different grain size environments, and so on. In addition, they are slowly degraded into compounds with lower chlorination levels. The pesticides are all insecticides used in agriculture and/or domestic applications (e.g. termite eradication). They are all neurotoxins. In addition to the original chemicals, several breakdown products are also measured (e.g. DDT, DDD and DDE), because they are toxic as well.

PAHs are derived from natural and man-made sources. Natural sources include coal, decaying vegetation, and oil seeps. Anthropogenic sources are spilled fuel and crude oil, and burning organic material including fuel, wood or plastics. All of these substances are transported long distances by the atmosphere and on ocean currents. Different classes of organisms have differing ability to metabolize PAHs. Vertebrates can metabolize or conjugate them and excrete them. It is the metabolism of certain compounds (e.g. benzo[a]pyrene) that generates carcinogenic by-products which renders them dangerous to health. Usually, high proportions of low molecular weight PAHs are associated with oil and petroleum releases. A high proportion of high weight PAHs is often linked to combustion by-products and/or long-term weathering. Not all high weight PAHs are indicative of pollution however. For example perylene is a harmless natural by-product of the breakdown of terrestrial plant material.

The last class of contaminants is tri-butyl tin (TBT) and it's degradation by-products di- and mono-butyl tin. TBT was used as an effective boat bottom paint because it is toxic to many invertebrates and algae. However, even at very low concentrations it causes toxicity, endocrine disruption, developmental abnormalities, and imposex (sex reversal) in non-target mollusks and other animals. It can persist in sediment for decades. Increasingly stringent restrictions on it's use were put in place and it was banned entirely by the International Maritime Organization in 2008. However it is still used as an antimicrobial preservative in a variety of materials and in cooling towers.

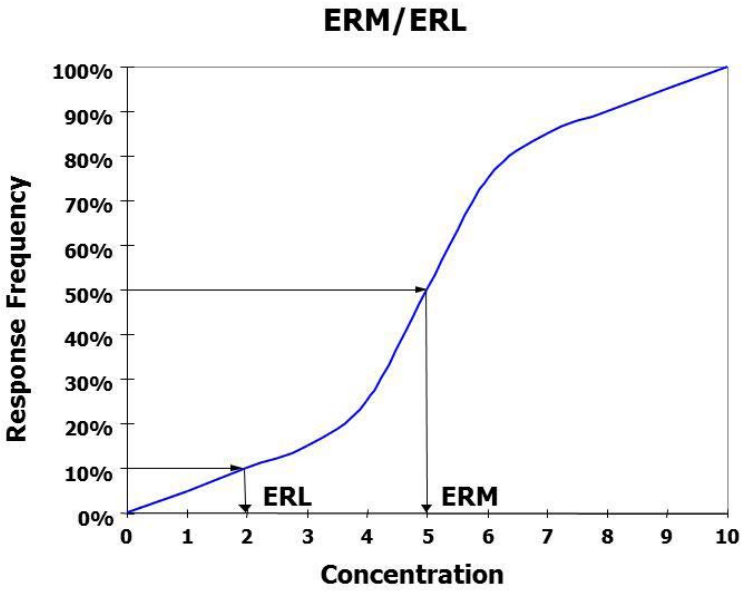

Figure 3. Graphical illustration of the ERL and

Contaminant Guidelines

Numerical sediment quality guidelines (SQG) developed by Long and Morgan (1990) and Long et al. (1995) known as ERM and ERL (effects range-median, effects range-low) express statistically derived levels of contamination, above which toxic effects would be expected to be observed with at least a 50% frequency (ERM), and below which effects were rarely (<10 %) expected (ERL) (Figure 3). Only a subset of the chemicals measured in Bioeffects studies have sufficient data available to calculate a guideline. The ERM quotient (ERM q) (Long et al. 1998) is the ratio of ERM value to sediment concentration for each chemical. This also normalizes the numbers to the same scale such that the relative toxicity of metals can be contrasted to DDT, for example. The mean quotient of the ERMs and observed contaminant concentrations can be calculated on a site by site basis. The calculation includes individual metals, low weight PAHs, high weight PAHs, total PCBs, and total DDT and its metabolites. Individual contaminants seldom occur in the environment by themselves, but are usually found as a mixture. These guidelines can be used to assess extent of contamination and expected degree of impact.

Other parameters have been measured in specific locations. Elevated bacterial loadings of fecal coliform and *Clostridium perfringens* are used as indicators of sewage pollution. In areas where oil pollution is suspected, aliphatic compounds (saturated organic hydrocarbons) plus specific compounds such as hopane, phytane and pristane have been measured to assess the presence or absence of petroleum. In some special studies, measurements of pharmaceuticals and other human related compounds (e.g. nicotine, solvents, current use insecticides) and their by-products were measured to assess urban runoff.

Table 1. List of metals and organic pollutants analyzed by the NS&T program.

Metals			
Ag	Silver	Mn	Manganese
Al	Aluminum	Ni	Nickle
As	Arsenic	Pb	Lead
Cd	Cadmium	Sb	Antimony
Cr	Chromium	Si	Silica
Cu	Copper	Sn	Tin
Fe	Iron	Zn	Zinc
PAHs			**Individual Alkyl Isomers**
Naphthalene	Phenanthrene	C4-Naphthobenzothiophenes	2-Methylnaphthalene
C1-Naphthalenes	C1-Phenanthrenes/Anthracenes	Benz(a)anthracene	1-Methylnaphthalene
C2-Naphthalenes	C2-Phenanthrenes/Anthracenes	Chrysene/Triphenylene	2,6-Dimethylnaphthalene
C3-Naphthalenes	C3-Phenanthrenes/Anthracenes	C1-Chrysenes	1,6,7-Trimethylnaphthalene
C4-Naphthalenes	C4-Phenanthrenes/Anthracenes	C2-Chrysenes	1-Methylfluorene
Benzothiophene	Dibenzothiophene	C3-Chrysenes	4-Methyldibenzothiophene
C1-Benzothiophenes	C1-Dibenzothiophenes	C4-Chrysenes	2/3-Methyldibenzothiophene
C2-Benzothiophenes	C2-Dibenzothiophenes	Benzo(b)fluoranthene	1-Methyldibenzothiophene
C3-Benzothiophenes	C3-Dibenzothiophenes	Benzo(k,j)fluoranthene	3-Methylphenanthrene
C4-Benzothiophenes	C4-Dibenzothiophene	Benzo(a)fluoranthene	2-Methylphenanthrene
Biphenyl	Fluoranthene	Benzo(e)pyrene	2-Methylanthracene
Acenaphthylene	Pyrene	Benzo(a)pyrene	4/9-Methylphenanthrene
Acenaphthene	C1-Fluoranthenes/Pyrenes	Perylene	1-Methylphenanthrene
Dibenzofuran	C2-Fluoranthenes/Pyrenes	Indeno(1,2,3-c,d)pyrene	3,6-Dimethylphenanthrene
Fluorene	C3-Fluoranthenes/Pyrenes	Dibenzo(a,h)anthracene	Retene
C1-Fluorenes	C4-Fluoranthenes/Pyrenes	C1-Dibenzo(a,h)anthracenes	2-Methylfluoranthene
C2-Fluorenes	Naphthobenzothiophene	C2-Dibenzo(a,h)anthracenes	Benzo(b)fluorene
C3-Fluorenes	C1-Naphthobenzothiophenes	C3-Dibenzo(a,h)anthracenes	
Carbazole	C2-Naphthobenzothiophenes	Benzo(g,h,i)perylene	
Anthracene	C3-Naphthobenzothiophenes		
Cyclodienes	**Other Chlorinated Pesticides**		
Aldrin	Alpha-HCH	1,2,3,4-Tetrachlorobenzene	
Dieldrin	Beta-HCH	1,2,4,5-Tetrachlorobenzene	
Endrin	Delta-HCH	Hexachlorobenzene	
Heptachlor	Gamma-HCH	Pentachloroanisole	
Heptachlor-Epoxide	2,4'-DDD	Pentachlorobenzene	
Oxychlordane	4,4'-DDD	Endosulfan II	
Alpha-Chlordane	2,4'-DDE	Endosulfan I	
Gamma-Chlordane	4,4'-DDE	Endosulfan Sulfate	
Trans-Nonachlor	2,4'-DDT	Mirex	
Cis-Nonachlor	4,4'-DDT	Chlorpyrifos	

Table 1. List of metals and organic pollutants analyzed by the NS&T program (cont.).

PCB Congeners			
PCB8/5	PCB66	PCB128	PCB180
PCB18	PCB70	PCB138/160	PCB183
PCB28	PCB74/61	PCB146	PCB187
PCB29	PCB87/115	PCB149/123	PCB194
PCB31	PCB95	PCB151	PCB195/208
PCB44	PCB99	PCB153/132	PCB199
PCB45	PCB101/90	PCB156/171/202	PCB201/157/173
PCB49	PCB105	PCB158	PCB206
PCB52	PCB110/77	PCB170/190	PCB209
PCB56/60	PCB118	PCB174	
Butyl Tins			
Monobutyltin			
Dibutyltin			
Tributyltin			

Benthic Communities

Critical habitats and food chains supporting many estuarine fish and wildlife species include the benthic environment. Soft sediment organisms occupy almost every trophic level in marine ecosystems. Benthic organisms play an important role in the estuarine environment. As major secondary consumers in the estuarine ecosystem, they represent an important link between primary producers and higher trophic levels for both pelagic and detritus-based food webs. Contaminants in the sediments often pose both ecological and human-health risks through degraded habitats, loss of fauna, biomagnification of contaminants in the coastal ecosystem, and human consumption of contaminated fish and wildlife. In many instances, fish consumption advisories are coincident with severely degraded sediments in coastal water bodies. Thus, characterizing sediment quality by describing benthic assemblages and delineating areas of sediment contamination, toxicity and body burdens in higher trophic levels are important information for coastal resource managers. Benthic assemblages are composed of a wide variety of animals (Figure 4), with a variety of reproductive modes, feeding guilds, life history characteristics, and physiological tolerances to environmental stressors, both natural and anthropogenic. Benthic assemblages respond to many stressors such as toxic pollution, eutrophication, sediment quality, habitat modification, and seasonal climate changes. Their composition, abundance, and biomass are also influenced by habitat conditions including salinity and sediment type. Benthic community studies have a long history of use in regional estuarine monitoring programs and have been proven to serve as an effective indicator for describing the extent and magnitude of pollution impacts in estuarine ecosystems, as well as for assessing

Figure 4. A large polychaete worm is an example of benthic infauna.

the effectiveness of management actions. Because they are relatively immobile, benthic communities are good indicators of habitat condition as they must integrate all the various stressors in a habitat. They are like the Canary in the mine shaft. Impacts of organic enrichment on marine benthos have shown that total biomass, relative proportion of deposit feeders, and abundance of species with 'opportunistic' life histories (e.g. high fecundity, short generation time, and rapid dispersal) increase. Some opportunistic taxonomic groups are known to be tolerant of chemical toxicants. Others are capable of thriving in physically disturbed habitats (e.g. high sedimentation, dredging operations, etc.) but not necessarily in contaminated areas. Other taxa respond negatively to both toxicants and excessive organic enrichment. The response of specific species to organic and toxic contamination is mediated by life history and feeding mode characteristics.

Toxicity Testing

Sediment contamination is a major environmental issue because of its potential toxic effects on biological resources. NS&T uses a suite of standard sediment toxicity tests to assess different modes of contaminant exposure to a variety of species and different assessment end-points. Typically, the amphipod test (bulk sediment, animal mortality test) (Figure 5), the sea urchin fertilization impairment and larval development impairment tests (pore water, reproductive impairment tests), the Microtox^{R} test (sediment extract, depressed bioluminescent response indicating metabolic impairment), and, in recent years, a Human Reporter Gene System (HRGS) P450 test (sediment extract, increased biochemical response indicating exposure to PAHs, PCBs and/or dioxins) were used in the study areas. Not all tests were run in all studies. Because biological systems are inherently variable, and biological effects of contaminants occur at different levels of biological organization, i.e., from cells to ecosystems, the test results can be ambiguous. Results from a suite of toxicity tests are used in the "weight of evidence" context to infer the incidence and severity of environmental toxicity.

For the amphipod and sea urchin tests, two levels of effect were used to declare test results to indicate toxicity: the test results were statistically lower than in the control, and second, the sample's mean response was also less than 20% of the control. These thresholds are referred to as demonstrating low or moderate toxicity, and demonstrating high toxicity, respectively. For the Microtox^{R} results, sample response significantly below

Figure 5. An amphipod, whole sediment toxicity bioassay in progress.

the controls indicated moderate toxicity. Samples with response significantly below a spiked standard were considered highly toxic. There are no clearly defined assessment end-points for P450 induction that signify a threshold of biological damage, and statistical procedures were employed to arrive at decision points. Based on a large data base, the lower statistical threshold of observed effect, or the minimal (background) level is approximately 12 expressed as mg Benzo[a]Pyrene/kg equivalents (B[a]P Eq) (that is, the same response as seen in a standard dilution series assay to 12mg/kg B[a]P). This is consistent with data from pristine sites in Alaska and California (Fairey et al. 1996). Based on field data, HRGS P450 values above 60 mg B[a]P Eq/kg were correlated with degraded benthic communities in San Diego and Mission Bays and is used as the threshold for the highly toxic threshold.

Synopsis

The following chapters are summaries of the technical documents produced over the course of the Bioeffects program since 1985. Each chapter addresses one specific study location. They all follow the same format for ease of comparison and consistent treatment of the information. A list of relevant technical documents which are much more detailed is also provided in the Appendix. The final chapter provides examples of information on a broader scale that use of the Bioeffects data base enables. These range from regional comparisons, to coast-wide, to national in scale.

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Chapter 1
Boston Harbor

1. STUDY AREA DESCRIPTION

Boston Harbor, Massachusetts, is an urbanized bay in the northeastern U.S., surrounded by the city of Boston and its outlying communities. The Boston metropolitan area ranked 10th in the nation in population in 2007, with an estimated population of 4.5 million people. The 108 km^2 waterbody consists of the harbor and several smaller coastal embayments with an average depth of 6.5 m (Figure 1a). At 29 ppt, Harbor salinities are vertically homogeneous and similar to salinities throughout the Gulf of Maine. Average tidal range is 3.5 m, and average residence time is 4–7 days. Freshwater inflow is dominated by the Neponset River and circulation is strongly affected by tidal influences and nontidal surface currents. Two large channels, President Roads and Nantasket Roads, connect the Harbor to Massachusetts Bay. Boston Harbor is also home to the Boston Harbor Islands National Park, which consists of 34 islands located around the greater Boston shoreline. Boston Harbor is an enriched coastal bay that has recently experienced a large, rapid reduction in wastewater loadings. The Harbor received wastewater treatment plant (WWTP) discharges off Deer Island from metropolitan Boston until 2000 when these discharges were diverted 15 km offshore for diffusion into the bottom-waters of Massachusetts Bay ending more than a century of direct WWTP discharges to the bay. While previous studies showed pathogen and toxic substance contamination of water, sediments and

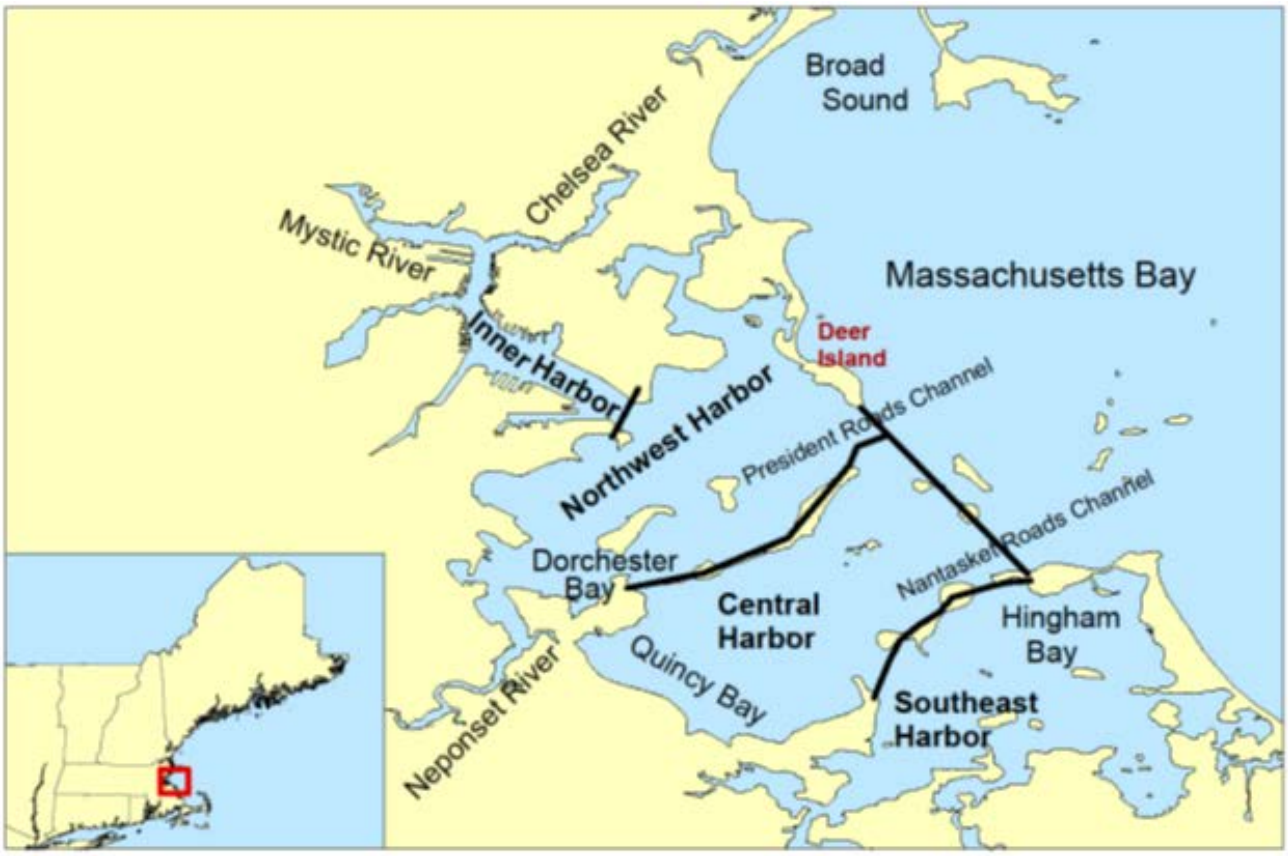


Figure 1a: Boston Harbor study area. The study area included the four major regions of Boston Harbor: (1) the inner harbor (including the lower Chelsea and Mystic rivers), (2) northwest harbor (including the Winthrop basin and Dorchester Bay), (3) central harbor (including Quincy Bay and Nantasket Roads), and (4) southeast harbor (including Hingham Bay

resident biota and many exceedances of sediment toxicity thresholds, sediment quality has improved. Thus tests on current sediments would be expected to show the most severe toxicity in the inner harbor and least severe in the southeast harbor, away from the previous point of discharge.

Sampling details

In 1993 a survey of the toxicity of sediments throughout Boston Harbor and vicinity was conducted to determine the magnitude and spatial extent of toxicity and the relationship between measures of toxicity and the concentrations of chemical toxicants in the sediments. Surficial sediments were collected from 55 stations in 19 strata throughout the Harbor (Figure 1b). The survey area covered approximately 57 km^2. Four toxicity bioassays were performed including: an amphipod survival test performed with whole sediments, a microbial bioluminescence test performed with organic solvent extracts of the sediments, and sea urchin fertilization and embryological development tests performed with the pore waters extracted from the sediments. These tests were chosen because they were consistent with the tests used in similar surveys performed elsewhere in the U.S. and they provide complementary but not duplicative information on toxicity. The results of these tests often are highly correlated with gradients in toxicant concentrations, and they are known to be dose-responsive to the kinds of toxicants commonly found in urban bays, such as Boston Harbor. Samples from these stations were also analyzed chemically for a broad suite of potentially toxic contaminants, including heavy metals, polynuclear aromatic hydrocarbons (PAHs), chlorinated pesticides and polychlorinated biphenyls (PCBs).

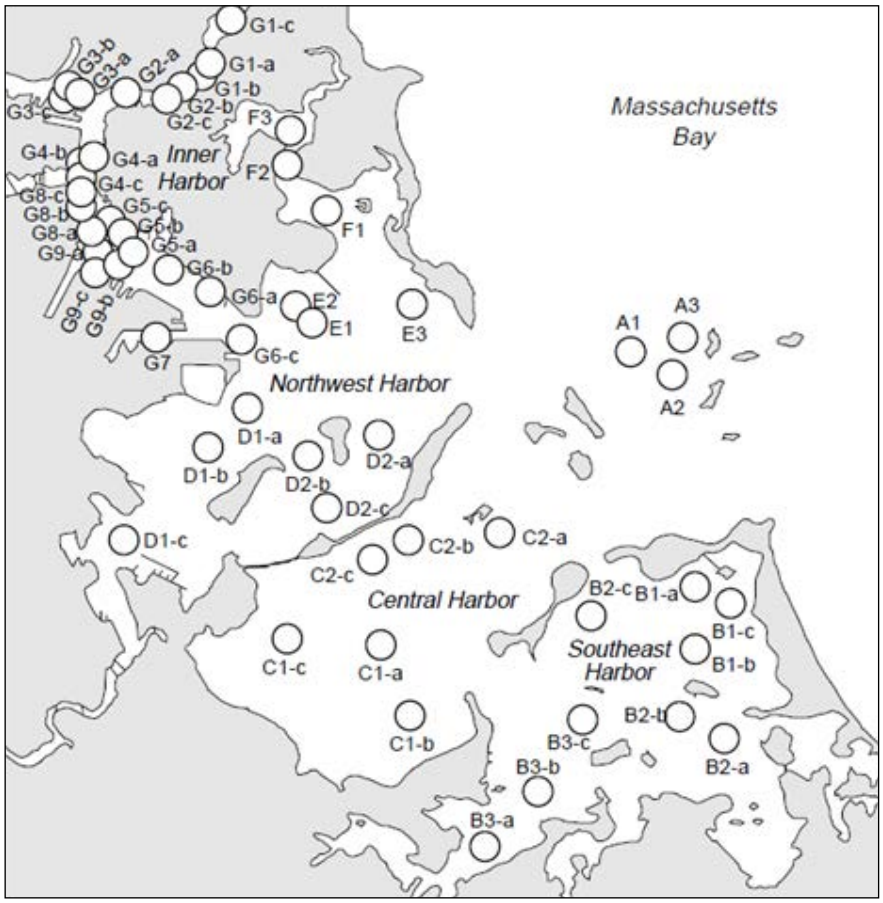


Figure 1b: Boston Harbor study area showing the 55 sampling locations.

2. RESULTS

2.1 Important Physical Drivers

Freshwater inflow to Boston Harbor is dominated by the Neponset River. Salinity is vertically homogeneous throughout the bay. Circulation is strongly affected by tidal influences and nontidal surface currents that together with counterclockwise circulation focus sediment deposition in the inner harbor. The bathymetry and geochemistry of the sediments have been documented and the patterns in the deposition of fine-grained materials have been shown to influence the distribution of toxicants.

2.2 Contamination Results

Overall, the concentrations of most potentially toxic contaminants were highest in the inner harbor, followed by the northwest harbor. For most chemicals, the concentrations were lowest in the southeast harbor and near the mouth of the harbor (e.g. for mercury and total PCBs, Figures 2, 3). Table 1 provides a summary of means, standard deviations, medians, ranges, and number of samples (count) for mercury concentrations (ppm) in surficial sediments for Boston Harbor and the four regions of the Harbor, based on all the available data sets. Maximum and mean concentrations usually paralleled each other and many of the maxima exceeded the respective ERM values by a considerable amount. MacDonald (1991) concluded that the contaminants of most toxicological concern included silver, chromium, mercury, and PCBs, followed by copper, lead, zinc, DDT and PAHs. Cadmium, arsenic, and nickel appear to be of less concern, since they rarely exceeded concentrations frequently associated with toxicity.

2.3 Toxicity Results

Toxicity was apparent throughout all regions of the study area with highest incidence of toxicity in portions of the inner harbor where chemical concentrations were the highest. Toxicity diminished beyond the entrance to the inner harbor. However, some of the inner harbor samples were not toxic and one sample each from central harbor and northwest harbor were the most toxic of the 55 samples tested. A cumulative toxicity index was calculated as the sum of percent amphipod survival, percent sea urchin fertilization (in 100% pore water), and percent sea urchin normal development (in 25% pore water). This index was formulated with the results of the tests performed with only the invertebrates and excluded the Microtox^{R} test results, since the animal bioassays were viewed in this survey as a test of potential toxicity. The index had a possible range of values of 0.0 to over 300. Since the data for all three of these endpoints usually are significant when test results are less than 80% of control values, a cumulative score of less than 240 was used as a critical value. Toxicity was lowest in portions of northwest harbor, central harbor, southeast harbor, and in an area beyond the entrance to Boston Harbor.

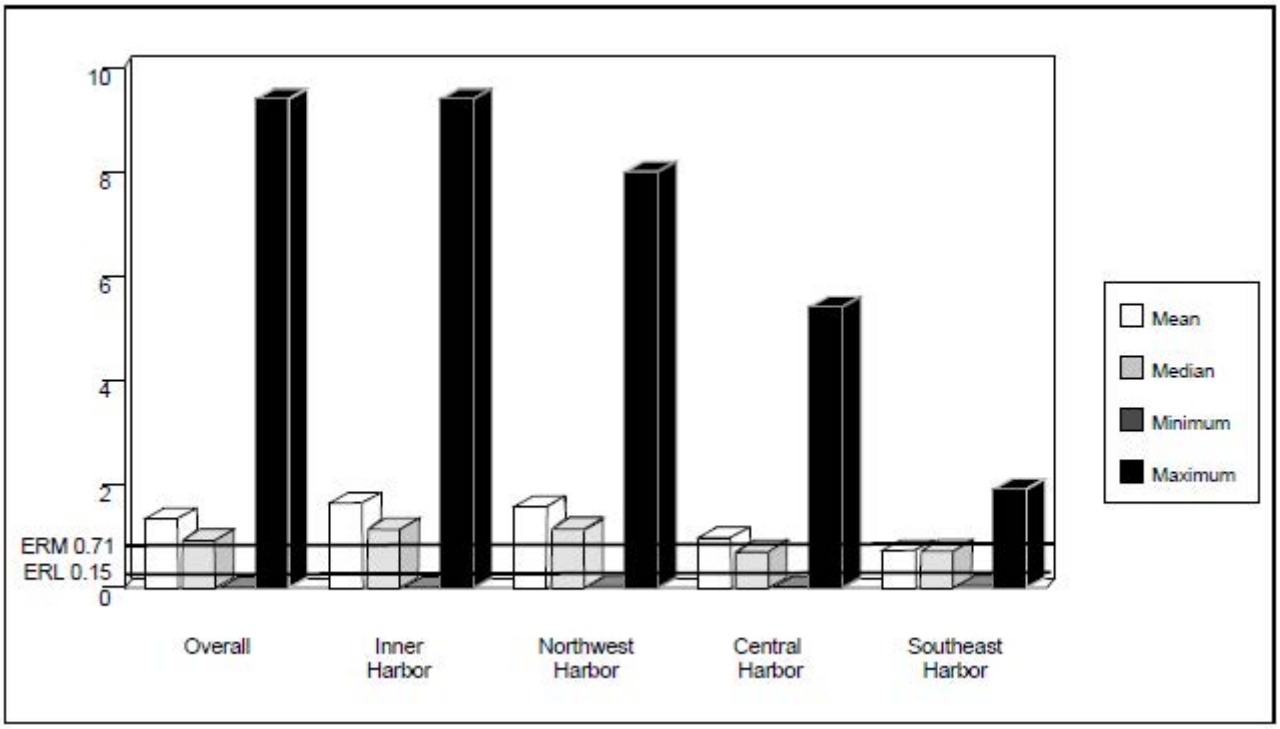


Figure 2: A comparison of the mean, median, minimum and maximum concentrations of mercury (ppm) in Boston Harbor with (Effects Range Low) ERL (0.15 ppm) and (Effects Range Median) ERM (0.71 ppm) values for mercury from Long et al. 1995).

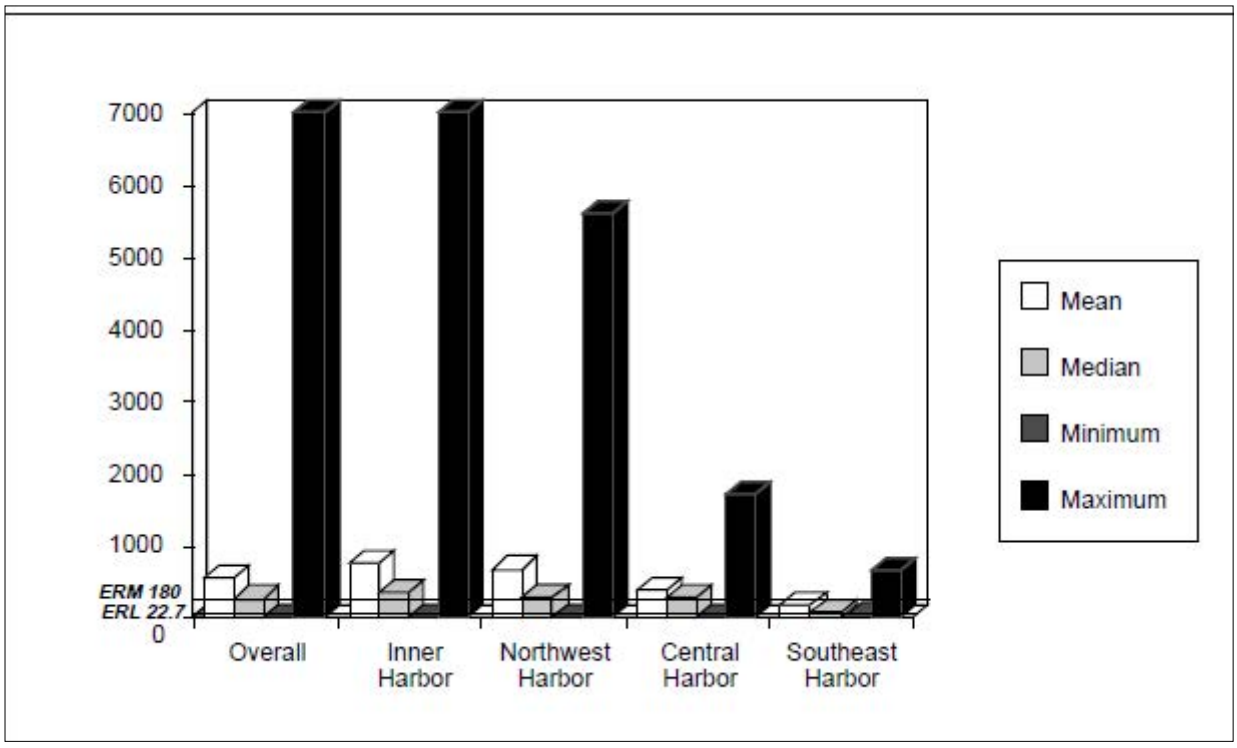


Figure 3: A comparison of the mean, median, minimum and maximum concentrations of total PCBs (ppb) in Boston Harbor from MacDonald (1991), with the (Effects Range Low) ERL (22.7 ppb) and (Effects Range Median) ERM (180 ppb) values for tPCBs (from Long et. al., 1995). These data exclude one sample with 51,000 ppb tPCB.

The sea urchin test of embryological development was most sensitive, indicating significant toxicity in all 55 samples of 100% pore water. This test, was highly sensitive, but it was not discriminatory, since all samples were identified as toxic. Tests performed with 25% pore water were less sensitive but they identified more clearly the differences in toxicity among samples (Table 2).

Table 1: Means, standard deviations, medians, ranges, and number of samples (count) for mercury concentrations (ppm) in surficial sediments for all of Boston Harbor and the four regions of the Harbor, based on all the available data sets.

	Mean	Standard Deviation	Median	Range	Count
OVERALL	1.33	1.34	0.92	0.006-9.40	433
INNER HARBOR	1.62	1.60	1.12	0.009-9.40	113
NORTHWEST HARBOR	1.56	1.39	1.15	0.026-8.00	167
CENTRAL HARBOR	0.96	1.08	0.69	0.006-5.40	90
SOUTHEAST HARBOR	0.71	0.49	0.70	0.040-1.90	63

Table 2: Estimates of the spatial extent of sediment toxicity (km^2 and percent of total area) in Boston Harbor based upon cumulative distribution functions of data from each test/dilution (critical value was <80% of controls).

Toxicity Test	Kilometer^2	% of Total	95% C.I.
Sea urchin development			
@ 100% pore water	56.8	100	n/a
@ 50% pore water	51.7	91.0	16.4
@ 25% pore water	27.2	47.9	34.8
Sea Urchin fertilization			
@ 100% pore water	3.8	6.6	11.3
@ 50% pore water	0.0	0.0	n/a
@ 25% pore water	0.0	0.0	n/a
Microbial bioluminescence	25.5	44.9	17.6
Amphipod survival	5.7	10.0	12.0
Total survey area: 56.8 km^2			

The microbial bioluminescence test was the next most sensitive, indicating toxicity (i.e., significant differences from controls) in 30 of the 55 samples. Microtox® tests were performed with organic extracts of the sediments. This is a test of the relative toxicity of extracts of the sediments, and, therefore, it is relatively

immune to the effects of environmental factors such as grain size and organic carbon. In the amphipod survival tests, 12 samples were significantly different from controls and six samples were highly toxic. The amphipod tests are the most widely and frequently used assays in sediment evaluations performed in North America. They are performed with adult crustaceans exposed to relatively unaltered, bulk sediments. *Ampelisca abdita* has shown relatively little sensitivity to environmental factors such as grain size and organic carbon. In the tests of sea urchin fertilization, only two of the samples were significantly toxic, one of which was highly toxic. The sensitivity of this test may have been reduced by a less than optimal sperm/egg ratio.

As expected, based upon the chemical data, many of the samples collected in the inner harbor were highly toxic in at least one of the tests. Except for the two sea urchin tests, the correlations among the different toxicity tests were not significant.

The estimates of the spatial extent of toxicity ranged widely depending upon the sensitivity of the four individual tests. The estimates of the extent of toxicity in the sea urchin development, microbial bioluminescence, amphipod survival, and sea urchin fertilization tests were 100%, 44.9%, 10.0%, and 6.6%, respectively (Table 2).

2.4 Benthic Infaunal Results

No benthic infaunal samples were collected in this study.

2.5 Correlations

Four different sequential steps were taken to identify toxicity/ chemistry relationships: (1) the single- chemical Spearman rank correlations, (2) the tallies of the number of ERM exceedances, (3) the ratios in average chemical concentrations between non-toxic and highly toxic samples, and (4) the ratios in average concentrations in highly toxic samples and respective sediment quality guideline values. Chemicals that showed the strongest concordance with the measures of toxicity and most likely contributed to toxicity included PCBs, chlorinated pesticides, PAHs, several trace metals, and ammonia (Table 3). It is also highly likely that other substances not measured in the chemical analyses, may have contributed to or caused toxicity in some samples. The data suggest that complex mixtures of toxic substances in the sediments contributed to the observed toxicity.

Statistical correlations between toxicity and concentrations of anthropogenic contaminants were strongest with the results of the Microtox® tests. The Microtox® test showed strong associations with numerous organic compounds as well as many trace metals. Microbial bioluminescence in organic solvent extracts was significantly correlated with nearly all of the trace metals, all of the grain size parameters, the ratio of simultaneously extracted metals and acid-volatile sulfide (SEM/AVS; metal concentrations that are found in an acid wash of the sediment strong enough to extract sulfides) , and with tetrabutyl tin. The correlations with silver, AVS, SEM/AVS ratios, and percent sand were particularly strong. These data suggest that microbial bioluminescence decreased with increasing metals concentrations, increasing percent fine sediments,

increasing AVS concentrations, and decreasing sand content. There were no significant correlations with concentrations of lead, manganese, or total SEM. Microbial bioluminescence was not significantly correlated with any individual PAHs, classes of PAHs, or sums of individual PAHs. In the tests of sea urchin fertilization there were no significant negative correlations with any of the individual bulk metals, organo-tins, or grain size parameters. However, fertilization success in 50% pore water was significantly correlated with SEM/AVS ratios (Rho = - 0.417, $p<0.05$). This correlative pattern was not observed in the tests of 100% or 25% pore water. Many of the correlation coefficients for amphipod survival and microbial bioluminescence had positive signs. None of the metals, organo-tins, or grain size parameters were negatively correlated with urchin embryo development, however, there was a significant positive correlation with percent sand.

Amphipod survival was not significantly correlated with any individual PAHs, classes of PAHs, or sums of individual PAHs. However, all but two of the correlation coefficients had negative signs, indicating a pattern of decreasing amphipod survival with increasing PAH concentrations.

3. SUMMARY

Results of chemical analyses indicated a consistent spatial pattern among the different chemicals and chemical groups: relatively high concentrations in the inner harbor, intermediate in the northwest and central harbors, and lowest in the southeast harbor and outside the harbor entrance. These results are consistent with locations of fine grained sediments. The concentrations of 17 contaminants either equaled or exceeded respective sediment quality guidelines in at least one sample. The concentrations of many contaminants were highly correlated with each other, indicating a strong pattern of co-variance among the different substances.

Toxicity in the 4 bioassay tests was most likely driven by complex mixtures of contaminants in the sediments, not by any single substance or class of chemicals. The chemical substances that most likely contributed to toxicity included the PCBs, chlorinated pesticides, PAHs, several trace metals, and ammonia. A toxicity identification evaluation procedure would be required to specifically identify which chemical(s) caused the observed toxicity.

The chemical contaminant data showed that 66.7% of the study area was above the Effects Range Low threshold and 16.7% of the total area was above the Effects Range Median (ERM). The contaminants of most toxicological concern included silver, chromium, mercury, and PCBs, followed by copper, lead, zinc, DDT and PAHs. Overall, the incidence of toxicity was highest in samples from the inner harbor, however, samples collected throughout the entire survey area were toxic in one or more of the end-points. Also, several samples within the inner harbor and lower Mystic River were decidedly non-toxic in these tests. A sample from the central harbor was the most toxic of the 55 samples tested. Toxicity diminished noticeably beyond the entrance to the inner harbor channel. However, there was an apparent pattern of relatively high toxicity down the axis of the harbor. Overall, toxicity was lowest in portions of northwest harbor, central harbor, and southeast harbor, and in the area sampled beyond the harbor entrance.

The survey area was estimated to cover approximately 56.8 km^2. Based upon the distribution functions of the data, each of the tests provided different estimates of the spatial extent of toxicity ranging from 0 – 100%. In the amphipod and Microtox^R tests, approximately 10% and 45%, respectively, of the area was estimated as toxic (i.e., test results were less than 80% of controls). In the sea urchin fertilization and embryological tests of 100% pore water, 6.6% and 100% of the area, respectively, was estimated as toxic. It was apparent from the chemical data that no single substance was the cause of toxicity in these samples. None of the individual anthropogenic substances that were quantified were strongly correlated with amphipod survival, sea urchin fertilization success or sea urchin embryological development.

Table 3: Spearman rank correlation coefficients (Rho, corrected for ties) for amphipod survival and microbial bioluminescence versus ammonia and trace metals concentrations (n=30). Higher values indicate stronger relationships with negative numbers indicative of decreasing survival or increasing negative impact with increasing contaminant concentrations. . (ns – not significant: * – statistically significant)

	Percent amphipod survival		Microbial bioluminescence	
Unionized NH3/Day 0	+0.151	ns		
Unionized NH3/day 4	+0.049	ns		
Unionized NH3/day 8	-0.144	ns		
Tetrabutyltin	-0.197	ns	-0.387	*
Tributyltin	-0.160	ns	-0.204	ns
Dibutyltin	-0.111	ns	-0.200	ns
Monobutyltin	+0.014	ns	-0.335	ns
Total butyltins	-0.153	ns	-0.219	ns
Ag	+0.210	ns	-0.629	**
Hg	+0.143	ns	-0.421	*
As	-0.068	ns	-0.490	*
Cd	-0.132	ns	-0.555	*
Cu	-0.005	ns	-0.565	*
Ni	+0.146	ns	-0.592	*
Pb	-0.165	ns	-0.296	ns
Se	+0.060	ns	-0.583	*
Sn	-0.007	ns	-0.394	*
Zn	-0.233	ns	-0.409	*
Cr	-0.189	ns	-0.386	*
Mn	+0.137	ns	-0.351	ns
Al	+0.248	ns	-0.569	*
Fe	+0.152	ns	-0.560	*
AVS	+0.213	ns	-0.669	**
Total SEM	-0.339	ns	-0.209	ns
SEM/AVS	-0.346	ns	+0.609	**
% SAND	-0.407	*	+0.701	**
% SILT	+0.359	ns	-0.607	**
% CLAY	+0.280	ns	-0.592	*
% TOC	-0.006	ns	-0.561	*

Chapter 2
Massachusetts Bay

1. STUDY AREA DESCRIPTION

2.

Massachusetts Bay is a large semi-enclosed coastal bay (768 km^2) that extends from the outer limit of Boston Harbor to the western boundary of the Gulf of Maine bounded by Stellwagen Bank National Marine Sanctuary (Figure 1). The Bay includes smaller coastal embayments, such as Gloucester Harbor and Nahant Bay. It is roughly 100 km long, 50 km wide, and has an average depth of 35 m. In most of the Bay, the flow-through flushing time for the surface waters ranges from 20 to 45 days. Tidal height is 2.7 m near Beverly Harbor in the northwest corner of the Bay.

Bay waters at 29 practical salinity units (psu) reflect salinities throughout the Gulf of Maine. The water column is well mixed from November through March and becomes density stratified in April and May when fresh water runoff is greatest from the spring snow melt. Thermal stratification develops in June through August and transitions to a well-mixed water column starting in September as water cools along with seasonal air temperatures. Circulation is strongly influenced by tides and nontidal surface currents. During much of the year, a weak counterclockwise circulation persists in Massachusetts Bay, driven by the southeastward coastal current from the Gulf of Maine; this flow pattern may reverse in the fall.

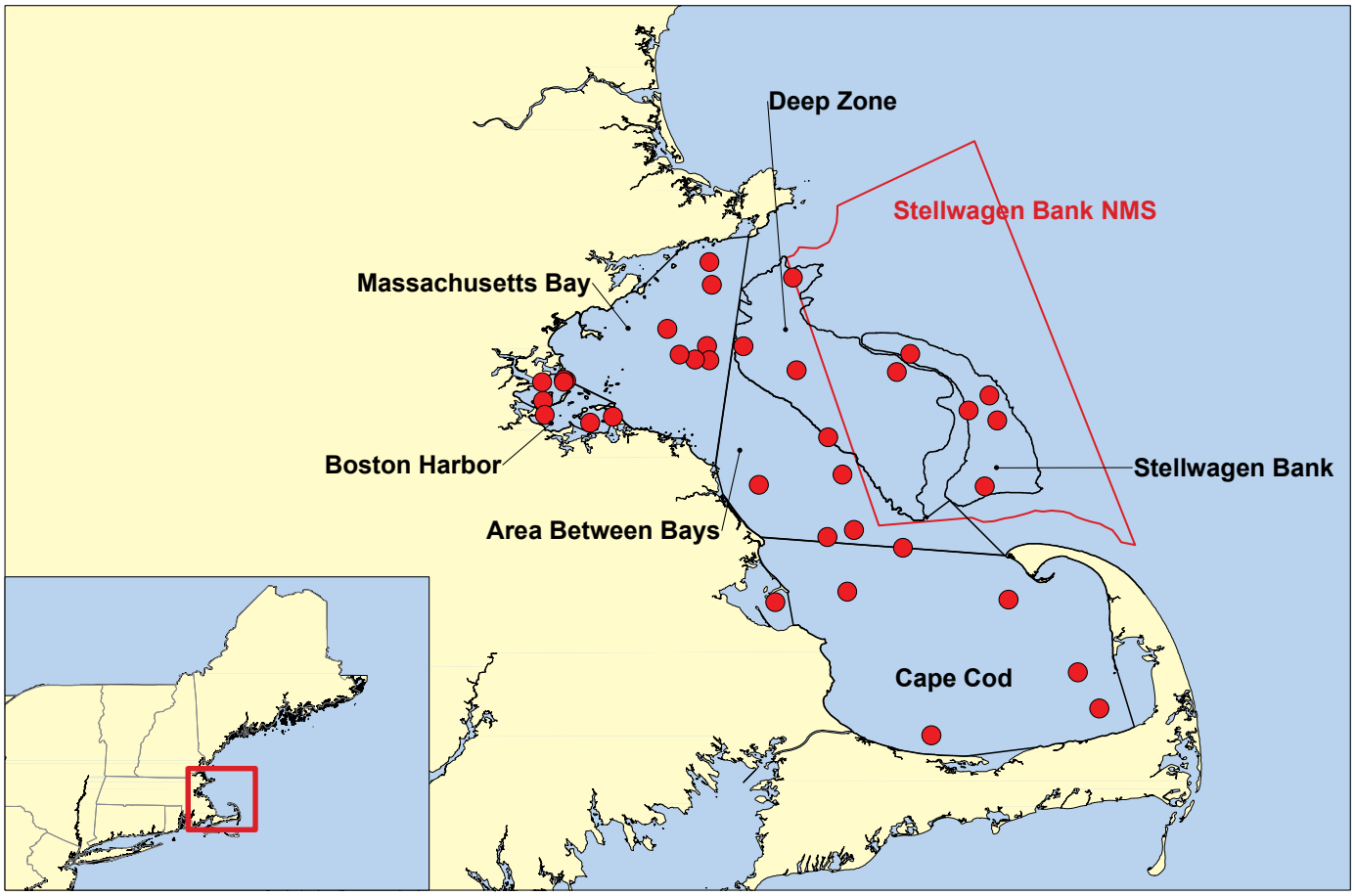


Figure 1: Sampling sites within the Massachusetts Bay study area and neighboring Boston Harbor, Cape Cod, and Stellwagen Bank.

Sampling Details

Sediment samples for chemical and benthic community analysis were collected at 33 sites (Figure 1). Toxicity bioassay samples were not collected. Only the upper 2-3 cm of the sediment was retained in order to assure collection of recently deposited materials and a second sample was taken at each site for benthic community analysis.

A broad suite of sediment contaminants were analyzed at each station, including 59 polycyclic aromatic hydrocarbons (PAHs), 15 chlorinated pesticides including DDT and its metabolites, 25 polychlorinated biphenyls (PCBs), 13 trace elements, and butyltins. Other parameters included grain size analysis, total organic/inorganic carbon (TOC/TIC), and percent solids.

Quantitative benthic community characterizations included enumeration of density (no. individuals per m^2), species richness (number represented at a site), evenness (Pielou's Index J'), and diversity (Shannon-Weiner Index), followed by pattern and classification analysis for delineation of taxa assemblages. Multivariate cluster analysis was employed to group site and species data.

Analyses were conducted to assess the temporal and spatial trends in contaminant concentrations (if any) in the region that may have implications for the Stellwagen Bank National Marine Sanctuary. Data include tissue body burden data for winter flounder (*Pleuronectes americanus*). Stations at near and far field were sampled for the purpose of assessing potential impacts from the POTW sewage outfall in Massachusetts Bay.

2. RESULTS

2.1 Important Physical Drivers

Internal waves are waves that occur at the interface between two water layers of differing densities, typically occurring when seasonally stratified water is forced over abrupt topographic features such as banks or ledges. These occur in the Massachusetts Bay in May through October when the water column is stratified. The internal waves disappear as they approach shallow water (25-40m) due to bottom attenuation. These waves can push surface chlorophyll and warmer surface waters downward resulting in higher benthic production. The downward movement of the water may also transport passively dispersed benthic invertebrate larvae and fish from surface to deeper waters and have additional benthic impacts by re-suspending bottom sediments.

Massachusetts Bay and adjacent waterbodies (i.e. Stellwagen Basin, Boston Harbor, Cape Cod Bay) are long-term sinks for fine-grained sediments and associated contaminants from all sources in the region. However, bottom deposits on the western shore of Massachusetts Bay are gravel, coarse sands, and bedrock. Fine sediments do not accumulate there because storm currents resuspend and displace them. Surficial sediment in Stellwagen Basin, Boston Harbor and Massachusetts Bay are composed of heterogeneous

materials with about 40% sand, 30% silt, and 20% clay. Bottom sediment texture characterization is important since fine grained sediments are typically found in depositional areas, contain more organic carbon, and accumulate higher concentrations of contaminants. Sample sites with coarser grained sediments are expected to have lower contaminant concentration levels compared to muddier (high silt and clay content) sites. Total organic carbon averaged 2.4% and varied widely from 8.5% in Boston Harbor to less than 0.1% on Stellwagen Bank. Spearman Rank correlation analysis on log10 normalized data shows that in general, contaminant concentrations were positively correlated with total organic carbon and fine grain sediment (silt and clay) and negatively correlated with sand content of the sediment.

2.2 *Contamination Results*

Spatial comparisons: Metal and organic contaminant concentrations were found to be significantly higher in sediments collected in and around Boston Harbor than in all other strata, including Massachusetts Bay (Figure 2). Intermediate concentrations were found in the middle and deeper areas of Massachusetts and Cape Cod Bays. The lowest contaminant concentrations were consistently found in the Stellwagen Bank sites, furthest from discharge sources. Contaminant data from the 2004 sampling effort are consistent with historical data with similar spatial distribution patterns found in the 1984-1991 data set. For most metal and organic contaminants, one-way ANOVA on the older Bioeffects and National Benthic Surveillance sediment data demonstrated that sites in Boston Harbor had the highest contaminant concentrations compared to the Salem Harbor and Plymouth, reference sites which are located north and south of Boston, respectively. There were 11 contaminants that exceeded the ERL (Effects Range Low) and 1 contaminant that exceeded the ERM (Effects Range Median) in Massachusetts Bay which was low compared to Boston Harbor (51 > ERL, 1> ERM) but higher than Stellwagen Bank (0 > ERL, 0 > ERM) stations.

When considered over the total area of Massachusetts Bay (excluding the Deep Bay), contaminant concentrations were above the ERL threshold in 36.4% of the area and above the ERM threshold in 1.5% of the area.

Temporal comparisons: While comparison of previous (1984-1993) and current (2004) data revealed that, in general, contaminant concentrations in the earlier sediment samples were somewhat higher than in current sediment samples, the differences were not significant. In Boston Harbor, contaminant concentrations in the past were somewhat higher than current levels but the data are highly variable. Within the range of variability, the data indicated either static or slowly declining levels, depending on the specific chemical. Overall, although the data show some slight declines, there are no significant differences between the old and current sediment data. Data from offshore samples also indicated that there was little difference in contaminant concentrations over time. Within the limited time of the existence of the offshore POTW discharge (2000-2004), this comparison suggest no pollution transfer from the opening of the new outfall, beyond that which was already being exported from Boston Harbor to Massachusetts Bay by existing physical transport processes. The Massachusetts Water Resources Authority (MWRA) and NOAA datasets

both indicated that in general, there was little difference in contaminant concentrations within the paired data sets.

Tissue concentrations: Temporal trends in tissue body burden from current and past tissue liver chemistry and the MWRA data from Massachusetts Bay are highly variable over time, and patterns are site specific. There were no statistically significant declines for any contaminant. For most trace elements variability is high, thus trends are not evident. Lead residue, which is considered a success story for pollution control due to its removal from gasoline, while lower than observed in the 1980s still shows high variability over time. Other trace elements such as Hg and Cd do not appear to have declined over time. Overall, persistent, chlorinated compounds that have been banned for decades show slowly declining concentrations. This attests to their persistence in the environment and suggests that there are still large reservoirs in the watershed and sediment deposits within the region that continue to release contaminants to the wider environment. Other contaminants do not show declining concentrations, likely the reflection of a balance between declines due to pollution control measures and increased in discharge due to increasing population pressure.

Overall, tissue contaminant concentrations were higher in organisms collected in and around Boston Harbor than those from remote sites, with intermediate concentrations in the Massachusetts Bay area

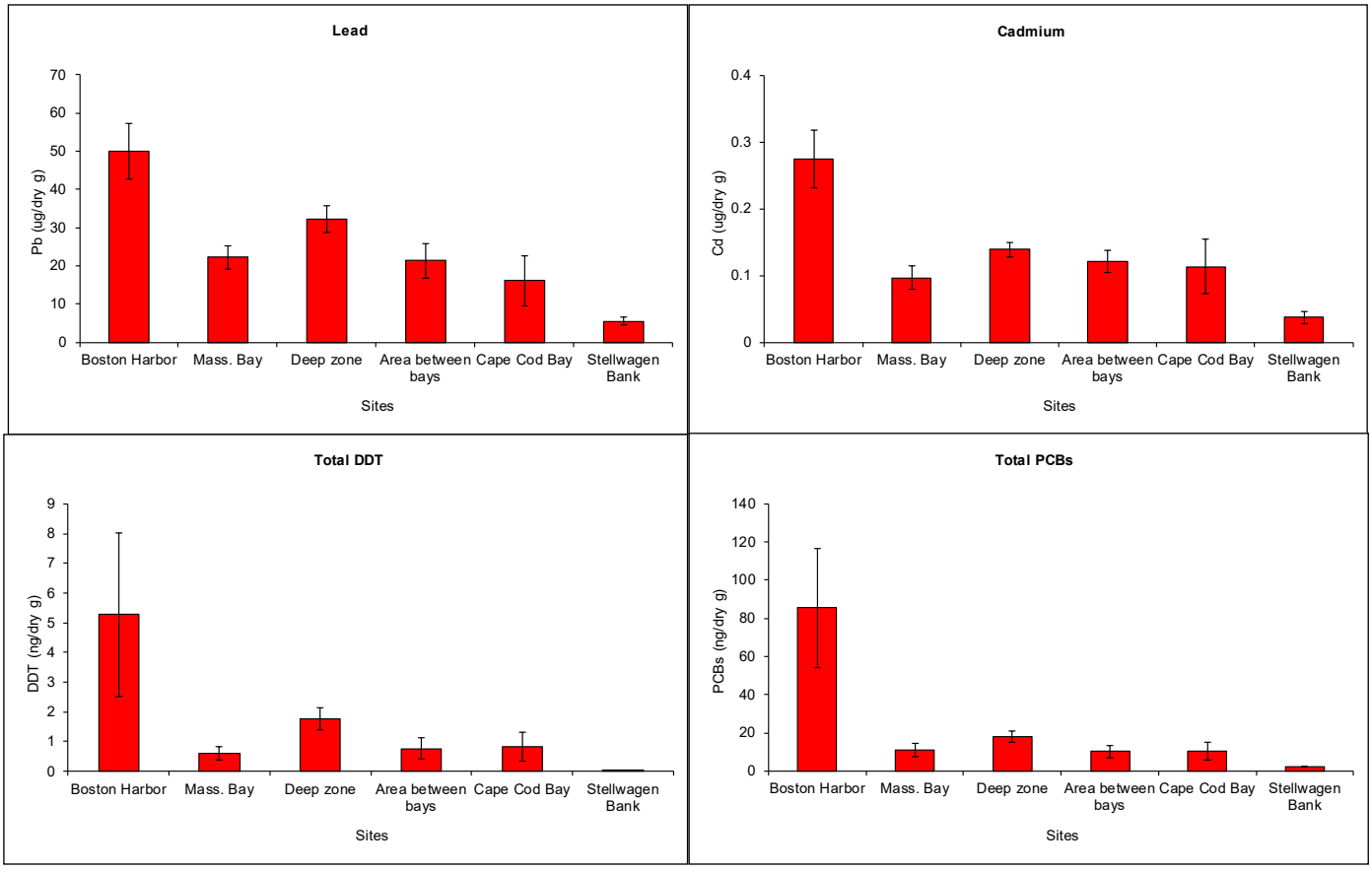


Figure 2: Concentration of select metals (Cd and Pb) and organics (total PCBs and DDT) in sediments within Massachusetts Bay. Note that results for Massachusetts Bay are about equal to all other strata with the exception of Boston Harbor.

between the harbor and Stellwagen Bank (Figure 2). These observations, like the sediment data, also suggest that export from Boston Harbor is a source of contamination for Massachusetts Bay and possibly for Stellwagen Bank.

2.3 Toxicity Results

No toxicity bioassay samples were taken in this study.

2.4 Benthic Infaunal Results

Multivariate cluster analysis was employed to group site and species data. These were then overlaid in order to produce a coherent pattern of association between sites and species. Analysis of all stations resulted in separation into 3 habitat zones; 1) Fine sand, deep, higher total organic carbon (TOC), high species diversity; 2) Muddy, shallow, low salinity, low species diversity; 3) Coarse sand, low TOC intermediate species diversity and cosmopolitan species (found throughout the region). Most Massachusetts Bay stations were contained within the fine sand group and were inhabited primarily by species in group C (Figures 3, 4) with higher diversity and greater number of species than the other two zones. Boston Harbor contained the muddy, shallow stations. Stellwagen Bank and near-shore sandy areas comprised the third habitat type.

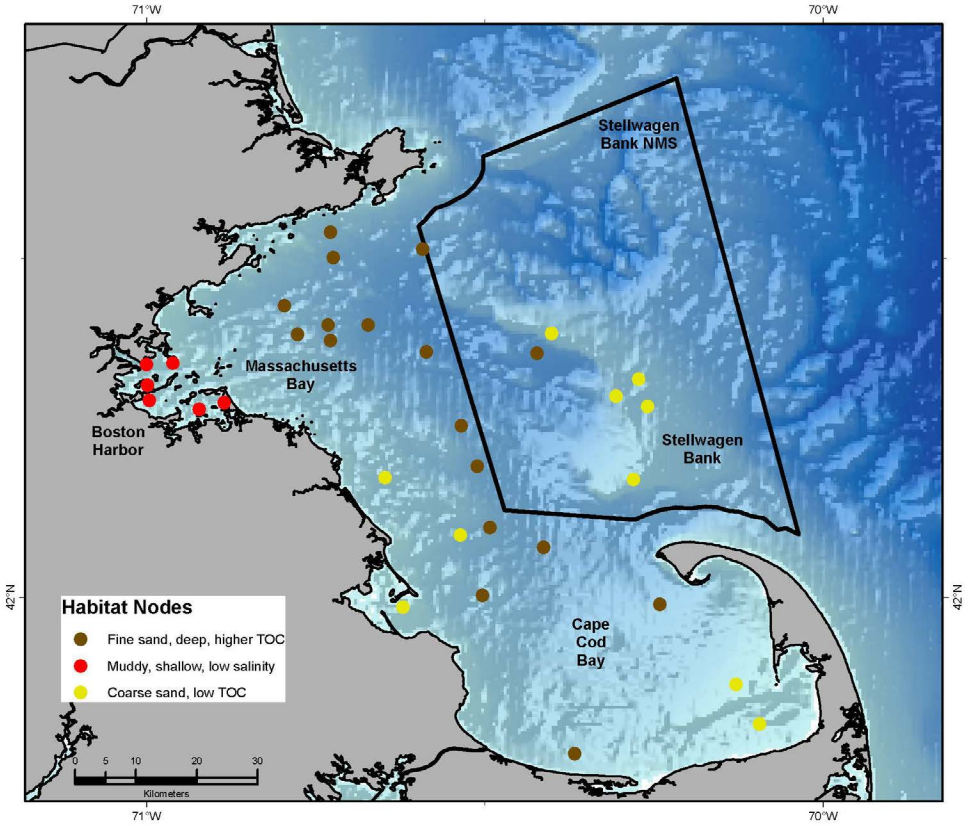


Figure 3: Location of sites representative of three major habitat nodes in the Boston Harbor / Massachusetts Bay region.

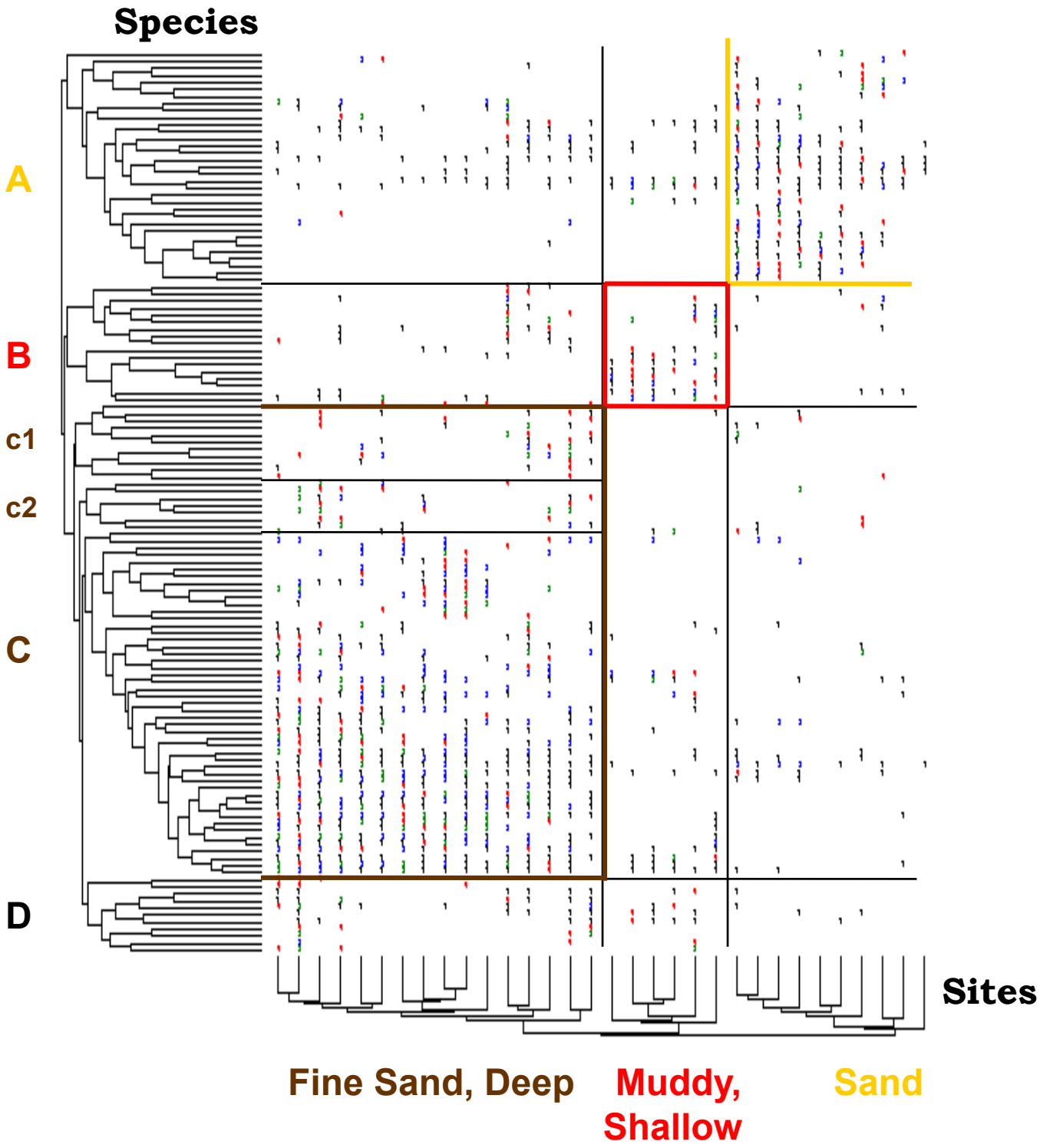


Figure 4: Nodal analysis displaying species clusters and site clusters for benthic community assessment in Massachusetts Bay and vicinity. Symbol color indicates species specific relative abundance in 25% increments: black=low, blue-medium-low, green=medium-high, and red=high

2.5 *Correlations*

Spearman Rank correlation analysis on log normalized data shows that in general, contaminant concentrations were positively correlated with total organic carbon and fine grain sediment (silt and clay) and negatively correlated with sand content of the sediment.

3. SUMMARY

In 2004, metal and organic contaminant concentrations were found to be significantly higher in the sediments collected in and around Boston Harbor than all other neighboring areas with intermediate concentrations found in Massachusetts Bay and the deep basin. Contaminant concentrations were above the ERL threshold in 27.3% of Massachusetts Bay area and above the ERM threshold in 9.1% of the area. The deep basin appears to be an accumulation zone. In Cape Cod Bay 16.7 % of the area showed contaminant concentrations above ERL thresholds but none above ERM thresholds. The lowest sediment contaminant concentrations were consistently found in the Stellwagen Bank sites; there were no concentrations above any ERL threshold. Contaminant data from the 2004 sampling effort are consistent with historical data, no significant changes were observed.

In Boston Harbor, contaminant concentrations in the past were somewhat higher than current levels. Within the range of variability, the data indicated static or slowly declining levels, depending on the specific chemical, though there are no significant differences in concentration between the old and current sediment data as a whole for any part of the study area.

Consistent with the sediment data, tissue contaminant concentrations were higher from sites in the vicinity of Boston Harbor. There is evidence of a gradient of contaminant concentration from inshore to offshore suggesting export of contaminants from Boston Harbor eastward to Massachusetts Bay and Stellwagen Bank and southward toward Cape Cod Bay via suspended sediments and/or the water column. Temporal trends in mussel and fish tissue body burdens are not strongly evident.

Overall, the persistent, chlorinated compounds that have been banned for decades show only slightly declining concentrations attesting to their persistence in the environment and suggesting that there are still large reservoirs in the watershed and sediments that continue to release contaminants.

The benthic community analysis demonstrates three major habitat zones, driven by sediment grain size, with salinity and depth as secondary factors. Species diversity is consistently lower in Boston Harbor than all locations. Diversity on Stellwagen Bank was also relatively low likely a result of the sandy habitat type, since contaminant concentrations are low. Diversity was relatively higher in Massachusetts Bay than in the other two areas, probably a result of the combination of organic content, more diverse habitat conditions, and finer grained sediment.

Chapter 3
Long Island Sound

1. STUDY AREA DESCRIPTION

Long Island Sound (LIS) is one of the major estuarine systems on the Atlantic coast of the United States. The LIS provides transportation links for commercial interests and recreational opportunities (swimming, sailing, sport fishing) for millions of residents and tourists. The LIS surface area is 3.37 x 103 km^2 with a volume of 64 x 109 m^3 and mean depth of 20 m. Maximum depths are >90 m at the eastern boundary near Block Island Sound. Two-thirds of the 44 x 10^3 km^2 drainage area of the Sound is in Connecticut, but also includes parts of New York, Massachusetts and Rhode Island creating jurisdictional issues and expanding the purview of marine environmental management to include issues of agricultural land-use practices and pesticide applications in these upland areas (Figure 1).

Figure 1. At its western end, the Sound is connected with New York Harbor through the East River. Freshwater enters the Sound from 4 major tributaries (Thames, Connecticut, Quinnipiac, and Housatonic Rivers) and from coastal runoff and drainage along the Connecticut and Long Island shores, with the Connecticut River accounting for 70% of total freshwater inflow.

The population of the watershed surrounding the Sound is approximately 9 million residents per the 2010 Census, half of which reside near the coast. Processed effluents and wastes are currently discharged directly into the Sound by 44 sewage treatment plants and many industries. Fishing and shellfishing grounds in the Sound are threatened both by overfishing and by declining environmental quality.

Sampling details

The sampling design for the Long Island Sound study deviated from that employed in other areas. In most Bioeffects studies, sampling stations were widely dispersed throughout the area of concern, using a stratified random approach that enables an estimate of the areal extent of degraded habitat. In Long Island Sound, however, in response to recommendations from the Toxics Subcommittee of the LISS Management Committee, this study was designed to determine the relative quality of sediments in selected bays surrounding Long Island Sound. In each of these bays, sediment samples were taken, usually along the upstream-downstream gradient of potential contaminant distribution. Three samples were collected for sediment toxicity testing and chemical analysis during August 4-12, 1991 from each of 20 sites within the coastal bays and harbors of Long Island Sound (Figure 2) plus the control site (CLIS). At each station surficial samples (1-3 cm depth) were taken for the following tests: 1) SEM/AVS, the ratio of simultaneously extracted metals (SEM) and acid-volatile sulfide (AVS) (metal concentrations that are found in an acid wash of the sediment strong enough to extract sulfides), 2) inorganic and organic contaminants and total organic carbon (TOC), 3) grain size, and 4) sediment toxicity. Sediment samples were tested for toxicity with three independent protocols: 1) a 10-day amphipod survival test in whole, solid-phase sediments with *Ampelisca abdita*, 2) a 48-hour exposure of clam larvae, *Mulinia lateralis*, to sediment elutriates, with normal development and survival as the endpoints, and 3) a microbial bioluminescence test (Microtox®) using solvent extracts of the sediments. Separate samples from these same stations were analyzed chemically for a broad suite of potentially toxic contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAH), chlorinated pesticides and polychlorinated biphenyls (PCBs).

For sediment contaminant concentrations the Effects Range-Low and Effects Range-Median values indicating threshold guidelines for contaminant concentrations were compared with measured values for 63 samples from the 21 sample stations. Two approaches were used in this comparison. First, the LIS sediment chemistry was compared against the guidelines on a constituent-by constituent basis to determine the number of exceedances for each contaminant. Secondly, cumulative hazard factors were calculated for each sample as follows. Concentrations between the ERL and ERM were assigned a value of 1.0 for each of the 33 contaminants (or groups of contaminants). Concentrations less than the ERL were assigned a value of zero, and concentrations that exceeded the ERM received a proportionately scaled value greater than 1.0. For each sample the individual contaminant values were summed to give composite hazard factors where higher values indicate higher hazard. Separate composite hazard factors were calculated for the 10 metals (taken together), the 7 chlorinated hydrocarbon components, and the 12 individual PAH constituents, as well as for all 33 components together. To facilitate visualization of relationships among toxicity and contaminants, the data were examined through the use of cluster analysis. The data were clustered on the basis of chemical and physical data, plus the toxicity data expressed as percent of control values. Spearman Rank Correlations were calculated for all parameters.

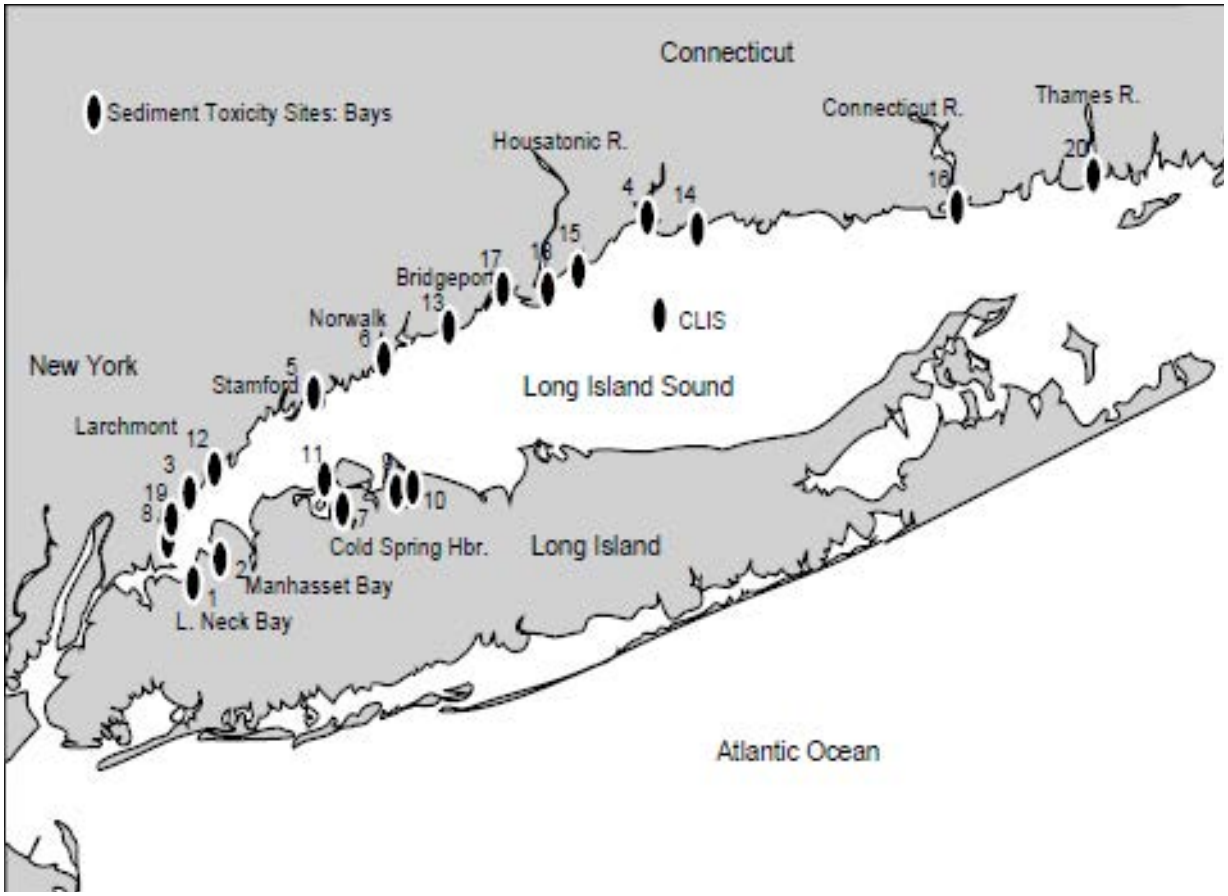


Figure 2. Sampling locations in Long Island Sound, the NS&T station numbers are also used in Figure 3.

2. RESULTS

2.1 Important Physical Drivers

Although there are 4 major tributaries, the Connecticut River accounts for 70% of total freshwater inflow. Because it enters well to the east it contributes only moderately to the overall estuarine circulation of the Sound. Inputs of deeper oceanic water to the eastern sound are modulated by the Eastern Sill, which crosses the Sound at a 72 deg 30 min W. There is a vigorous estuarine circulation, with flow eastward out of the estuary in the upper water column and inward westward movement strengthening with depth over the central and north section of the Sound. Shortly after its establishment in 1906, the New York Metropolitan Sewerage Commission surveyed New York Harbor, and concluded that the East River, as an oscillating tidal strait, was unsatisfactory for sewage disposal. No concerted effort was focused on the water quality problems of LIS, however, until the early 1970's when it became clear that uncontrolled development,

including channelization, was leading to modified salinity regimes, decreased water circulation, decreased stream flow, low groundwater levels and increased urban runoff, leading to greatly impaired water quality. Processed effluents and wastes are currently discharged directly into the waters of the Sound by 44 sewage treatment plants and many industries. Many additional point sources discharge into the rivers entering the Sound. Understanding the significance of these various pollutant sources and managing their inputs, is complicated by a wide variety of non-point source pollutant contributions to the Sound, including atmospheric contaminants and local runoff from urban areas.

2.2 Contamination Results

Essentially all of the metallic and organic contaminants analyzed in this study are consistently very highly correlated with one another and with TOC (Table 1). Using mercury, PCBs and PAH as examples, there is a high degree of covariance among contaminants. This very strong co-variance among the contaminants precludes any firm conclusions about the specific causal relationships between toxicity and particular contaminants.

Table 1. Spearman Rank Correlations (Rho) among sediment contaminant concentrations in sediments collected at three stations from 21 sites in Long Island Sound coastal embayments (N=63). Note that the higher the value the stronger correlation. tCHCIP is total chlorinated pesticides, TOC is total organic carbon, tPAH is total polycyclic aromatic hydrocarbons.

Contaminant	Cadmium	Lead	tPAH	%TOC	% Fines
Metals					
Arsenic	+0.513***	+0.687***	+0.484***	+0.650***	+0.360**
Chromium	+0.718***	+0.875***	+0.675***	+0.833***	+0.495***
Copper	+0.776***	+0.846***	+0.740***	+0.815***	+0.363**
Mercury	+0.820***	+0.940***	+0.784***	+0.922***	+0.540***
Selenium	+0.786***	+0.869***	+0.555***	+0.885***	+0.477***
Silver	+0.802***	+0.902***	+0.693***	+0.868***	+0.475***
Tin	+0.828***	+0.938***	+0.738***	+0.884***	+0.439***
Zinc	+0.854***	+0.952***	+0.695***	+0.936***	+0.532***
Organics					
tPCBs	+0.677***	+0.718***	+0.880***	+0.734***	+0.353**
tDDT	+0.694***	+0.756***	+0.873***	+0.739***	+0.353**
tCHCIP	+0.476***	+0.618***	+0.342**	+0.657***	+0.421***

*p<0.05; **p<0.01; ***p<0.001

Long Island Sound sites are frequently in the upper 25th percentile of nationwide NS&T sites for contaminant levels, and concentrations show a decreasing pattern from west to east in the Sound (Figure 3). Several other contaminants exhibited patterns very similar to those represented in Figure 3. For example, silver, cadmium, chromium, mercury, and nickel exhibited distributions very similar to those shown for Cu and Pb. Total chlordane, dieldrin, and PAHs showed patterns generally similar to those illustrated for PCBs and

DDT, except that for dieldrin the LIS sediments showed a broader and lower (20-80th percentiles) distribution relative to sites nationwide.

Figure 3 and Table 2 also illustrate that the concentration ranges of sediment contaminants found in LIS exceeded sediment quality guidelines (i.e. ERM) at several stations. At stations where sediment concentrations approach or exceed the ERM for lead and/or PCBs, it is probable that contaminant-related biological effects will be observed at these areas.

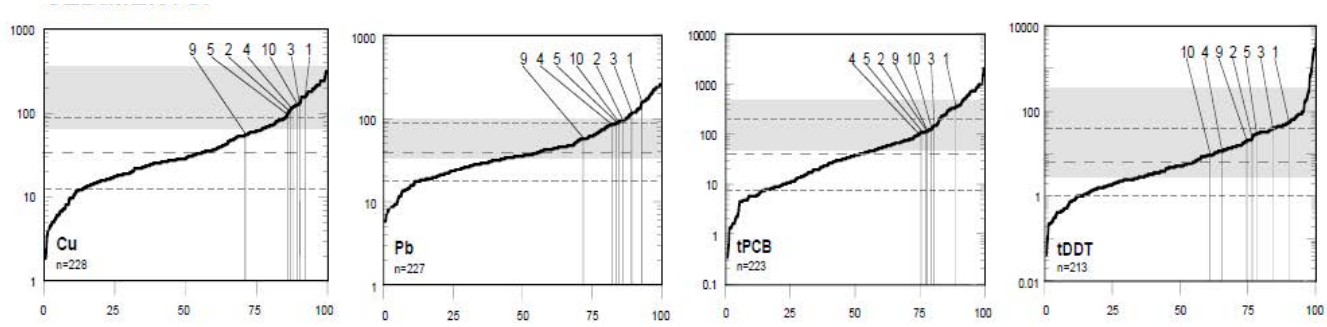


Figure 3. Concentrations of selected contaminants in NS&T samples from Long Island Sound (for Site Numbers refer to Figure 2), and their percentile ranks among NS&T sites nationwide. The lower and upper bounds of the shaded areas represent ERL and ERM values.

2.3 Toxicity Results

Results of the toxicity tests indicate that sediment toxicity is widespread in the coastal bays of LIS. Only 11 of the 60 bay stations showed no significant toxicity in any of three bioassay tests and none of the 20 bays was non-toxic in all tests at all three stations. The bay indicated to have the greatest sediment toxicity in this survey was Manhasset Bay, NY, with all three stations significantly toxic in all three tests. Several other bays gave multiple hits at the three stations with the three tests, as well: Oyster Bay, NY (8 hits); Little Neck Bay, NY (7hits); Echo Bay, Cold Spring Harbor, Larchmont Harbor and Pelham Bay (6 hits). The least toxic bays included Branford Harbor and Connecticut River, CT, each with only one hit at one station; along with Northport Harbor NY, Southport Harbor CT, Milford Harbor CT, and Thames River, CT, each with only two hits. The Central Long Island Sound (CLIS) control site also showed one hit at one of its three stations (Figure 4).

Table 2. Cumulative Hazard Factors and ERM exceedances in each of the three samples per bay. (tHmw -total high molecular weight, tLmw - total low molecular weight.)

Bay	Cummulative Hazard Factor	ERM Exceedances		Bay	Cummulative Hazard Factor	ERM Exceedances		Bay	Cummulative Hazard Factor	ERM Exceedances
1	17.58	tHmw PAH, Hg, Zn,		8	0.06	none		15	0.24	none
1	15.30	tHmw PAH, Hg, Ag		8	7.60	none		15	1.11	none
1	20.22	tHmw & tLmw, Hg, Ag		8	9.09	Hg, Ag		15	0.11	none
2	20.51	DDE, tDDT, tPCB, Hg, Pb,		9	4.84	none		16	0.24	none
		chlordane, dieldrin		9	1.16	none		16	1.78	none
2	9.57	Hg, Ag		9	2.31	none		16	1.01	none
2	10.04	Hg		10	1.78	none		17	3.77	none
3	13.61	Hg, Ag		10	1.69	none		17	3.24	tDDT
3	4.84	none		10	0.68	none		17	18.59	tHmw & tLmw PAH, Cu
3	6.44	none		11	2.85	none		18	10.50	tHmwPAH, chlordane
4	8.32	tDDT, Ag		11	1.77	none		18	10.70	tHmwPAH, tPCB, Cu
4	2.06	none		11	0.56	none		18	2.25	none
4	1.37	none		12	5.40	none		19	16.24	Hg, Zn, dieldrin
5	15.33	tHmw PAH, chlordane		12	6.06	none		19	14.67	Hg, Ag
5	3.31	none		12	4.17	none		19	21.81	tHmw & tLmw PAH, Hg, Ag
5	0.30	none		13	0.08	none		20	12.85	none
6	5.14	Hg, dieldrin		13	0.27	none		20	1.63	none
6	2.18	none		13	1.11	none		20	1.78	none
6	1.08	none		14	0.25	none		CLIS	1.15	none
7	2.63	none		14	1.23	none		CLS	0.93	none
7	2.41	none		14	0.44	none		CLIS	1.16	none
7	2.41	none								

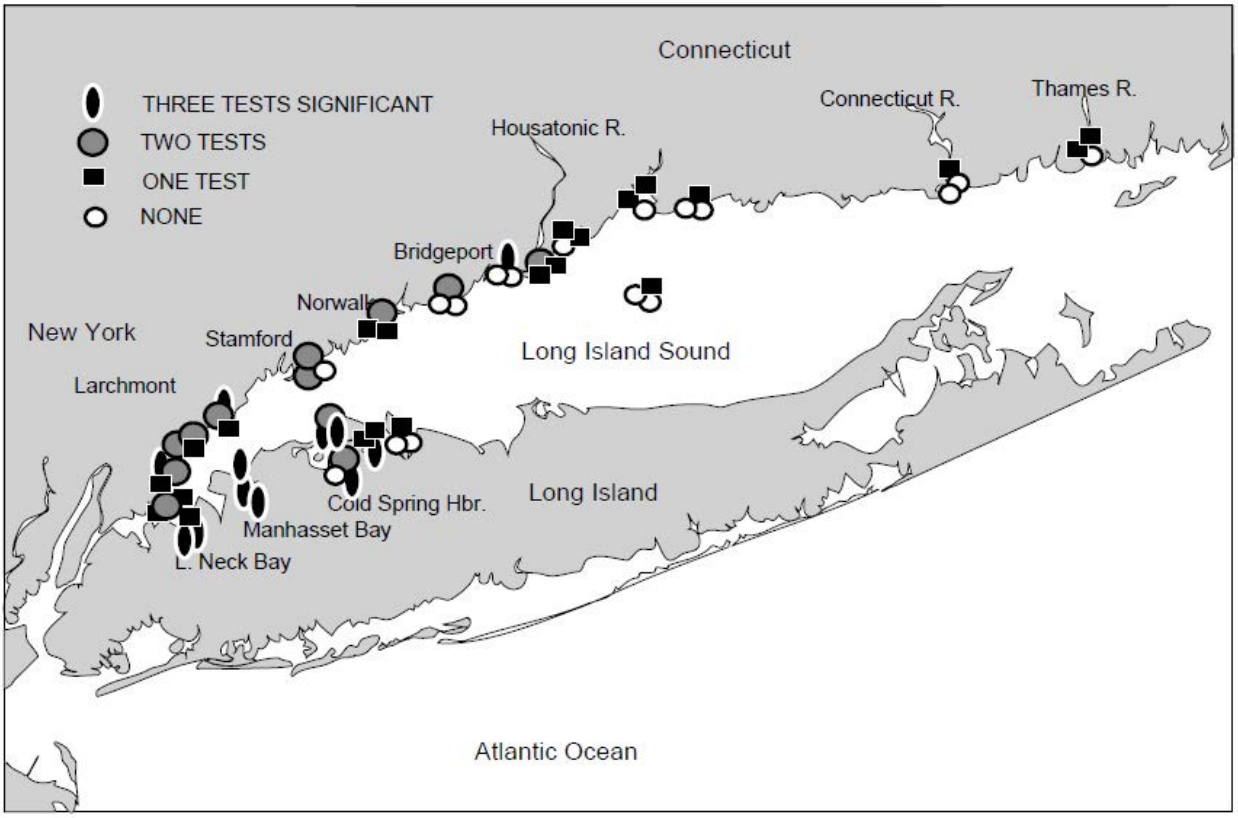


Figure 4. Sampling locations in Long Island Sound where sediments were significantly toxic in three, two, one, or no tests. "Significant" includes statistically significant (p = .05) reduction from and <80% of control survival for *Ampelisca* and *Mulinia* or <70% of control for Microtox^{R}.

The Microtox^{R} response to organic extracts of sediments appears to respond to bulk chemical contaminant concentrations, independent of the TOC content of the sediments. Although organic contaminants probably contribute most or all of this toxicity measure, the metals typically covary strongly with the organics (and with the proportion of clay/silt and TOC) in the sediments (but are not efficiently extracted from the sediment by organic solvents used to prepare the test solutions). Results of the solid phase sediment toxicity test with amphipods by contrast showed stronger correlations with contaminant concentrations after normalization to TOC or fine grained sediments than with concentrations based on dry weight, indicating an effect of both grain size and TOC on toxicity. This effect probably results from differences in the bioavailability of contaminants as well as absolute concentration. The elutriate test with *Mulinia* showed an intermediate degree of TOC-modulating effect, but still suggested that this test, like Microtox^{R}, was largely responsive to bulk contaminant levels in the sediments.

2.4 Benthic Infaunal Results

No benthic infaunal samples were taken in this study because interpretive methods were still in development.

2.5 Cluster analyses and Correlations

Cluster Analysis: The stations were resolved into two major clusters (Figure 5):

(A) The upper cluster contains the most highly contaminated stations, as well as most of the stations that exhibited significant toxicity in more than one test. None of the stations were nontoxic in all of the tests.

(B) The lower cluster contains all of the stations that were non-toxic in any test, most of the stations that were toxic in only one test, and those stations (11-C, 9-B, 13-A, 18-D, and 8-A; all clustered together in the bottommost subcluster of the diagram) at which significant toxicity was noted without any notable corresponding measurements of contamination. Station 17-A, notably non-toxic despite exceedance of the ERM value for tDDT, appears within this major cluster as a separate subcluster unto itself.

Correlations: The toxicities estimated by Microtox® were highly statistically significantly correlated with %TOC in the sediments, and with the % fines (clay plus silt) and a broad suite of organic (PAHs, PCBs, DDTs, and other chlorinated pesticides) and inorganic (Cd, Cr, Cu, Hg, Pb, and Sn) contaminants in the sediments (Table 3). Of 35 samples with TOC greater than 2.0%, 34 were significantly toxic in the Microtox^{R} test, whereas only 6 of the 28 samples with TOC less than 2.0% were toxic in the Microtox® test.

Toxicities measured by the other three endpoints were less strongly correlated with %TOC and were also significantly correlated with the suite of metals, but generally not with % fines. The correlations with organic contaminants were much lower and more variable than for Microtox®. Of the 35 samples with TOC greater than 2.0%, 20 (57.1 %) were significantly toxic to amphipods, and a similar fraction (12/28, or 42.9%) of those samples with TOC less than 2.0% were also toxic. Essentially all of the metallic and organic contaminants analyzed in this study are consistently very highly correlated with one another and with TOC.

Although the normal development and survival endpoints for *Mulinia lateralis* were positively correlated with each other, the normal development endpoint was not sensitive or consistent with other endpoints. Only five of the samples (8.33%) from LIS bays showed statistically significant reductions of normal development. The lowest value (83% of the control; station 17I, Bridgeport Harbor) coincided with significant toxicity to both the amphipod and *Mulinia* survival endpoints. Only two of the other four samples that showed reduced normal development were toxic to *Ampelisca* and both these samples had greater than 80% survival. None of these four samples were toxic to the *Mulinia* embryo survival endpoint. With 35 significant reductions of EC-50 (58%), the Microtox^{R} endpoint was about equally sensitive as amphipod bioassays. However, these two endpoints were not significantly correlated with one another by site, and the concordance between Microtox^{R} and amphipod survival was not nearly as strong overall as between *Mulinia* survival and amphipod survival.

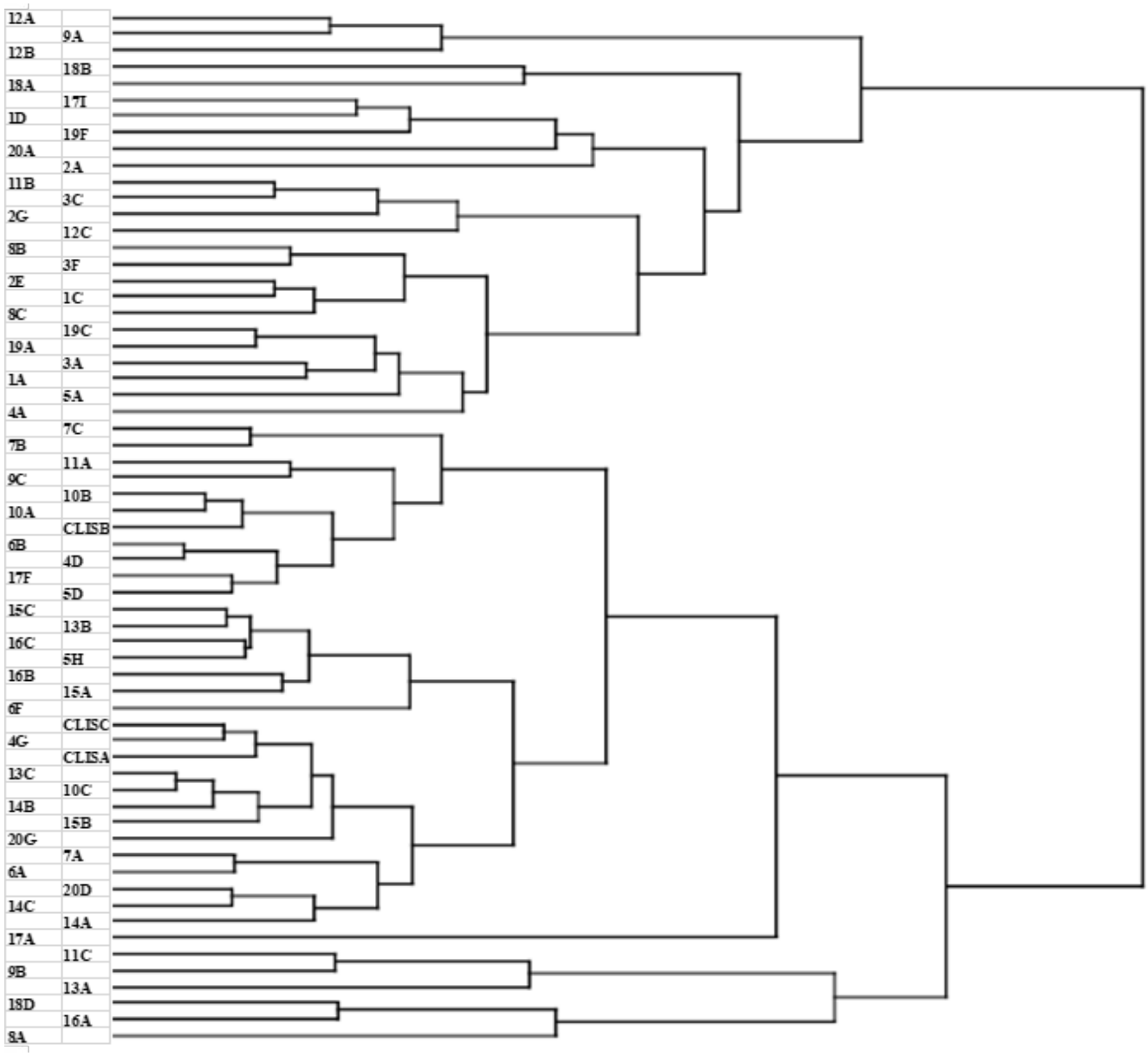


Figure 5. Cluster diagram for the 63 stations sampled in coastal bays of Long Island Sound, based on physical and chemical parameters plus the results of toxicity tests on survival of *Ampelisca abdita* and *Mulinia lateralis* and on inhibition of bioluminescence (Microtox^{R}), all expressed as percent of control values. (CLIS A-C = Control Long Island Sound A through C)

Table 3. Spearman Rank Correlations (Rho_ for results of the Microtox[R] assay with various contaminants and contaminant categories normalized either to dry weight, percent silt plus clay (percent fines), total organic carbon, or aluminum content of the sediments for 63 stations sampled in peripheral bays of Long Island Sound and for the 49 non-sandy stations (<42% sand) stations considered alone. . *p<0.05; **p<0.01; ***p<0.001

	dry wt	% fines	Aluminum or TOC	dry wt	% fines	Aluminum or TOC
	63 stas	63 stas	63 stas	49 stas	49 stas	49 stas
Silver (Ag)	-0.639***	-0.250	-0.635***	-0.509***	-0.510***	-0.526***
Cadmium (Cd)	-0.671***	-0.162	-0.630***	-0.610***	-0.590***	-0.601***
Copper (Cu)	-0.535***	-0.123	-0.529***	-0.561***	-0.493***	-0.627***
Mercury (Hg)	-0.712***	-0.406**	-0.699***	-0.599***	-0.586***	-0.628***
Lead (Pb)	-0.687***	-0.167	-0.667***	-0.578***	-0.584***	-0.600***
Zinc (Zn)	-0.686***	-0.122	-0.667***	-0.609***	-0.577***	-0.610***
tPAH	-0.495***	-0.139	+0.089	-0.485***	-0.491***	-0.159
Sum PCB	-0.486***	-0.110	+0.044	-0.483***	-0.457**	-0.196
Sum DDT	-0.522***	-0.229	+0.233	-0.513***	-0.503***	-0.138
Sum Pesticides	-0.552***	-0.311*	-0.203	-0.473***	-0.488***	-0.274
TOC	-0.757***			-0.659***		
%silt+clay	-0.411***			-0.044		
Aluminum (Al)%	-0.020			+0.040		

Of the 35 stations toxic to Microtox[R], 28 (75%) were toxic also to amphipod survival and 21 (60%) reduced amphipod survival to less than 80%. Viewed conversely, only 28 (58.3%) of the 48 stations significantly toxic to amphipods were also significantly toxic to Microtox[R]; and only 21 (66%) of the 32 stations causing less than 80% survival in amphipods were significantly toxic to Microtox[R]. The lack of consistency among toxicity test results is not unexpected: it reflects differences in sensitivity among test organisms, as well as differences in mode of exposure and contaminant bioavailability among the tests.

However, essentially all of the metallic and organic contaminants analyzed in this study are consistently highly correlated with one another and with TOC. This very strong co-variance among the contaminants precludes any firm conclusions about the specific causal relationships between toxicity and particular contaminants. From correlative analyses alone, however, one can nonetheless gain considerable insight on the relative responsiveness of the three most sensitive toxicity assays to different contaminant categories.

3. SUMMARY

The primary component of variability in the toxicity data results from the strongly covarying concentrations of many sediment contaminants. The cluster analysis demonstrated substantial influence of sediment grain size and TOC on the resultant clustering of stations. Although the cluster diagrams supported the primary associations between toxicity and chemical contamination, they also illustrated that with only a few exceptions, contamination and associated toxicity were distributed across many of the bays, and were frequently more dependent on sediment characteristics at the individual stations than upon baywide contamination characteristics.

Most of the stations (and bays) that exhibited toxicity also showed demonstrable chemical contamination, and many stations exceeded ERMs for one or more chemicals. The presence of additional contaminants, not analyzed in this study, may also contribute to the toxicity measured in these samples. While no particular contaminants are identified as a primary source of toxicity, the consistent elevation of an extensive suite of contaminants in the toxic samples for all three tests broadly supports a contaminant basis for the observed toxicity. The most contaminated sites, in terms of a cumulative hazard factor based on those chemicals for which ERLs and ERMs have been calculated, were Little Neck Bay, Pelham Bay, Manhasset Bay, NY, and Housatonic River, CT, respectively. Relatively high cumulative hazard factors were also observed at single stations within Echo Bay, NY, and Stamford Harbor, Thames River, and New Haven Harbor, CT.

Chapter 4
Hudson-Raritan Estuary

1. STUDY AREA DESCRIPTION

The Hudson-Raritan Estuary is a very large, highly urbanized estuarine system with an estimated 5 million people in the watershed. It is bounded to the east by the New York Bight and Long Island Sound, and bounded to the west, south and north by highly urbanized and industrialized areas of New York and New Jersey. It is a mixing zone for four major rivers and many wastewater treatment plants and other point-source discharges. For the purposes of this report, it includes the waters of the extreme western Long Island Sound, the East River, the lower Hudson River, upper and lower New York Harbors, Kill van Kull, Arthur Kill, the lower Passaic River, the lower Hackensack River, Newark Bay, the lower Raritan River, Raritan Bay, Sandy Hook Bay and the waters of the outer harbor east to the Rockaway-Sandy Hook (Figure 1).

This estuary has been highly impacted by many human-induced factors. Many of the historical wetlands have been filled, much of the water body has been channelized for navigation, and huge industrial and residential complexes have been built along the shores. Contaminants are discharged from wastewater treatment plants, combined sewer overflows, urban stormwater runoff, petrochemical factories, illegal dumping, atmospheric deposition and accidental spills. Wastewater treatment plant discharges are estimated to contribute 40-60% of the total input of several trace metals into the estuary while 20-40% is contributed by tributary rivers, and 10-30 % by urban runoff. Based on the limited data available for organic compounds, wastewater and tributary rivers each contribute about 40% of the total PCB load. Over 1,453 accidental discharges occurred, mostly in the lower Passaic River, Arthur Kill, Newark Bay, and Kill van Kull, between 1982 and 1991 resulting in release of more than 18 million gallons of hazardous materials and petroleum products. Previous studies have indicated that concentrations of many potentially toxic chemicals are highly elevated in the Hudson- Raritan Estuary.

Figure 1: The Hudson Raritan Estuary study site.

Sampling Details

Sediment contaminant and toxicity samples: The survey was conducted in two phases: 39 locations were sampled in triplicate (117 samples) in 13 strata throughout the entire estuary during 1991 (Phase 1), and an additional 57 individual samples were collected in Newark Bay and vicinity (central Newark Bay, northern Arthur Kill, Kill van Kull on the north shore of the island, the Passaic and Hackensack Rivers, and upper New York Harbor) in 1993 (Phase 2). In the second phase, the area was divided into five strata that were approximately equal in size such that the data from each sample would have approximately equal spatial weight, plus one sample from upper New York Harbor. Toxicity bioassays tests were performed on each sample. During Phase 1, three independent tests were performed: (1) a 10- day, mortality bioassay of solid-phase sediments with the amphipod *Ampelisca abdita*; (2) a 48-hour liquid phase test of pore water with the embryos of the bivalve *Mulinia lateralis* in which both percent survival and normal embryological development were recorded; and (3) a 15-minute microbial bioluminescence test (Microtox^{R}) of organic solvent extracts. Only the amphipod tests were performed on the samples collected during Phase 2. Based on the bioassay results, samples were selected for chemical analyses that represented gradients in toxicity. Chemical analyses of selected samples included trace elements, polycyclic aromatic hydrocarbons (PAHs), chlorinated pesticides and other hydrocarbons. Also, during Phase 2 the concentrations of numerous chlorinated dioxins and furans were determined.

Benthic community samples: A PONAR dredge (area = 0.04 m^2) was used to collect replicate bottom samples at each of 72 stations in the Hudson Raritan Bay Estuary (phase 1). Macroinfaunal samples were sieved through a 0.5 mm mesh screen and preserved with 10% formalin.

2. RESULTS

2.1 Important Physical Drivers

Dredging for navigational purposes occurs periodically to ensure that the shipping channels remain open. Many contaminants are associated with fine-grained sediments that accumulate in these navigational channels, and can be released and transported elsewhere. The inter-connected bays, rivers and tidal straits lead to complex estuarine circulation patterns. Tidal height at the mouth of the East River is ~1.4 m.

2.2 Contamination Results

The contaminants that occurred at or above ERM levels include; PCBs, PAHs, DDT, many trace metals. Areas in which relatively high concentrations of contaminants were observed, and for which there is thus a high potential for toxicity, include Newark Bay, Arthur Kill, lower Jamaica Bay, lower Hackensack River, Gowanus Canal that drains into the upper harbor from Brooklyn, and the bays adjoining the upper East River/western Long Island Sound. Relative to these areas, contaminant concentrations were lowest in lower New York Harbor and northwest of Sandy Hook, the East River, Harlem River that divides Manhattan from yhe mainland, lower Hudson River, and eastern Raritan Bay. Concentrations of dioxins and furans above background levels in sediments and marine biota have been reported for the lower Passaic River with decreasing concentrations downstream in Newark Bay and New York Harbor. In addition, concentrations of PAHs and many trace elements were found at concentrations above ERM values in samples collected in the lower Passaic River, lower Hackensack River, and Newark Bay (Table 1).

Table 1. Regions of Hudson Raritan estuary in which concentrations of selected sediment contaminants exceeded respective ranges of Effects Range Low (ERL) and Effects Range Median (ERM) values. nd-no data

Region	Cd	Cr	Cu	Hg	Ni	Pb	Zn	tPCB	tDDT	tPAH
East River	-	*	*	*	-	***	*	**	*	nd
East R. bays	*	***	*	***	*	***	***	***	nd	nd
Harlem River	-	-	-	*	-	***	*	*	nd	nd
Wards Island	*	***	***	**	*	***	***	***	nd	nd
Hudson River	-	*	*	*	-	***	*	**	nd	-
Upper Bay	-	*	*	***	*	**	*	**	nd	*
Gowanus Canal	***	***	*	***	***	***	***	nd	nd	nd
Kill van Kull	*	nd	nd	***	nd	***	***	nd	nd	*
Newark Bay	**	***	***	***	***	***	***	***	***	***
Hackensack R.	**	***	**	***	***	***	***	nd	nd	nd
Passaic River	*	***	*	**	**	***	**	***	nd	***
Arthur Kill	**	*	***	***	***	***	***	***	***	*
Raritan Bay	nd	nd	nd	***	nd	nd	nd	**	*	*
W. Raritan Bay(I)	**	***	***	nd	*	***	***	nd	nd	nd
C. Raritan Bay(II)	*	**	**	nd	*	***	***	nd	nd	nd
N. Raritan Bay(III)	*	**	*	nd	*	**	**	nd	nd	nd
S. Raritan Bay(IV)	-	**	*	nd	*	**	**	nd	nd	nd
Lower Bay	**	*	*	**	nd	*	nd	**	*	*
Jamaica Bay(I)	-	**	*	**	*	***	**	**	*	nd
Jamaica Bay(II)	-	**	*	**	-	**	*	**	*	*

Table 2 summarizes the frequency of guideline exceedances for those chemicals or classes of chemicals that showed a statistically significant positive correlation with toxicity in at least one of the tests. None of the samples had concentrations of silver, arsenic, or cadmium that equaled or exceeded the respective ERM values (Table 2). The ERM value for chromium was exceeded in only one sample (12a from the East River). The guideline values for mercury, p,p'-DDT, p,p'-DDE, fluoranthene, phenanthrene, and total high molecular weight PAHs were equaled or exceeded most frequently. The ERM value for mercury was exceeded in 30 samples. EPA Sediment Quality Criteria (SQC) values for fluoranthene and phenanthrene were exceeded in many samples. Many of the chemicals quantified in samples 7b, 9b, 11b, 12a, 17c, and 18c equaled or exceeded their respective guideline concentrations, often by a factor of 2x or greater (Table 2).

Table 2: Regions of Hudson Raritan estuary in which concentrations of selected sediment contaminants exceeded respective ranges of Effects Range Median (ERM) and EPA Sediment Quality Criteria (SQC) values. See Figures 3 – 5 for locations of sites referred to in this table.

Chemical Substance	Guideline	Number of Samples in which ERM or EPA SQC values were exceeded	Samples in which the ERM or SQC was exceeded
Silver	(ERM=3.7a)	0	
Arsenic	(ERM=70a)	0	
Cadmium	(ERM=9.6a)	0	
Chromium	(ERM=370a)	1	12a
Copper	(ERM=270a)	2	12a, 18c
Mercury	(ERM=0.71a	30	1a, 6c, 7b, 8c, 9b, 10a, 10b, 11b, 12a, 12b, 13a, 16a, 16b, 17b, 17c, 18a, 18c, 22c, 23a, 24c, 25a, 26a, 26c, 29a, 30a, 30b, 30c, 33b, 36c
Nickel	(ERM=51.6a)	3	11b, 12a, 17c
Lead	(ERM=218a)	8	8c, 9b, 12a, 10b, 11b, 12b, 17c, 18c
Zinc	(ERM=410a)	5	9b, 12a, 18c, 30a, 33b
p,p'-DDE	(ERM=27a)	12	9b, 11b, 12a, 12b, 17b, 17c, 18a, 18c, 22c, 23a, 24c, 33b
p,p'-DDT	(ERM=7b)	14	9b, 11b, 12a, 12b, 16a, 16b, 17b, 17c, 18a, 18c, 22c, 23a, 29a, 36c
total PAHs	(ERM=44792a)	4	7b, 8c, 9b, 10b
total Low Wt PAHs	(ERM=3160a)	9	7b, 8c, 9b, 10b, 11b, 12a, 12b, 16a, 17c
total High Wt PAHs	(ERM=9600a)	14	7b, 8c, 9b, 10b, 11b, 12a, 12b, 14a, 16a, 16b, 17b, 17c, 23a, 26c
Fluoranthene/toc	(SQC=300c)	20	7b, 7c, 8c, 9b, 10b, 11b, 12a, 12b, 13a, 14a, 16a, 16b, 17b, 17c, 18a, 18c, 22c, 23a, 35a, 36c
Acenaphthene/toc	(SQC=240c)	2	9b, 10b
Phenanthrene/toc	(SQC=240c)	14	7b, 8c, 9b, 10b, 11b, 16a, 17c, 12b, 13a, 16b, 18a, 22c, 12a, 26c

[a]Effects Range-Median values from Long et al. (1995)

[b]Effects Range-Median values from Long and Morgan (1990)

[c]Sediment Quality Criteria from U.S. EPA (1994)

2.3 Toxicity Results

Toxicity test results were compared with responses in controls to determine statistical significance. Note that amphipods are very sensitive to grain size and TOC, these variables were measured and taken into account when analyzing toxicity data. Results from phase 1 showed that 46.2% of the samples were significantly toxic (i.e., different from controls) in the amphipod tests (Figure 2), 26.6% were significantly toxic in either of the bivalve embryo tests (Figure 3a, b), and 40.5% were significantly toxic in the microbial bioluminescence tests (Figure 4). Overall, 69.2% of the samples were toxic in at least one of the four test end-points (Figure 5). Approximately 5.7% of the area was toxic in all four of these tests.

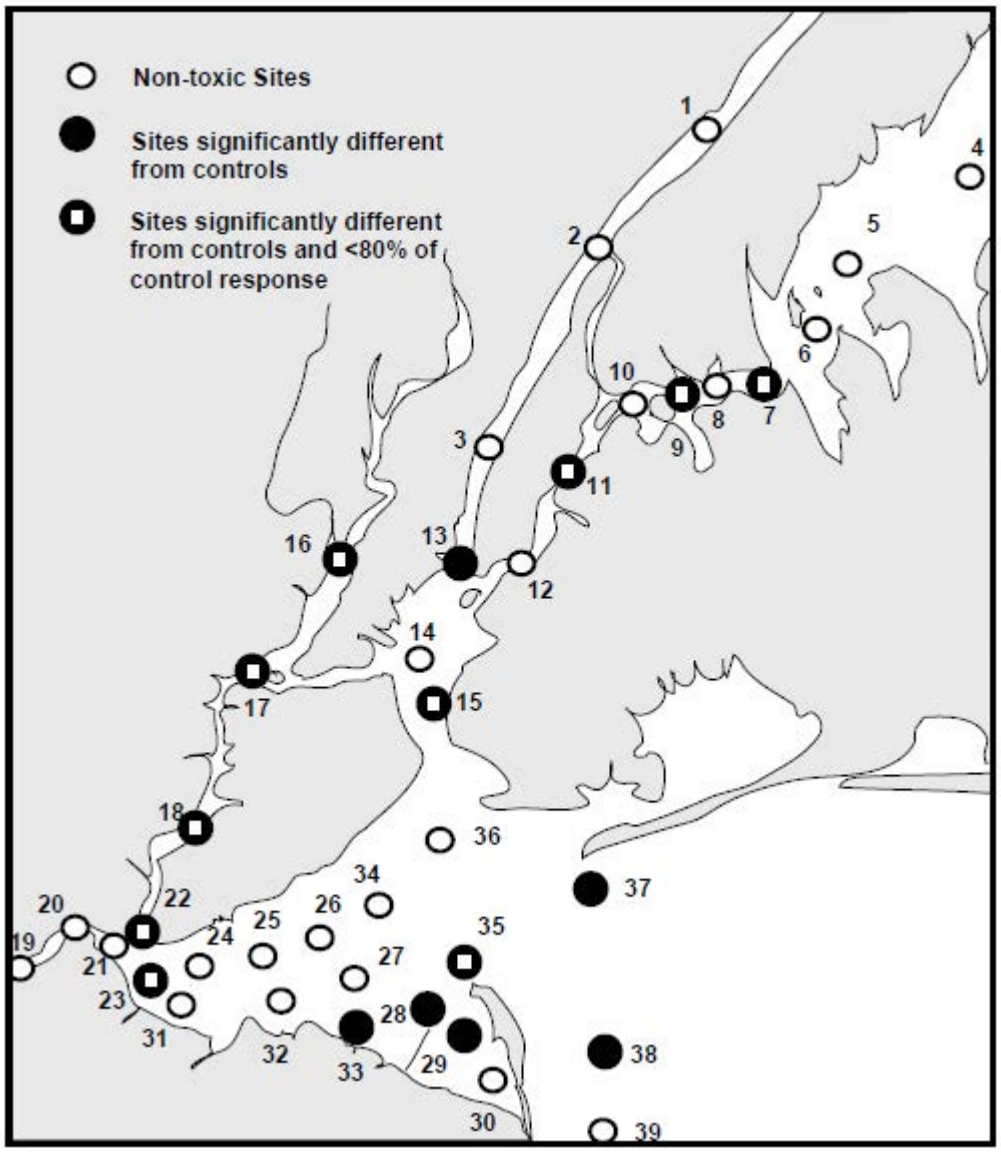


Figure 2: Sampling sites in which the sediments were significantly toxic to *Ampelisca abdita* (average of three stations, alpha <0.05).

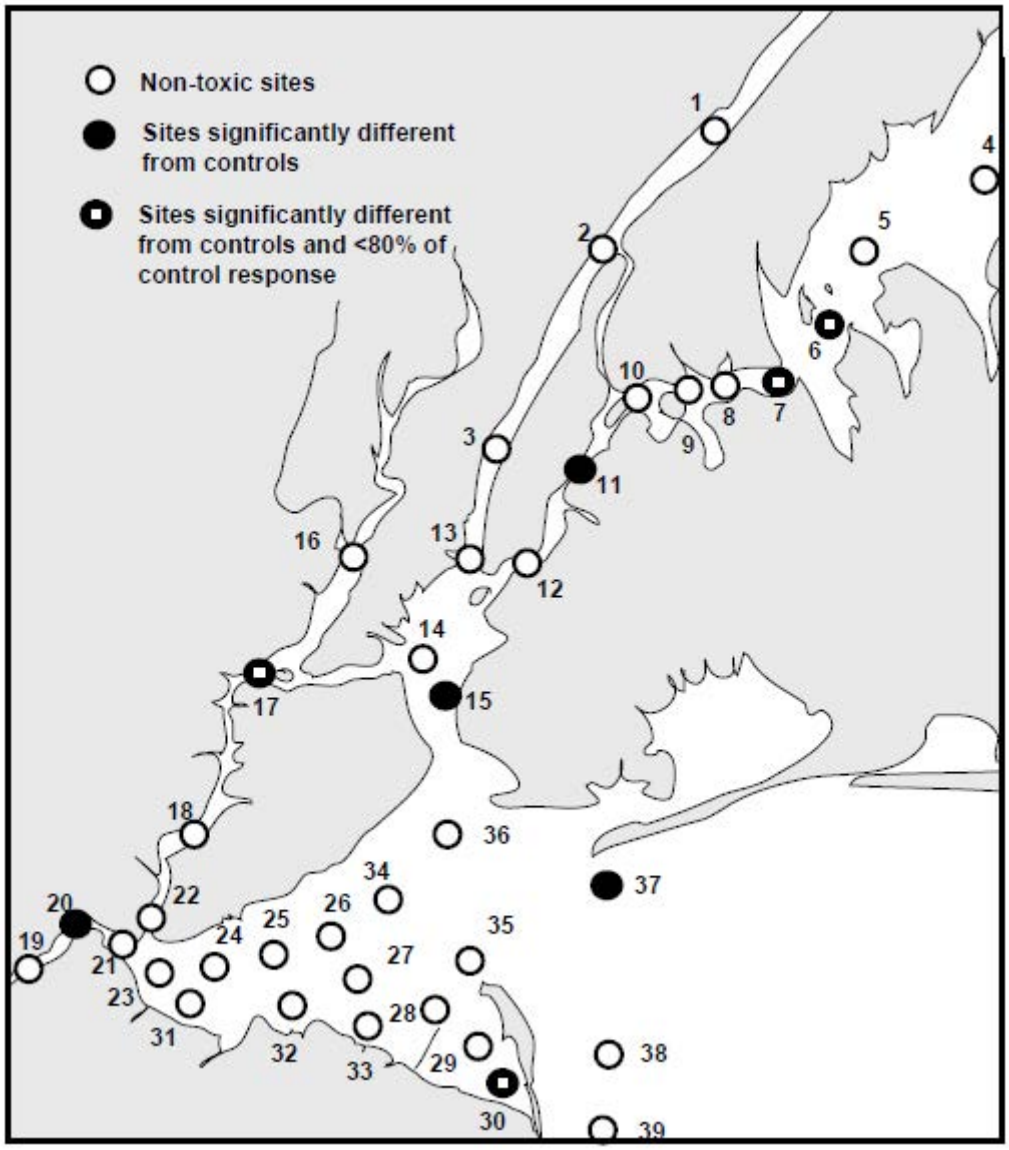


Figure 3: a) Sampling sites in which the sediment pore water were significantly toxic to *Mulinia lateralis* larvae (average of three stations, alpha <0.05).

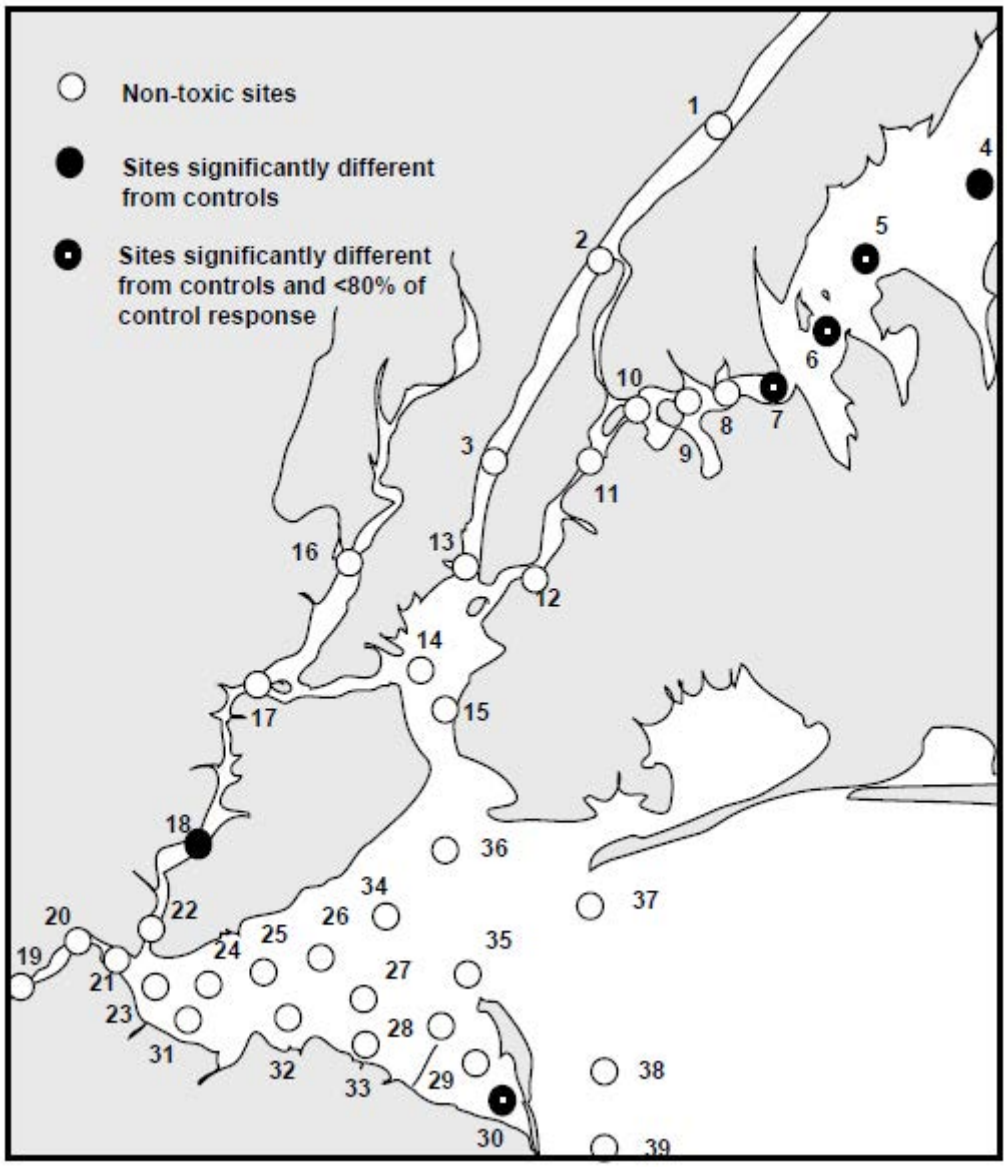


Figure 3: b) Sampling sites in which the sediment pore water were significantly toxic to *Mulinia lateralis* larvae normal development (average of three stations, alpha <0.05)

Within the Newark Bay/lower Passaic River/lower Hackensack River/northern Arthur Kill region, however, 85% of the area was toxic to amphipods. Toxicity extended throughout much of the study area and no clear boundary or limit to toxicity was apparent. Rather, each toxicity test indicated somewhat different patterns, possibly reflecting different sensitivities to the substances in the samples. Overall, toxicity was most severe in the East River and diminished eastward into Long Island Sound and southward into upper New York Harbor. Also, toxicity was relatively high in Newark Bay, Arthur Kill, and western Raritan Bay and diminished southward and eastward toward the mouth of the estuary. There was 100% mortality of amphipods observed in samples from Newark Bay, Arthur Kill and the East River. Toxicity was relatively low in the lower Hudson River, upper New York Harbor, and portions of lower New York Harbor and northern Raritan Bay, especially in samples that were relatively high in sand content.

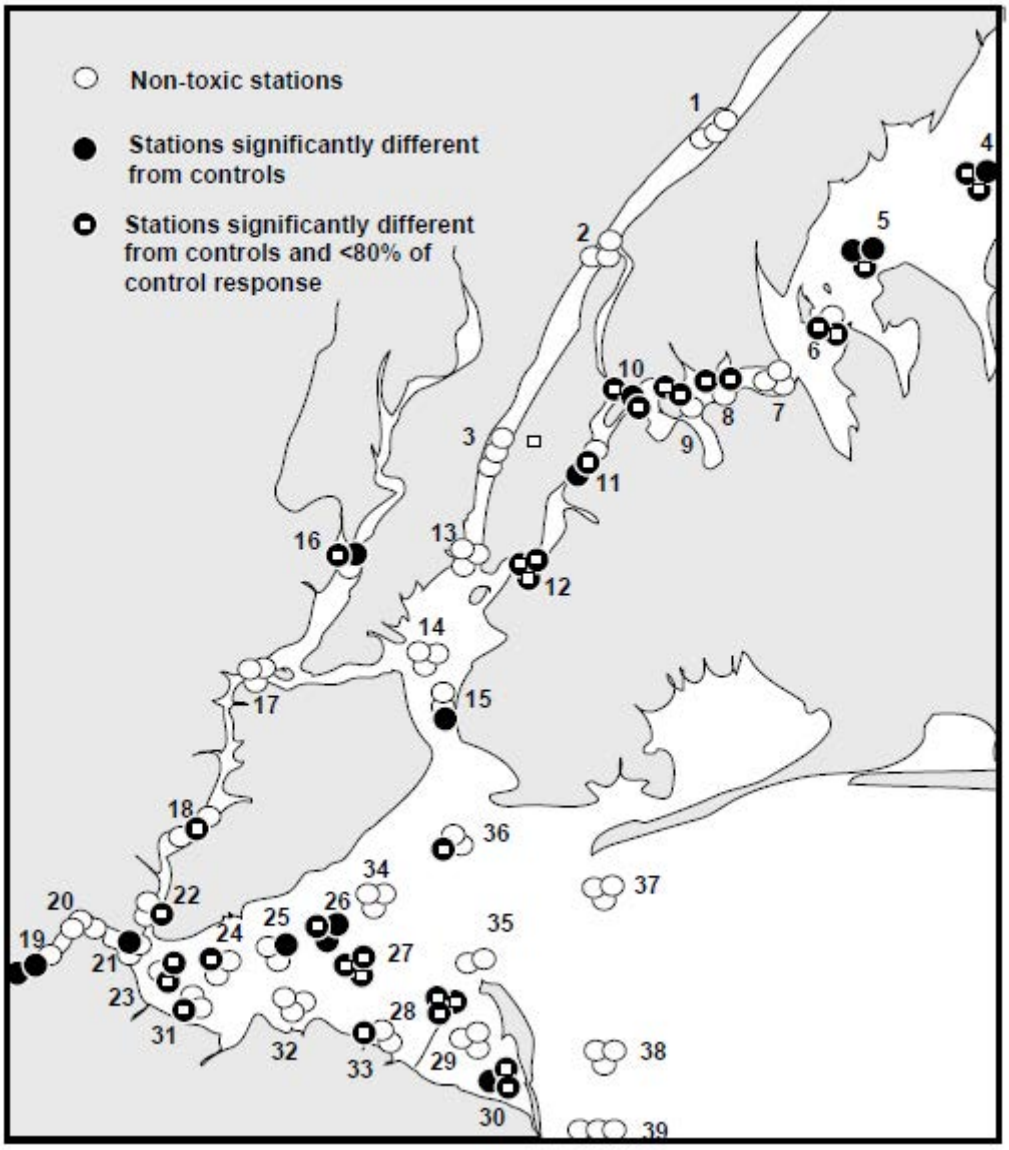


Figure 4: Sampling sites in which sediment extracts were significantly toxic to microbial bioluminescence (average of three stations, alpha <0.05).

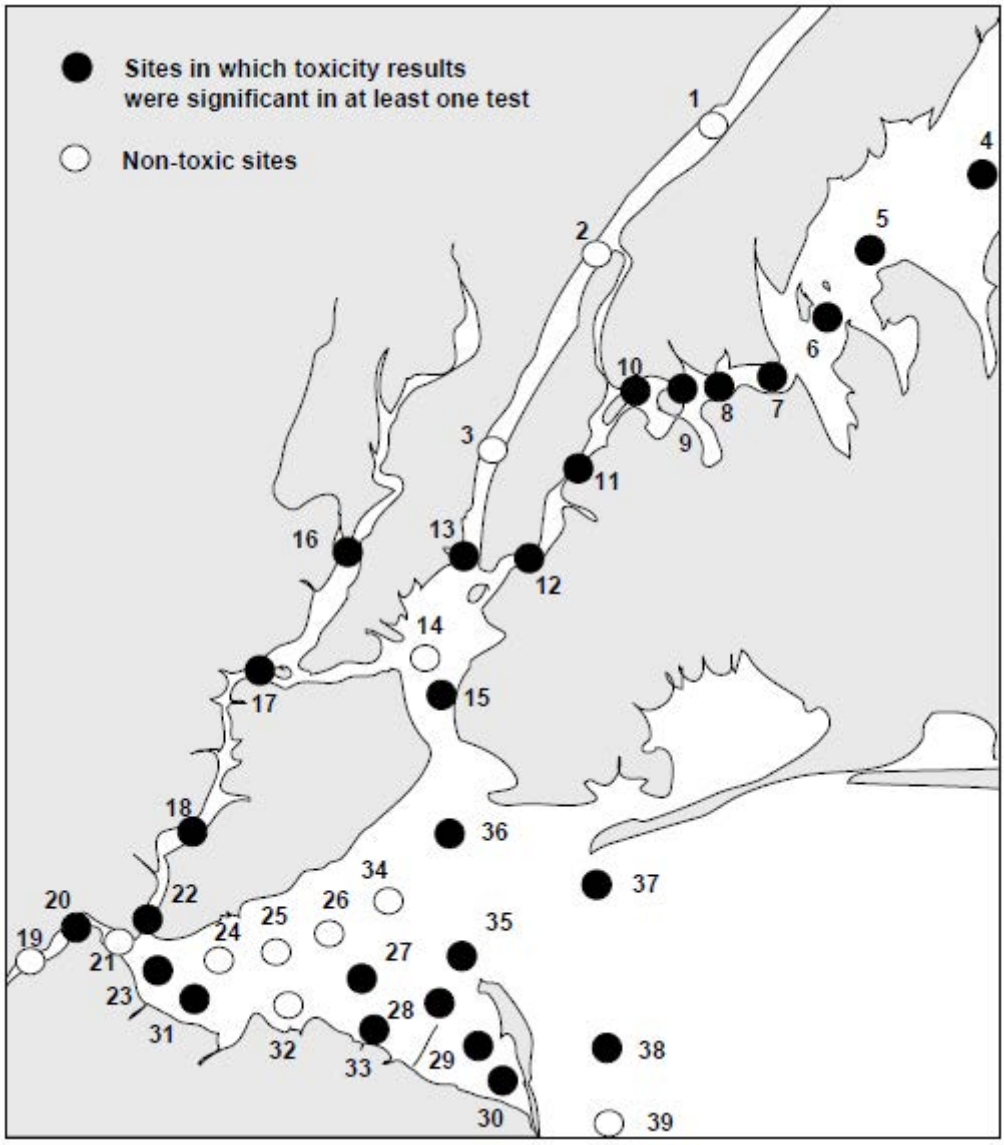


Figure 5: Sampling sites in which the mean toxicity test results were significantly different from controls in at least one of the four tests or not toxic in any test (average of three stations).

2.4 Benthic Infaunal Results

A total of 30,099 organisms representing 129 taxa were identified from the 72 stations. Polychaetes were the most numerous organisms present representing 48% of the total assemblage, followed in abundance by bivalves (23.1%) and oligochaetes (8.6%). Polychaetes represented 54.3% of the total number of taxa followed by amphipods (11.6%), bivalves (10.9%), other malacostracan taxa (7.8%) and gastropods (7%).

Taxa diversity and densities varied considerably among stations. The polychaetes, Mediomastus (LPIL) and Hypereteone heteropoda were the most widely distributed taxa being found at 83% and 79% of stations, respectively. ANOVA analyses were performed on transformed density data and taxa richness data. There were differences in mean densities and number of taxa among stations. Taxa diversity (H') varied from 0.7 to 2.4 and taxa evenness (J') ranged from 0.31 – 0.93.

Normal (station) and inverse (species) classification analyses were performed on the data set including only species representing a minimum of 0.26% of total individuals. This included 24 taxa accounting for 96.8% of the total assemblage. Numerical classification of the 72 stations can be interpreted on a three-group level (~14-20% level of similarity). Group A contained station 8 and was dominated by two taxa which were either absent or had low densities at the remaining stations. Station 8 had ERM and SQC exceedances of mercury, lead, total PAH, high and how weight PAH, flouranthene and phenanthrene.

Group B was represented by stations 17, 18, and 20. Stations 17 and 18 in Newark Bay, were shown to have exceedances of mercury, nickel, lead, zinc, p,p'DDE, p,p'-DDT, low and high weight PAHs, flouranthene, and phenanthrene (Table 2). By contrast, Group C represented by stations 2, 4, 7, 42 and 45 had the highest station densities and did not show any exceedances of any contaminant. Likewise, Group D representing stations 47, 40, 41 and 48 had no exceedances of any of the listed contaminants (Table 2). Relating infaunal results with chemistry and toxicity data is difficult but the stations with exceedances of ERM and SQC were shown to be stations where toxicity was observed, such as Stations 17 and 18 in the Newark River (Table 2, Figures 3-5).

2.5 Correlations

The concentrations of individual and total simultaneously extracted metals (SEM) were not significantly correlated with the results of the tests of amphipod survival, bivalve survival, and bivalve development. Similarly, the SEM/Acid Volatile Sulfide (AVS) ratios, which is an indicator of potential toxicity to sediment-dwelling organisms, was not significantly correlated with any of the tests, and, a probably spurious positive association was indicated with amphipod survival, bivalve survival, bivalve development, and microbial bioluminescence. However, the concentrations of many of the individual simultaneously extracted metals, notably lead, were significantly correlated with the Microtox® results.

The data from each of the individual bioassay tests were correlated with each other to different degrees and indicated overlap in toxicity patterns. Toxicity to amphipods and microbial bioluminescence in samples from the Hudson Raritan was highly correlated with the concentrations of polycyclic aromatic hydrocarbons

(PAHs; see Table 3). The concentrations of these compounds in highly toxic samples often exceeded ERMs (Table 2) and in stations where exceedances were noted, diversity was reduced and mortality was high. Toxicity to amphipods and microbial bioluminescence were moderately correlated with some trace metals, such as lead and zinc. Generally, correlations between the results of the bivalve embryo tests and the concentrations of all chemicals were poor (Table 3).

Table 3. Spearman-rank correlations (Rho, corrected for ties) between four toxicity end-points (as percent of controls) and the concentrations of PAHs in Hudson-Raritan Estuary sediments (n=38). Note that the larger the number, the greater the response, the more negatively affected by an increased concentration of each PAH.

	Amphipod	**Bivalve**		**Bivalve**		**Microbial**
	Survival	**Survival**		**Development**		**Bioluminescence**
naphthalene	-0.524*	-0.22	ns	-0.198	ns	-0.577**
2-methylnaph.	-0.512*	-0.289	ns	-0.294	ns	0.653***
1-methylnaph.	-0.552**	-0.306	ns	-0.291	ns	-0.673***
biphenyl	-0.537*	-0.246	ns	-0.263	ns	-0.640***
2,6-methylnaph.	-0.567**	-0.337*		-0.32	ns	-0.695***
acenaphthylene	-0.414*	-0.247	ns	-0.208	ns	-0.652***
acenaphthene	-0.595**	-0.272	ns	-0.224	ns	-0.620**
1,6,7-trimethylnaph.	-0.673***	-0.342*		-0.258	ns	-0.625***
fluorene	-0.623***	-0.31	ns	-0.27	ns	-0.634***
phenanthrene	-0.579**	-0.331*		-0.24	ns	-0.641***
anthracene	-0.576**	-0.321	ns	-0.283	ns	-0.673***
1-methylphenanth.	-0.579**	-0.371*		-0.252	ns	-0.636***
fluoranthene	-0.574**	-0.264	ns	-0.163	ns	-0.608**
pyrene	-0.589**	-0.327*		-0.233	ns	-0.615**
benz(a)anthracene	-0.561**	-0.279	ns	-0.188	ns	-0.604**
chrysene	-0.522*	-0.292	ns	-0.184	ns	-0.526*
benzo(b)fluoranth.	-0.582**	-0.283	ns	-0.215	ns	-0.615**
benzo(k)fluoranth.	-0.464*	-0.16	ns	-0.1	ns	-0.489*
benzo(e)pyrene	-0.592**	-0.262	ns	-0.233	ns	-0.631***
benzo(a)pyrene	-0.538*	-0.279	ns	-0.228	ns	-0.615**
perylene	-0.580**	-0.289	ns	-0.236	ns	-0.563**
indeno(1,2,3)pyrene	-0.549**	-0.207	ns	-0.165	ns	-0.587**
dibenzo(a,h)anth.	-0.549**	-0.291	ns	-0.224	ns	-0.628***
benzo(g,h,i)perylene	-0.480*	-0.249	ns	-0.196	ns	-0.630***
Group A(petroleum)	-0.468*	-0.293	ns	-0.315	ns	-0.625***
Group B(combustion)	-0.576**	-0.294	ns	-0.206	ns	-0.602**
sum low PAHs	-0.592**	-0.32	ns	-0.266	ns	-0.650***
sum high PAHs	-0.471*	-0.128	ns	-0.06	ns	-0.512*
sum total PAHs	-0.495*	-0.312	ns	-0.241	ns	-0.603**
acenaphthene/toc	-0.641***	-0.164	ns	-0.083	ns	-0.437*
phenanthrene/toc	-0.571**	-0.178	ns	-0.055	ns	-0.398*
fluoranthene/toc	-0.559**	-0.139	ns	-0.022	ns	-0.418*
*p<0.05, **p<0.001, ***p<0.0001						

3. SUMMARY

PAHs concentrations in toxic samples were greater on average than concentrations in nontoxic samples and at several stations were above ERM and SQC thresholds (Table 2). The strong relationships between measures of toxicity and the concentrations of the PAHs were driven, in large part, by the samples from the upper East River that were highly toxic and highly contaminated with PAHs. The concentrations of some trace elements and chlorinated pesticides were correlated with the inhibition of microbial bioluminescence. These were also stations where concentrations of contaminants were greater than ERM and SQC thresholds. Results of Spearman rank correlations of contaminant concentrations and the bivalve embryo tests were rarely correlated. Spearman rank correlations of contaminant concentrations and amphipod survival in other samples showed significant positive relationships with higher concentrations of chlorinated hydrocarbons, especially PCBs, pesticides, and dioxins. The Spearman rank correlation test also showed that amphipod survival decreased with increasing concentrations of lead, mercury, and zinc in the samples (Table 3).

Approximately 25% of the study area exhibited toxicity in the bivalve embryo survival tests; 30% was toxic in the bivalve embryo development tests; 38% was toxic in the amphipod survival tests; and approximately 39% of the area was toxic to microbial bioluminescence. Approximately 5.7% of the area was toxic in all four of these tests. Since a probabilistic, random-stratified sampling design was not used in Phase 1, the estimates of the spatial extent of toxicity may not be precise.

Within the Newark Bay/lower Passaic River/lower Hackensack River/northern Arthur Kill region, however, 85% of the area was toxic to amphipod survival – these locations also had stations where many contaminants were above ERM and SQC threshold values (Table 2). Since a probabilistic, random-stratified sampling was used in Phase 2, the estimate of the spatial extent of toxicity in the Newark Bay area may be much more accurate that the estimate for the entire survey area.

Chapter 5
Delaware Bay

1 STUDY AREA DESCRIPTION

Delaware Bay is one of the largest drowned river valley coastal plain estuaries on the US east coast. Dilution of sea water by fresh water flow is evident on the continental shelf beyond the mouth of the bay. Within the bay, salinity is generally above 20 ppt up to the region where the bay begins to narrow near Money Is., NJ. Salinity steadily decreases in the upstream direction toward Philadelphia. The water column may exhibit salinity stratification but is generally well mixed to the bottom, even in the channel areas during storms. From southern Philadelphia upstream, the river is tidal fresh.

The major source of freshwater input is from the Delaware River. The watershed drains portions of New York, Pennsylvania, New Jersey and Delaware. The largest tributary is the Schuylkill River, which joins the Delaware River in Philadelphia. It is a major source of both conventional and toxic contaminants, including PCBs. Philadelphia is one of the oldest and largest urban centers on the US east coast with a metropolitan area population over 1.5 million. Philadelphia has numerous municipal point and non-point source releases, industrial and petrochemical discharges, and extensive commercial and naval ship traffic and port facilities. Trenton, NJ, Camden, NJ, and Wilmington, DE are also industrial centers with numerous municipal and industrial contaminant sources. Three of the basin's States maintain fish consumption advisories due to PCBs and chlorinated pesticides.

Sampling Details

To characterize the entire system, samples were taken from offshore stations on the continental shelf north and south of the bay mouth, throughout the open bay, up the estuary into tidal fresh areas, and up to the fall line. The system was divided into 20 sampling strata with 73 sample sites (Figure 1). Strata 19 and 20 were added to the original design to include the tidal-fresh area up to the fall line. Several tributary sampling stations were also established to assist in local investigations and site specific evaluations.

2. RESULTS

2.1 Important physical drivers

Outside of three relict river channels and actively dredged areas, most of the bay is less than 10 m deep. The ancient river channels range from less than 10 to 46 m deep and run north-west from the mouth of the bay. Tide height is 1.6m. At the mouth of the bay, Cape May shoals restrict the entrance to the bay on the north side, with characteristic flood tidal shoals behind it. Tidal flow velocities are strongest in the channels, and net sediment flux is actually in the upstream direction in the main bay area because ebb tidal velocities are relatively weaker due to the shoreline configuration and Coriolis effects. Dilution of sea water by fresh water flow is evident on the continental shelf beyond the mouth of the estuary where salinities are in the mid-20s ppt. Sediments in the central bay are characteristically coarser in grain size, and the bathymetry exhibits distinct sand wave and sand ribbon patterns perpendicular to channels and boundary shoals from prehistoric river levees. Broad flat shoals in the south and the large north-east expanse of the bay are characteristically fine grained depositional zones with few bathymetric features. Further upstream, the estuary narrows significantly and the influence of lateral water movement on depositional patterns is reduced.

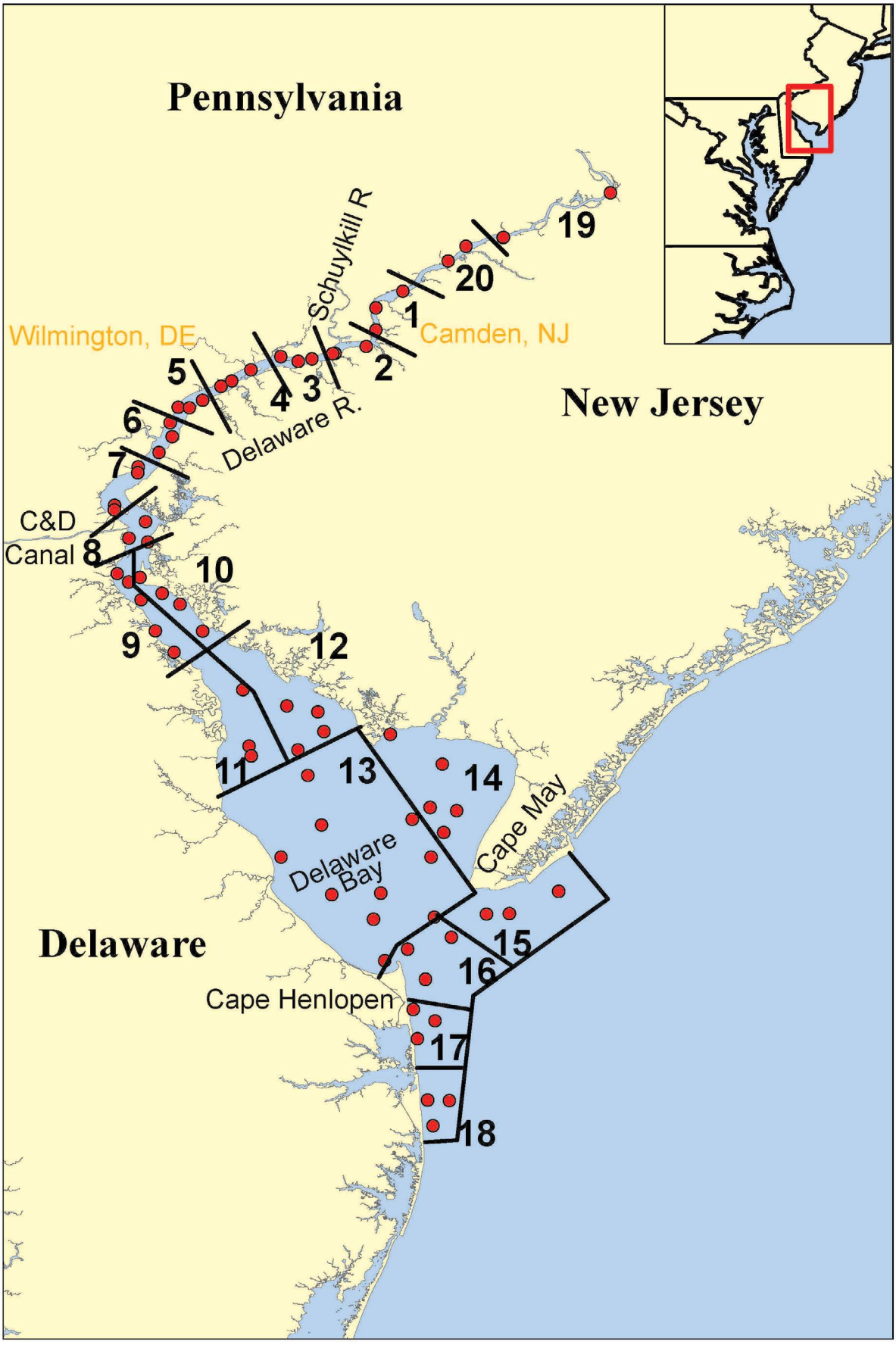


Figure 1. Sample strata (large type) and stations in Delaware Bay and surrounding areas.

2.2 Contamination results

The tidal-fresh portion of the study area in the vicinity of Philadelphia was heavily contaminated with metals, pesticides, PCBs and PAHs. The freshwater/saltwater mixing zone and selected portions of the upper estuarine zone to below the C&D canal were also contaminated. Contaminant concentrations varied greatly from station to station, depending on exact location. In general, the concentrations of all chemical constituents were either relatively high or low at a given site, that is, where organic contaminant concentrations were high, metals were high. Examples of stations with contamination by one class of chemicals but not others were rare. Most of the freshwater sites exceeded one or more sediment quality guideline Effects Range- Low (ERL) concentrations for PCBs and/or PAHs (Table 1). While the total dioxin and furan concentrations were relatively high in the estuarine sites, the vast majority was in the form of the octachlorinated compounds that are three orders of magnitude less toxic than the tetrachloro congeners. The concentration of DDT and it's breakdown products showed a similar distribution as PCBs, but elevated concentrations were not distributed as far downstream. All but two samples from the freshwater zone exceeded the ERL for p,p'DDE. Seven samples exceeded the Effects Range – Median (ERM) guideline. Eleven samples in the estuarine zone exceeded the ERL, of which two exceeded the ERM. The concentration of other chlorinated pesticides was dominated by chlordane and related cyclodienes. These compounds were found over a more widespread area than DDT. Metals contamination followed the same pattern as organic contaminants, with selected stations exhibiting elevated concentrations of multiple metals. Metals concentrations were frequently above ERL concentrations in the freshwater and upper estuarine zone. Mercury, nickel and, zinc exceeded ERMs in some locations.

Table 1. Spatial extent (km^2) of area where ERL or ERMs were exceeded in 20 strata in Delaware Bay sediments.

Stratum	Total Area	area ERL	area ERM
19	13.90	13.89	9.26
20	13.90	13.89	4.63
1	7.09	7.09	4.73
2	10.87	10.87	7.24
3	18.33	18.33	6.11
4	16.81	16.81	5.60
5	14.27	14.27	9.51
6	21.81	21.81	0.00
7	35.75	35.75	0.00
8	38.77	38.77	12.92
9	55.37	55.37	13.84
10	69.57	69.57	17.39
11	247.71	61.93	0.00
12	210.95	0.00	0.00
13	891.29	0.00	0.00
14	336.16	67.23	0.00
15	96.52	0.00	0.00
16	97.41	0.00	0.00
17	83.99	28.00	0.00
18	66.32	0.00	0.00
Total	**2346.78**	**473.58**	**91.25**
%		**20.18**	**3.89**

2.3 Toxicity Results

Bioassay results were highly variable. Significantly elevated amphipod mortality was observed at only 3 stations, which were among the most polluted with heavy metals and PAHs (Table 2). Significant toxicity in the sea urchin fertilization test was limited to saline stations. The Microtox^{R} results were the most variable of the toxicity bioassays both in terms of response level and distribution of significant responses. The most extreme values were from the vicinity of the C&D canal. The P-450 results were significant primarily in the freshwater strata and upper estuarine stations. This bioassay tracked very closely with PAH concentrations and chlorinated dioxins, furans, and/or PCBs regardless of salinity.

2.4 Benthic Infaunal Results

A total of 20,060 organisms, representing 239 taxa, were identified, including the small watershed, special study samples. A small proportion of stations contained a large number of species that were very limited in spatial distribution. This makes interpretation of the data difficult using conventional statistical methods. Organism density was highly skewed with respect to the density of individual taxa within stations, and between stations as a whole. High density stations were generally dominated by very large numbers of an individual taxon. There was no apparent pattern, with high and low density stations in all salinity zones. Most of the freshwater stations were dominated by Tubificids and/or *Limnodrilus hoffmeisteri*, which are commonly regarded as pollution indicator taxa. Species diversity and abundance were generally lowest in the freshwater/saltwater interface zone.

Table 2. Spatial extent of significant sediment toxicity by stratum in Delaware Bay (square kilometers and percent of study area), as estimated by laboratory bioassay tests.

Stratum	Total Area	Amphipod Mortality	Sea Urchin Fertilization	Microtox	P450 B[a]P eq
19	13.90	0	0	0	4.63
20	13.90	0	0	4.63	4.63
1	7.09	0	0	2.36	4.72
2	10.87	0	0	7.24	7.24
3	18.33	6.11	0	6.11	6.11
4	16.81	0	0	5.60	11.20
5	14.23	4.76	4.76	9.52	9.52
6	21.81	0	7.27	14.54	0
7	35.75	0	11.92	11.92	0
8	38.77	12.92	0	12.92	12.92
9	55.37	0	0	27.68	0
10	69.57	0	0	52.17	0
11	247.71	0	0	185.79	0
12	210.95	0	0	105.48	0
13	891.29	0	89.13	445.65	0
14	336.16	0	134.46	268.92	0
15	96.52	0	0	32.17	0
16	97.41	0	0	64.94	0
17	83099	0	0	0	0
18	66.32	0	0	0	0
Total km^2	2346.78	23.79 (1.01%)	247.54 (10.55%)	1312.06 (55.91%)	60.97 (2.6%)

A cluster analysis technique (called nodal analysis) was developed for the Delaware and Chesapeake studies to detect patterns of species associations that identify similar biological communities based on species composition. Cluster analyses resolved into nodes for 1-Tidal-fresh muddy sites, 2- Tidal-fresh sandy sites, 3- Fresh/Salt transition, 4- Upper (oligohaline) estuary, 5- Lower estuary depositional flats, 6- Deep lower estuary/ocean sites (Figure 2). The lower estuary deep sites were generally found in the ancient drowned river channels, as opposed to depositional flats which were sometimes adjacent to each other. One site (#64, see Figure 1) at the mouth of the Bay was unique. The site is a very poor habitat by all biological measures. It is located on a mound in the ebb tidal shoal and is probably subject to severe physical stresses during tidal flux and storms. Its benthic community exhibits characteristics of a stressful habitat. However, from a contaminant point of view, it is a pristine site. It is a drowned dune composed of 99% sand with 0.07% TOC.

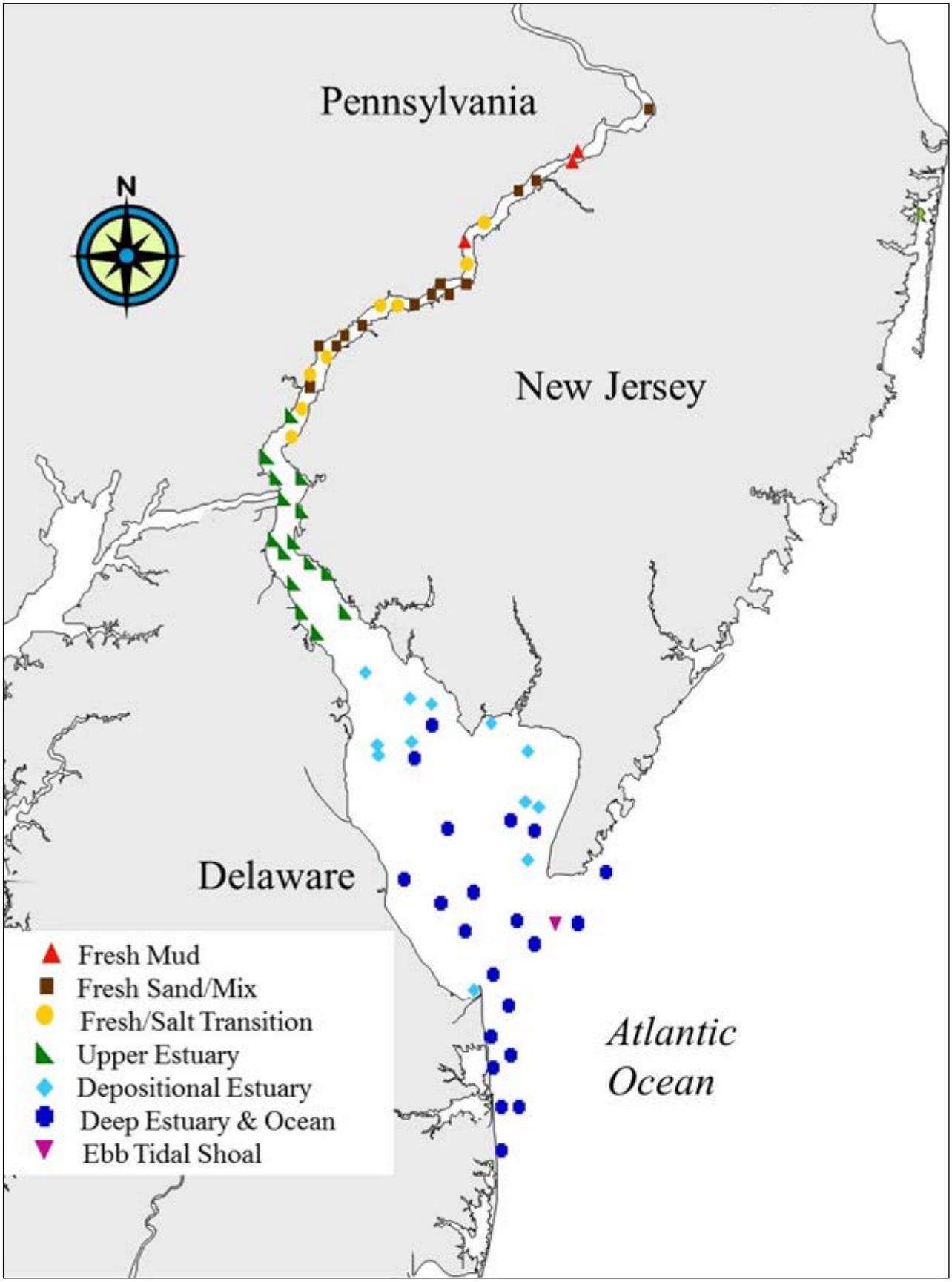


Figure 2. Benthic community nodal analysis results for Delaware Bay

2.5 Correlations

Species richness was strongly correlated with grain size. The majority of the biologically diverse stations were found on the continental shelf in coarse grained sediment, with some estuarine stations demonstrating this trend also. This relationship between species richness and sediment texture may prove to be a useful modifying factor in assessing coastal community indices, similar to how TOC and grain size are used to normalize organic contaminants and metals concentrations. Animal abundance however, did not follow the trend, but rather peaked in fine grained sediments. The relationship between sediment texture and abundance or number of species did not apply in the freshwater strata. This may be due to a combination of factors ranging from altered grain size characteristics due to dredging to altered species composition due to contaminant impacts and structural habitat alterations.

Because chemical concentrations tended to be either high or low for all constituents at a given station, interpretation of benthic community and toxicological results with respect to cause and effect is difficult. Direct statistical correlations of toxicity with individual chemical constituents were only discernible where concentrations were at the extremes of observed concentrations. Bioassay results tended to show the highest significance at stations with high pollutant concentrations, but not all stations with high pollutant concentrations showed highly significant responses. This was interpreted as an indication that organisms can tolerate chemical contamination up to a certain threshold level, beyond which effects are observable. Below these levels, the relationships are influenced by a myriad of other factors.

3. SUMMARY

PCB contamination is prevalent in the tidal fresh and upper estuarine zone, but not in the main Bay. Shoal areas have higher concentrations than the channels. Some of the worst pollution for a variety of contaminants is in the vicinity of the Schuylkill River and Little Tinicum Island, as well as locations above Philadelphia. Whether the PCBs accumulation rates in the channel are lower, or the sediment-bound material has been removed by previous dredging and is prevented from settling due to shipping activities and maintenance dredging has not been addressed. According to a Monitoring Report from the Delaware River Basin Commission (DRBC, 2004), concentrations of PCBs and chlorinated pesticides had not declined to acceptable levels, and inputs continue from municipal and non-point releases.

More than 90% of the Virginian EMAP Province stations were below the ERL for total PCBs (EPA, 1994), whereas 55% of the freshwater stations in the Delaware River exceeded the ERL. Similarly, concentrations of chlordane and DDT in the tidal fresh reaches of the Delaware estuary were routinely above the 90th percentile of observed concentrations. Because metals have naturally occurring sources, the concentration of metals which constitute anthropogenic enrichment (normalized to Al) is element specific. Also, the data are highly variable from station to station, but selected locations in the upper reaches of Delaware Bay are enriched with As, Cd, Cu Hg, Pb, Sn, and Zn, compared to the Virginian Province database (EPA, 1994). Chromium and Ni showed borderline enrichment levels. Riedel and Sanders (1998) concluded that seston

(phytoplankton and other suspended particulate material and/or microorganisms) were substantially enriched with Pb and Zn and moderately enriched with As, Se and Cd in Delaware Bay. The DRBC (1994) identified multiple sources for metals contamination, and concluded that for Cd, Cu, Pb, Ag, and Zn, natural sources are unlikely to account for the observed distribution of these metals. They also concluded that the Delaware and Schuylkill Rivers are not the predominant source, but that point sources on the mainstem and smaller tributaries, and non-point sources were the major sources of metals contamination.

Low weight ($\leq$ 3 rings) and high weight ($\geq$ 4 rings) PAHs were generally present in equal concentrations on a mass basis. Alkyl-substituted PAHs were much more prevalent in the low weight category than in the high weight category. This indicates a pyrogenic source for the high weight PAHs, whereas the low weight PAHs are likely a mixture of pyrogenic sources and fuel spills. The mass of PAHs in the sediment was much higher than previously documented.

Station 56 (a depositional site behind Cape Henlopen) is an anomalous site with respect to the surrounding stations. The sediment grain size characteristics are much more fine grained that the surrounding area. Organic carbon content of the sediment was also high. Clearly this is a consequence of the physical constraints on current velocity imposed by the natural shoals behind Cape Henlopen and the artificial breakwater constructed to provide protected anchorage for ships in transit. The actual sampling site is adjacent to, but not in the anchorage area. Contaminant levels are elevated above other stations in the stratum, but only slightly, and all concentrations are low. However, both the Microtox® and sea urchin fertilization bioassays showed significant responses. No explanation for the results is readily apparent, but this area may warrant further investigation.

The Partnership for the Delaware Estuary monitors contaminants in the water column and fish tissue, but not sediments. Zinc, copper, and nickel exceeded EPA water quality criteria in selected locations. Arsenic, cyanide, and mercury also indicate potential exceedances. Fish tissues are assessed for carcinogens and systemic toxic substances. Fish tissue screening values were not exceeded for systemic contaminants for which toxicity limits exist, but chlorinated pesticides, PCBs, and dioxin/furans exceed risk-based carcinogen screening values in fish tissue in specific species and locations in the estuary.

Chapter 6
Chesapeake Bay

1. STUDY AREA DESCRIPTION

Chesapeake Bay is the largest estuarine system in the contiguous United States. Including tidal tributaries, the Bay has approximately 18,694 km of shoreline (more than the entire US West Coast). The watershed is over 165,000 km^2 (64,000 miles^2), and includes portions of six states (Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia plus the District of Columbia). The population of the watershed exceeds 15 million people. There are 150 rivers and streams in the Chesapeake drainage basin. Within the watershed, five major rivers the Susquehanna, Potomac, Rappahannock, York and James provide almost 90% of the freshwater to the Bay (Figure 1 a-c). The Bay receives an equal volume of water from the Atlantic Ocean through tidal exchange. Salinity varies from fresh in Susquehanna Flats to 34ppt at the mouth of the bay.

Toxic contaminants enter the Bay via atmospheric deposition, dissolved and particulate runoff from the watershed or direct discharge. While contaminants enter the Bay from several sources, sediments accumulate many toxic contaminants and thus reveal the status of input for these constituents. In the watershed, loading estimates indicate that the major sources of contaminants are point sources, stormwater runoff, atmospheric deposition, and spills. Point sources and urban runoff in the Bay proper contribute large quantities of contaminants. Pesticide inputs to the Bay have not been quantified but estimates range from 584-4,754 kg of insecticides and 4,275-17,108 kg of herbicides (Hartwell, 2011). Baltimore Harbor and the Elizabeth River remain among the most contaminated areas in the Unites States.

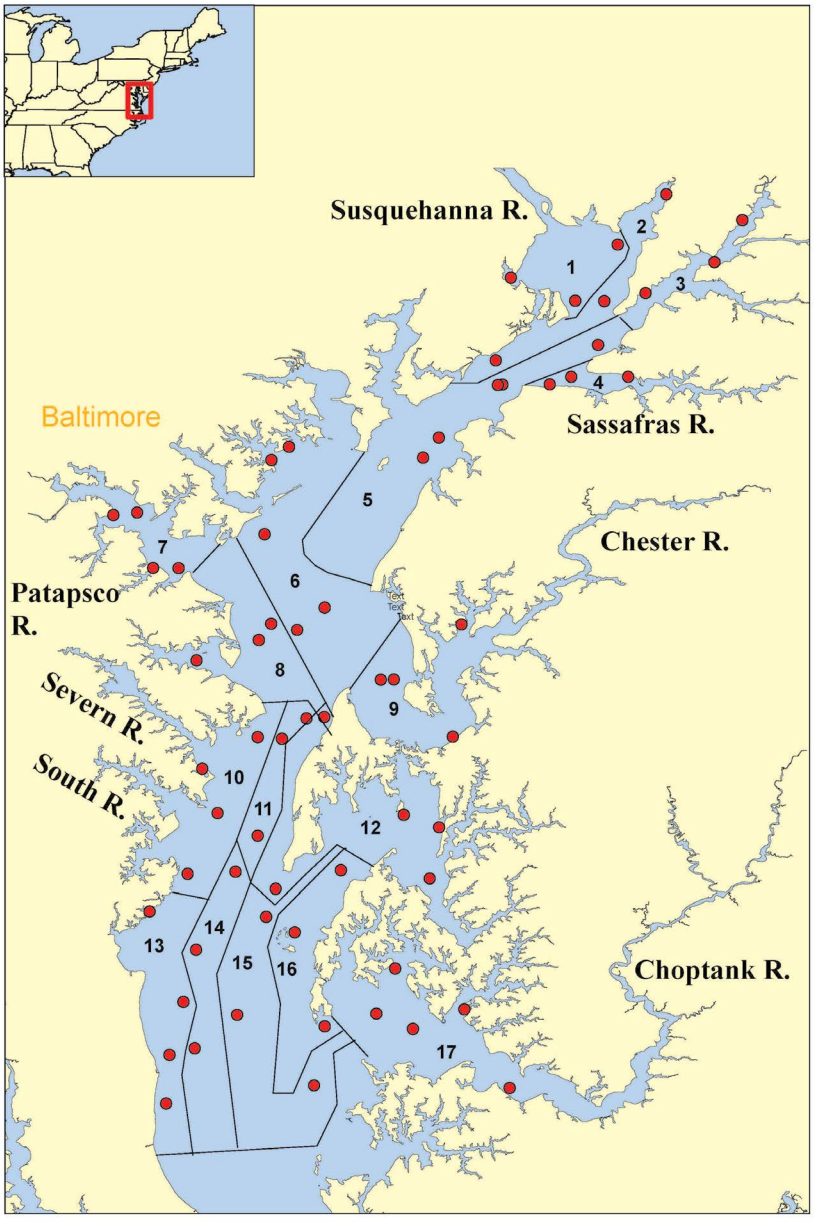


Figure 1a. Chesapeake Bay northern strata and sampling sites.

In the mainstem, deep sediment core analyses indicate that sediment accumulation rates are 2-10 times higher in the northern Bay than in the middle and lower Bay, and that sedimentation rates are 2-10 times higher than before European settlement throughout the Bay (NOAA 1998). The core samples show a decline in selected PAH compounds over the past several de-

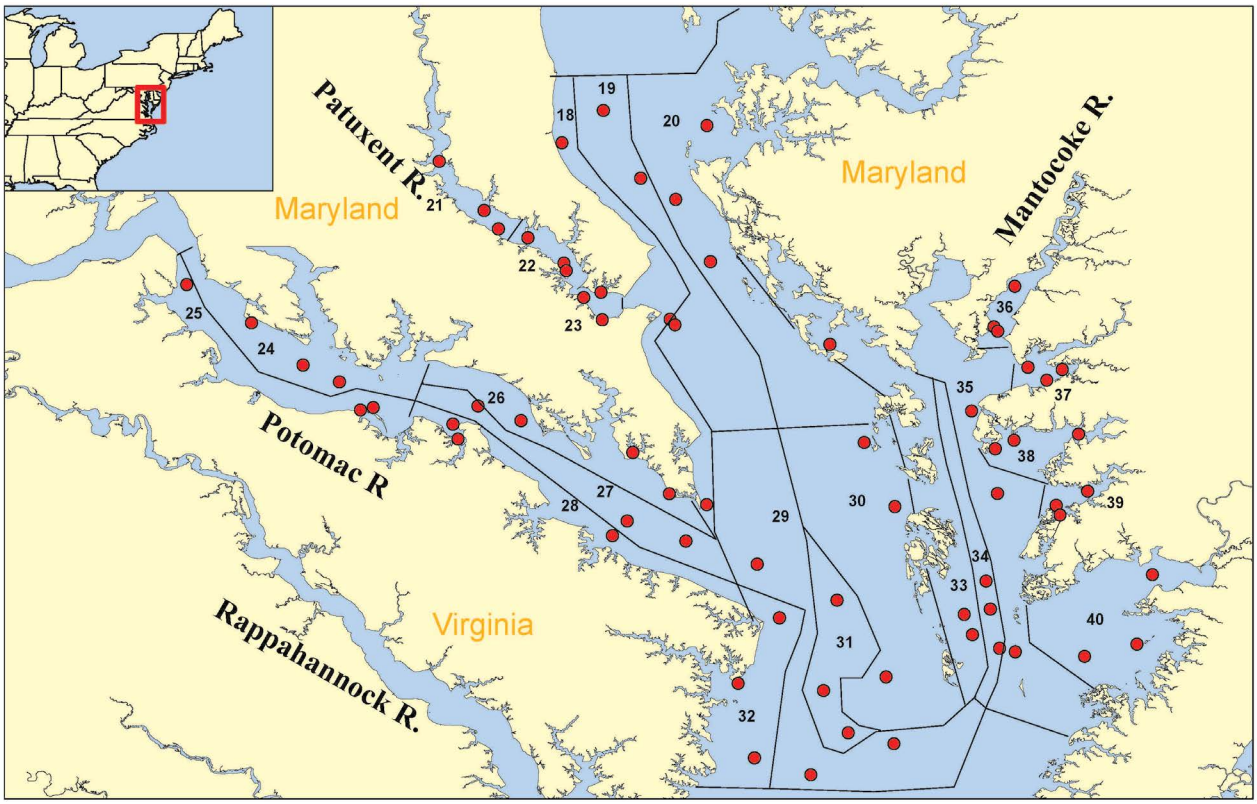


Figure 1b Chesapeake Bay middle strata and sampling sites.

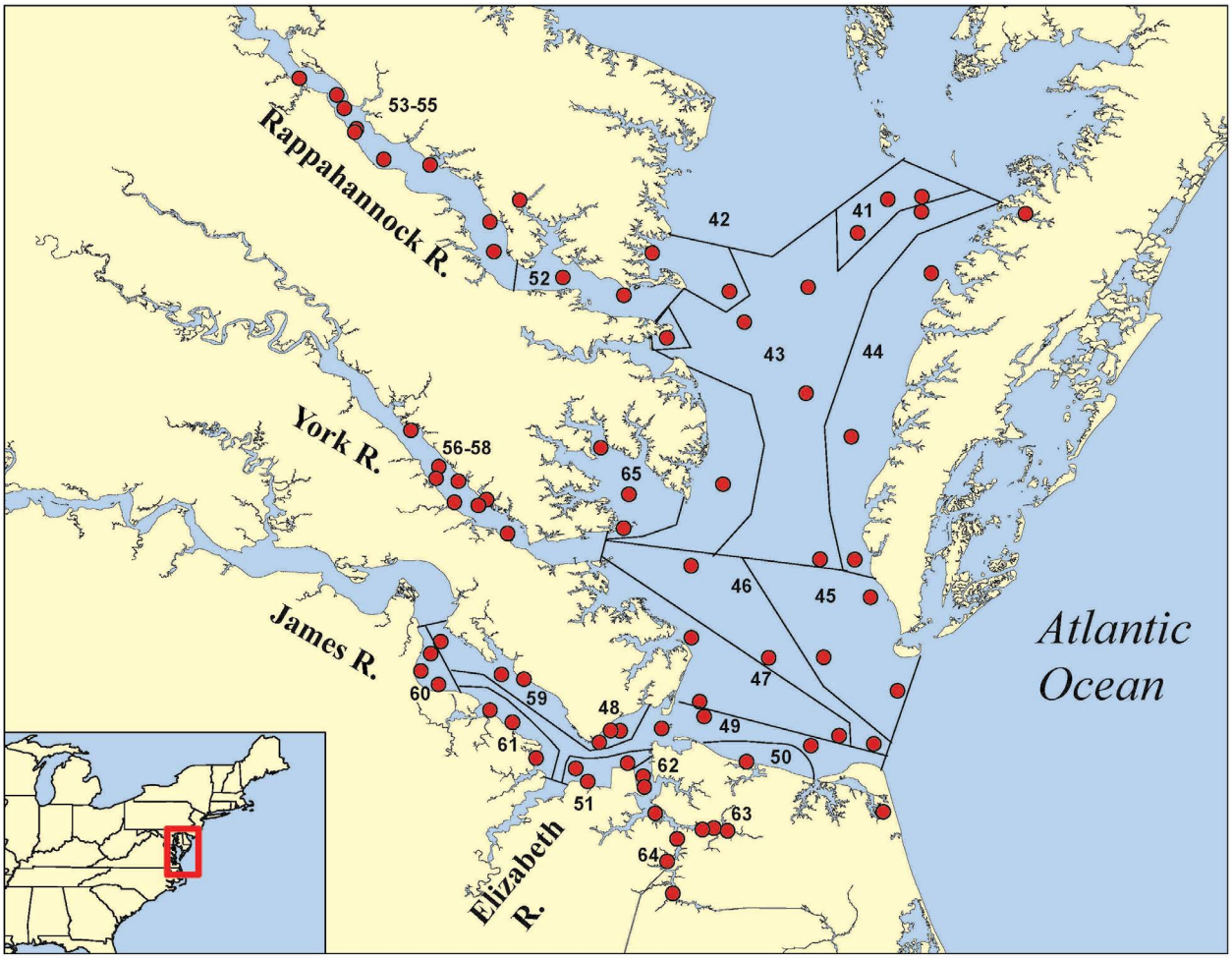


Figure 1c. Chesapeake Bay southern strata and sampling sites.

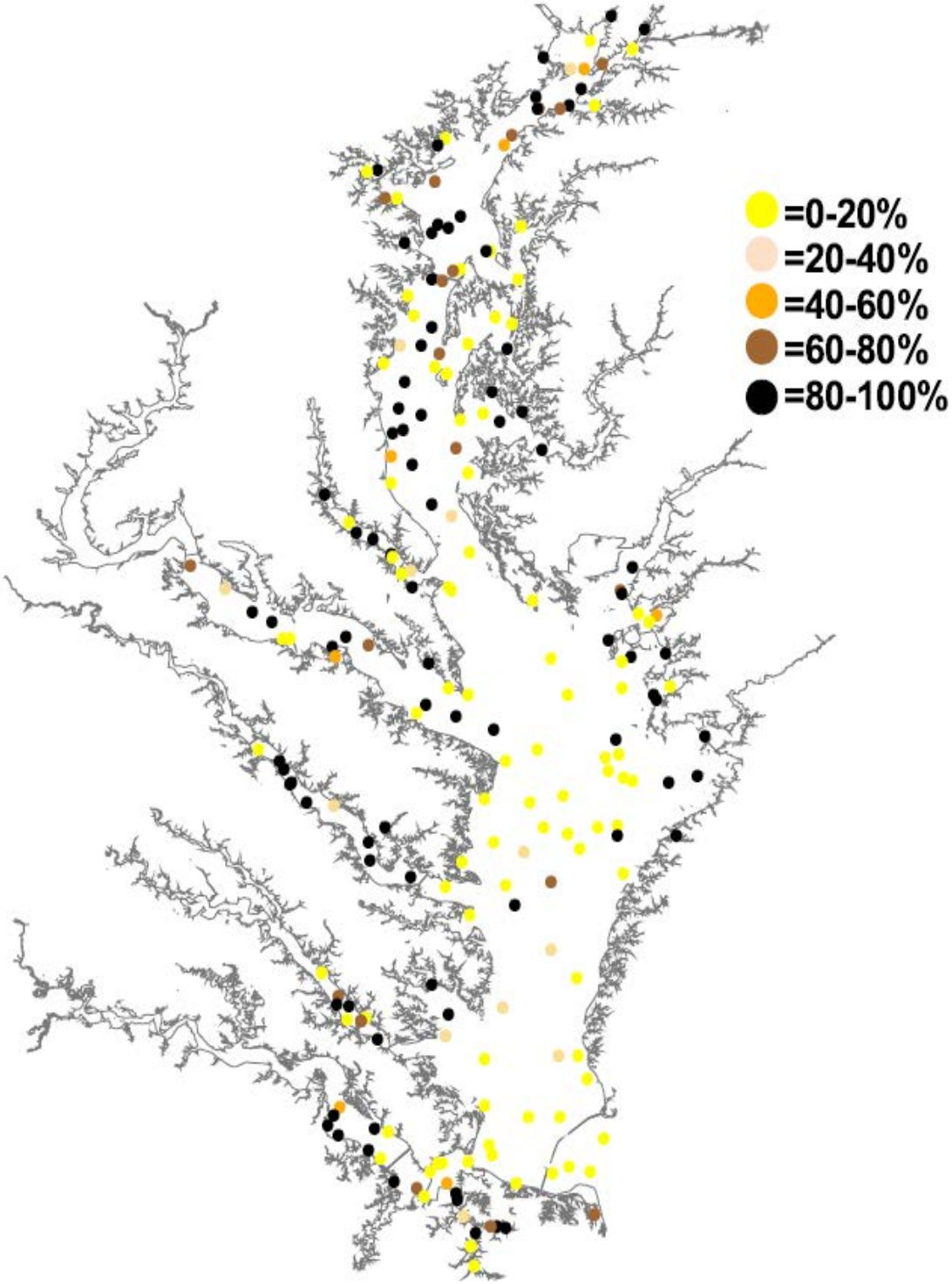


Figure 2. Percent fine grained sediment (silt + clay) in Chesapeake Bay sediments.

cades, but absolute concentrations are still 1 to 2 orders of magnitude above "pristine" conditions. Core data also indicate that concentrations of PAHs, PCBs and, organochlorine pesticides do not demonstrate consistent trends over 25 years, but remain 10 times lower than sediments in the tributaries. In contrast, tri-butyltin (TBT) concentrations in the deep cores have declined significantly since its use was severely restricted beginning in 1988.

Sampling Details

Chesapeake Bay was divided into sixty-five strata from north to south (Figure 1a-c). The focus of the sampling design was the larger open expanses of the Bay system. A total of 210 sites were sampled over 3 years.

2. RESULTS

2.1 Important physical drivers

In the upper Bay and tributaries, sediments are finegrained silts and clays (Figure 2). Sediments in the middle Bay are mostly made of silts and clays derived from shoreline erosion. In the lower Bay, by contrast, the sediments are sandy. These particles come from shore erosion and inputs from the Atlantic Ocean. The introduction of European-style agriculture and large scale clearing of the watershed produced massive shifts in sediment dynamics of the Bay watershed. As early as the mid-1700s, some navigable rivers were filled in by sediment and sedimentation caused several colonial seaports to become landlocked. Sediments in the tributaries tended to be muddier upstream and coarser near the mouths of the rivers, however sandbars were present in all locations. Sediments in eastern shore embayments also tended to have finer grained sediment than in the mainstem. Sediments in the central deep trough were uniformly fine grained depositional material.

2.2 Contamination results

Most of the mainstem of the Bay was relatively uncontaminated. Depositional areas in the Susquehanna Flats area and the upper portions of the deep trough had higher concentrations of contaminants than the middle and lower Bay (Figure 3). Most tributaries had higher contaminant concentrations than the mainstem. Of the large western tributaries, the Potomac and the James Rivers showed the most elevated concen-

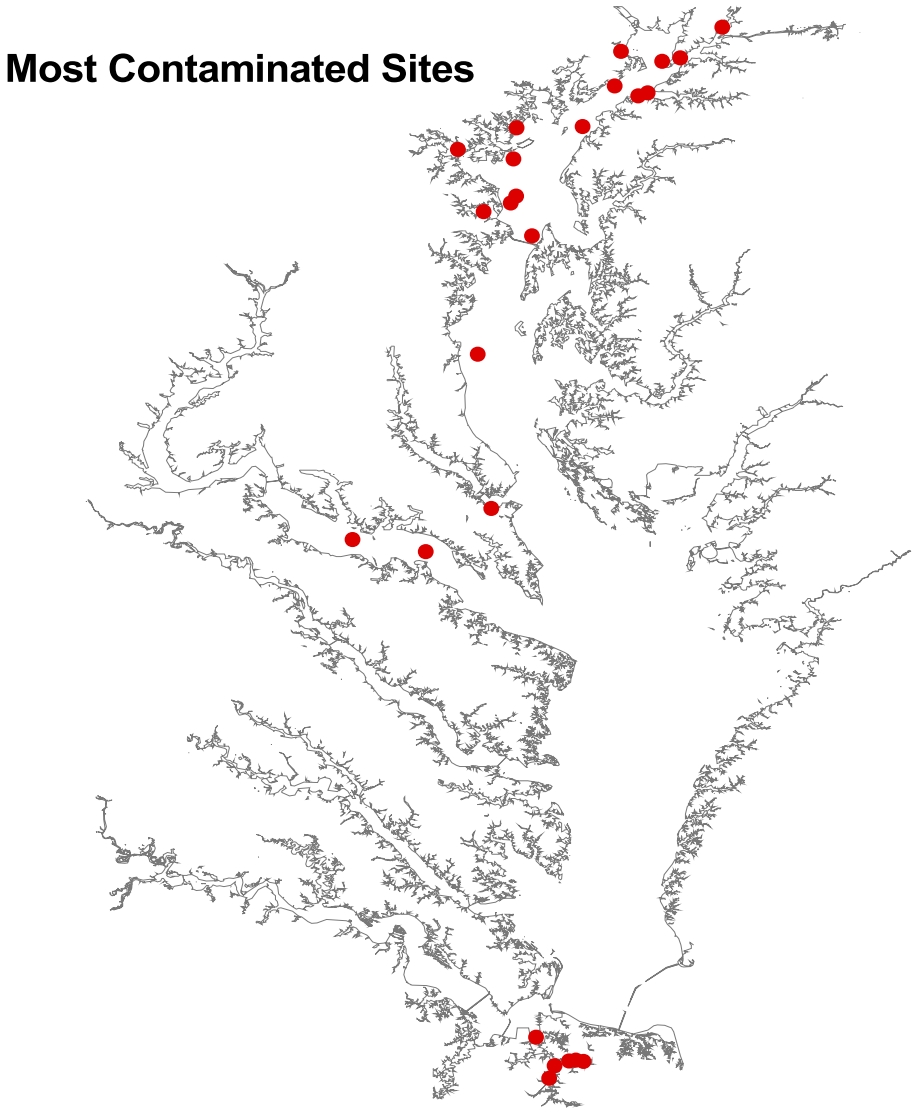


Figure 3. Distribution of sites in the top 10th percentile of contaminant concentration in Chesapeake Bay sediments.

trations. Most embayments were as clean as the lower mainstem, with the exception of areas off the Gunpowder River above Baltimore, and nearshore stations in Tangier and Pocomoke Sounds, where pesticide concentrations were elevated. Virtually all of the sites comprising the top 10th percentile of contaminated sites were found in the Elizabeth River, Baltimore Harbor, and the Susquehanna Flats or the deep trough. In the tributaries, the load of PAHs have a larger proportion of pyrogenic (e.g. combustion by-products) compounds than in the mainstem.

Table 1. Spatial extent (km^2) of area where ERL or ERMs were exceeded in 65 strata in Chesapeake Bay sediments.

Stratum	Total Area	area ERL	area ERM		Stratum	Total Area	area ERL	area ERM
1	75.9	50.6	0.0		34	41.0	13.7	0.0
2	92.1	92.1	0.0		35	371.0	0.0	0.0
3	39.0	13.0	0.0		36	28.1	18.7	0.0
4	36.8	24.5	0.0		37	27.7	0.0	0.0
5	250.0	250.0	0.0		38	56.6	18.9	0.0
6	247.6	198.1	49.5		39	21.9	14.6	0.0
7	44.0	33.0	11.0		40	197.1	65.7	0.0
8	132.1	99.1	66.0		41	53.9	0.0	0.0
9	97.3	73.0	0.0		42	444.6	0.0	0.0
10	109.8	54.9	0.0		43	837.2	502.3	0.0
11	66.3	66.3	0.0		44	426.0	106.5	0.0
12	95.3	47.6	0.0		45	254.5	84.8	0.0
13	133.6	100.2	33.4		46	209.7	0.0	0.0
14	108.1	108.1	0.0		47	253.1	0.0	0.0
15	102.7	68.4	0.0		48	31.7	0.0	0.0
16	146.3	0.0	0.0		49	168.3	0.0	0.0
17	154.2	115.6	0.0		50	73.1	36.6	0.0
18	95.4	0.0	0.0		51	26.2	8.7	0.0
19	324.0	216.0	0.0		52	100.6	67.1	33.5
20	412.2	137.4	0.0		53	66.3	44.2	0.0
21	46.2	30.8	0.0		54	49.4	49.4	0.0
22	34.3	22.9	0.0		55	48.1	32.0	0.0
23	18.6	6.2	0.0		56	46.8	15.6	0.0
24	105.9	70.6	0.0		57	30.2	30.2	0.0
25	79.0	26.3	0.0		58	42.0	28.0	0.0
26	69.3	23.1	0.0		59	46.3	30.9	0.0
27	177.1	177.1	0.0		60	27.4	27.4	0.0
28	85.4	56.9	0.0		61	86.7	57.8	0.0
29	371.5	123.8	0.0		62	33.2	33.2	0.0
30	519.8	0.0	0.0		63	5.7	5.7	3.8
31	123.5	0.0	0.0		64	6.5	6.5	2.2
32	235.8	0.0	0.0		65	119.5	79.7	0.0
33	259.8	0.0	0.0		**Total**	**9119.5**	**3664.1**	**199.5**
					%		**40.2**	**2.2**

Table 2. Spatial extent (km^2) of areas where bioassays demonstrated toxicity in 65 strata in Chesapeake Bay sediments, as estimated by laboratory bioassay tests.

STRATUM	total area	Amphipod Mortality	P450 B[a]Peq	Sea Urchin Fertilization		STRATUM	total area	Amphipod Mortality	P450 B[a]Peq	Sea Urchin Fertilization
1	75.9	0.0	0.0	0.0		34	41.0	0.0	0.0	0.0
2	92.1	0.0	61.4	92.1		35	371.0	0.0	0.0	0.0
3	39.0	0.0	13.0	13.0		36	28.1	0.0	0.0	0.0
4	36.8	0.0	12.3	12.3		37	27.7	0.0	0.0	0.0
5	250.0	0.0	0.0	200.0		38	56.6	0.0	0.0	0.0
6	247.6	0.0	0.0	0.0		39	21.9	0.0	0.0	14.6
7	44.0	0.0	22.0	22.0		40	197.1	0.0	0.0	65.7
8	132.1	0.0	0.0	33.0		41	53.9	0.0	0.0	0.0
9	97.3	0.0	0.0	0.0		42	444.6	0.0	0.0	222.3
10	109.8	0.0	0.0	27.5		43	837.2	0.0	0.0	669.7
11	66.3	0.0	22.1	44.2		44	426.0	0.0	0.0	106.5
12	95.3	0.0	0.0	47.6		45	254.5	0.0	0.0	0.0
13	133.6	0.0	0.0	66.8		46	209.7	0.0	0.0	69.9
14	108.1	0.0	0.0	36.0		47	253.1	0.0	0.0	0.0
15	102.7	0.0	0.0	68.4		48	31.7	0.0	0.0	0.0
16	146.3	0.0	0.0	0.0		49	168.3	0.0	0.0	0.0
17	154.2	0.0	0.0	30.8		50	73.1	0.0	0.0	36.6
18	95.4	0.0	0.0	0.0		51	17.5	0.0	0.0	8.7
19	324.0	0.0	0.0	216.0		52	100.6	0.0	0.0	42.3
20	412.2	0.0	0.0	137.4		53	66.3	0.0	0.0	22.1
21	46.2	0.0	0.0	0.0		54	49.4	0.0	0.0	33.0
22	34.3	0.0	0.0	22.9		55	48.1	0.0	0.0	0.0
23	18.6	0.0	0.0	0.0		56	46.8	0.0	0.0	15.6
24	105.9	0.0	0.0	70.6		57	30.2	0.0	0.0	20.2
25	79.0	0.0	0.0	0.0		58	42.0	0.0	0.0	14.0
26	69.3	0.0	0.0	69.3		59	46.3	0.0	0.0	15.4
27	177.1	0.0	0.0	177.1		60	27.4	0.0	0.0	9.1
28	85.4	0.0	0.0	56.9		61	86.7	0.0	0.0	0.0
29	371.5	0.0	123.8	0.0		62	33.2	0.0	0.0	33.2
30	519.8	0.0	0.0	0.0		63	5.7	0.0	0.0	0.0
31	123.5	0.0	0.0	0.0		64	6.5	0.0	2.2	2.2
32	235.8	0.0	0.0	0.0		65	119.5	0.0	0.0	119.5
33	259.8	0.0	0.0	0.0		**Total km**	**9119.5**	**0.0**	**256.8**	**2964.7**
						%		**0.0**	**2.82**	**32.51**

The distribution of metals was similar to the organic contaminants. Metals concentrations were also elevated at the one station in the vicinity of Hart Miller Island, which receives dredge spoil from Baltimore Harbor. Chlorinated pesticides were found throughout the Bay. The distribution of elevated concentrations was compound specific. Concentrations of TBT in the Susquehanna flats, while elevated compared to the lower mainstem sites, were not typically as high as several of the tributary stations. Contaminant concentrations exceeded ERLs throughout the bay, but ERM exceedances were primarily confined to harbor areas (Table 1).

2.3 Toxicity Results

Most significant toxicity responses were from stations in the Susquehanna Flats and the tributaries, however this was test-specific. None of the amphipod bioassays yielded significant toxicity (Table 2). In contrast, 73 of the sea urchin fertilization bioassays were significant. The HRGS P450 bioassay showed responses at most of the stations in the Susquehanna Flats, the deep trough, the Potomac and Elizabeth Rivers, and some other scattered sites. The spatial extent of impaired habitat (as defined by significant observed toxicity) varied widely. Based on strata areas, the spatial extent of impaired habitat ranged from zero to 32.5 % depending on the selected bioassay. .

2.4 Benthic Infaunal Results

In the benthic community, polychaete and oligochaete worms were the most dominant group, both in terms of organism abundance and number of taxa. Clams and snails were the next most abundant taxa, but were characterized by very high numbers of a relatively few species. The vast majority of crustaceans were amphipods. Species richness was site specific, varying considerably from one site to the next. Abundance varied by several orders of magnitude, even in adjacent sampling stations. The constricted region of the Bay west of Kent Island and south of the Bay Bridge generally had a low species diversity (Figure 4). This area

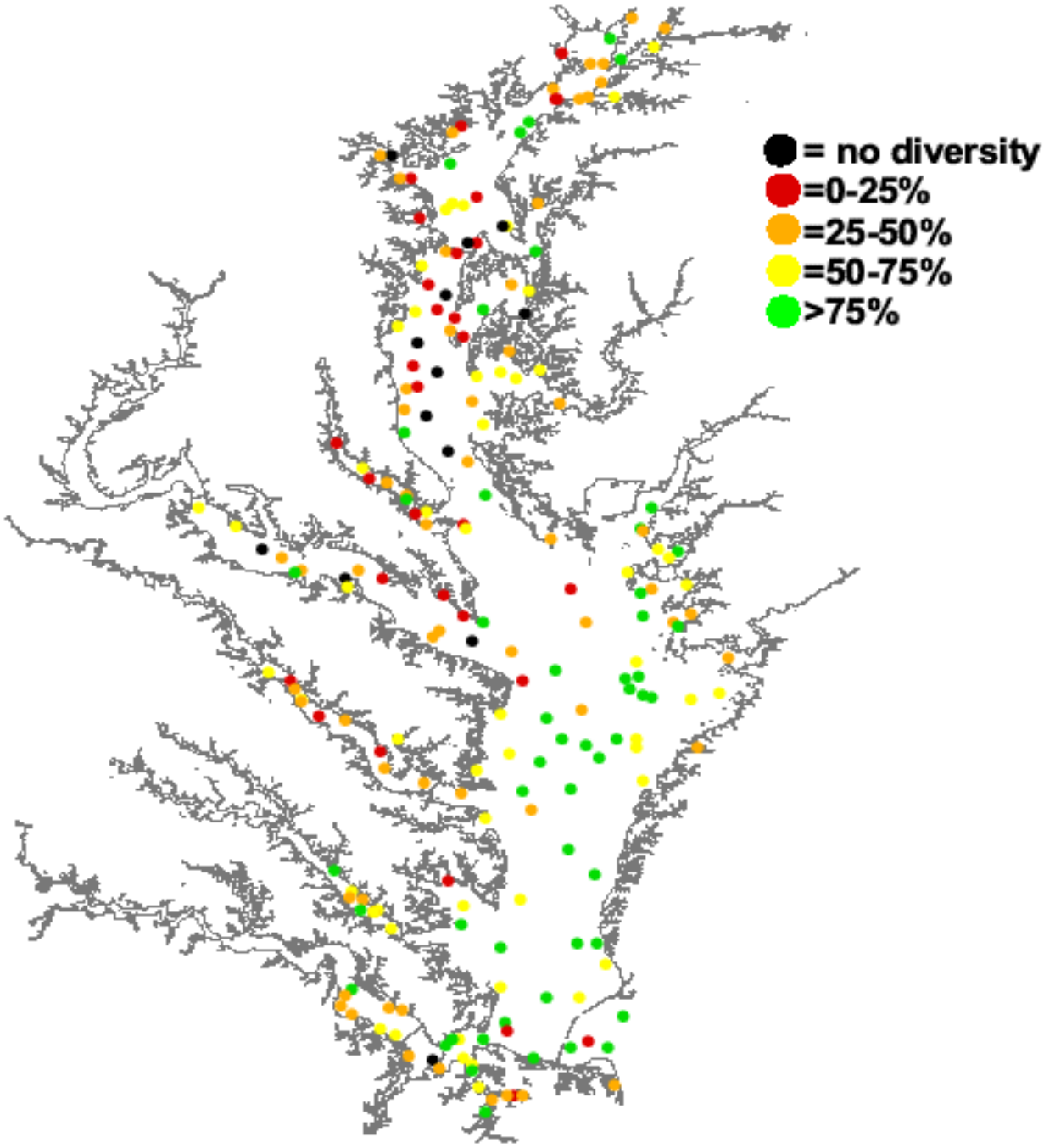


Figure 4. distribution of species diversity, by percentile rank, in Chesapeake Bay sediments.

is dominated by deep trough habitats and the associated low oxygen stress. There were fewer species in the western tributaries corresponding to the deep areas in the Patuxent, Potomac, and Rappahannock Rivers. The lowest values in the mainstem were from the central deep trough. The highest values were near the mouth of the Bay.

2.5 Correlations

The community attributes of species richness, abundance, and diversity were significantly, and negatively correlated with all but one of the contaminant groups. They were also consistently negatively correlated with the bioassay results.

A cluster analysis technique (called nodal analysis) was developed for the Delaware and Chesapeake studies to detect patterns of species associations that identify similar biological communities based on species composition. Cluster analyses resolved into nodes for 1-Susquehanna Flats, 2- the upper Bay between Baltimore and the Choptank River plus the upper reaches of the major western tributaries, 3- Tangier Sound and the lower reaches of the western tributaries, 4- sandy sites throughout the lower Bay, 5- the Bay mouth (Figure 5). These latter three had overlapping, but distinct community makeup. In contrast, the Susquehanna Flats node and upper Bay/upper tributary node shared fewer species, and these tended to be cosmopolitan taxa.

3. SUMMARY

Grain size and salinity were the primary factors which determine biological community distributions in the Chesapeake Bay mainstem. Each of the major western tributaries also contained distinct mesohaline and polyhaline benthic communities that mimicked the distribution in the mainstem, although they were not physically connected and maintain themselves independently in each subsystem.

Chemical contamination and toxicity responses are more closely correlated to each other than either of these two parameters are with benthic community metrics. When viewed in detail, the benthic community does respond to contamination in measurable fashion, however, certain relationships need to be understood to clarify the relationships.

Diversity, and number of species declined with increasing chemical concentrations. This was partly due to the distribution of fine grained sediments, where elevated contaminant levels were found, and the characteristics of the resident communities in fine grained vs sandy sediments. Resident communities found in muddy areas are inherently different from the areas with coarser grained sediments. However, observed toxicity increased with increasing contaminant values, and that impact cannot be ignored when evaluating community impact. Abundance did not decline as sharply as species richness with increasing contamination, suggesting that pollution tolerant species are able to grow and reproduce in contaminated areas in the absence of competitors, predators, and/or indirect effects on the habitat. In the most stressed areas, all biological indices declined.

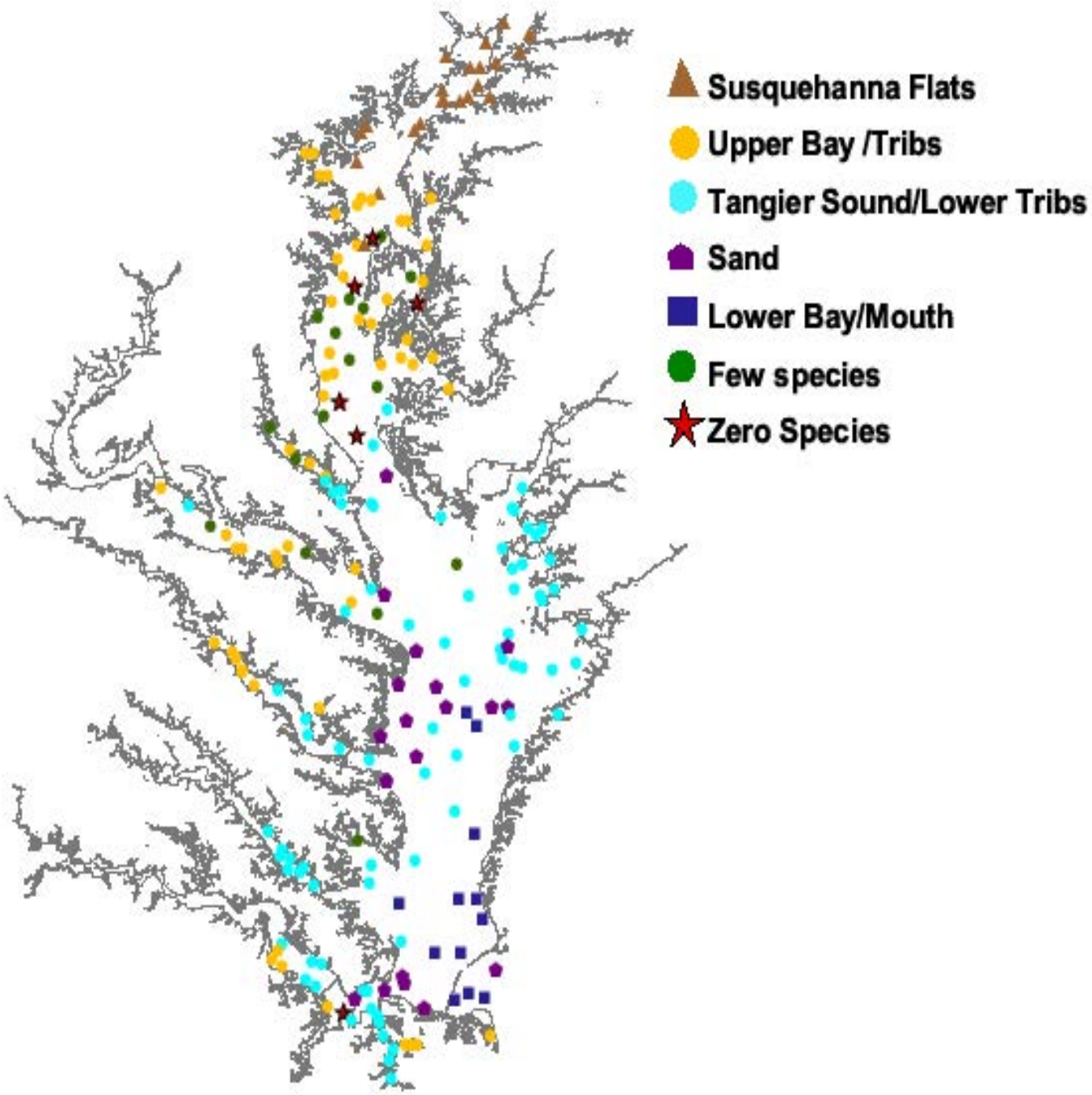


Figure 5. Distribution of species association nodes in Chesapeake Bay sediments.

Previous studies in Baltimore Harbor demonstrate steep gradients in contaminant concentrations from the heads of the various tributaries down into the Patapsco subestuary (Baker et. al. 1997). Concentrations reported in this NS&T study were considerably lower than what has been reported at locations upstream in the Patapsco system because the focus of the study was the open Bay, not the small tributaries. In previous studies of the Elizabeth River, contaminant concentrations were also seen to be highly variable on a site

specific basis due to a combination of historical sources of pollution and sediment characteristics. The Eastern Branch contaminant concentrations were as high, if not higher, than the Southern Branch even though the Eastern Branch is primarily residential along the shoreline of the upper reaches. The areas in Hampton Roads and Norfolk cannot be compared in the same way because the sediments are sandy. While industrial, and shipping-related activity is intense, sediment in Hampton Roads were not as contaminated as one might presume because it is not a depositional environment, and it is well flushed. The Elizabeth River was also contaminated with metals, but not at the same concentrations as the Patapsco.

A recent review of available data by the EPA, USGS and F&WS concludes that PAHs , PCBs, mercury and current use pesticides are widespread contaminants in the Bay, with PCBs and mercury causing serious impairments (EPA et al. 2012). Dioxin, petroleum, persistent chlorinated pesticides, chromium, lead, and zinc are causing localized impairments. The status and impact of atrazine, pharmaceuticals, PBDEs, and endocrine disruptors are not sufficiently known, but are of concern. It is suspected that the increased incidence of disease and parasitic infestations, intersex development, tumors, and reproductive failures in certain fish species are associated with localized chemical contamination.

Chapter 7
South Carolina and Georgia

1. STUDY AREA DESCRIPTION

The overall goal of this study was to provide a characterization of the toxicological condition of sediments in selected estuaries of South Carolina and Georgia and surrounding channels, as a measure, or indicator, of adverse biological effects of toxic chemicals. The study area included Winyah Bay, Charleston Harbor, Leadenwah Creek, Savannah River, and St. Simons Sound (Figure 1).

The Charleston Harbor survey area included the Ashley River below I-95, the Cooper River from approximately Goose Creek, and Wando River from approximately Nowell Creek, Charleston Harbor, and

Figure 1. South Carolina and Georgia coastline.

Figure 2. Locations of sampling stations in Charleston Harbor.

stretched seaward to the mouth of the harbor at Fort Sumter (Figure 2). In Leadenwah Creek (Figure 3), samples were collected from the head of the creek to its junction with the North Edisto River estuary. In Winyah Bay (Figure 4), the study area included the lower Sampit River, Georgetown Harbor, and lower Winyah Bay seaward to approximately the junction with the Intracoastal Waterway. In St. Simons Sound the study area included the lower Turtle River, Brunswick Harbor (East River), Brunswick River, the Back River, Terry Creek, the lower estuary seaward to the mouth of the bay (Figure 5). In the Savannah River the study area extended from approximately Interstate 95 to the mouth of the river and included several industrial harbors and the south river channel that parallels the Savannah River seaward to approximately Cockspur Island (Figures 6-8).

Scattered among the estuaries of South Carolina and Georgia are a number of hazardous waste sites with very high chemical concentrations. One site adjacent to Purvis Creek in St. Simons Sound that was near a defunct chemical manufacturer had extremely high PCB and mercury concentrations in sediments and fish (Bronstein, 1995). Several small sites in and adjacent to Charleston Harbor have had a history of elevated concentrations of different chemicals and have been the focus of remedial investigations. Analyses of age-dated sediment cores from the Savannah River estuary have shown a history of contamination by anthropogenic chemicals, including mercury, chromium, lead, PAHs, dieldrin, DDT and PCBs during the 1950s and 1960s (Alexander et al., 1994). Concentrations have gradually decreased during the past 20-30

years and recently-deposited, surficial sediments have lower chemical concentrations. Sources of pollution in Charleston Harbor include industrial and municipal point sources, urban and suburban nonpoint sources, septic tank overflows, and runoff from forested, urban, and agricultural watersheds (Matthews et al., 1980).

A health advisory that warned people not to eat fish and shellfish because of high dioxin concentrations in the Sampit River, a tributary to the Winyah Bay, was lifted in 1992. Pesticide use in the Winyah Bay watershed has been very high relative to the size of the watershed (South Carolina Sea Grant Consortium, 1992). Leadenwah Creek, a small tributary to the North Edisto River estuary, receives considerable agricultural runoff (Scott et al., 1990; 1993). Runoff of pesticides from nearby vegetable farms has caused major fish kills, and other impacts to fish, oysters, and macropelagic fauna (Scott et al., 1988; Scott et al., 1993; Fulton, 1989). Toxicity of the sediment-associated pesticides fenvalerate and endosulfan to meiobenthic animals (small benthic invertebrates) has been demonstrated in laboratory tests performed with samples collected from Leadenwah Creek and *in situ* toxicity bioassays and pelagic biomonitoring studies.

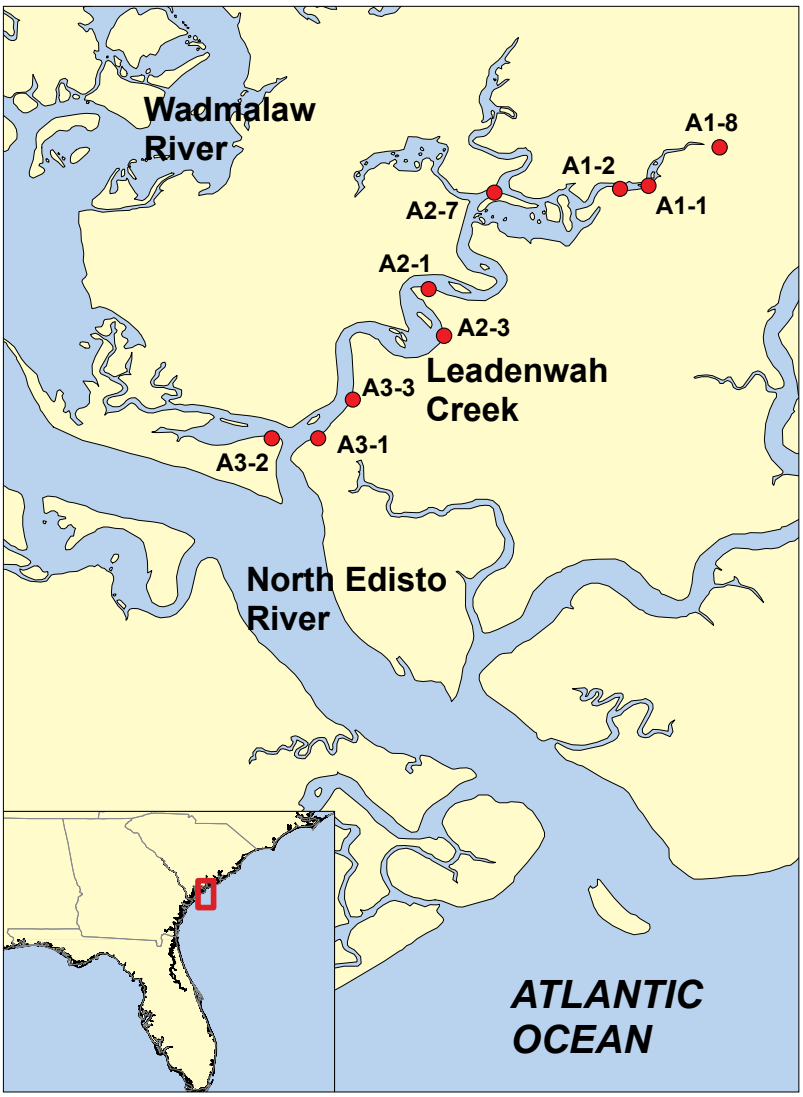


Figure 3. Locations of sampling stations in Leadenwah Creek.

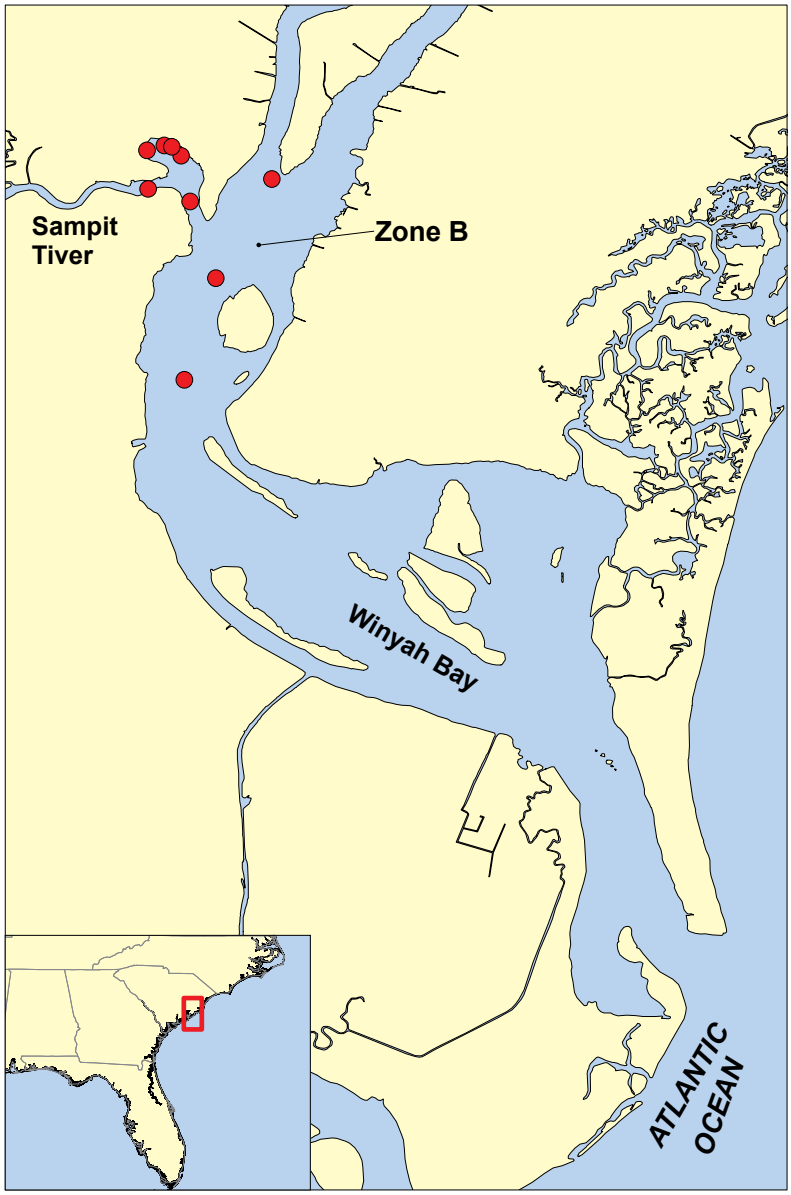


Figure 4. Locations of sampling stations in Winyah Bay.

Sampling Details

The study areas included saltwater portions of these five estuaries. Large strata were established in the open waters of the bays where toxicant concentrations were expected to be uniformly low. Relatively small strata were established in urban harbors, bayous and tributaries nearer suspected sources in which conditions were expected to be heterogeneous or transitional. Sampling effort was more intense in the small strata than in the large strata. The large strata were roughly equivalent in size to each other; small strata were roughly equivalent in size to each other. An example of this can be seen for the Savannah River, in which strata were established to be representative of the numerous channels and tributaries of the River. For this project, each of the five study areas was stratified (sub-divided) into approximately equal strata and samples were collected from randomly chosen locations.

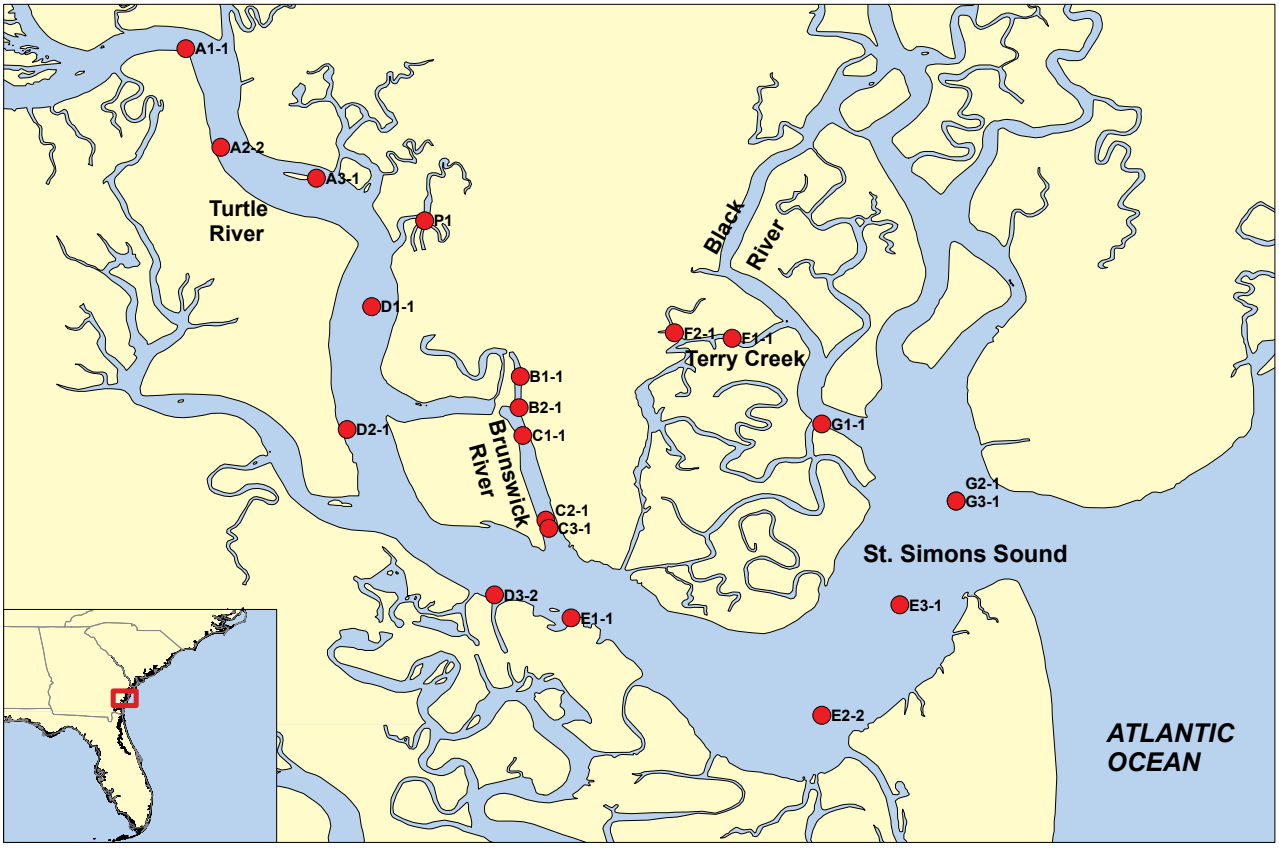


Figure 5. Locations of sampling stations in St. Simons Sound.

Figure 6. Locations of sampling stations in the lower Savannah River.

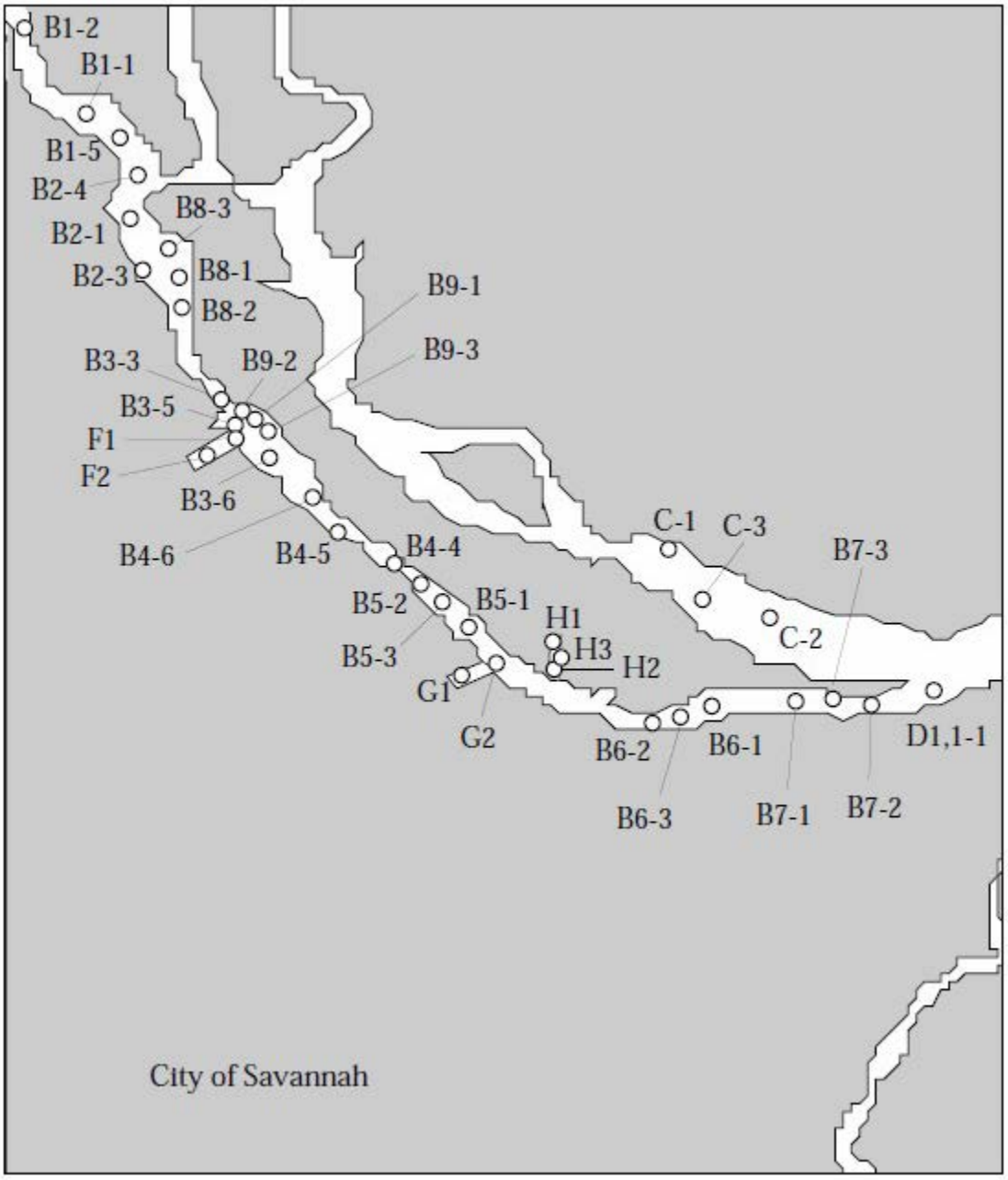


Figure 7. Locations of sampling stations in the Mid-Savannah River.

Sample Collection: Charleston Harbor, Winyah Bay, and Leadenwah Creek were sampled during May-June, 1993, and St. Simons Sound and Savannah River were sampled in June-July, 1994.

In Charleston Harbor, 63 samples were collected, 52 were chosen randomly by NOAA and 9 were chosen at specific locations by the Charleston Harbor Project (CHP). Nine samples were collected in Leadenwah Creek, a tributary to the North Edisto River previously impacted by agricultural runoff. In Winyah Bay nine samples were collected. In St. Simons Sound, 20 samples were collected. In the Savannah River, 60 samples were collected throughout three different segments of the system. Multiple toxicity tests were performed on all sediment samples. Chemical analyses were performed on a subset of samples from each estuary for trace metals, butyltins, PAHs, chlorinated pesticides and PCBs following a review and evaluation of the toxicity test results.

2. RESULTS

2.1 Important Physical Drivers

In the Charleston Harbor area, sediment texture differed considerably among stations. Samples collected in the lower harbor (Zone C) were predominantly sand. Samples from the Ashley River were predominantly sand in the lower and upper stretches of the river and finer-grained silts and clays in the mid-river reaches. Texture also was heterogeneous in the Cooper River; some samples were primarily sand and others were mainly silts and clays. In the Wando River most samples were primarily sand. As expected, based upon the texture, the total organic carbon (TOC) content varied considerably among stations TOC content was relatively low (less than 1%) in most samples from the lower harbor, Wando River, lower Ashley River and a few scattered stations in the Cooper River. Most of the samples from the upper Ashley and Cooper river stations had 2-5% TOC. At the uppermost station in Leadenwah Creek, the sediments were primarily sand and the concentrations of silt + clay increased down the estuary toward the confluence with the North Edisto River. Similarly, the concentrations of TOC increased down the estuary from less than 1% to over 3%.

Sediment samples collected in the Georgetown Harbor and entrance channel of Winyah Bay were primarily silts and clays, while the three samples from the mainstem of Winyah Bay had some sand. Percent sand decreased down the bay from station B5 to station B7. As expected, the concentrations of aluminum also were high in the harbor stations and were relatively lower in the bay stations. In following with the grain size, the TOC content was highest (3-5%) in the harbor stations and lower further downstream.

In the St. Simon Sound study area, sediment samples from most stations in the Turtle River and the lower Sound (stratum G) were sandy, while samples from the Brunswick Harbor (strata B and C) and upper Back River/Terry Creek (stratum F) were dominated by fine-grained materials. TOC content was relatively low (<2%) in most of the sandy stations and somewhat higher (>3%) in samples from stations with high percent silt and clay. Terry Creek and Brunswick Harbor stations had the highest TOC concentrations.

With some exceptions scattered through the area, most stations in the upper Savannah River strata had primarily fine-grained sediments. Sediments in many of the B, G, and H strata were sticky clay with silt and some sands. A few stations in the C and B strata, however, were primarily sand with little or no silts and clays. In the lower sections of Savannah River, in contrast, many samples were primarily sand. Stations in the D and E strata often were sandy with minor amounts of fines. However, sediments from Zone E had only small amounts of sand and were primarily clay. Six samples from strata A, the most inland stratum, had variable amounts of sand, silt, and clay in mixed sediments. Total organic carbon content ranged from less than 1% to nearly 8%. Most samples, however, had 2-4% TOC, with low concentrations in sandy samples and high concentrations in fine-grained samples.

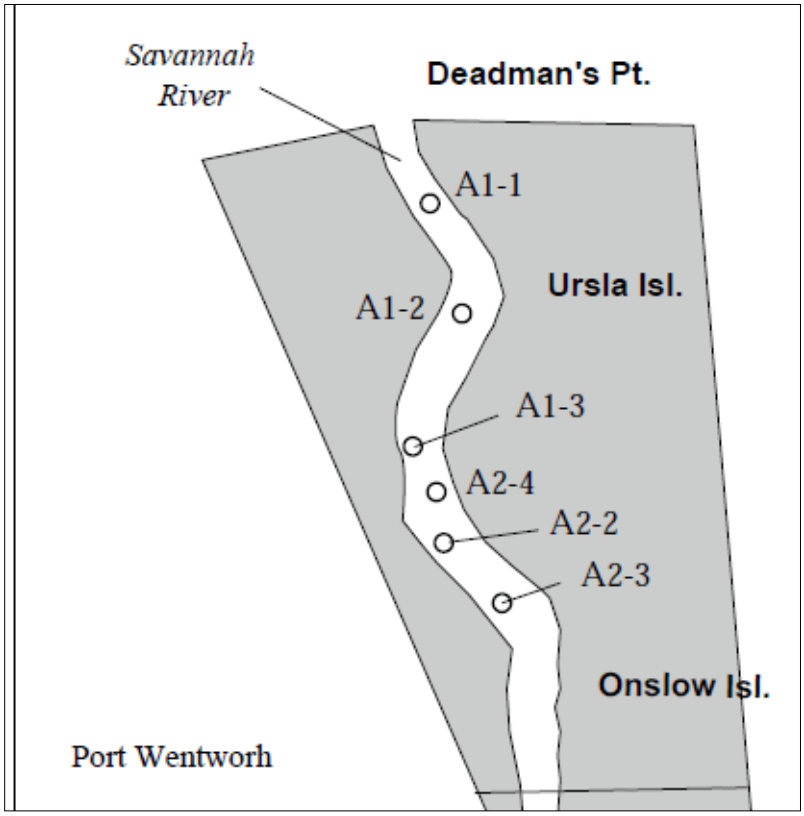


Figure 8. Locations of sampling stations in the upper Savannah River. (Zone A)

2.2 Contamination Results

Average concentrations of major organic compounds were often highest in St. Simons Sound. The average concentrations of total analyzed PAHs were similar in St. Simons Sound and Charleston Harbor (approximately 2,000 ng/g). The concentrations of total DDT (sum of DDT plus metabolites) were relatively low in all regions, except for one sample from St. Simons Sound (15.9 ng/g). The average concentration of total DDTs, including the one sample from St. Simons Sound was 2.03 ng/g, without that sample, the average was 1.94 ng/g. The average concentrations of total PCBs were elevated considerably in St. Simons Sound, again as the result of one sample with extremely high PCB concentrations (1,776 ng/g). The average concentration of total PCBs, including the one high sample from St. Simons Sound was 27.7 ng/g, without that sample, the average was 16.4 ng/g.

Generally, the concentrations of most trace metals differed very little among the different regions of the study area. For example, the concentrations of silver were similar throughout the study areas, ranging from ranged from 0.12 to 0.48. The concentrations of chromium, lead and zinc, however, were slightly higher in Winyah Bay as compared to the other regions.

The concentrations of all 27 substances for which numerical guidelines (Long et al., 1995b) exist were compared to the guideline values to identify which toxicants may have been elevated (Table 1). Arsenic exceeded the ERL value of 8.2 ppm in 64 samples but not the ERM value of 70 ppm. The concentrations of cadmium, chromium, copper, lead, and zinc exceeded their respective ERL values in 3-9 samples. The

mercury concentration in one sample from the lower Cooper River (Zone H) exceeded the ERM value of 0.71 ppm. The concentrations of all individual PAHs were elevated relative to respective ERL values in 4 to 44 samples (Table 1). In addition, the concentrations of anthracene, pyrene, and the sum of low molecular weight PAHs exceeded their respective ERM values in one or two samples in Zone D in the lower Ashley River, and in St. Simon Sound, Brunswick Harbor (Zone B), and Zone F in Terry Creek). Chlorinated hydrocarbon (PCBs, DDTs) were elevated in numerous samples relative to ERL values, but did not exceed the ERM values in any samples.

2.3 Toxicity Results

Toxicity was most prevalent among the Winyah Bay samples, where significant toxicity occurred in a total of 21 (47%) of all the tests combined. The incidence of toxicity was lower in the tests performed with samples from Charleston Harbor and Savannah River (31% and 34%, respectively), and lowest in the samples from St. Simons Sound (23%) and Leadenwah Creek (7%).

The tests of amphipod survival were least sensitive, indicating significant results in 8 of 163 samples (5%) tested from all areas. In the urchin fertilization tests with 100% porewater and the microbial bioluminescence tests, 39% and 36%, respectively, of the samples were toxic. The incidence of significant toxicity was highest (62%, 50 of 81 samples) in the sea urchin development tests with 100% porewater. Some of the toxicity tests showed strong concordance on the most and least toxic samples, while others demonstrated little concordance with each other among results. The test endpoints measured with the sea urchins agreed relatively well and both showed good agreement with the Microtox^{R} tests. However, none showed good concordance with the results of the amphipod tests. Therefore, spatial patterns in toxicity, based upon all of the results, were difficult to tease out of the data. The amphipod tests, the least sensitive tests performed, indicated very high toxicity in one sample from Terry Creek, a tributary to St. Simons Sound, and a sample from the upper Savannah River.

The total study area encompassed approximately 88 km^2, including 41 km^2 in Charleston Harbor (Table 2), the largest estuary studied. In the amphipod survival tests, "toxic" samples, as defined by the critical value (<80% of controls), were observed only in samples from the Savannah River and St. Simons Sound. The spatial extent of toxicity in amphipod survival tests in these two estuaries was approximately 0.2 and 0.1 km^2, equivalent to 0.3% of the total study area. In the sea urchin fertilization tests, the spatial extent of toxicity was approximately 18.7 km^2 (21.3% of the total area), most of which (12.5 km^2) occurred in Charleston Harbor. In Winyah Bay, toxic samples in the urchin fertilization tests represented about 3.1 km^2 (42.2% of this small estuary).

The estimated spatial extent of toxicity was highest in the Microtox^{R} tests (48% of the total area, Table 2). In these tests, toxicity was most pervasive in Winyah Bay and Savannah River, 70% and 57% of these areas, respectively. Approximately 43% and 46% of Charleston Harbor and St. Simons Sound, respectively, were toxic in these tests. Only one sample, representing 20% of the area, was toxic from Leadenwah Creek.

2.4 Benthic Infauna

Samples for benthic infaunal analysis were not collected for this project.

Table 1. Numbers of samples (out of 140 analyzed) in which ERL and ERM values were exceeded.

Chemical	Number of samples exceeding ERL value	Number of samples exceeding ERM value
silver	none	none
arsenic	64	none
cadmium	8	none
chromium	9	none
copper	5	none
mercury	20	2
nickel	33	none
lead	4	none
zinc	3	none
naphthalene	4	none
2-methyl naphthalene	10	none
acenaphthylene	13	none
acenaphthene	44	none
fluorene	39	none
phenanthrene	21	none
anthracene	25	1
fluoranthene	11	none
pyrene	11	1
benzo(a)anthracene	12	none
chrysene	12	none
benz(a)pyrene	6	none
dibenzo(a,h)anthracene	6	none
sum LPAHs	8	2
sum HPAHs	31	none
total PAHs	16	none
p,p'-DDE	1	none
total DDTs	32	none
total PCBs	16	none

2.5 Correlations

Because the majority of the samples indicated non-toxic results in the amphipod tests, correlations between chemical concentrations and amphipod survival were not significant. There was considerable evidence suggesting that toxicity observed in the other tests was associated with elevated concentrations of mixtures of many different substances, most notably, some trace metals, PAHs, and un-ionized ammonia. The concentrations of some trace metals (notably copper) exceeded background levels, exceeded effects-based guideline values, and showed strong associations with some measures of toxicity. The concentrations of some individual PAHs and classes of PAHs, similarly, were elevated above effects-based guidelines, were correlated with toxicity results, and showed strong associative patterns with toxicity. Ammonia probably contributed to toxicity in some of samples tested for sea urchin development, but, played only a minor or no role in contributing to toxicity in the Microtox^{R}, urchin fertilization and amphipod tests. Also, as expected, it appeared that the composition of the chemical mixtures varied among the different estuaries. For example, in Charleston Harbor microbial bioluminescence was correlated with many trace metal concentrations and urchin fertilization was correlated only with PAHs and other organics, while in the Savannah River

Table 2. Estimates of the spatial extent of toxicity, expressed as km^2 and percent of each area, based on results of three toxicity tests.

Survey Region	Total survey area (km^2)	Amphipod mortality	Urchin fertilization	Microbial bioluminescence
Winyah Bay	7.3	0	3.1 (42.2%)	5.1 (70.0%)
Charleston Harbor	41.1	0	12.5 (30.4%)	17.6 (42.9%)
Leadenwah Creek	1.7	0	0	0.3 (20.1 %)
Savannah River	13.1	0.2 (1.2%)	2.4 (18.4%)	7.5 (57.1%)
St. Simons Sound	24.6	0.1 (0.4%)	0.7 (2.6%)	11.4 (46.4 %)
Total area	87.8	0.3 (0.3%)	18.7 (21.3%)	41.9 (47.7%)

* Based upon bioassay responses <80% of controls

microbial bioluminescence was not correlated with many chemicals and urchin fertilization was strongly correlated with many substances. In conclusion, although the concentrations of some substances were elevated above background levels and effects-based guideline values and many substances showed significant correlations with toxicity; there were none that could be considered unequivocally as chemicals of highest concern.

3. SUMMARY

Surficial sediment samples were analyzed from 162 locations within five estuaries - Charleston Harbor, Winyah Bay, Leadenwah Creek, Savannah River, and St. Simons Sound - in coastal areas of South Carolina and Georgia in a survey of sediment toxicity performed in 1993 and 1994. Chemical analyses for a suite of trace metals, organic compounds, and sedimentological factors were performed with portions of most samples. All samples were tested for toxicity with a battery of complimentary laboratory bioassays. The laboratory bioassays consisted of amphipod survival tests in whole sediments, microbial bioluminescence (Microtox^R) tests of organic solvent extracts of sediments, and sea urchin fertilization and embryo development tests in sediment porewater.

The concentrations of some trace metals exceeded background levels, exceeded some effects-based guidelines concentrations, and showed strong correlative associations with toxicity. The concentrations of many individual and classes of PAHs also were elevated in samples that were also determined to be significantly toxic. The concentrations of chlorinated organic compounds [e.g., polychlorinated biphenyls (PCBs)] were elevated in a few samples.

Toxicity tests performed with invertebrates and Microtox^R often indicated strong correlations with mixtures of potentially toxic substances, the composition of which differed among estuaries and toxicity tests. The concentrations of substances such as copper and high molecular weight PAHs showed evidence suggesting they could have contributed to toxicity. The concentrations of ammonia were sufficiently elevated only in a small minority of samples to contribute substantially to toxicity.

Overall, most samples (with some notable exceptions) from this survey area were somewhat less contaminated and toxic than samples from other U.S. estuaries. The spatial extent of toxicity was somewhat

lower than the nationwide averages, as estimated with data from over 20 large estuaries studied nationally subsequent to this study.

Chapter 8
St. Lucie Estuary

1. STUDY AREA DESCRIPTION

Located in southeast Florida, St. Lucie Estuary (SLE) and its watershed are economically important for agriculture in the region (Florida Department of Environmental Protection [FDEP], 2008). The St. Lucie Estuary is composed of the South Fork and the North Fork, both of which converge to form the middle and lower estuary that extends eastward into the Indian Lagoon (Figure 1).

Largely in response to increasing human population along the coast and typical of south Florida coastal regions, the SLE and watershed has experienced considerable alterations due to increased agricultural and urban development. Construction of canals and water control structures intended for navigation, irrigation and the release of water, contributed to alter the natural hydrology of the basin (FDEP, 2008). The C-44 canal serves as a flood control conveyance for Lake Okeechobee and transports water from the lake into the South Fork. In addition to C-44, the canals C-23 and C-24, which discharge to the North Fork provide connections between their respective sub-basins (FDEP, 2008). These canals have altered the timing (excess wet season flows, insufficient dry season flows), distribution, quality, and volume of freshwater entering the estuary (Haunert et al., 1994). Heavy freshwater discharge following the 1998 El Nino event was associated with observations of unusually large incidences of fish with external deformities as well as other water quality-related problems, further exacerbating concerns about the ecological conditions of the estuary and status of its renewable resources. Prompted by widespread concern about the water quality and biological resources of the estuary, the St. Lucie River Issue Team (SLRIT), established under the South Florida Ecosystem Restoration Working Group, identified and recommended funding of several research projects in 2000 to address water quality-related resource management issues in the estuary and its watershed. This study, performed under a Joint Project Agreement between NOAA and State of Florida, was designed to characterize the estuary in terms of chemical contamination and its associated adverse biological effects, environmental toxicity, benthic community condition, and describe the extent and severity of habiat degradation using the sediment quality triad approach.

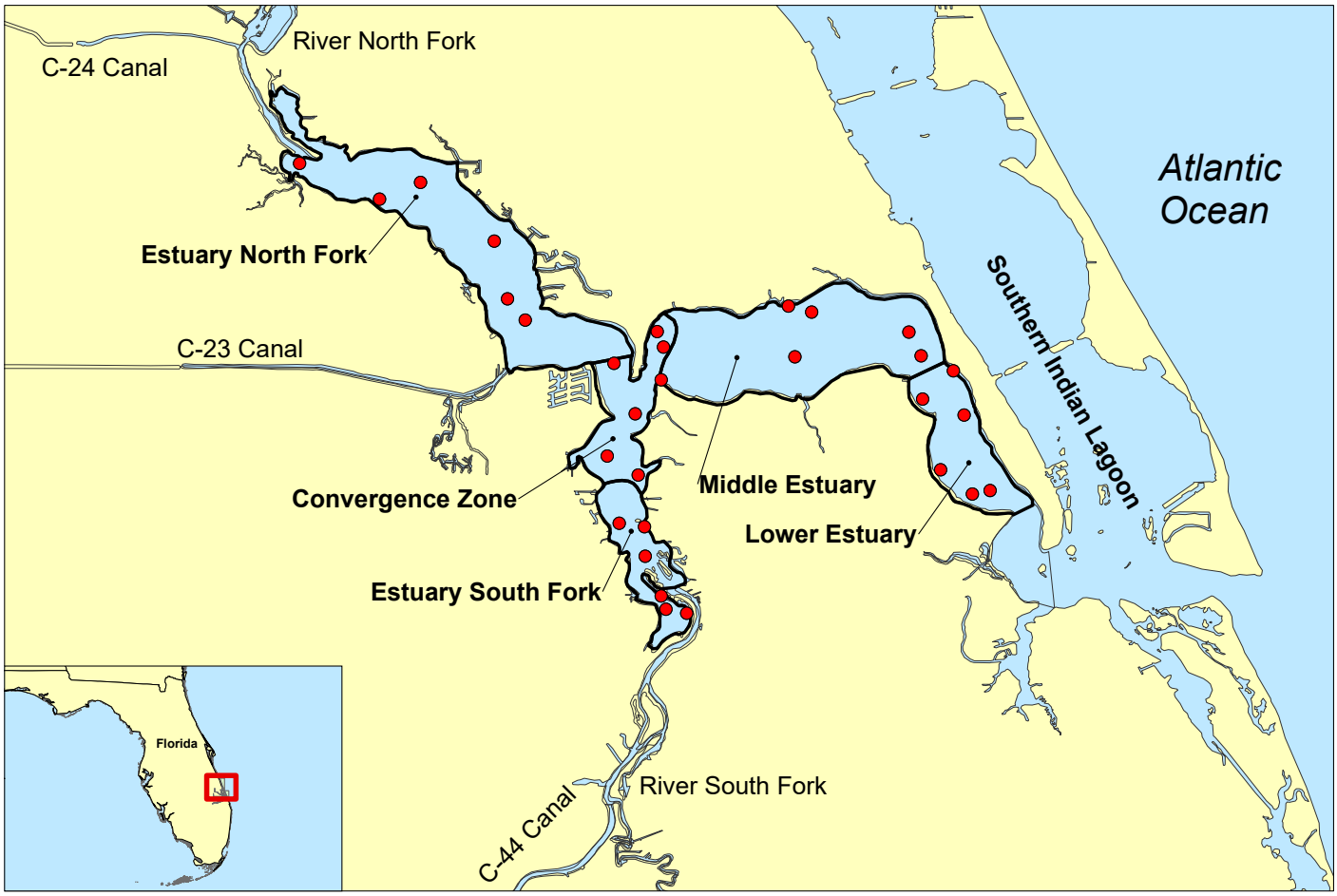


Figure 1. St Lucie Estuary strata. The estuary was divided into five strata based on the hydrology and different waterbodies Stratum 1 (North Fork), stratum 2 (South Fork), stratum 3 (Convergence Zone), stratum 4 (Middle Estuary), and stratum 5 (Lower Estuary).

Sampling Details

The estuary was divided into five strata based on the hydrology and different waterbodies in the St. Lucie estuarine system(Figure 1): North Fork (stratum 1), South Fork (stratum 2), Convergence Zone (stratum 3), Middle Estuary (stratum 4) and Lower Estuary (stratum 5). Within each stratum, six randomly selected sampling sites were located using a stratified random sampling design.

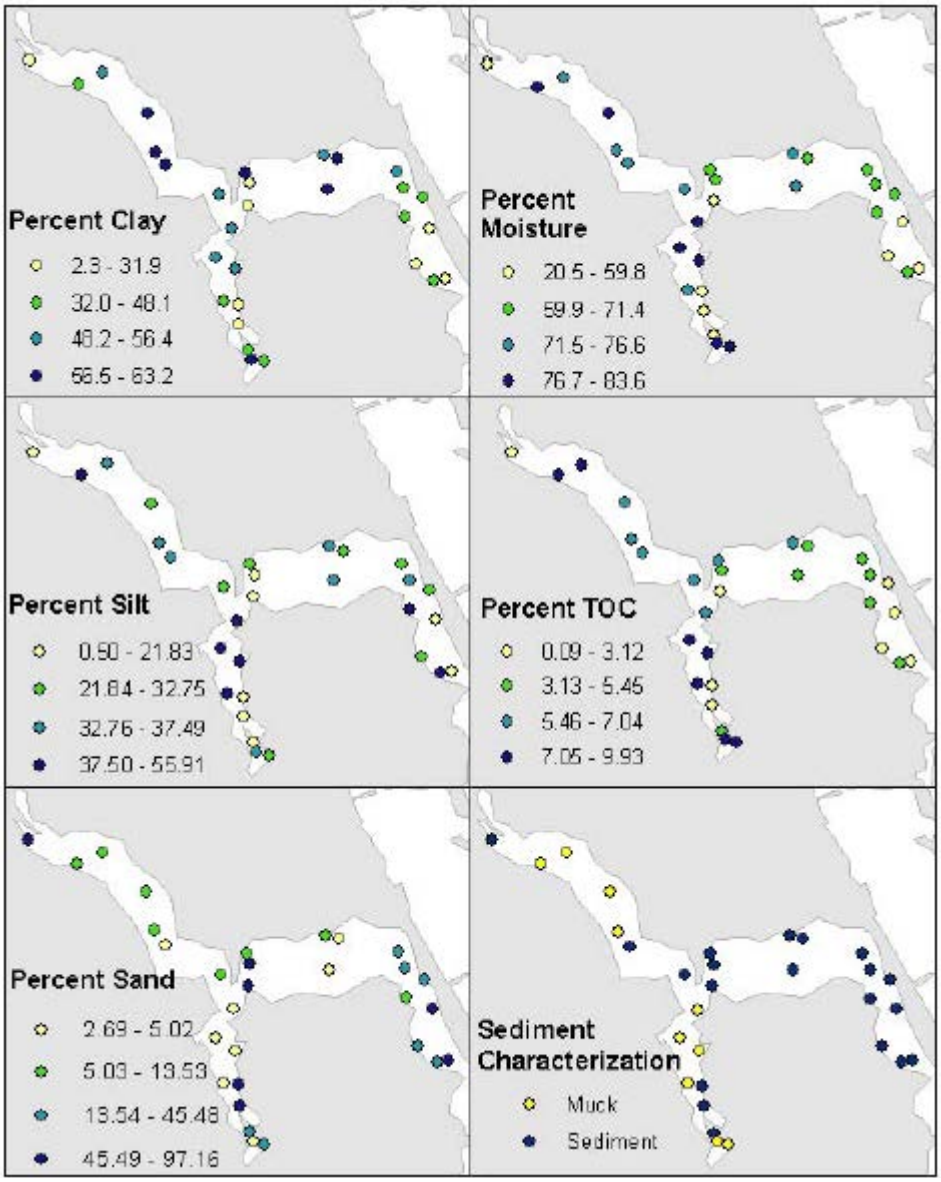
Surficial sediment samples from the 30 sites were analyzed for the suite of inorganic and organic contaminants routinely measured by the National Status and Trends Program and for benthic infauna community structure. Toxicity was determined only at 15 sites (3 sites per stratum) using a suite of three laboratory tests: (1) percent survival of marine amphipods (*Ampelisca abdita,* and *Eohaustorius estuarias*) in 10-day tests of solid- phase (bulk) sediments; (2) fertilization success of the sea urchin *Arbacia punctulata* in one hour tests of the sediment pore water; and (3) , cytochrome P-450 human reporter gene system (HRGS) assays were performed using organic extracts of sediment. Additionally, juvenile clams (*Mercenaria mercenaria*) survival bioassays were conducted.

2. RESULTS

2.1 Important Physical Drivers

Sediment composition varied considerably and ranged from 98% sand at Station 24 to 87% silt+ clay at Station 18 (Figure 2). Muck sediments defined by clay/silt > 60%, TOC > 6%, and water content > 75 % were found in the North Fork, Convergence Zone and South Forks (Figure 2). Salinities (from 17 ppt to 38.1 ppt) and bottom dissolved oxygen (from 2.82 g/L to 6.81 g/L) varied greatly in the entire estuary (Figure 3).

Figure 2. Sediment characteristics for the thirty stratified random sites



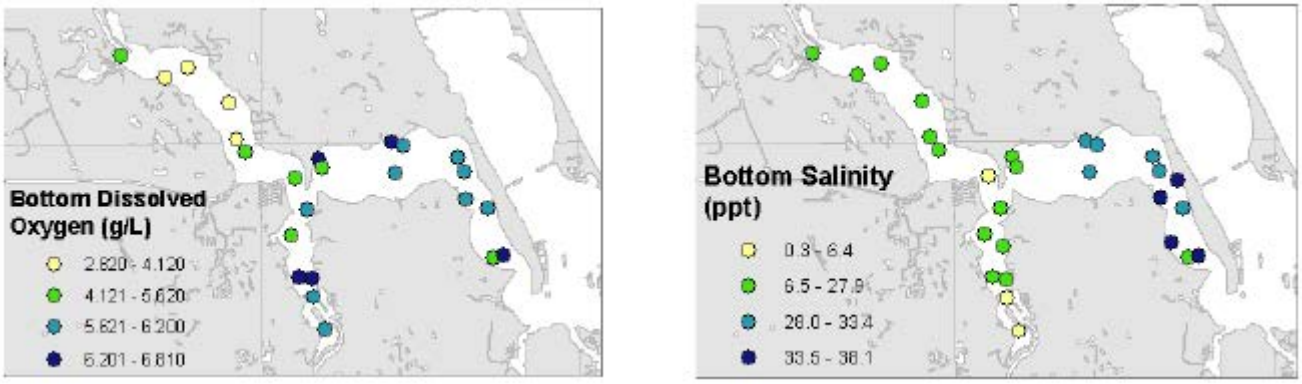


Figure 3. Bottom water dissolved oxygen and salinity concentrations.

2.2 Contamination Results

Overall, the level of chemical contamination in the estuary was low, notably in terms of contaminants that generally occur in urbanized estuaries, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). Aggregated totals of chemical concentrations by chemical class in sediment were compared to NS&T Mussel Watch percentiles. St. Lucie sediments exhibited moderate to high levels of contamination relative to concentrations observed among all samples nationally. More than 80 percent of the St. Lucie sediments have concentrations that exceeded 50th percentiles of those observed on a national basis (NS&T 1996-1997 data, http://egisws02.nos.noaa.gov/nsandt/index.html#).

Metal concentration in sediments were compared to threshold effects level (TEL) and probable effects level (PEL) sediment quality guidelines (MacDonald et. al., 1996). Of the nine metals (arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver and zinc) analyzed, 36% exceeded the TEL and 1% exceeded the PEL. Exceedances were highly variable for TEL (10% arsenic, 0% cadmium, 67% chromium, 63% copper, 7% lead, 16% mercury, 73% nickel, 3 % silver, 23% Zinc) and the PEL (3% copper, 7% mercury). Overall, level of metal contamination was low. However, this study has identified copper as a contaminant of concern in the estuary. Copper concentration was high, notably in the North Fork stratum where its mean value was 75 µg/g (parts per million) with occasional values exceeding 100 µg/g. In relatively pristine coastal environments, copper levels in sediment reached 15µg/g. Potential sources of copper in an estuary include extensive use of copper-based fungicides in the estuary's watershed, notably as in citrus orchards and vegetable crops, as algaecide in suburban areas, and leaching of copper-based anti-fouling paints on boats.

2.3 Toxicity Results

The severity and spatial extent of sediment toxicity varied considerably, depending on the sensitivity of the specific test employed and life stages of the test organisms. For the burrowing amphipod *Euhaustorius estuarius*, the toxicity assessment showed a more sensitive response in comparison with the survival test of *Ampelisca abdita* (Figure 4). The juvenile clams (*Mercenaria mercenaria*) survival assay showed a wide range of mortality following exposure (10 days incubation) to the St. Lucie Estuary sediments (Figure

5). Over 80 percent of the study area was found to be toxic using the juvenile clam assay. The sea urchin fertilization test showed sediment porewater to be toxic in over one-half of the study area. In comparison, NOAA's nationwide data on sediment toxicity showed about 6 percent of the studied areas, comprising of over 7,000 sq km in 25 coastal bays and estuaries, to be toxic.

The P450 HRGS response from exposure to St. Lucie sediment extract was generally very low (Figure 6). A mean value of 8.4 µg B[a]P Eq/g was calculated for the 15 randomly selected sites, with an upper confidence limit of 11.8 µg B[a]P Eq/g (Figure 6). Although there is no critical threshold value to denote toxicity of sediment from this test, statistical analyses of NOAA's nationwide HRGS data (1,309 samples) from 19 coastal regions suggested that induction values at or below 11 µg B[a]P Eq/g represent background concentrations in coastal bays and estuaries; at 32 µg B[a]P Eq/g there is the potential for toxicological impacts on biota (Anderson et al., 2005). The HRGS values in St. Lucie Estuary are similar to those observed in Biscayne Bay in 1996 (mean value of 8.2 µg B[a]P Eq/g).

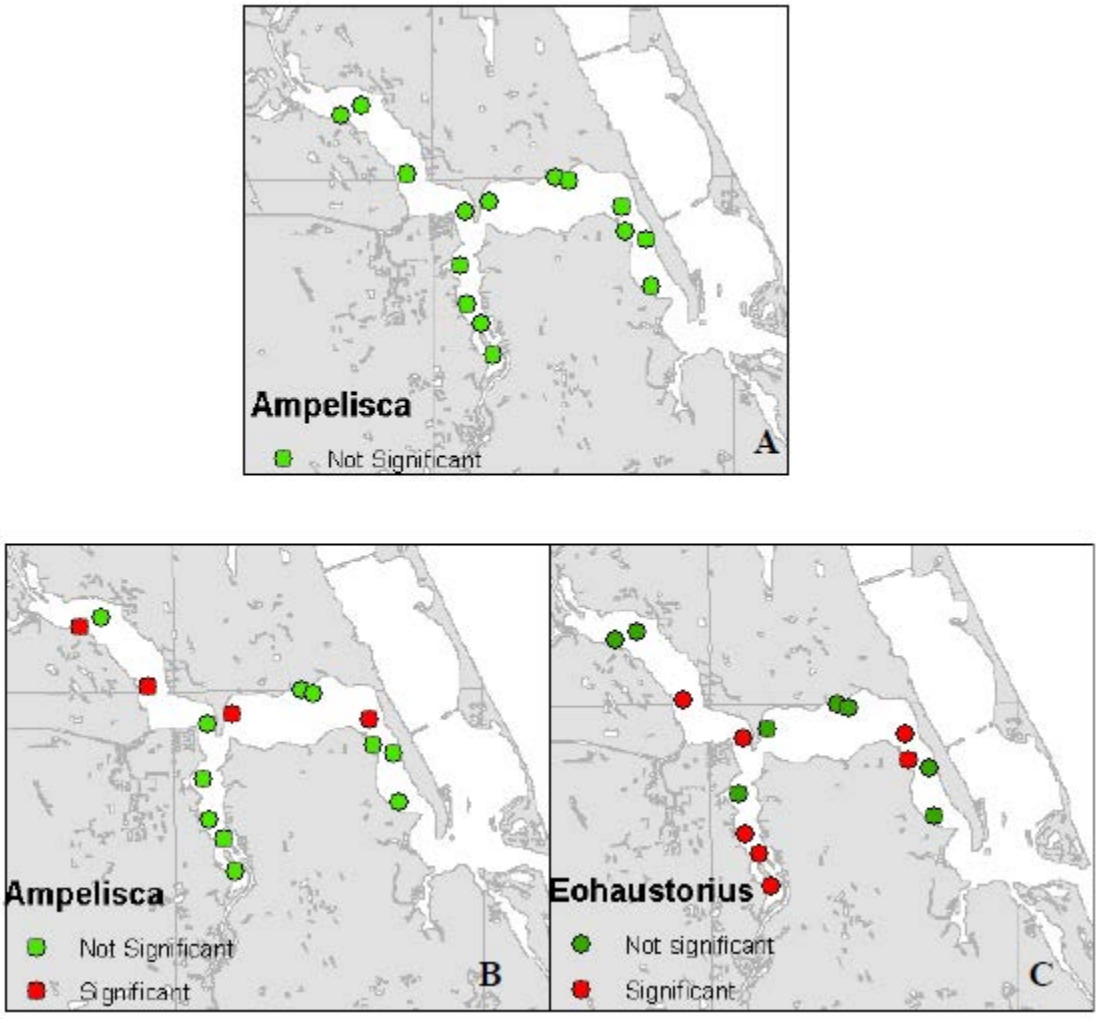


Figure 4. Results from the 2001 (A) and 2002 (B & C) amphipod sediment toxicity tests depicting sites.

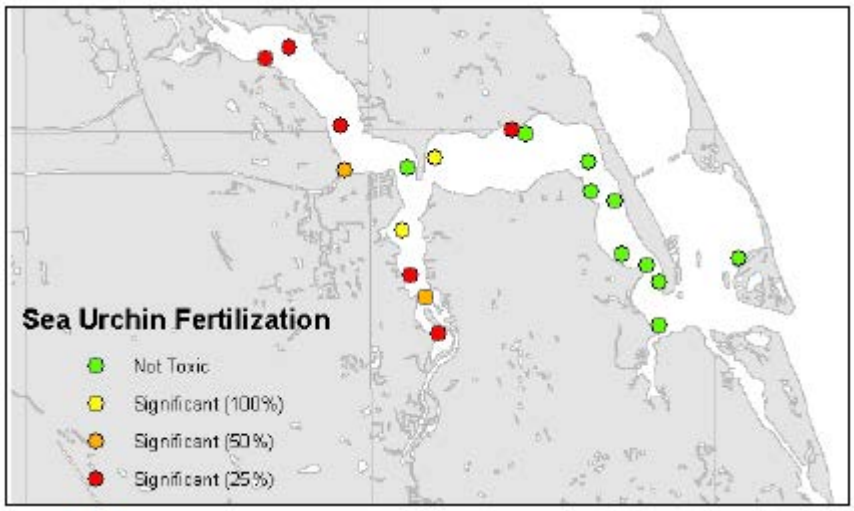


Figure 5. Sea urchin fertilization toxicity tests with porewater at 25%, 50% and 100%, dilution. Sites that are significantly different from the control at the various porewater dilution are indicated. Sites that are significantly different from the controls have sediments that are potentially toxic.

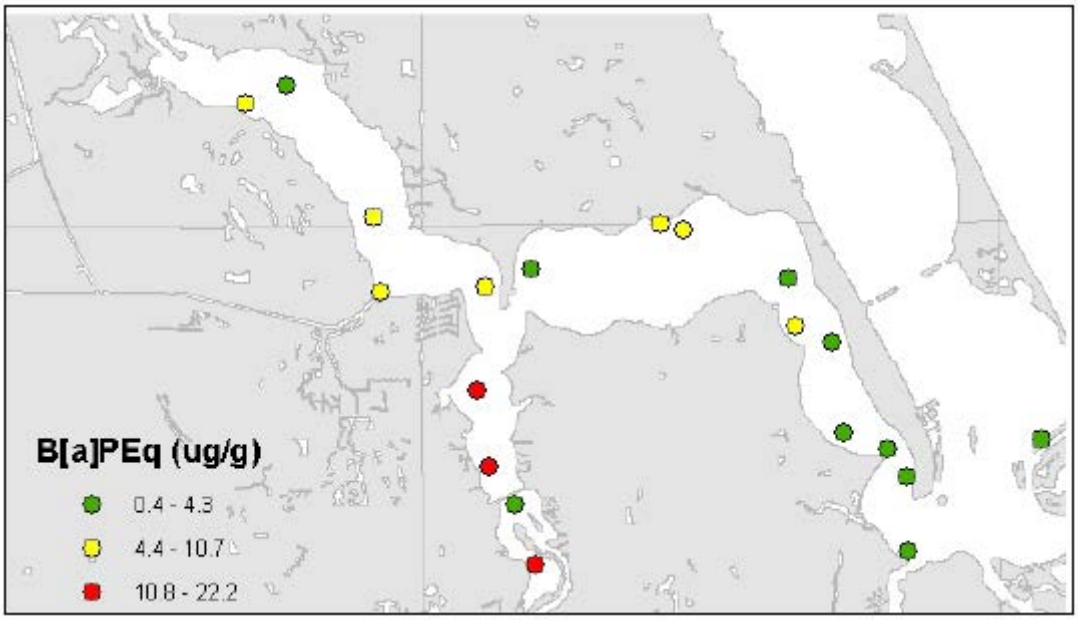


Figure 6. P450 HRGS reported as benzo[a]pyrene equivalent units. Elevated values were found in the South Fork and convergence zone where the highest PAH concentrations exist.

2.4 Benthic Infaunal Results

The characterization of the benthic infauna communities yielded a total of 7,429 organisms, representing 148 taxa. The dominant taxa identified were the polychaete, *Sternaspis scutata*, the bivalve, *Mulinia lateralis*, the malacostracans, *Ampelisca abdita*, and the polychaete, *Mediomastus* representing 23.4%, 21.7%, 13.7%, and 10.8% % of the total individuals collected. The polychaete, *Glycinde solitaria*, was the most widely distributed taxon being found at 83% of the stations. Taxa richness varied broadly and ranged from 2.0 (± 1.0) to 53. Taxa diversity (H') ranged from 0.64 to 2.98 while taxa evenness (J') spatial

variation was more narrow and ranged from 0.33 to 1.00. Species density exhibited considerable site-specific variation ranging from 66.7 organisms/m^2 (± 52.0) to 12,275 organisms/m^2.

2.5 Correlations

In the St. Lucie Estuary, habitat physical characteristics (sediment grain size, salinity) were found to be significantly correlated with the community attributes of species richness, abundance, and diversity. Taxa richness was positively correlated with the percent gravel + sand in the sediments (Spearman's Rho = 0.748, P > Rho = < 0.0001) and inversely correlated with the percent silt + clay (Spearman's Rho = -0.746, P > Rho = <0.0001) and salinity (Spearman's Rho = -0.382, P > Rho = 0.0449). Site specific densities were also positively correlated with the percent gravel + sand in the sediments (Spearman's Rho = 0.466, P > Rho = 0.0095) and inversely correlated with the percent silt + clay (Spearman's Rho = -0.462, P > Rho = 0.0102) and salinity (Spearman's Rho = -0.380, P > Rho = 0.0458).

2.6 Sediment Quality Triad Analyses

To detect patterns of association between benthic community distribution, observed toxicity, and chemical contamination, the Sediment Quality Triad (SQT) tool was applied. The SQT reduces large amounts of sediment toxicity, sediment contaminant and faunal diversity data data into readily perceptible graphics and presents results as a weight of evidence matrix of the three separate scores. The three types of data were integrated in a graphical composite to allow comparison among sites and correlation with other parameters of associations that identify similar biological communities based on species composition (Figure 7). The results of the SQT index indicate that strata 1 and 2 were relatively highly degraded.

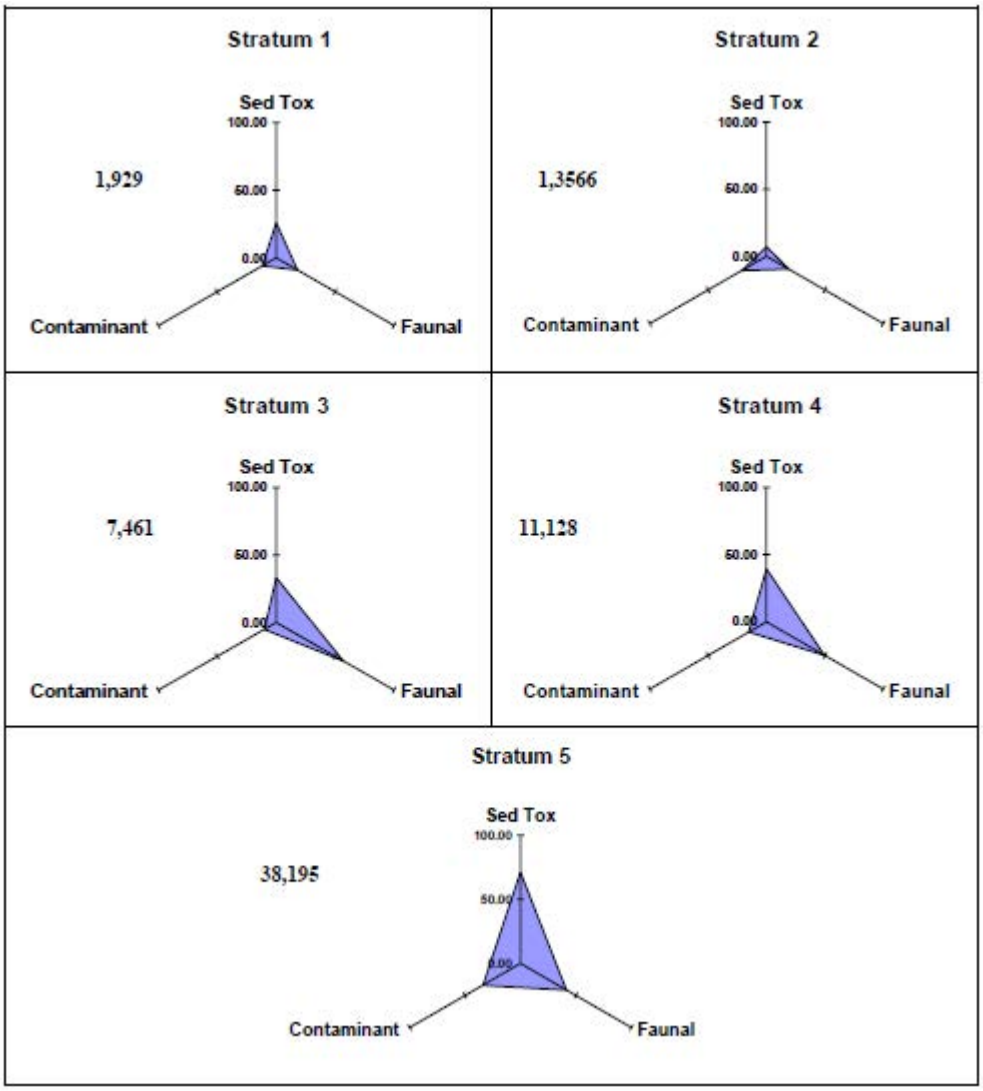


Figure 7. Schematic presentation of the Sediment Quality Triad data for five sampling strata in the St. Lucie Estuary. Numbers in bold type represent the volume of the triangles in arbitrary units (smallest area indicates the most degraded stratum).

3. SUMMARY

Integrating data from levels of contamination, severity of toxicity, and changes in the benthic infaunal community structure showed that the North Fork and South Fork portions of the St. Lucie Estuary were relatively highly degraded, whereas the lower portion of the estuary, leading to the southern Indian River Lagoon, was less impacted. Because sediment contamination is relatively low in the estuary with the exception of copper, observed sediment toxicity and habitat degradation as evidenced by benthic infauna distribution may be linked to other factors. Community attributes were found to be significantly linked to habitat physical characteristics suggesting that salinity and grain size were the primary factors that determine biological community distributions in the St. Lucie Estuary.

Sediment bioassays using two species of amphipods did not demonstrate significant sediment toxicity; however, using juvenile seed clams as test organisms, over 80 percent of the study area was found to be toxic. The sea urchin fertilization bioassay showed sediment porewater to be toxic in over one-half of the study area. The P450 Human Reporter Gene System (HRGS) response was low, consistent with low concentrations of PAHs and PCBs.

Even though the overall level of contamination was low, this study has identified copper as a contaminant of concern in the estuary from several lines of evidence; (1) the observed levels of copper approached or exceeded sediment quality guidelines that have been developed for Florida coastal waters; (2) indication, from a logistic model based on nationwide data on sediment toxicity, of a more than 50 percent probability of mortality in amphipods if exposed to sediment with the high copper concentrations observed in the estuary; (3) copper-spiked sediment bioassays using juvenile seed clams, which indicated that ambient concentrations of copper in the estuary far exceeded the "lowest observed effects concentration" and approached the copper concentration that would cause 50 percent mortality in test animals.

Chapter 9
Biscayne Bay

1. STUDY AREA DESCRIPTION

Biscayne Bay is a very large estuarine-like lagoon (60 km long and 16 km at its widest extent) located at the eastern tip of Florida peninsula in Miami-Dade County. Receiving freshwater from the Oleta and Miami Rivers, the bay is a part of the Atlantic intercoastal waterway and it is bordered to the east by barrier islands and to west by mangrove shoreline. Biscayne Bay's diverse marine ecosystems provide habitats for lush seagrass beds, fish, shellfish, manatees and, coral reefs.

Construction of major canals through the watersheds has caused a decrease in groundwater flow to the bay, eliminated many tributaries and impacted water quality in the bay. A South Florida Water Management District report (SFWMD, 1994) concluded that water and sediment quality degradation were problems in Biscayne Bay. They identified chronic problems with contamination by sewage in portions of Biscayne Bay and identified trace metals, chlorinated hydrocarbons, petroleum hydrocarbons, and tributyl tins as substances which had accumulated in the sediments of the central bay. Leachates from the Munisport landfill and ammonia in North Bay were identified as potential sources of ecological stress. In general, sources of contaminants in the bay are diffuse and include watershed runoff (solid and liquid wastes), industrial activities and atmospheric deposition. As industrial, commercial and residential development increases, stormwater has become a major pollutant to the environment. Thus, pollution in Biscayne Bay includes litter, oil and other vehicle fluids, and any other chemicals that are on the ground. Because groundwater (the Biscayne aquifer) is shallow, it is a general concept that any contaminant that spills on the ground has the potential to enter the aquifer, which is the source of drinking water in Miami-Dade County.

To mitigate impacts of environmental stressors resulting from development and extensive dredging, which led to significant ecological degradation, Biscayne Bay was designated as a state aquatic preserve in 1975. However, because no bay-wide information had been generated on the toxicological condition of the bay sediments, the NOAA NS&T program, in 1995, selected the bay for a sediment quality survey in order to provide a characterization of the toxicological condition of sediments in Biscayne Bay and vicinity, including saltwater reaches of key tributaries. The objectives of the survey were to determine: (1) the incidence and degree of toxicity of sediments throughout the study area; (2) the spatial patterns (or gradients) in chemical contamination and toxicity, if any, throughout the study area; (3) the aerial extent of chemical contamination and toxicity; and (4) the statistical relationships between measures of toxicity and concentrations of chemicals in the sediments. During 1995 and 1996, 226 sediment samples were collected from randomly-chosen locations and tested for toxicity and analyzed for chemical concentrations (Figure 1).

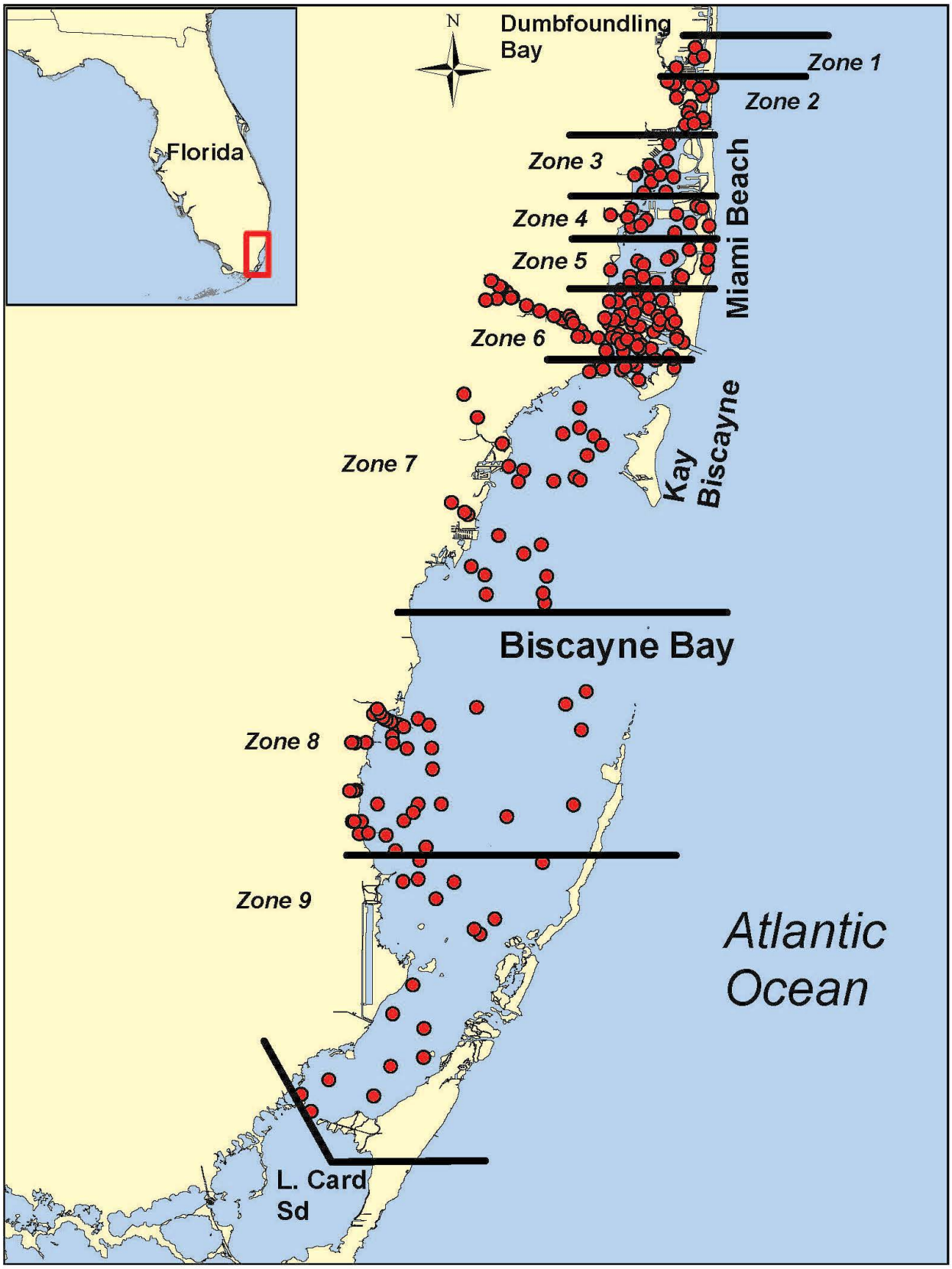


Figure 1. Map of Biscayne Bay study area showing sampling stations and relative locations of strata (Zones).

Sampling Details

The study area extended from Dumfoundling Bay in the north to the Little Card Sound Bridge in the south and was divided into nine strata (sampling zones) that conformed to the major physiographic basins of the study area (Figure 1). Zone 1 was the northern-most region and included Dumbfoundling Bay, Maule Lake, Oleta River, and a portion of the Intracoastal Waterway (ICW). Zone 2 extended southward along the ICW to the Broad Ave. Causeway. Zone 3 extended from the Broad Avenue Causeway to the 76th Street Causeway and included the lower Biscayne Canal. Zone 4 ranged from the 76th Street Causeway south to the Julia Tuttle Causeway and included the Little River and Indian Creek. In Zone 5, samples were collected between the Julia Tuttle Causeway and the MacArthur Causeway. Zone 6 included the Port of Miami from MacArthur Causeway to the Rickenbacker Causeway and the lower Miami River/Seybold Canal/Tamiami Canal from Brickell Point to the railroad bridge. Zone 7 extended from the Rickenbacker Causeway south to the 25°35' latitude and included portions of Coral Gables Canal and Snapper Creek Canal seaward of the saltwater control structures. Zone 8 extended from the 25°35' latitude to the vicinity of Turkey Point and included portions of Black Creek/Gould's portions of Coral Gables Canal and Snapper Creek Canal seaward of the saltwater control structures. Zone 8 extended from the 25°35' latitude to the vicinity of Turkey Point and included portions of Black Creek/Gould's Canal, Princeton Canal, Military Canal, Mowry Canal, and North Canal. In the southernmost area, Zone 9 extended from the vicinity of Turkey Point to the Little Card Sound Bridge. The study area encompassed a total of 484 km^2. The relatively small strata were established in canals and urban harbors nearer suspected sources in which conditions were expected to be heterogeneous or transitional. As a result, sampling effort was more intense in the smaller strata than in the large strata. The large strata were roughly equivalent in size to each other and the small strata were roughly equivalent in size to each other.

Between 1995 and 1996 a total of 226 sediment samples were collected from randomly-chosen locations in all the Zones. Multiple toxicity tests and complete chemical analyses were performed on all 226 sediment samples. Toxicity was determined using a suite of four laboratory tests: (1) percent survival of marine amphipods (*Ampelisca abdita*) in 10-day tests of solid-phase (bulk) sediments; (2) changes in bioluminescent activity of a marine bacterium, *Photobacterium phosphoreum*, in 15-minute Microtox® bioassays of organic extracts; (3) fertilization success of the sea urchin (*Arbacia punctulata*) in one hour tests of the sediment pore water; and (4) normal embryological development of *A.punctulata* in 48-hour tests of the pore water. In addition, cytochrome P-450 human reporter gene system (HRGS) assays were performed on 121 samples. The concentrations of trace and major metals, chlorinated pesticides, polychlorinated biphenyl (PCBs) and polyyclic aromatic hydrocarbons (PAHs) were measured in all samples according to the quality control procedures of the NS&T program. Additionally, sedimentological features such as sediment grain size, total organic (TOC) and inorganic (TIC) carbon content were determined in all samples.

Data from samples collected during 1995 and 1996 were merged and treated as equivalent and comparable.

Chemical concentrations were compared with the ERL and ERM values of Long et al. (1995) developed for NOAA and the Threshold Effects Level (TEL) and Probable Effects Level (PEL) values of MacDonald et al (1996) developed for the state of Florida. Spatial patterns in toxicity and chemical compounds were estimated by plotting data on base maps of each sampling Zone. In addition, the toxicity/chemistry correlations were determined for the combined dataset.

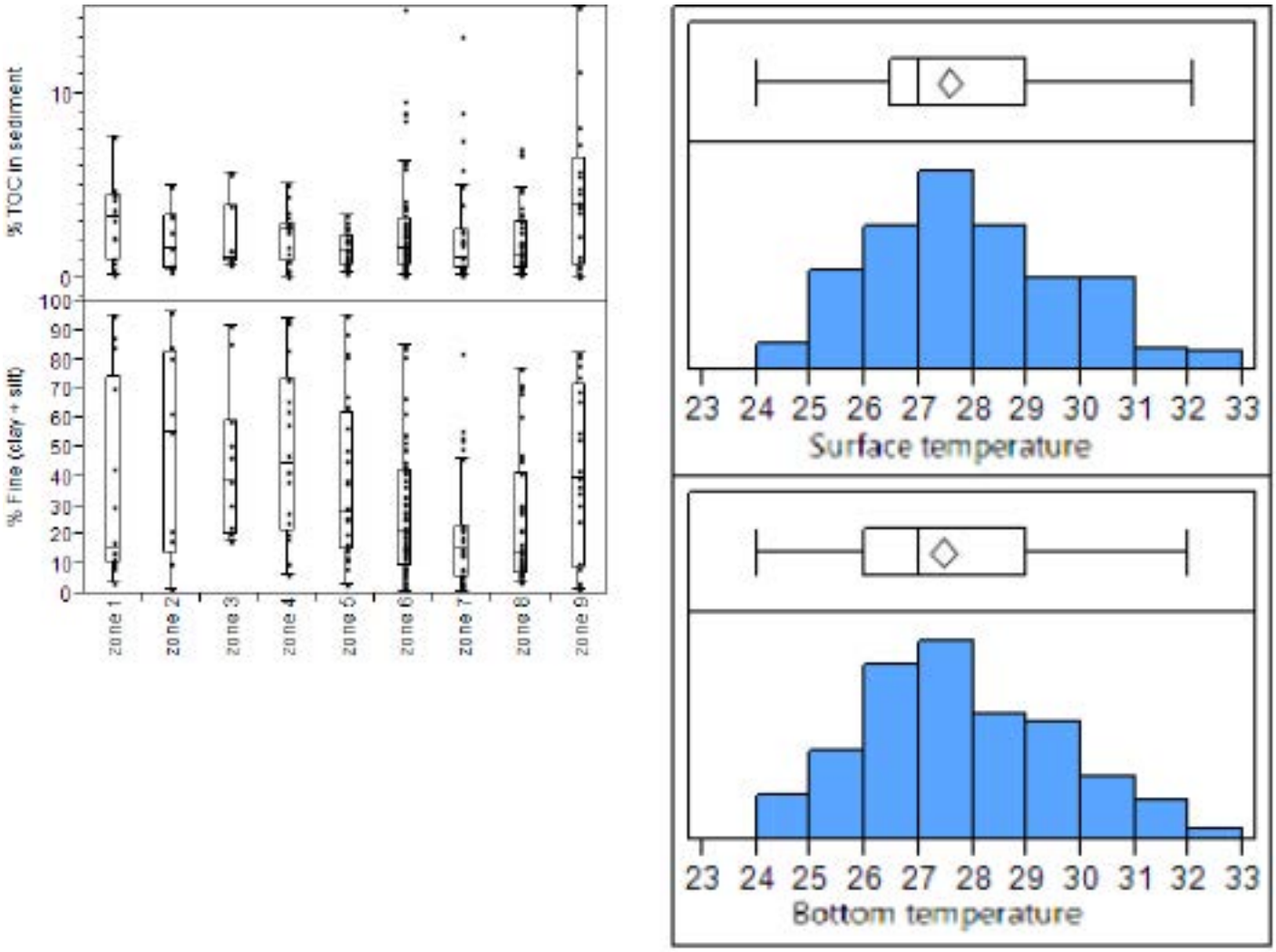


Figure 2. Distribution of sediment grain size and TOC (left), and water temperature (°C) in the study area of Biscayne Bay. Figure shows mean and standard deviation.

2. RESULTS

2.1 Important Physical Drivers

Sediments physical parameters (grain size and TOC) were widely variable in the study area and within each Zone. With relatively low TOC content, sediments in Zones 1 through 5 tended to be muddier with the highest percent mud (% clay + % silt) found in Zone 4. Zones 7 and 8 were sandier with low average TOC

content. Zone 9 was muddy with very high TOC content. The water column was fairly well mixed with the average values of water temperature and salinity showing little difference between surface and bottom of the water column (Figure 2). Bottom salinity measurements demonstrated a distinct gradient of expected low values in rivers and river mouths (0.0 – 5.0 ppt), medium values (5.0 – 25.5 ppt) in coastal areas and values of 25.5 – 37.8 ppt in open waters of the study area (Figure 3).

2.2 Contamination Results

In Zone 1, chemical concentrations were highest in samples collected in Maule Lake and lowest in the samples from the lower Oleta River and parts of the Intracoastal Waterway. Concentrations of lead in some locations exceeded the ERL value of 46.7 ppm. Concentrations of total PCBs exceeded the ERL value of 22.7 ppb in seven other stations. The concentration of total PAHs at stations near the mouth of Royal Glades Canal was extremely high, exceeding the ERM value of 44,792 ppb. Chemical concentrations were considerably lower in Zone 2**.** None of the metals or PAHs had concentration that equaled or exceeded their respective ERL values. However, the concentrations of PCBs exceeded the ERL at most stations within this Zone. In Zones 3 and 4 contaminant concentrations were elevated in samples from peripheral tributaries to the bay and lowest towards the middle of the bay. In the peripheral areas, concentrations of lead, zinc, and total PCBs in many samples exceeded ERM values. In Zone 5, concentrations of lead, zinc, and total PAHs were below the ERL values in most samples; however, the concentrations of PCBs were above the ERL, but below the ERM. All 21 samples from Zone 6 including the lower Miami River stations had relatively high concentrations of many chemical substances, including lead, zinc, PAHs, and PCBs**.** Concentrations often exceeded respective ERL values and frequently exceeded the ERMs. All of the highest concentrations encountered in the 226 samples analyzed in the study were observed in this Zone. Seaward of the mouth of the Miami River, chemical concentrations diminished sharply and continued to gradually decrease eastward toward the ocean.

South of the Rickenbacker Causeway (Zone 7), chemical concentrations in the many samples collected in the open waters of Biscayne Bay were low. In contrast, samples from Coral Gables Canal and Snapper Creek Canal had relatively high concentrations. Several samples from this Zone, including Coral Gables Canal, appeared to show some influence from mainland sources.

Zone 8 had very low concentrations of lead, zinc, and PAHs. Although PCB concentrations often exceeded ERL values, concentrations of the other organic compounds never exceeded their respective ERL values. Concentrations of lead, zinc, PAHs, and PCBs were very low in all 12 samples from Zone 9. All concentrations were well below ERL levels in this Zone.

The Florida Department of Environmental Regulation (Schropp et al., 1990; Schropp and Windom, 1988) determined that in Florida, and generally throughout the southeast coastal plain, trace metal concentrations

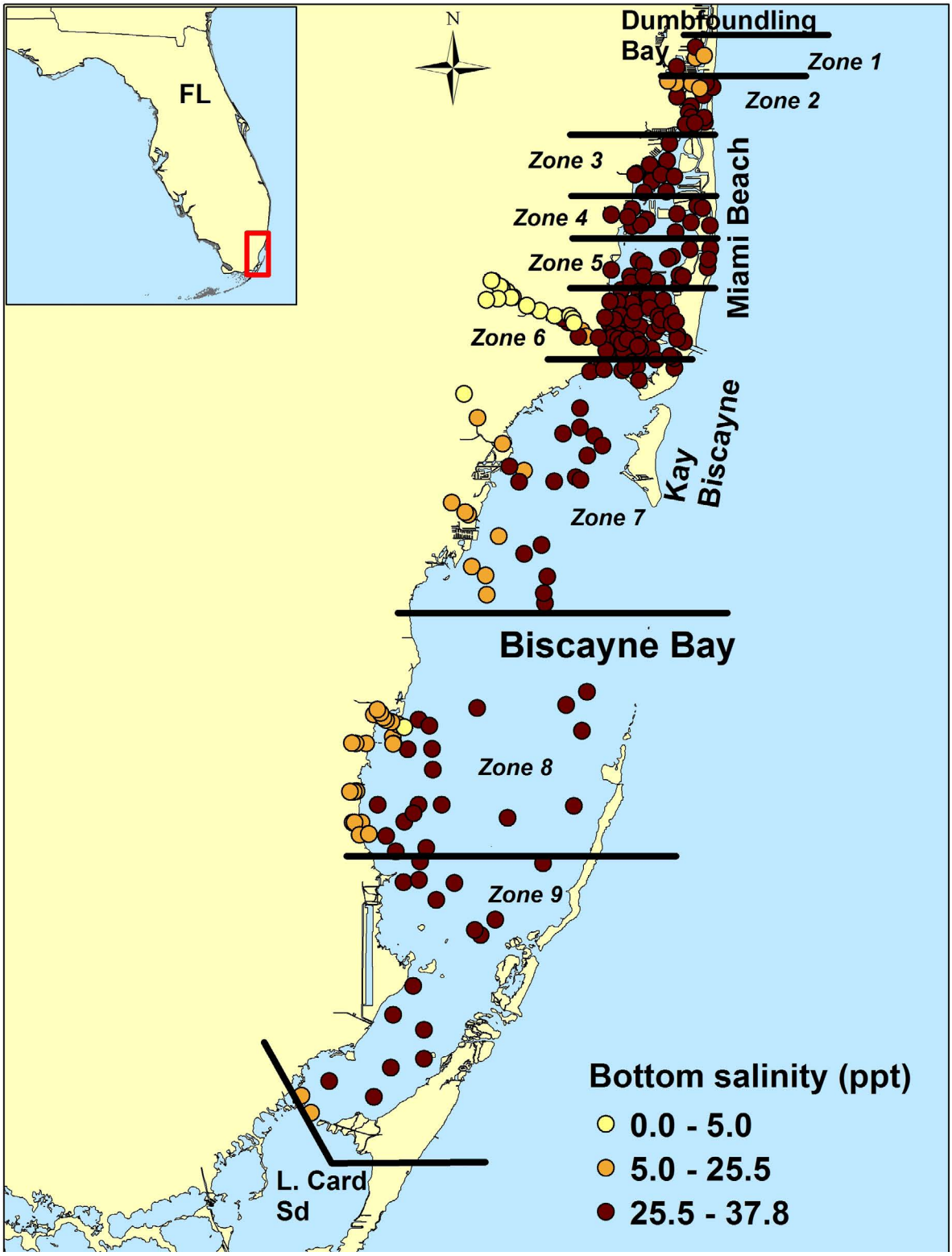


Figure 3. Distribution of bottom salinity in the study area of Biscayne Bay.

can be expressed as a function of the amount of aluminum and metals in sediments, based on naturally occurring geochemical relationships. The correlation of natural metals relationships with aluminum were determined and bracketed by the 95% confidence interval. Stations with corresponding values above the upper 95% confidence limit were considered to be "enriched". In Biscayne Bay, cadmium, chromium, nickel, copper, lead, and zinc concentrations were found to be enriched in various samples.

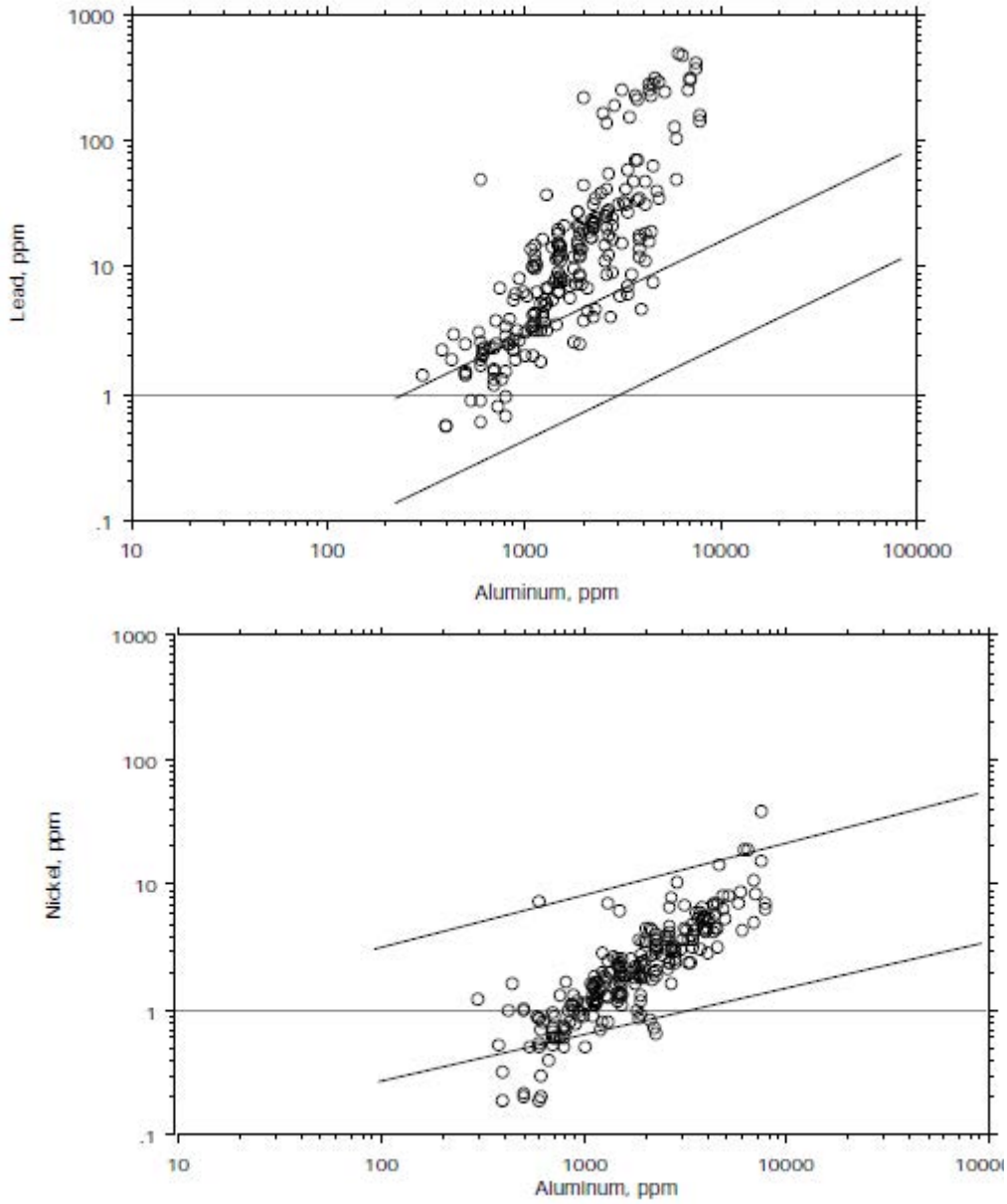


Figure 4. Concentrations of lead and nickel vs aluminum relative to upper and lower 95% confidence limits of metal:aluminum ratios in sediments from reference areas (from Schropp et al., 1990).

Results for lead and nickel are used in Figure 4 to illustrate the metal enrichment assessment.

The spatial extent of elevated chemical concentrations was 2% or less for all substances. Significant contamination was restricted to the small peripheral canals and tributaries of the system. Of the 226 samples analyzed, 33 (14.6%) had at least one chemical concentration that exceeded a mid-range numerical sediment quality guideline. These 33 samples represented about an area of about 3.5 km2 (0.7% of the total). Both the percentages of samples that exceeded numerical guidelines and the surficial extent of contamination as compared to the guidelines were lower than observed elsewhere in comparable studies in U.S. estuaries (Table 1).

Table 1. Number of samples in which SQG were exceeded for each compound and the surface area (km^2 and % total area) represented by the samples in which the ERMs were exceeded.

	TEL	ERL	PEL	ERM	ER^2	ERM
Contaminant	exceeded	exceeded	exceeded	exceeded	km2	% of area
arsenic	90	70	0	0	0	0
cadmium	27	18	3	1	0.03	0.01
chromium	8	4	0	0	0	0
copper	75	44	18	8	0.08	0.02
lead	52	37	27	19	2.06	0.43
mercury	71	62	15	15	2.12	0.44
nickel	4	1	0	0	0	0
silver	30	23	10	0	0	0
zinc	29	24	12	8	0.21	0.04
chlordanes	7	nd	3	nd	nd	nd
dieldrins	19	nd	2	nd	nd	nd
total_PAHs	33	19	4	1	0.06	0.01
Total_DDTs	68	99	14	19	2.23	0.46
Total_PCBs	106	106	30	31	6.37	1.32

TEL and PEL values from McDonald et al. (1996) and ERL and ERM values from Long et al., (1995)
Nd = no guideline available.

2.3 Toxicity Results

A wide range of toxicity was observed throughout the survey area. Overall, the data indicated that the sediments collected in the peripheral tributaries were much more toxic than those from the open water basins of the bay. In the amphipod tests, 49 of 226 samples (21.7%) were significantly different from controls (Table 2). Samples from the lower Miami River were most toxic in the amphipod survival tests, the least sensitive of the four tests performed. In the sea urchin fertilization tests, 44% of the samples were toxic in 100% pore water, 20% were toxic when samples were diluted by 50%, and only 6% were toxic in tests in 25% pore water. A slightly higher percentage of the 1996 samples was toxic than the 1995 samples, reflecting the influence mainly of samples from Zone 6. In the most sensitive bioassay, 77% of samples were toxic in the urchin embryological development tests performed with 100% pore water. In the Microtox^R tests, 58% of samples were toxic. The majority of the toxic samples were collected in 1995, again, reflecting the influence of the Miami River samples on the results. P-450 HRGS assay results exceeded 11.1 ug B[a}P equivalents/g in 36 (30%) of the 121 samples tested; however, none exceeded 37.1 ug B[a}P equivalents/g. The cytochrome P-450 HRGS assays also indicated higher induction rates in samples from canals and tributaries, indicative of the presence of mixtures of organic compounds.

For the amphipod survival tests, highly significant toxicity was observed in samples that represented 62 km^2, 13% of a total of 484 km^2 (Table 3.) This estimate is similar to the average of 10.9% calculated from studies

performed throughout other U.S. bays and estuaries. The spatial extent of toxicity in the sea urchin tests of fertilization success in 100% pore waters was 47%, again, similar to the national average of 42.6%. In the Microtox® tests, toxicity was apparent over 51% of the area, slightly lower than the national average of 61%. Highly elevated and moderately elevated responses in the P-450 HRGS assays occurred in samples collected in 1996 that represented 3.3% and 0.0%, respectively, of the study area.

In the southern reaches of Zone 8, there were 13 samples that formed a ribbon of toxicity from the shoreline across the bay to the ocean. These samples were highly toxic in one or more tests, often including the amphipod survival test. Samples collected to the north and south of this band were not toxic in the amphipod test. The data from the chemical analyses indicated these samples were not highly contaminated. Except for a few samples with slightly elevated ammonia levels, concentrations of chemicals for which analyses were performed were below or near the detection limits. The lack of correspondence between measures of toxicity and chemical concentrations in the 13 samples suggests that other substances for which analyses were not performed were present at toxicologically significant concentrations.

Table 2. Number and percent of significant sediment toxicity bioassay results.

	1995	1995	1996	1996	Total	Total
Toxicity test/end point	toxic/ total	percent	toxic/ total	percent	toxic/ total	percent
Amphipod survival	47/105	38.8	2/121	1.7	49/226	21.7
Urchin fertilization						
100 % porewater	36/105	34.3	64/121	52.9	100/226	44.2
50% porewater	14/105	13.3	30/121	24.8	44/226	19.5
25% porewater	6/105	5.7	8/121	6.6	14/226	6.2
Urchin development						
100 % porewater	66/105	62.9	108/121	89.3	174/226	77
50% porewater	26/105	24.8	43/121	35.5	69/226	30.5
25% porewater	10/105	9.5	4/121	3.3	14/226	6.2
Microtox®	94/105	99.5	37/121	30.6	131/226	58

2.4 Benthic Infaunal Results

Benthic community assessment was not done in this study.

Table 3: Spatial extent of sediment toxicity in each test performed during 1995 and 1996.

Toxicity test/end point	1995 km^2	1995 % of total	1996 km^2	1996 % of total	Total km^2	Total % of total
Amphipod survival	52.9	24.8	9.4	3.5	62.3	12.9
Urchin fertilization						
100 % porewater	109.7	51.5	119.8	44.2	229.5	47.4
50 % porewater	54	25.4	50.2	21.4	104.2	21.5
25 % porewater	54.1	25.4	5.1	1.9	59.2	12.2
Urchin development						
100 % porewater	176.8	83.1	231.2	85.2	408	84.3
50 % porewater	95.5	44.9	75.4	27.8	170.9	35.3
25 % porewater	77.3	36.3	5.2	1.9	82.5	17
Microtox EC50	203.8	95.8	44.6	16.4	248.4	51.3
Cytochrome P-450 RGS						
>11.1 ug BaP/g [a]	nd		8.8	3.3	8.8	3.3
>37.1 ug BaP/g	nd		0	0	0	0

[a] critical values of 11.1 and 37.1 ug/g determined from data distribution within the national database

2.5 Correlations

Many metals and organic compounds that were elevated relative to numerical guidelines of highest concern showed strongest concordance with measures of toxicity. Substances that met these criteria, included copper, lead, mercury, DDTs and PCBs (Table 4). Elevated concentrations of mixtures of trace metals, PAHs, PCBs, and other chlorinated substances from samples collected in the lower Miami River were highly correlated with reduced amphipod survival. Somewhat different mixtures of substances were highly correlated with toxicity observed in the urchin tests performed on samples from the canals of south bay. Results of the P-450 HRGS assays were highly correlated with mixtures of high molecular weight PAHs, PCBs, and other organic compounds.

3. SUMMARY

Wide ranges in both chemical concentrations and toxicity were observed throughout the survey area. The study indicated that the concentrations of chemical mixtures were sufficiently elevated in some sediment to contribute to acute and sublethal toxicity in laboratory tests. Concentrations of individual chemicals were elevated in only a very small portion of the total survey area - restricted mainly to the narrow canals and tributaries. The toxicity tests confirmed that toxicity, as measured with the acute amphipod survival test, was restricted in surficial extent to a small percentage of the area. However, toxicity as measured with the sublethal urchin and Microtox^R tests was much more pervasive.

Table 4. Spearman-rank correlation coefficients (rho, corrected for ties) and probable significance levels for results of four toxicity tests and chemical concentrations in 226 sediment samples from Biscayne Bay.

Chemical	Amphipod survival		Urchin fertilization		Urchin development		Microbial bioluminescence	
Un-ionized ammonia	-0.129	ns	-0.195	**	-0.573	****	na	
aluminum	-0.075	ns	-0.189	**	0.024	ns	-0.368	****
antimony	-0.118	ns	-0.077	ns	-0.095	ns	-0.082	ns
arsenic	0.025	ns	-0.033	ns	-0.043	ns	-0.159	*
cadmium	-0.191	**	-0.096	ns	0.093	ns	-0.460	****
chromium	-0.048	ns	-0.169	*	0.129	ns	-0.415	****
copper	-0.124	ns	-0.161	*	0.083	ns	-0.391	****
iron	-0.111	ns	-0.046	ns	0.063	ns	-0.337	****
lead	-0.095	ns	-0.132	*	0.049	ns	-0.329	****
manganese	-0.023	ns	-0.108	ns	-0.123	ns	-0.304	****
mercury	-0.108	ns	-0.083	ns	0.080	ns	-0.191	**
nickel	-0.131	*	-0.179	**	0.087	ns	0.438	****
selenium	0.028	ns	-0.260	****	-0.048	ns	-0.333	****
silver	-0.079	ns	-0.104	ns	0.102	ns	-0.339	****
thallium	-0.059	ns	0.078	ns	0.068	ns	-0.172	*
tin	-0.149	*	-0.165	*	0.001	ns	-0.235	***
zinc	-0.132	*	-0.135	*	0.038	ns	-0.362	****
percent sand	-0.098	ns	0.265	****	-0.001	ns	0.226	***
percent silt	0.061	ns	-0.250	***	0.053	ns	-0.276	****
percent clay	0.196	**	-0.277	****	-0.108	ns	-0.065	ns
percent fines	0.098	ns	-0.267	****	0.001	ns	-0.229	***
percent TOC	-0.048	ns	-0.232	***	-0.001	ns	-0.306	****
AVS	-0.035	ns	-0.371	****	-0.138	*	-0.458	****
sum 7 LPAHs	-0.093	ns	-0.102	ns	0.019	ns	-0.255	****
sum all LPAHs	-0.142	*	-0.093	ns	0.024	ns	-0.331	****
sum 6 HPAHs	-0.088	ns	-0.078	ns	0.091	ns	-0.296	****
sum all HPAHs	0.086	ns	-0.083	ns	0.082	ns	-0.292	****
sum 13 PAHs	-0.079	ns	-0.092	ns	0.075	ns	-0.291	****
sum all PAHs	-0.105	ns	-0.088	ns	0.056	ns	-0.315	****
hexachlorobenzene	-0.158	*	0.093	ns	0.010	ns	-0.123	ns
sum of HCHs	-0.115	ns	-0.259	****	-0.244	***	0.147	ns
heptachlor	-0.298	****	0.033	ns	0.217	ns	-0.148	*
heptachlor epoxide	-0.187	*	0.015	ns	0.033	ns	-0.149	*
aldrin	-0.293	****	0.078	ns	0.129	ns	-0.245	***
total chlordanes	-0.155	*	-0.128	ns	0.051	ns	-0.277	****
trans-nonachlor	-0.257	****	-0.023	ns	-0.051	ns	-0.154	*
cis-nonachlor	-0.180	*	-0.061	ns	0.069	ns	-0.281	****
dieldrin	-0.139	*	-0.040	ns	0.120	ns	-0.298	****
o, p'-DDE	-0.188	*	-0.114	ns	-0.018	ns	-0.189	*
p, p'-DDE	-0.119	ns	-0.096	ns	0.097	ns	-0.367	****
o, p'-DDD	-0.234	***	-0.039	ns	0.001	ns	-0.235	***
o, p'-DDT	-0.055	ns	-0.027	ns	0.115	ns	-0.124	ns
p, p'-DDT	-0.186	*	0.001	ns	0.148	ns	-0.311	****
total DDTs	-0.135	*	-0.097	ns	0.082	ns	-0.281	****
mirex	-0.153	*	-0.049	ns	0.001	ns	-0.104	ns
oxychlordane	-0.281	****	-0.001	ns	0.021	ns	-0.109	ns
endosulfan	-0.194	*	-0.012	ns	0.132	ns	-0.081	ns
endrin	0.055	ns	-0.069	ns	-0.037	ns	-0.066	ns
PCBs 5 + 8	-0.201	*	0.042	ns	-0.049	ns	0.048	ns
PCB 105	-0.114	ns	-0.022	ns	0.125	ns	-0.264	****
PCBs 153 + 132	-0.117	ns	-0.038	ns	0.157	ns	-0.274	****
PCB 206	-0.156	*	0.001	ns	0.043	ns	-0.220	**
PCB 209	-0.363	****	0.135	ns	0.114	ns	-0.147	*
total PCBs	-0.127	ns	-0.070	ns	0.136	ns	-0.247	***
Sums of chemical:ERM quotients								
• 9 metals	-0.119	ns	-0.114	ns	0.058	ns	-0.319	****
• 13 PAHs	-0.080	ns	-0.097	ns	0.060	ns	-0.280	****
• 3 COHs	-0.133	ns	-0.084	ns	0.080	ns	-0.312	****
• 25 chemicals	-0.110	ns	-0.084	ns	-0.080	ns	-0.313	****

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$
**** $p < 0.0001$

In general, the estimates of the spatial extent of toxicity measured in four tests in Biscayne Bay were similar to the "national average" estimates compiled from many other surveys previously conducted by NOAA, suggesting that Biscayne Bay sediments are not unusually toxic relative to sediments from other areas. These data also agreed well with observations made by the U. S. Environmental Protection Agency (EPA) of the surficial extent of toxicity in large estuarine provinces. In the Louisianian, Virginian, and Carolinian provinces, EPA estimated that 8.4%, 10%, and 2%, respectively, of these survey areas were toxic in tests of amphipod survival (Long et al., 1996).

The weight of evidence strongly suggests that in the lower Miami River, toxicity as measured in the amphipod survival tests could have been caused, by mixtures of PAHs, PCBs, chlordane pesticides, lead, and HCHs. In the canals of the south bay, both toxicity and contamination were less severe and the identities of chemicals that most probably contributed to toxicity were less clear. Concentrations of PAHs, PCBs, and several trace metals, however, may have been sufficient to contribute to toxicity in the sensitive sublethal urchin tests. Throughout the entire area, ammonia appeared to be a major contributor to toxicity observed in the urchin embryological development tests, but not to the other tests. A section of the southern Biscayne Bay showed high toxicity that could not be explained with the chemical data. Results of many of the toxicity tests were highly significant in the samples from this section of the bay, yet they were surrounded by many stations in which there was little or no toxicity. Concentrations of chemicals for which analyses were performed were uniformly low, usually near or below detection limits. Therefore, the data suggest that chemical substances other than those for which analyses were performed likely caused or contributed to the toxic conditions in these samples.

Chapter 10
St. Thomas East End Reserves

1. STUDY AREA DESCRIPTION

The St. Thomas East End Reserves (STEER) is a collection of Marine Reserves and Wildlife Sanctuaries (Inner Mangrove Lagoon, Cas Cay/Mangrove Lagoon, Jersey Bay, St James, Great Bay, and Compass Point Salt Pond Marine Reserve and Wildlife Sanctuary) located on the southeastern end of the island of St. Thomas, U.S. Virgin Islands (USVI) (Figure1). Within the STEER, there are extensive mangrove forests, seagrass beds, coral reefs, lagoons, and cays. In 1979, the Mangrove Lagoon/Benner Bay area, along with Vessup Bay, were designated by the USVI government as Areas of Particular Concern, due to the abundance of important, but threatened, natural resources, and the desire to preserve and, as needed, restore these areas.

The STEER is thought to be one of the most valuable nursery areas remaining in St. Thomas, with many species of fish and shellfish spending some portion of their lives in the protected areas around the mangroves and in the extensive seagrass beds. Fishing is not allowed in most parts of STEER, and where it is allowed (e.g., for baitfish), a Department of Planning and Natural Resources permit is required. The abundance of natural resources has contributed to the STEER being a popular destination for recreational activities, ranging from swimming, camping, snorkeling and SCUBA, to boating and ecotourism.

The largest mangrove system in St. Thomas occurs along the shores of Mangrove Lagoon/Benner Bay. There are extensive areas of seagrass in Benner and Jersey Bays. At one time, seagrasses were also abundant in Mangrove Lagoon. There are significant coral reef areas in Jersey Bay and also south of Cas and Patricia Cays. The STEER is a relatively shallow system, supporting both patch and fringing reefs.

Sampling Details

In 2011, sediment samples were collected from 24 sites for chemical contaminant analysis, toxicity bioassays (amphipod survival, sea urchin fertilization, and P450), and benthic infaunal community analysis. This was part of a much larger effort that included water column monitoring for nutrients, storm water contaminants, and sedimentation; tissue contaminant body burdens for fish, conch and coral; coral health assessment; sediment coring for contaminant analyses through time; and a biogeographic assessment of fish and epifaunal communities (Pait et al., 2016).

The STEER was subdivided into five strata based on habitat and geography (e.g., hard bottom areas, seagrass beds, mangroves, etc., Figure 1). Five sampling points on soft bottom sediments were then randomly selected in each stratum. In addition to the work in 2011, preliminary field work took place in May 2010. From that effort, a total of 13 sediment samples were taken. However, as samples were collected from targeted sites and were not selected randomly, they are not included in the statistical comparisons between strata, nor were they included in the calculation of the mean (average) concentration of sediment contaminants in the STEER.

2. RESULTS

2.1 Important Physical Drivers

The eastern ¾ of the area is exposed to open ocean currents, tidal movement, and wind driven currents, only partly in the lee of St. James and Little St. James Islands. In the west is Mangrove Lagoon which is a restricted body of water behind mangrove stands, reefs, and cays forming an embayment, and is open to the ocean by two narrow channels. Over time, shoals have built up at the openings of the channels which restricts water flow. Due to the restricted water flow through the entrances, a portion of circulating water is redirected up through Benner Bay east of Mangrove Lagoon along the eastern side of Bovoni Cay and out to open water. Circulation is clockwise through Mangrove Lagoon and Benner Bay, but may be reversed by wind driven forcing. There are two watersheds which drain into the STEER, the Jersey Bay and the Red Hook watersheds. The largest is the Jersey Bay watershed which empties into Mangrove Lagoon/ Benner Bay and Jersey Bay. Approximately one-third of the population of the island of St. Thomas resides in the Mangrove Lagoon/Benner Bay watershed. There are a multitude of land uses within the watersheds that drain into the STEER, including a large active landfill, numerous marinas and boatyards, a number of resorts, various commercial/industrial activities, an EPA Superfund Site, a horse racetrack, and residential areas served by individual septic systems, some of which are failing. The western side of Mangrove Lagoon contains the Bovoni Landfill. The landfill covers approximately 330 acres, with nearly 40 acres directly adjacent to Mangrove Lagoon. On the northern side of Mangrove Lagoon is a horse racetrack. During construction of the racetrack, the mangrove delta draining Turpentine Gut, the largest, and only perennial stream on St. Thomas, was altered by filling and diverting the delta, and forming a single channel, resulting in additional sediment being deposited directly into Mangrove Lagoon. Mangrove Lagoon and, to a certain extent Benner Bay, had more fine grained sediments than what was seen to the east, which were more open to ocean currents and wind-driven exchange, although there were site-specific exceptions.

2.2 Contamination Results

There was a pattern of higher concentrations of chemical contaminants in Mangrove Lagoon and northern Benner Bay than the other strata (Figure 2). Three sites, two of which were in Mangrove Lagoon, were above the National Status and Trends Program (NS&T) median for total polycyclic aromatic hydrocarbons (PAHs) (395 ng/g.). From the preliminary sampling in 2010, the highest concentration of total PAHs was found in Mangrove Lagoon, at 951 ng/g. In other NS&T studies, the mean concentration of total PAHs was 52.3 ±8.7 ng/g in Vieques, Puerto Rico and 80.6 ±25.5 ng/g in southwest Puerto Rico. Total PAHs in the sediments were well below the NOAA effects range median (ERM) and effects range low (ERL). Ratios of specific indicator PAH compounds indicate pyrogenic sources (e.g. burned fuel) for most sites where PAHs were elevated. The mean concentration of total polychlorinated biphenyls (PCBs) found in the STEER was 1.00 ±0.32 ng/g. As with the PAHs, there was a pattern of somewhat elevated levels of total PCBs in Mangrove Lagoon and in the northern Benner Bay areas. However, statistical tests indicated no significant variation in total PCBs concentration across the five strata due to high variability. In other NS&T studies, mean total PCBs concentrations were 2.09 ±0.50 ng/g in Jobos Bay, 2.86 ±0.14 ng/g, in Vieques,

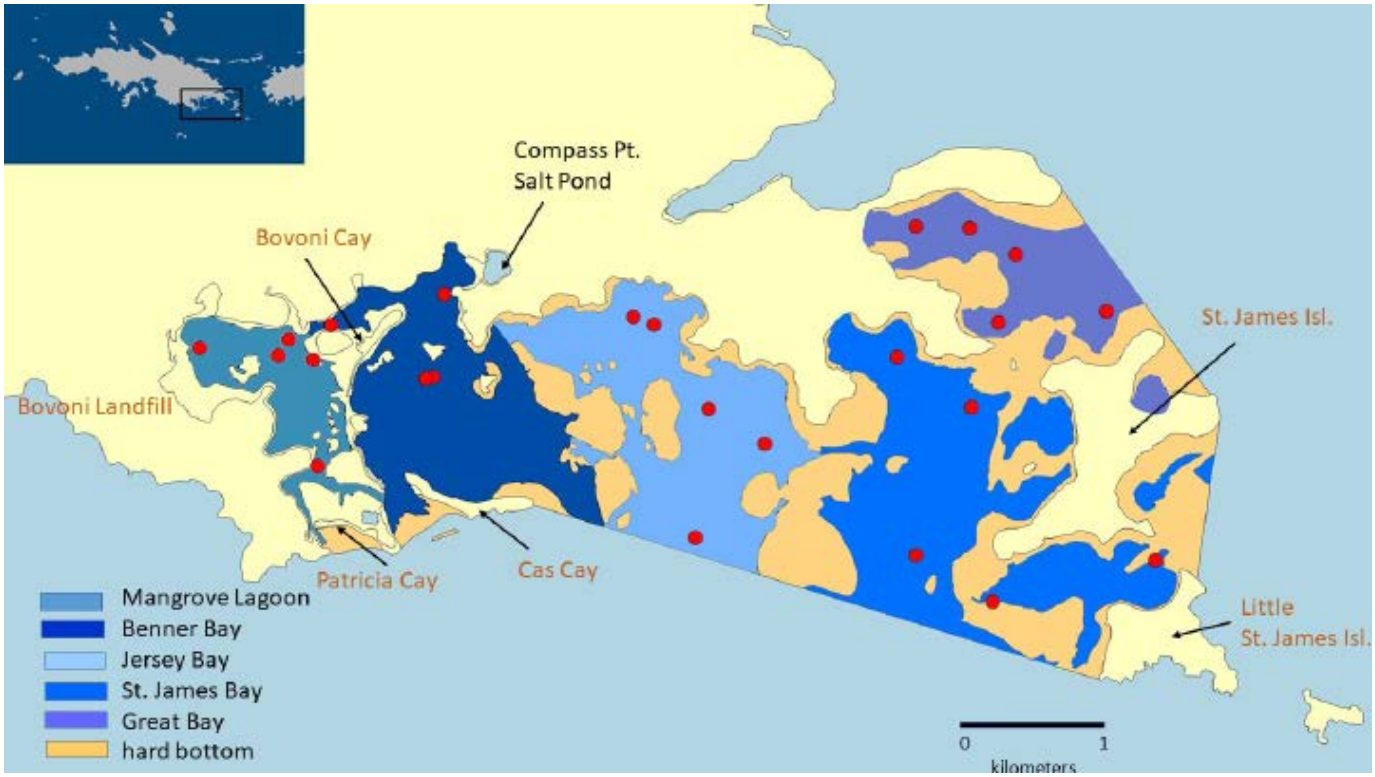


Figure 1. Map of the St Thomas East End Reserves sampling strata and sample points.

and 12.1 ±2.26 ng/g in southwest Puerto Rico. Four of the five sites from the stratified random sampling in Mangrove Lagoon and northern Benner Bay had a total PCB concentration above the NS&T median of 2.2 ng/g. All four of the 2010 targeted sample were above the NS&T median value. One sample in Benner Bay (65.9 ng/g) from the targeted sampling was above the NS&T 85th percentile (23.7 ng/g) for total PCBs and was higher than the ERL. There was a highly significant positive correlation between percent fine grained sediments and the concentrations of total PAHs and PCBs.

Higher concentrations of total DDT were found in Benner Bay and Mangrove Lagoon than the other strata. In other regional studies, a mean total DDT concentration of 2.10 ±1.26 ng/g in southwest Puerto Rico , 0.54 ±0.10 ng/g in Jobos Bay, and 23.6 ±16.5 ng/g n Vieques were detected (Pait et al., 2010). The concentration of total DDT at Benner Bay (3.61 ng/g) from the 2010 targeted sampling was also above the ERL (1.58 ng/g). However, none of the sites sampled in the STEER had a concentration above the DDT ERM.

Most of the results for other pesticides were below detection limits. The highest concentration of chlordane (alpha and gamma isomers) detected in STEER sediments was 0.85 ng/g at the mouth of Turpentine Gut. None of the sites had a chlordane concentration above the ERM.

The mean concentration of tributyltin (TBT) in the sediments in the STEER was 1.85 ±1.30 ng Sn/g. The highest concentration of TBT detected in STEER sediments was in Benner Bay, with a concentration of 31 ng Sn/g. However, of the samples analyzed from 2010, the concentration of TBT was a maximum of 248 ng Sn/g. The NS&T data base median concentration of TBT in sediments is 0.16 ng Sn/g. The NS&T 85th

percentile for TBT is 1.38 ng Sn/g. Previously, the highest concentration of TBT detected in the STEER (248 ng Sn/g) represented the third highest detection ever in sediments in NOAA's NS&T Program. The only two higher TBT concentrations from the Program were from Superfund sites in the Elizabeth River in the southern Chesapeake Bay area, and Elliot Bay in Puget Sound. Sediment cores collected in a follow-up study in 2013 revealed massive reservoirs of TBT (8,800 ng Sn/g) buried in the sediments in Benner Bay (Hartwell et al., 2016). In regional studies, Pait et al. (2008) detected a mean TBT concentration of 0.01 ±0.01 ng Sn/g in southwest Puerto Rico, 0.05 ±0.02 ng Sn/g in Vieques, Puerto Rico, and 0.56 ±0.28 ng Sn/g in Jobos Bay. It should also be noted, that 15 of the 24 sediment samples taken in the STEER had no detectable TBT.

Virtually all the trace elements showed a pattern of decreasing concentrations from Mangrove Lagoon and Benner Bay toward the east. Most were below NOAA ERL levels at all locations. Lead, mercury and zinc were present above ERL levels at one or two individual stations. Copper was present at concentrations in excess of the ERL at multiple locations, and exceeded the ERM at a targeted site from the 2010 samples. Copper, zinc, and mercury were found at a few selected sites at concentrations above that which would be predicted based upon background levels normalized to aluminum. All of these sites were in either Mangrove Lagoon or Benner Bay. The concentrations of aluminum and iron are considerably higher in Mangrove

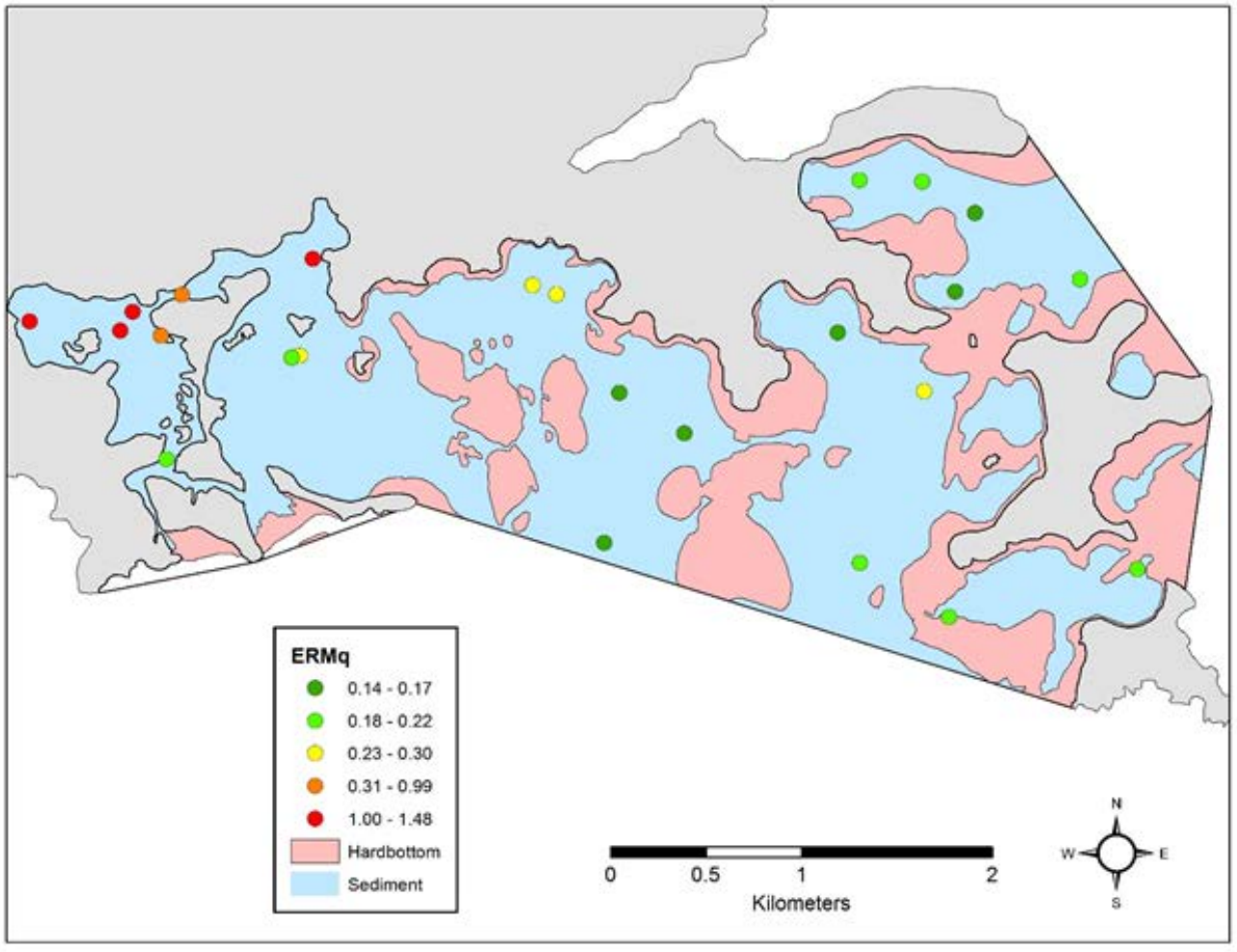


Figure 2. Total ERMq for all contaminants in the STEER.

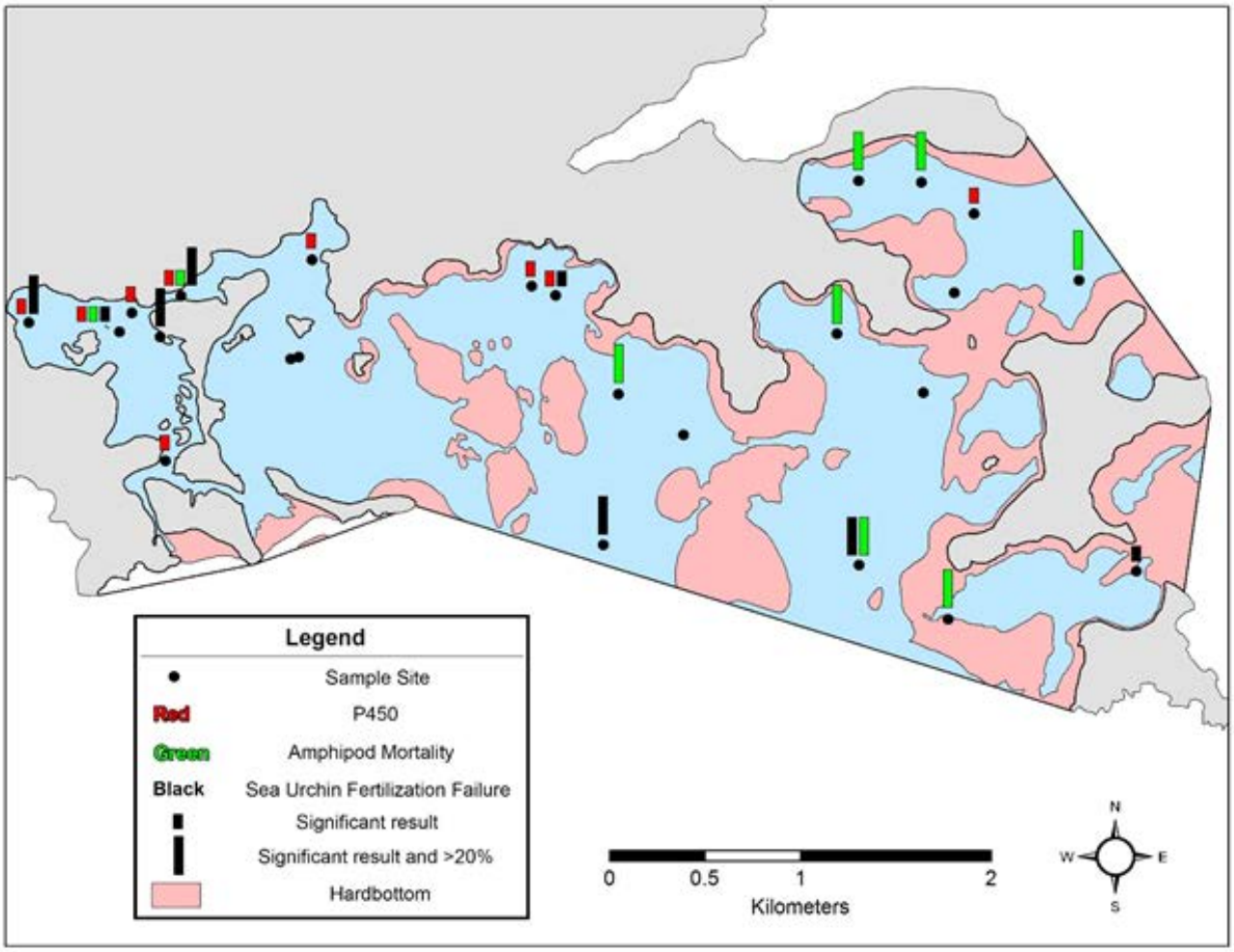


Figure 3. Significant toxicity bioassay results from the STEER.

Lagoon and Benner Bay than in the other strata, indicating that terrestrial sources of sediment may be more dominant there than in the rest of the STEER.

Higher levels of the bacteria *Clostridium perfringens* were found primarily in Mangrove Lagoon, with lower concentrations in most other locations. There are no standards for C. perfringens, but the high levels within Mangrove Lagoon indicate there is a need to reduce wastewater, storm water and various sources of inputs for this pathogen, and other pathogenic microorganisms that may be present as well. Reducing the levels of bacterial contamination would not only benefit ecological health, but human health as well.

2.3 Toxicity Results

Significant amphipod mortality occurred throughout the STEER study area. The highest mortality values observed were in the eastern strata. This may be influenced by sediment grain size. All the amphipod bioassays with mortality elevated above 20% were in sediments that were greater than 60% sand and gravel. Half of the significant sea urchin fertilization bioassays were in sediment from Mangrove Lagoon or the canal joining it to Benner Bay. Jersey Bay and St. James Bay also showed significant toxicity in two locations. Most of the significant P450 responses were in the western strata, including all

of the Mangrove Lagoon sites. Results of the test for the relative contribution of labile versus persistent contaminants indicated that the cells were responding to PAHs, not PCBs. Taken together, the bioassay results indicate a significant gradient of effect from west to east within the STEER (Figure 3). Toxic responses occurred in all strata, but the western portion of the study area exhibited significant results from multiple bioassays.

With the exception of TBT and copper, extremely high concentrations of individual chemical pollutants were not seen. However, the observed widespread toxicological responses indicated the interaction of a variety of factors, including multiple contaminants, physicochemical characteristics of the sediment, and likely chemical pollutants beyond the standard list of analytes that may vary from stratum to stratum. The areal extent of contaminant ERL/ERM exceedances and toxicity are summarized in Table 1.

2.4 Benthic Infaunal Results

A total of 333 taxa and 10,605 individuals were counted from the sediment samples. Of these, 168 were rare or unique taxa (occurring at only one or two stations). Annelids were the dominant taxa, followed by mollusks and arthropods. Less than 1% of the animals were echinoderms. Throughout the STEER, abundance was dominated by two dozen taxa while a large number of taxa were only represented by a few individuals. Abundance was more uniform on average than diversity or number of species, but some locations had extremely low abundance and some sites extremely high abundance. Site 1-1P in Mangrove Lagoon only had four species and five organisms in total. Site 2-16P had over 1,000 organisms.

Gradients of diversity and species richness were seen from low in the west to higher in the eastern strata (Figure 4). With two exceptions (Sites 1-4P and 2-19P), diversity was higher in the eastern strata than in Mangrove Lagoon and Benner Bay. Number of species and diversity were negatively correlated with the ERM and PAH concentrations.

Statistical analysis revealed site groups divided cleanly between Stratum 1 and 2 (Mangrove Lagoon and Benner Bay) vs 3, 4, and 5. There was almost no overlap in species makeup between the site groups. In Mangrove Lagoon and Benner Bay, there were 25 species, versus 109 species found in the other three strata. Species that were found in Mangrove Lagoon and Benner Bay were generally rarely found or were completely absent in the other three strata, and vice versa. A third group of 26 species were found at sites 1-4P and 2-19P. These species were rarely found elsewhere in either Mangrove Lagoon and Benner Bay, or the other three strata. These two sites had a unique species assemblage, different from the other areas. Both site 1-4P, in the lower part of Mangrove Lagoon away from the influence of Turpentine Gut and the landfill, and 2-19P in central Benner Bay had sediment that was predominantly sand, unlike most of the other sites in those strata.

Pollution tolerant species of annelids make up a much larger proportion of the organisms in Mangrove Lagoon and Benner Bay than in the other strata. The weight of evidence between the toxicity, diversity, community makeup, and chemical contamination indicate pollution impacts in Benner Bay and, especially, in Mangrove Lagoon.

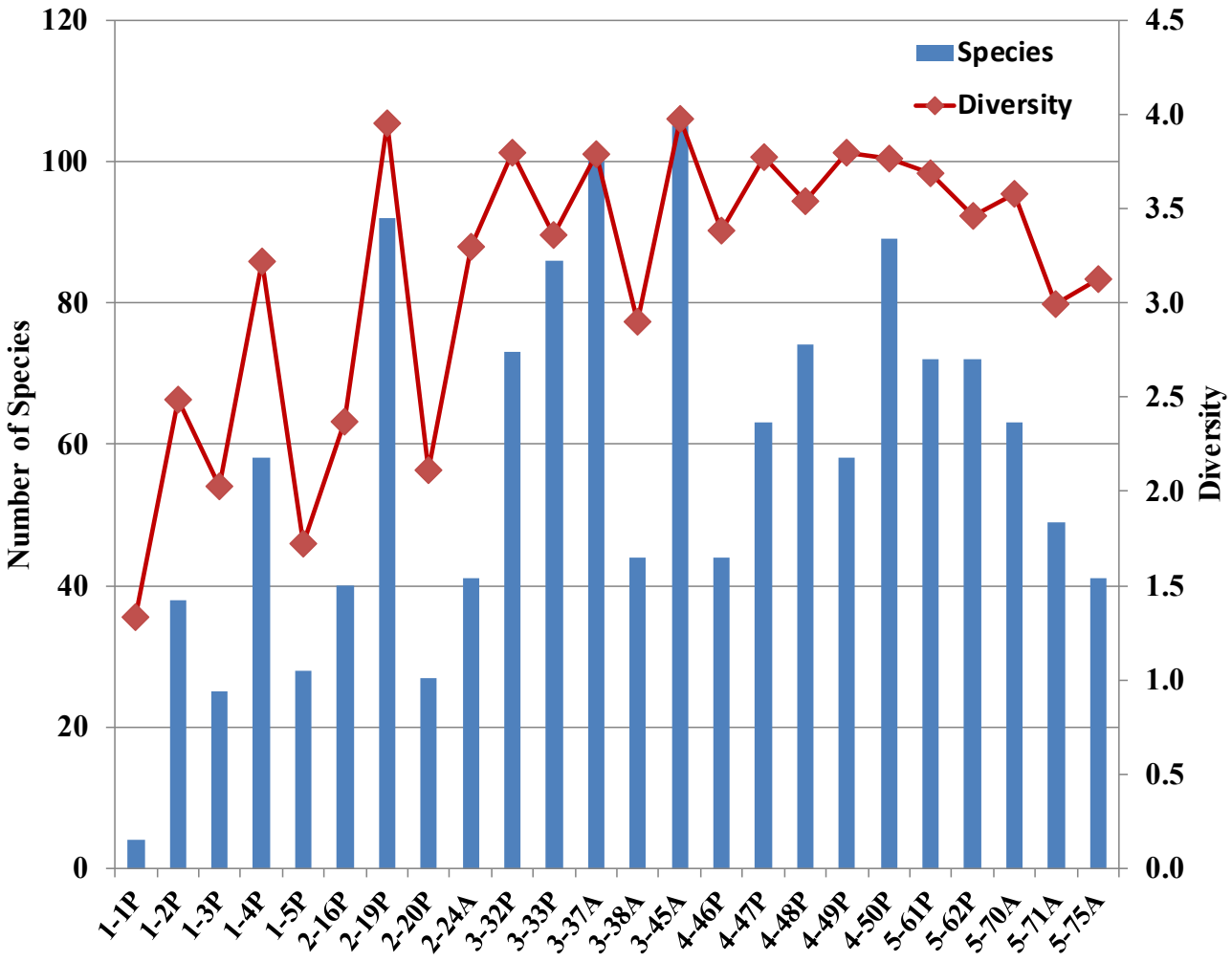


Figure 4. Species diversity and number of species found in the sediments in STEER.

2.5 Correlations

The community attributes of species richness and diversity were significantly, and negatively, correlated with all but one of the contaminant groups (total DDT vs species richness). They were also significantly negatively correlated with the presence of fine-grained sediment. This is confounded with the positive correlations between fine-grained sediment and the contaminant groups. Thus, muddy sediments had higher contaminant concentrations and less diverse animal communities, but which is the causative parameter(s) cannot be shown with these data. Abundance was not significantly correlated with any chemical or physical parameter. Diversity and richness were also negatively correlated with the P450 results, but again, this is confounded with grain size.

3. SUMMARY

Elevated levels of chemical contaminants were primarily found in Mangrove Lagoon and in northern Benner Bay. There is a large landfill adjacent to Mangrove Lagoon, that may contribute a variety of contaminants, as well as input from various commercial/industrial sources, and residential/urbanized areas in the watershed via Turpentine Gut. Land use around northern Benner Bay appears dominated by marina-related activities, which may be a source of chemical contaminants to the STEER. Tributyltin, or TBT, was found at extremely high levels in the northern Benner Bay. Copper and zinc were elevated at several locations in Benner Bay and Mangrove Lagoon. A number of other chemical contaminants including zinc, lead, copper, mercury, total PCBs, and total DDT, were above ERLs at one or more sites in the STEER, indicating that impacts may be occurring in some of the more sensitive species or life stages that may be present.

Bioassays results indicated a significant gradient (high to low) of effects from west to east in the STEER. The widespread toxicological responses likely indicate the interaction of multiple chemicals, including those beyond the standard suite of NS&T analytes, along with other physicochemical characteristics which also vary between strata.

The benthic infaunal analysis correlated with the chemical contaminant and bioassay data, indicating gradients of diversity and species richness, with impacts seen in the western strata, especially in Mangrove Lagoon, decreasing towards the east. This is confounded with gradients of sediment grain size however.

The community composition of animals in the sediments of Mangrove Lagoon and Benner Bay were distinct in terms of the species found from the other three strata in the STEER. Furthermore, the species found in Mangrove Lagoon and Benner Bay were for the most part absent from the other strata and vice versa, likely due in part to natural and anthropogenic stressors found in Mangrove Lagoon and Benner Bay.

Chapter 11
Tampa Bay

1. STUDY AREA DESCTIPTION

The Tampa Bay estuary is the largest estuarine system in Florida. It is highly complex and composed of numerous basins or subdivisions (Figure 1). Unlike other estuaries with single riverine freshwater input at the heads, freshwater sources of Tampa Bay are distributed among hundreds of small tributaries. The dominant river systems that flush into the bay include the Hillsborough, Alafia (in Hillsborough Bay), Manatee (at Bradenton) and little Manatee Rivers (at Gulf City). Parts of the estuary are bordered by highly industrialized and urbanized areas and other parts are bordered by mangroves, bayous, and other relatively rural areas. Toxic chemicals enter the estuary from urban runoff, industrial point sources, municipal wastewater discharges, atmospheric deposition, accidental spills, illegal dumping, pesticide applications and other agricultural practices. Toxic chemicals are known to exist in the sediments and biota of the estuary (Long et al., 1991).

The National Status and Trends (NS&T) Program of NOAA has monitored the concentrations of selected toxicants in sediments, oysters, and bottom-dwelling fish in Tampa Bay since 1986 (Long et al., 1991). Data developed in studies of sediments and bivalve mollusks indicate that many potentially toxic chemicals occur in relatively high concentrations in the lower Hillsborough River, northern Hillsborough Bay, and some peripheral harbors and ports. Contaminant concentrations were moderate or intermediate in middle Tampa Bay, and parts of Boca Ciega Bay, and generally were lowest in Old Tampa Bay and lower Tampa Bay. Elevated contaminant concentrations generally occur in marinas and industrial harbors, and near storm drains and drainage ditches scattered around the perimeter of the estuary. The chemical data provide evidence that portions of the estuary are contaminated, but that alone does not demonstrate that the chemicals represent a significant problem to the biota of the estuary. Thus, sediment toxicity assays were also conducted to provide bioeffects information.

The objectives of the sediment quality surveys summarized in this report were to determine: (1) the spatial extent and patterns in toxicity; (2) the severity or magnitude of toxicity; and (3) the relationships between toxicity and the concentrations of toxicants and other potential causative factors

Sampling Details

Based on background information, the survey was designed to sample areas that were expected to have multiple sources and to represent conditions in accumulation zones within each of the regions of the estuary. Between 1991 (phase 1) and 1992 (phase 2), 55 sites were sampled in triplicate (three stations per site) totaling 165 samples: (1) Ybor Channel/northern Hillsborough Bay, (2) western Old Tampa Bay, (3) St. Petersburg along the Middle Tampa Bay shoreline, and (4) off Gulfport including Boca Ciega Bay (Figure 1). The sediment samples were analyzed for the suite of inorganic and organic contaminants routinely measured by the National Status and Trends program. Sediment toxicity tests included Microtox^{R} test, an amphipod whole sediment survival bioassay, and sea urchin pore water egg fertilization bioassay, all of which provide different insight to sediment quality in Tampa Bay.

Figure 1. Map of Tampa Bay estuarine system showing major regions and locations of Phases 1 and 2 sampling sites.

The areal extent of toxicity in Tampa Bay was determined by plotting the results of the toxicity tests against the size of the portions of the bay that were sampled. The size of the portions sampled (743.7 km^2) was determined with a Uchida model KP-80N planimeter.

2. RESULTS

2.1 Important Physical Drivers

The study area was very shallow with depth ranging from 1.5 m at the near-shore sites to 15.0 m at sites located in vicinities of channels (Ybor Channel). Based on combined measurement from phases 1 and 2 of the study, results indicated that grain size varied broadly from sand to clay (Figure 2). Sediments were muddier with high content of clay and silt in region (1) of the study area (Ybor Channel/northern Hillsborough Bay). In the regions (2), Old Tampa Bay and (3), St. Petersburg along the Middle Tampa Bay shoreline, sediments were coarser with fine sand particles. In the region (4) off Gulfport toward Boca Ciega Bay, sediments varied from fine sand to clay. TOC contents were high in sediment samples from Ybor Channel and in the northern Hillsborough Bay. TOC contents virtually mirror grain size distribution and were elevated in areas of the bay where sediments were finer or muddier.

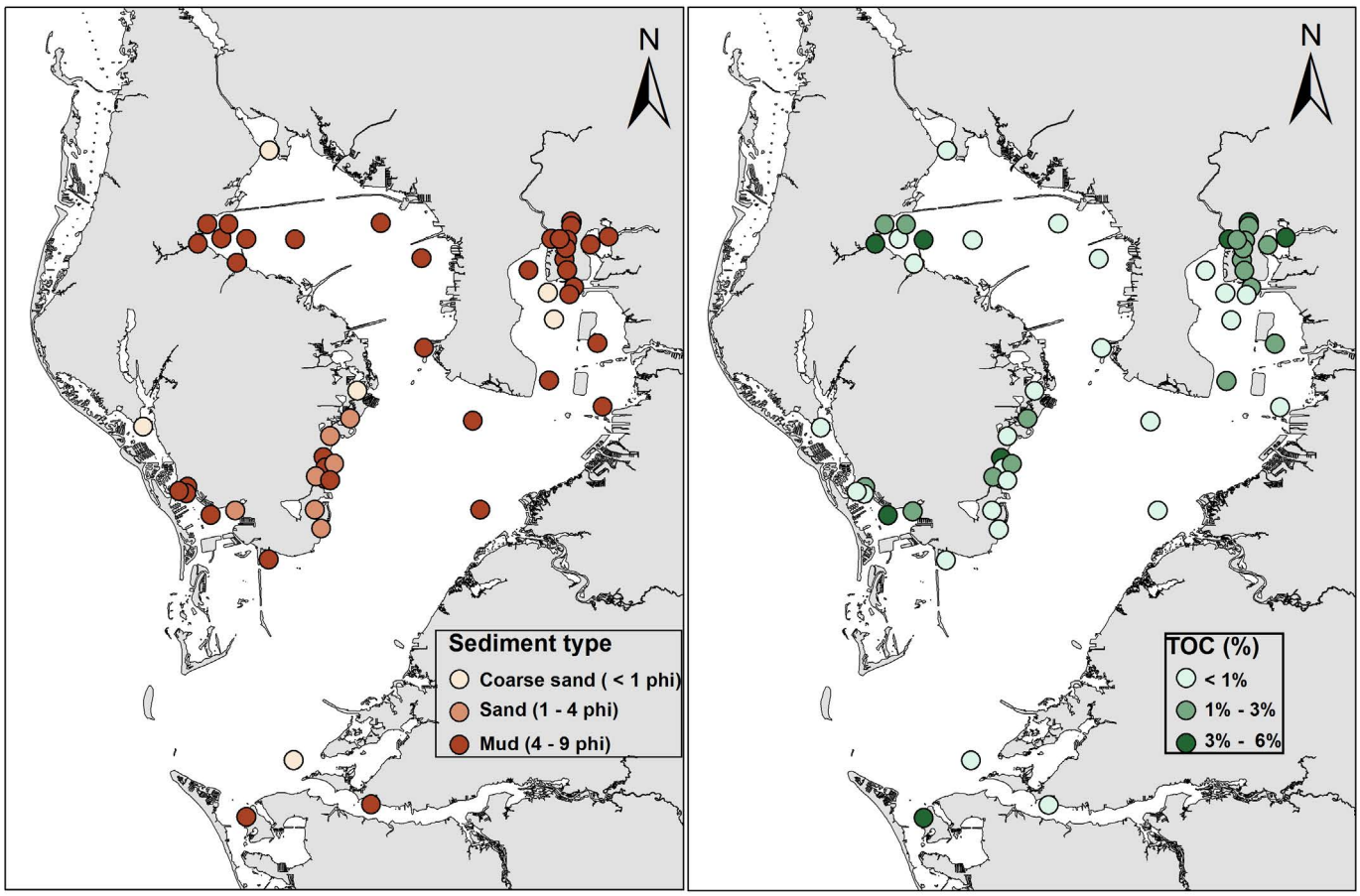


Figure 2. Sediment characteristics in Tampa Bay based on distribution of grain size and total organic carbon content (TOC).

2.2 Contamination Results

Results from Phases 1 and 2 were merged to determine concentration distribution in the entire Tampa Bay study area. Contaminant concentrations varied broadly and the results indicated that concentrations of organic compounds in Tampa Bay sediments was strongly influenced by total organic carbon content, especially at extremely high and low levels. Ybor Channel and Hillsborough Bay had the maximum concentrations of total DDTs and total PCBs (Figure 3). The highest concentrations of chromium, copper, mercury, lead, vanadium, zinc were also recorded in the Ybor Channel locations (Figure 3). Sediments from western Old Tampa Bay, Bayboro Harbor, and Boca Ciega Bay were moderately contaminated. Sediments from St. Petersburg toward the Middle and Lower Tampa Bay areas were among the least contaminated.

Compared to other studies in the early 90's, Tampa Bay sites ranked number 1 (most contaminated) in the concentrations of Ag, Cd, Cu, Pb, Hg, Zn, total DDT (DDTs), chlordane, dieldrin, mirex, total PCBs (PCBs), and total PAHs (PAH). However, none of the average trace metal concentrations in the toxic samples equaled or exceeded the respective ERM guideline values. The average concentrations of cadmium, copper, lead, mercury, and zinc in the toxic samples exceeded the respective ERL values. Furthermore, metal concentrations correlated with grain size illustrating the significance of sediment grain size in the spatial distribution of metals concentrations among sites. The concentrations of several PAHs, endrin, total PCBs, and total DDTs in some samples equaled or exceeded sediment quality guidelines.

The concentrations of cadmium, copper, lead, and zinc in samples that were significantly toxic to amphipods often exceeded the expected background levels normalized to aluminum content.

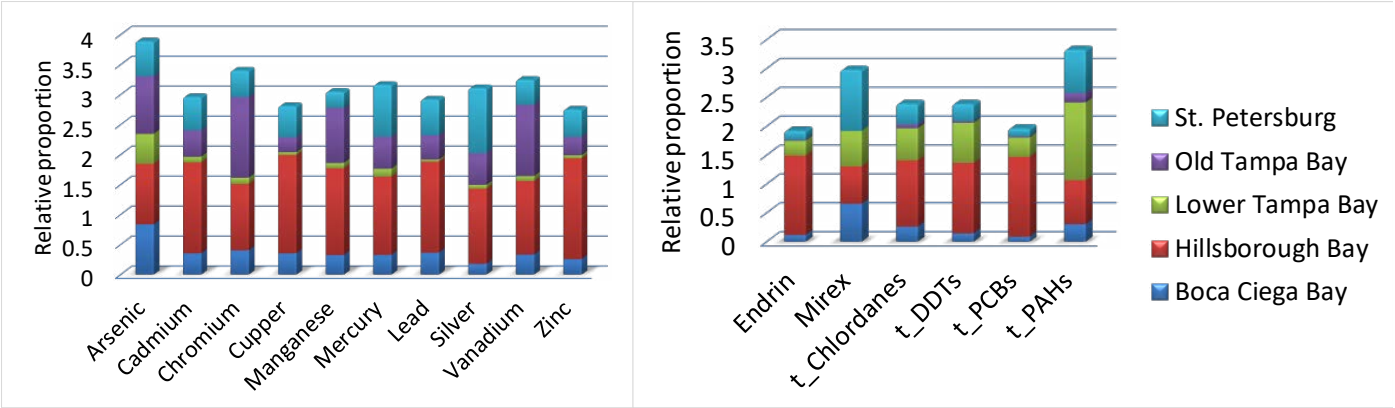


Figure 3. Mean-normalized metal and organic compounds showing concentration distribution in sediment from different region of Tampa Bay, Florida.

2.3 Toxicity Results

Percent sea urchin fertilization success (Table 1) generally increased as the concentration of the pore water was reduced. The mean EC50's indicated that sites 1-5 in the Ybor Channel, site 22 near Gulf Port in Boca Ciega Bay, and site 27 in Cockroach Bay were the most toxic. Sediment toxicity was very patchy in the sites sampled along the St. Petersburg shoreline, but most of the nontoxic samples were collected in Safety Harbor and Old Tampa Bay.

Percent survival among *A. abdita* in sediment (Table 1) ranged from 39.0% to 99.0%. At most sites, the mean percent survival among the replicate samples (n=3) often were very similar, indicating that conditions within the sites usually were relatively homogeneous. However, amphipod survival was highly variable across the study area. The majority of the individual samples that were toxic in the amphipod test were collected in northeastern Hillsborough Bay, particularly in Ybor Channel, the mouth of the Hillsborough River, McKay Bay, Sparkman Channel, and west of the Davis Islands, all in Tampa. This test showed little indication of toxicity in southern Hillsborough Bay, Old Tampa Bay, middle Tampa Bay, and lower Tampa Bay (Figure 4).

Table 1. Numbers (and percentages) of Tampa Bay stations and sites indicated as significantly toxic (different from the control) and numerically significant (>80%, or 70% of the controls) in each of the three toxicity tests.

	Number of Stations (%)		Number of Sites (%)	
Toxicity Test	Statistically[a] Significant	Numerically[b] Significant	Statistically[a] Significant	Numerically[b] Significant
Amphipod survival				
Phase 1 (n=90)	10 (11%)	4 (4%)	6 (20%)	1 (3%)
Phase 2 (n=75)	0	0	0	0
Sea urchin fertilization				
Phase 1 (n=90)				
•100%	77 (85%)	74 (82%)	24 (80%)	19 (63%)
•50%	51 (57%)	37 (41%)	14 (47%)	11 (37%)
•25%	34 (38%)	22 (24%)	10 (33%)	7 (23%)
Phase 2 (n=75)				
•100%	53 (71%)	48 (64%)	18 (72%)	16 (64%)
•50%	48 (53%)	34 (45%)	14 ((56%)	13 (52%)
•25%	33 (44%)	24 (32%)	11 (44%)	8 (32%)
Microtox™ bioluminescence				
Phase 1 (n=90)				
	24 (27%)	16 (18%)	2 (7%)	2 (7%)

Microtox® tests were performed with organic solvent extracts from 89 samples. An EC50 value (the sediment concentrations that caused a 50% reduction in bioluminescence) was calculated from the test results for each sample. Microtox® test results for this study are summarized in Table 1. The EC50 for the control was 0.044 mg/mL. Among the 89 samples, the EC50's ranged from 0.005 to 0.575 mg/mL (lower EC50 values are more toxic). Variability among sampling stations was relatively high in the study area. A

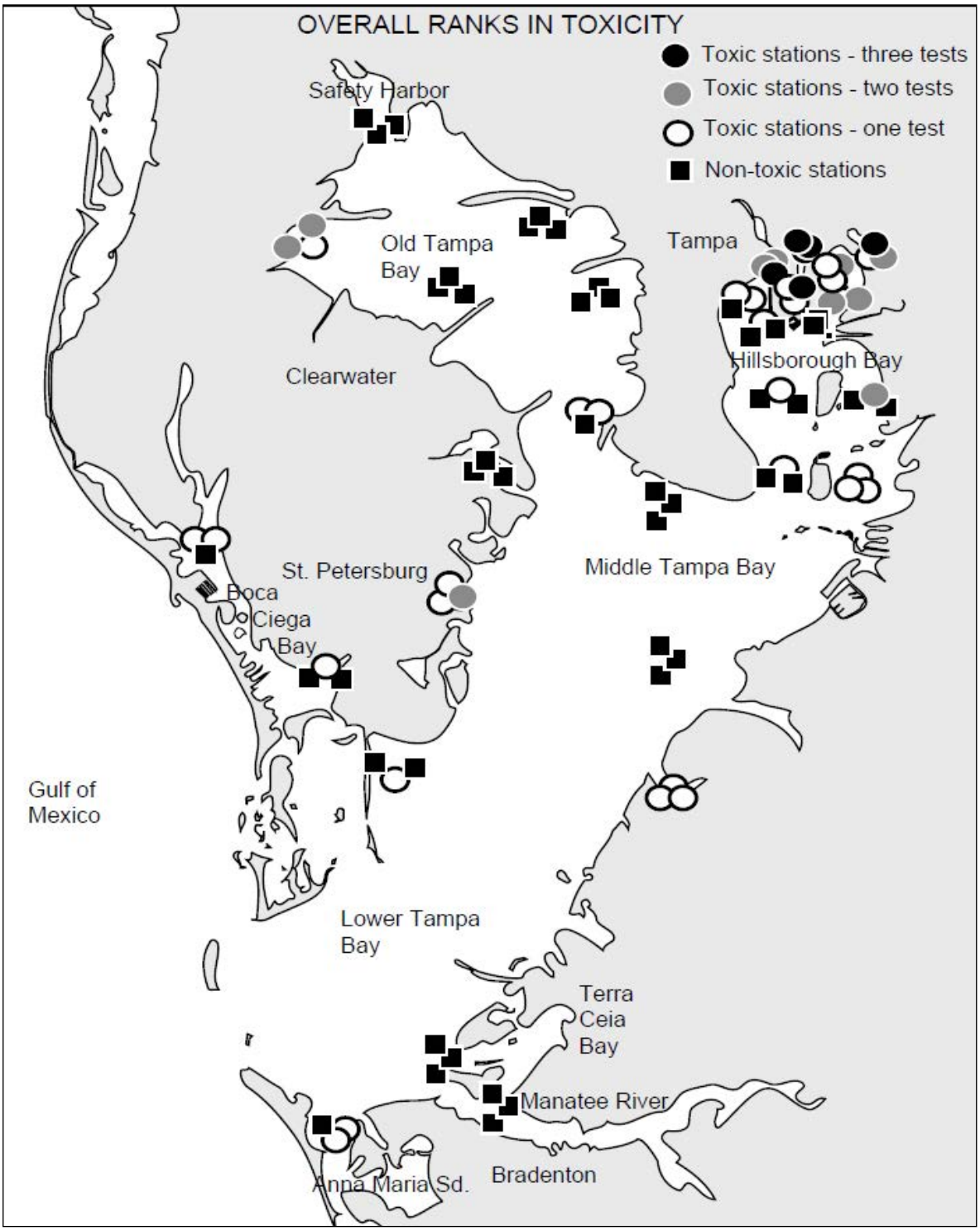


Figure 4. Distribution of toxicity in sampling stations in Tampa Bay as determined by Phase 1 results from three toxicity tests (amphipod survival, Microtox ™ bioluminescence, and sea urching fertilization @ 25% pore water).

total of 24 stations were significantly different from controls, but only two site means were significantly toxic.

The sea urchin fertilization tests were most sensitive, followed by the Microtox^{R} test, while the amphipod test was least sensitive. In the estuary-wide survey performed in Phase 1, 85% of the samples were toxic in the 100% pore water tests with sea urchin fertilization. In the Phase 2 survey of four selected areas, a total of 71% of the samples were toxic in this test. The statistical tests of the data for each site incorporate the within-site variability observed among the three stations at a site. Nevertheless, sediments from many of the sites (80% in 1991 and 72% in 1992) were significantly toxic, as tested by sea urchin fertilization in undiluted pore water. In the Microtox® tests, 27% of the stations and 7% of the sites were toxic. In Phase 1, 10% of the stations and 20% of the sites were toxic in the amphipod tests, whereas in Phase 2 none of the stations or sites were significantly toxic.

The overall pattern indicated by the three tests (Figure 3) is that toxicity was highest in northern Hillsborough Bay and gradually diminished toward the mouth of the bay. Sediments from western Old Tampa Bay, Bayboro Harbor, and Boca Ciega Bay were moderately toxic. Sediments from Safety Harbor, much of Old Tampa Bay, Bayou Grande, and middle Tampa Bay were among the least toxic

The estimates of the spatial extent of toxicity (Table 2) were summarized, based upon the data from the three toxicity tests. Good concordance was evident among the amphipod, Microtox^{R}, and sea urchin tests. The areas that were toxic in the Microtox^{R} and amphipod tests invariably were toxic in the sea urchin tests. Two sites in Phase 1 (number 1 in the mouth of the Hillsborough River and number 2 in Ybor Channel), encompassing about 0.6 km^2, were toxic in all three pore water concentrations and in the Microtox® test. An area of about 0.45 km^2 (site 2 in Phase 1) was toxic in all three tests and at all three pore water concentrations in the sea urchin tests.

Table 2. Estimates of the spatial extent of sediment toxicity in the Tampa Bay estuary, based upon the results of three toxicity tests. Areas were defined as "toxic" when results were less than 80% of the control values.

Test	Area (km^2)	Percent of total area
Sea urchin fertilization		
100 % pore water	463.6	84.3
100% and 50% pore water	59.2	10.8
100%, 50% and 25% pore water	12.9	2.3
Microtox^{R}	0.6	0.1
Amphipod	0.45	0.08

2.4 Benthic Infaunal Results

Benthic infaunal measurements were taken during this study.

2.5 Correlations

In the Phase 1 tests, the correlation between percent amphipod survival and percent sea urchin fertilization (in 100% pore water) was Rho=+0.505 (p=0.0001, n=89). This correlation was relatively strong and highly significant. Similarly, the correlation between percent fertilization and the Microtox^{R} EC50s was very strong and highly significant (Rho=+0.564, p=0.0001, n=89). With the combined Phase 1 and Phase 2 data (n=141), the correlations between amphipod survival and sea urchin fertilization were significant, but weaker than in the Phase 1 data set

As expected, some regional differences were apparent in the correlations. The correlations between trace metals and sea urchin fertilization were strongest in Hillsborough Bay and weakest in Boca Ciega Bay. The correlations between both unionized ammonia and sediment grain size and urchin fertilization were lowest in western Old Tampa Bay. Different combinations of trace metals and physical/chemical properties were the most highly correlated with fertilization success in the different regions: lead, zinc, and TOC in Hillsborough Bay; cadmium, lead, and TOC in western Old Tampa Bay; zinc, arsenic, and nickel in middle Tampa Bay; and sulfides and silver in Boca Ciega Bay.

3. SUMMARY

Contaminant concentration varied broadly with Hillsborough Bay being the most contaminated and St. Petersburg along the Middle Tampa Bay shoreline the least contaminated. Sediments from Gulfport including Boca Ciega Bay were moderately contaminated. In general, Tampa Bay site ranked number 1 (most contaminated) in the concentrations of Ag, Cd, Cu, Pb, Hg, Zn, total DDTs, chlordane, dieldrin, mirex, total PCBs, and total PAHs.

The three toxicity tests provided overlapping and complementary estimates of the spatial patterns and extent of toxicity. Collectively, the amphipod test, the Microtox^{R} test, and the sea urchin test performed with the most diluted pore water concentration indicated that about 0.5 - 0.6 km^2 of Tampa Bay were highly toxic. In contrast, the area in which sediments were toxic to sea urchin egg fertilization with undiluted pore water covered over 464 km^2 within the Tampa Bay estuary.

The overall pattern indicated by the three tests is that toxicity was highest in northern Hillsborough Bay and gradually diminished toward the mouth of Hillsborough Bay. Sediments from western Old Tampa Bay, Bayboro Harbor, and Boca Ciega Bay were moderately toxic. Sediments from Safety Harbor, much of Old Tampa Bay, Bayou Grande, and middle Tampa Bay were among the least toxic. Among the chemicals that were measured, the organic compounds were most likely to contribute to the observed toxicity. These chemicals were highly correlated with toxicity and they occurred at concentrations previously associated with adverse biological effects.

Chapter 12
Florida Panhandle

1. STUDY AREA DESCRIPTION

Apalachicola, Choctawhatchee, Pensacola and St. Andrew Bays are located in the western Florida panhandle (Figure 1). This study used the NOAA's sediment quality triad approach to determine: (1) the spatial patterns in toxicity throughout each bay, (2) the spatial extent of toxicity throughout and among the bays, (3) the severity or degree of toxicity, and (4) the relationships between chemical contamination and toxicity.

Pensacola Bay is a system of four major water bodies, Escambia Bay, Pensacola Bay, Blackwater Bay and East Bay (Figure 2), which together form one of the largest estuarine systems of Florida (over 394 km^2) (Seal et al., 1994). The eastern area of this estuarine system was relatively undeveloped, but its western portion includes the urban center of Pensacola, industrial facilities along Bayou Chico, the Escambia River, and Escambia Bay (Paulic et al., 1994). Previous studies found elevated concentrations of PAHs in sediments from Pensacola Bay and Indian Bayou in Escambia Bay (Seal et al., 1994).

Choctawhatchee River is the most significant freshwater tributary of the Choctawhatchee Bay estuary that has a surface area of 318 km^2 and average depth of 7 m (Seal et al., 1994) (Figure 2). Aside from the city of Fort Walton Beach and town of Destin, the bay's development in the watershed was sparse. Previous investigations throughout Choctawhatchee Bay have shown minimal enrichment, however elevated concentrations of several metals and PAHs were detected in Destin Harbor (Seal et al., 1994).

The St. Andrew Bay estuarine system has a surface area of 254 km^2. This estuarine system includes: West Bay, North Bay, East Bay and the main basin of St. Andrew Bay (Figure 2). The drainage area includes the urban centers of Panama City, Lynn Haven, and Panama City Beach, however, the majority of the watershed is forested and in silviculture (Paulic et al, 1994). Elevated concentrations of metals and organic contaminants have been documented in the bay (NOAA, 1991).

The Apalachicola Basin encompasses nearly 520 km^2 of estuary, including St. Vincent Sound, East Bay, Apalachicola Bay and St. George Sound (Figure 2). The major freshwater inflow to the bay is the Apalachicola River, which is part of the tri-river system that includes Chattahoochee and Flint Rivers. The estuary is highly productive, providing over 90% of the Florida oyster harvest, as well as supporting commercial fin fishing and other shellfish industries (Seal et al, 1994). A previous assessment by the NS&T showed minimal contaminant concentrations.

Several factors lead to the decision to conduct a survey of sediment bioeffects in this area. First, very high concentrations of organic compounds (DDT, PCB) had been found by the NOAA NS&T Program in sediments and biota of Choctawhatchee and St. Andrew bays, bringing attention to the area from a nationwide perspective. Second, the state of Florida wanted to explore the potential for biological effects in the marine environment and provide supplemental data for the statewide sediment quality guidelines. Third, the bays of the western Florida panhandle support abundant populations of living marine resources

Figure 1. Study area encompassing Pensacola, Choctawhatchee, St. Andrew, and Apalachicola bays.

that could be at risk from toxic contamination. Collectively, these factors lead to the decision to determine if contamination of the sediments in the western Florida panhandle was sufficiently high to warrant concern for resident biota.

The survey was conducted over two years: Pensacola Bay and St. Andrew Bay were sampled in 1993; and Choctawhatchee Bay, Apalachicola Bay and Bayou Chico (a sub-basin of Pensacola Bay) were sampled during 1994.

Sampling Details

Stratified, random sampling designs based on the EMAP-Estuaries surveys (Schimmel et al., 1994) were used in the bays. Each bay was subdivided into irregular-shaped strata. Large strata were established in the open waters of the bays where toxicant concentrations were expected to be uniformly low. In contrast, relatively small strata were established in urban harbors and bayous nearer suspected contaminant sources in which conditions were expected to be heterogeneous or transitional. A total of 123 surficial sediment samples were collected throughout the study areas.

Multiple toxicity bioassays were conducted on all samples, and chemical analyses were performed on 102 of the 123 samples. Sediment samples were analyzed for the suite of inorganic and organic contaminants routinely measured by the NS&T program as well as for sediment grain size, and total organic content (TOC). Toxicological bioassays were conducted to determine survival, reproductive success, morphological development, metabolic activity, and genotoxicity. Toxicity testing included an amphipod survival bioassay

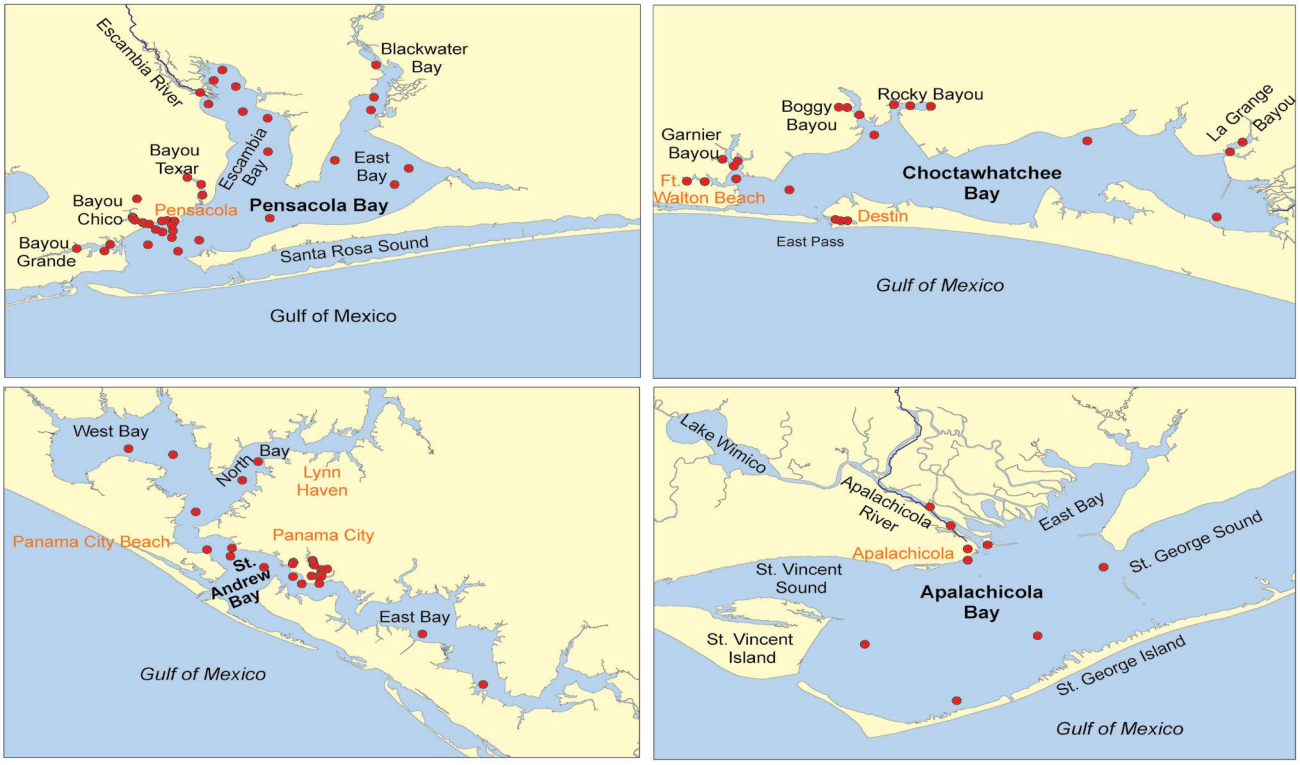


Figure 2. Locations of sampling stations in Pensacola, Choctawhatchee, St. Andrew and Apalachicola Bays

(*Ampelisca abdita*), the sea urchin (*Arbacia punctulata*) fertilization success and development bioassay using sediment porewater, and microbial bioluminescence Microtox^{R} and Mutatox^{R} bioassays.

The data were treated separately for each bay. However, in the case of Bayou Chico, the 1994 data were merged with those from Apalachicola Bay since the data sets for both bays were too small to analyze alone and these two areas showed relatively high and relatively low toxicity, respectively. In addition, the toxicity/chemistry correlations were determined for the entire combined data set formed by merging the data from all the bays.

2. RESULTS

2.1 Important Physical Drivers

In Pensacola Bay, water depths at the sampling stations ranged from 1.2 to 10.0 meters, and the temperature, salinity, and dissolved oxygen concentrations indicated the water column at most stations were relatively well mixed. Most sediments in Pensacola Bay were fine silts and clays, often sulfurous and odiforous, occasionally with petroleum sheens. TOC in Pensacola Bay sediments (Bayou Chico) varied from 0.4 % to 7 %. In Choctawhatchee Bay most sampling stations were 2 to 6 meters deep with bottom and surface temperatures indicating a well-mixed water column. Sediments had TOC that varied from 0.02 to 12.7 % and were olivine-colored silty clays. Except for a few stations that were up to 12 meters deep, most stations in St. Andrew Bay were 2 - 6 meters deep. Sediments from St. Andrew Bay were mostly silty clays either grey or olivine in color, and usually with numerous benthic organisms. Apalachicola Bay stations ranged in depth from 1.6 to 5.4 meters. With about 0.5 % TOC on average, most sediments from Apalachicola Bay

stations were brown to olivine sandy mud, whereas at stations in the Apalachicola River, sediment were silty clay with some sand.

2.2 Contamination Results

Mean-normalized (sample concentration/mean concentration on a chemical by chemical basis) heavy metal and organic compounds in the four western Florida panhandle bays are shown in Figure 3a and 3b. Total mercury concentrations were elevated in Bayou Texar and near the Pensacola Harbor. Lead concentrations were relatively high in the urban bayous of Chico, Escambia, Texar and near the Pensacola Harbor. Pensacola Bay had the highest concentrations of zinc compared to the other three bays (Figure 3a). In Pensacola Bay, PAH concentrations were elevated in urban bayous such as Bayou Texar and Bayou Chico, but were lower in the main basin system. Samples from inner Bayou Chico had the highest PCB concentrations relative to all other samples from Pensacola Bay

In Chocyawhatchee Bay, relatively high concentrations of total mercury occurred in samples from Garnier Bayou, Boggy Bayou, and Rocky Bayou, but low concentrations were found elsewhere in the bay. The concentrations of lead showed a distributional pattern similar to that of mercury in this bay system (Figure 3a). Organic analyses of samples from Choctawhatchee Bay, including many from adjoining bayous showed that PAH concentrations were highest at stations in Garnier Bayou and relatively low in samples from the other stations. Concentrations of total PCBs were high in samples from Garnier Bayou and Boggy Bayou.

In St. Andrew Bay, samples from Watsons Bayou and Massalino Bay had the highest concentrations of both mercury and lead. Samples from Watson Bayou and Massalino Bayou in Panama City had the highest PAH concentrations. PAH concentrations decreased relatively quickly beyond the mouths of these two urban bayous. The concentrations of total PCBs showed a similar pattern.

Heavy metal concentrations in sediment samples from Apalachicola Bay were considerably lower than those in the other three bays (Figure 3a). For instance, the minimum concentration values for mercury and lead were recorded in Apalachicola Bay. Concentrations of organic contaminants varied broadly in sediment from Apalachicola Bay (Figure 3b). Organochlorine pesticides (chlordanes, DDTs, dieldrins) had relatively low concentrations compared to the other bays. However, the highest concentrations of PCBs were detected in sediments from Apalachicola Bay, particularly in samples from stations located at the mouth of the Apalachicola River (Figure 3b).

The Florida Department of Environmental Regulation (Schropp et al., 1990, Schropp and Windom, 1988) determined that in Florida, and generally throughout the southeast coastal plain, trace metal concentrations can be expressed as a function of the amount of aluminum and metals in sediments, based on naturally occurring geochemical relationships in the earth's crust. The correlation of natural metals relationships with aluminum were determined and bracketed by the 95% confidence interval. Stations with corresponding values above the upper 95% confidence limit were considered to be "enriched" (Figure 4).

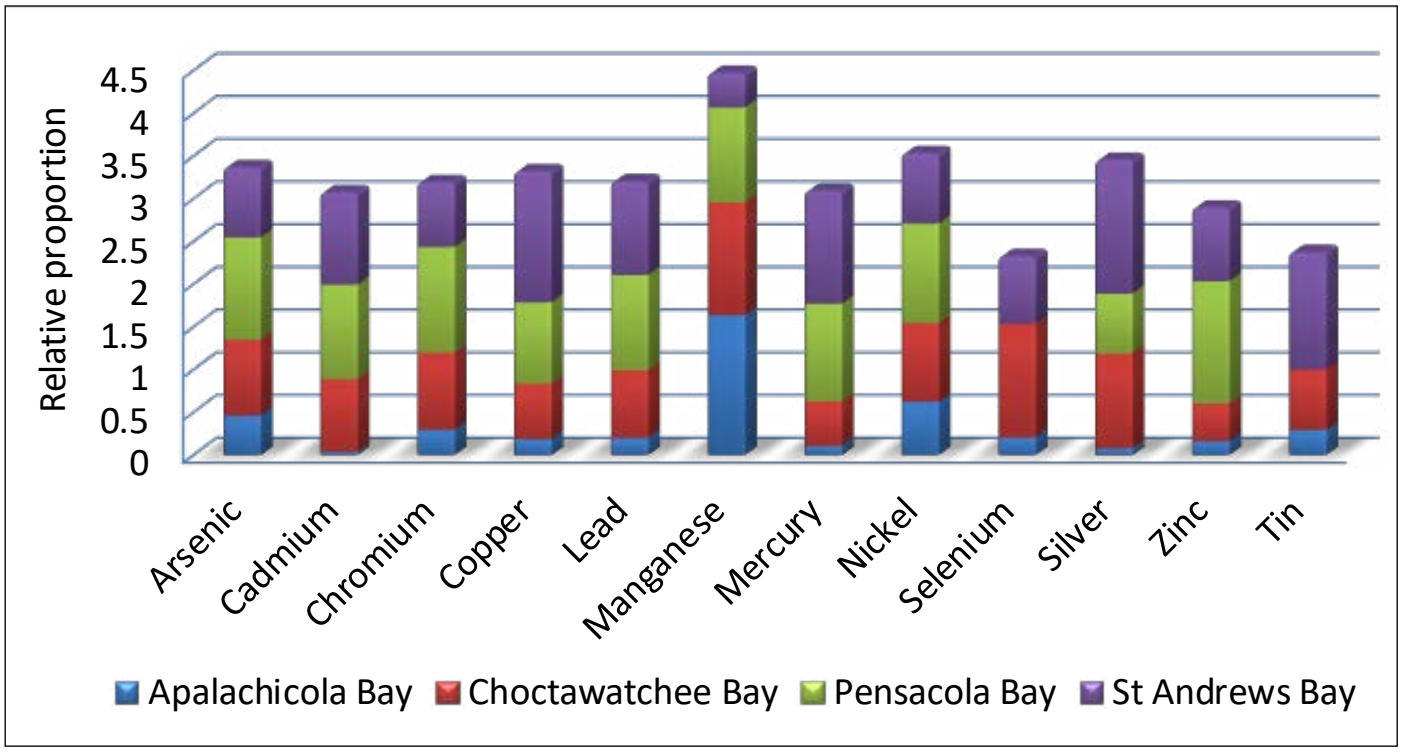


Figure 3a. Mean-normalized metals in the four western Florida panhandle bays..

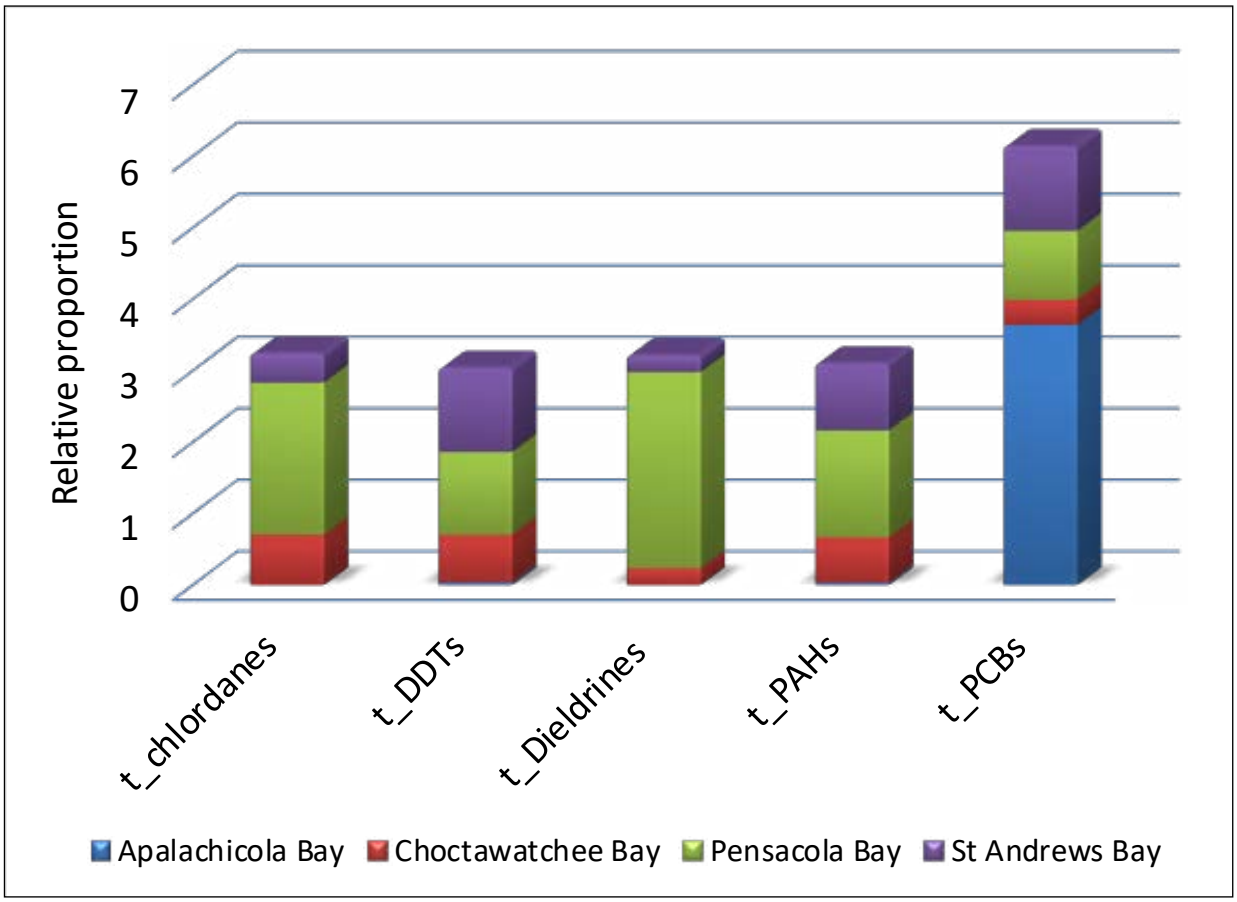


Figure 3b. Mean-normalized organic compounds in the four western Florida panhandle bays.

In Pensacola Bay concentrations of copper, lead, and zinc were elevated above expected background in all samples from Bayou Chico. Cadmium and chromium were elevated in some of the Bayou Chico samples. Lead and zinc were enriched in most of the Choctawhatchee Bay sediments and cadmium, chromium and copper were elevated in many samples from there (Figure 4). In St. Andrew Bay a slightly different mixture; copper, lead, and zinc, were enriched in many samples along with cadmium in some samples. None of the samples from Apalachicola Bay that were analyzed had enriched metals concentrations. While the original report has all the results outputs, in this summary, we only used two graphs to exemplify the metal enrichment assessment (Figure 4).

Chemical concentrations expressed in dry wt. were compared with the ERM values of Long et al. (1989) developed for NOAA and the PEL values of MacDonald (1993 and 1994) developed for the state of Florida. The number of samples that exceeded the respective guidelines were determined for each bay (Table 1). Concentrations of several trace metals, PAHs, and chlorinated organic hydrocarbons equaled or exceeded respective guideline values. Notably, in Pensacola Bay, the ERM values were exceeded for concentrations of lead, zinc, DDTs, and PCBs. The ERM values were exceed for silver, and DDTs in Choctawhatchee

Table 1. Number of stations in which chemical concentrations were at or above their respective SQG thresholds.

	Pensacola Bay		Choctawhatchee Bay		St. Andrew Bay		Apalachicoa Bay	
	ERM	PEL	ERM	PEL	ERM	PEL	ERM	PEL
Arsenic								
Cadmium								
Copper		3			1	5		
Lead	1	1			1	2		
Mercury		1			1	1		
Nickel								
Silver			2	2		4		
Zinc	5	9			1	4		
						2		
Dieldrin						1		
Total DDTs	6	7	1	1		4		
Total PAHs		2						
Total PCBs	1	1				1		

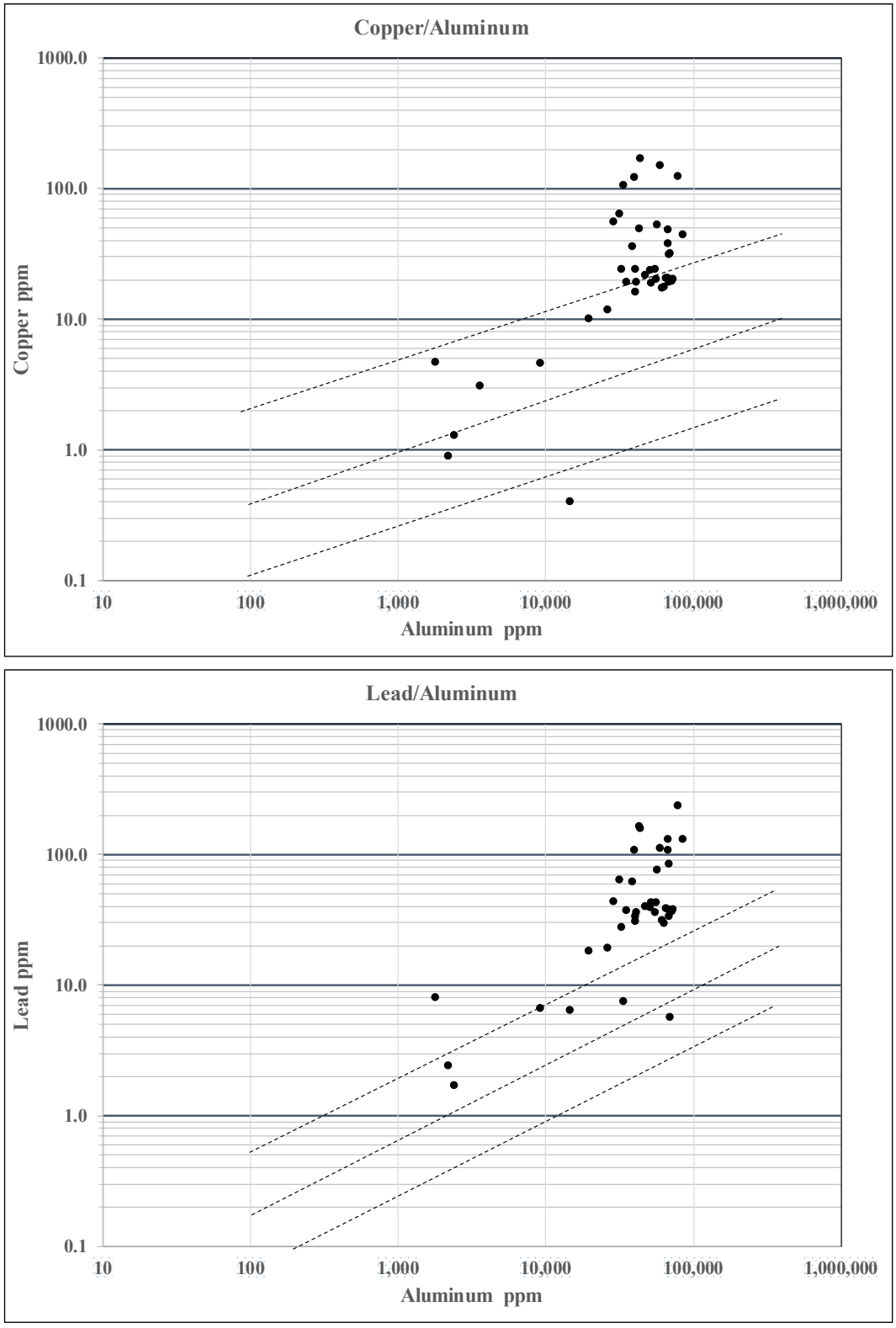


Figure 4. Concentrations of copper (above) and lead (below) in Pensacola Bay sediments, compared to expected background concentrations based upon normalization to aluminum. The 95% confidence intervals are shown above and below the mean metal concentrations.

Bay; whereas, copper, lead, mercury and zinc exceeded the ERM in St. Andrew Bay. No metals nor organic contaminants were found to have concentrations above ERM and PEL guidelines in Apalachicola Bay.

2.3 Toxicity Results

Some of the bioassays showed agreement and concordance among test results, while others failed to show significant concordance. Therefore, different toxicity bioassays identified overlapping but generally different patterns in toxicity. The amphipod bioassay data showed a general lack of toxicity. Only three stations throughout all four bays were significantly toxic in the amphipod bioassays; one in Apalachicola Bay, one in Choctawhatchee Bay, and one in Bayou Chico Bay in the Pensacola Bay estuary. Amphipod survival was also less than 80% of controls in only one sample, which was collected from Bayou Chico.

The data from the Microtox^{R} bioassays indicated that the majority of the samples from the four bays were toxic. Toxicity in this bioassay was pervasive, extending throughout most or all of each bay. Mean test results often were less than 10% of reference response levels. All of the samples from Choctawhatchee Bay, St. Andrew Bay, and Bayou Chico were significantly different from controls. All except one sample from Apalachicola Bay were toxic and all except eight samples from Pensacola Bay were toxic. Nontoxic samples came from an upstream station in the Apalachicola River, several stations near the mouth of, and scattered throughout Pensacola Bay.

Results of the bioassays conducted in Year 2 revealed that 22 of 52 samples produced a strong genotoxic response (Table 2). All stations tested in Bayou Chico provided a genotoxic response. In contrast, only one of the nine samples from Apalachicola Bay showed a genotoxic response and five of the samples showed no genotoxicity.

The sea urchin fertilization bioassays showed relatively high toxicity in several bayous of Choctawhatchee Bay, Watsons Bayou in St. Andrew Bay, and Bayou Chico of Pensacola Bay, as compared to the remainder of the study area. There was relatively low toxicity in most of the main basins of Pensacola and St. Andrew Bays. Most of the 1994 samples from Bayou Chico were highly toxic in all porewater concentrations, whereas none collected in 1993 was toxic in any porewater concentrations. Two samples each in the lower Apalachicola River and lower Apalachicola Bay were toxic in 100% porewater. Among the 123 samples tested, 38 (31%) were significantly toxic in tests of 100% porewater.

All five laboratory bioassays with the exception of Mutatox^{R} indicated the presence of toxicity in western Florida samples. Amphipod survival was the least sensitive bioassay, indicating highly significant toxicity in only one of the 123 samples (0.8% of the total). MicrotoxR bioassays, in contrast, indicated that 91.9% of the samples were highly toxic. In the sea urchin bioassays of 100% porewater, 26.0% and 35.0% of the samples were highly toxic in assays of fertilization success and normal embryological development.

Table 2. Estimates of the spatial extent of toxicity in Western Florida bays with results of five different bioassays. (nd - none detected).

	Pensacola		Choctawhatchee		St. Andrew		Apalachicola		All bays	
	Area km^2	% total	Area km^2	% total	Area km^2	% total	Area km^2	% total	Area km^2	% total
Total area	273		255		127		188		842	
Amphipod survival	0.04	0.02	0	0	0	0			0.04	0.01
Urchin development										
100%WQAP	5.4	2	116	45.4	7.2	5.6	158	84	286	
50%WQAP	0.6	0.2	0.75	0.3	0.12	0.1	0	0	1.5	
25%WQAP	0.2	0.1	0	0	0	0	0	0	0.2	
Urchin fertilization										
100%WQAP	14.4	5.3	113	44.5	2.3	1.8	63.6	33.9	193	
50%WQAP	0.3	0.1	35.7	13.9	0	0	0	0	36	
25%WQAP	0.3	0.1	0.1	0.04	0	0	0	0	0.4	0.04
Microtox	263	96.4	255	100	127	100	187	99.6	832	98.7
Mutatox	nd		nd		nd		nd		nd	

The entire four bay survey area encompassed approximately 850 km^2 of the western Florida panhandle (Table 2). All five laboratory bioassays with the exception of Mutatox^R indicated the presence of toxicity in western Florida samples. Amphipod survival was the least sensitive bioassay, indicating highly significant toxicity in only one of the 123 samples (0.8% of the total). Microtox^R bioassays, in contrast, indicated that 91.9% of the samples were highly toxic. In the sea urchin bioassays of 100% porewater, 26.0% and 35.0% of the samples were highly toxic in assays of fertilization success and normal embryological development

2.4 Benthic Infaunal Results

Benthic infauna were not sampled in this study.

2.5 Correlations

The associations between toxicity and concentrations of potentially toxic substances in Choctawhatchee Bay were strongest for the urchin fertilization bioassays in which a large gradient in response was observed. Most notable among these were the concentrations of total DDTs, silver, total PAHs, and dieldrin.

Concentrations of zinc, total PAHs, total DDTs, and dieldrin were most closely associated with toxicity in Pensacola Bay. To a lesser extent, cadmium, copper, lead, low molecular weight PAHs, and in the case of urchin embryo development, unionized ammonia, were moderately associated with toxicity in Pensacola Bay. Spearman-rank correlations failed to show significant correlations between toxicity and chemical concentrations in samples from Bayou Chico and Apalachicola Bay. However, there were numerous obvious associations between elevated chemical levels and toxicity. Of note, samples from Bayou Chico had considerably higher chemical concentrations than those from Apalachicola Bay.

3. SUMMARY

Based upon the chemistry data acquired as a part of this survey, concentrations of many trace metals, pesticides, and polynuclear aromatic hydrocarbons (PAHs) were considerably higher in the urbanized bayous of Pensacola, Choctawhatchee, and St. Andrew Bays than in the main basins of those systems or in Apalachicola Bay. Trace metals concentrations exceeded background levels as predicted by geochemical normalization using metal-to-aluminum ratios, suggesting problematic metals loadings from upland sources. Lead, mercury, copper and zinc were most frequently enriched, with no stations showing enrichment with respect to arsenic and nickel. Additionally, the concentrations of many different substances exceeded applicable toxicity thresholds or guideline values (ERL, ERM and PEL) in some samples collected during this survey. Noteworthy among these chemicals were copper, lead, zinc, total PAHs, total DDTs and dieldrin. Overall, these data suggest that most chemical substances were elevated in concentration in urban bayous, especially Bayou Chico in Pensacola Bay, but each substance had a unique distributional pattern within the bays.

Overall, the highest incidence of toxicity occurred among the Bayou Chico samples, followed by Choctawhatchee Bay, Apalachicola Bay, St. Andrew Bay, and Pensacola Bay. All of the Bayou Chico samples were toxic in the sea urchin development, Microtox^{R}, and Mutatox^{R} bioassays; and all except one sample were highly toxic in the urchin fertilization bioassays. In addition, the only sample that was highly toxic in the amphipod survival bioassays was collected in Bayou Chico. In Choctawhatchee Bay, all samples were toxic in Microtox^{R} bioassays, most were toxic in Mutatox^{R}, urchin fertilization and urchin development bioassays. In all four bays, the associations between toxicity and concentrations of potentially toxic substances were strongest for zinc, PAHs, DDTs, and dieldrin, and to a lesser extent, cadmium, copper, and lead.

The data from this survey indicated that sediments in some regions of the study area were contaminated relative to background conditions and effects-based numerical guidelines. In addition, there were indications that toxicity occurred throughout the entire region as measured in the most sensitive bioassays. The most severe toxic responses and the highest incidences of toxicity occurred in Bayou Chico. The toxicity bioassay results generally paralleled the concentrations of potentially toxic substances in the samples.

Chapter 13
Sabine Lake

1 STUDY AREA DESCRIPTION

Sabine Lake is an inland estuary that straddles the Texas/Louisiana border near Beaumont, Texas. Sabine Lake was chosen for the survey based upon the likelihood of chemical contamination within sediments of the area and an interest expressed by the State of Texas. Trace metal concentrations in sediments have been reported as relatively low (even depleted relative to other nearby areas) in the Sabine-Neches estuary, which includes Sabine Lake, the Sabine~Neches and Port Arthur Canals, and Sabine Pass (Ravichandran et al., 1995). However, Harrell and McConnell (1995) reported detectable concentrations of dioxins and furans in the clam *Rangia cuneata* in the Neches River, which flows into Sabine Lake, downstream from a pulp mill. There is a huge complex of petroleum – related industries along the Neches and Sabine rivers, particularly many refineries and transhipment docks near Beaumont on the Neches River, and Port Arthur on Lake Sabine. Crude oil and petroleum products are shipped and piped on- and offshore in this area.

Sampling Details

The study area encompassed all of Sabine Lake, portions of the Sabine River, and Neches River, portions of the Neches-Sabine Canal at the confluence of the two rivers, portions of Sabine Pass channel entrance, and an area in the Gulf of Mexico near the entrance channel (Figure 1). Strata established within channels were further subdivided into three substrata to improve spatial coverage.

Sediments from a total of 66 stations (Figure 2) were collected in 1995 aboard of the NOAA vessel *Ferrel*. Samples for benthic community analyses were collected at one station randomly chosen within each stratum. Triplicate samples were collected at each station with a Young-modified, petite (0.04 m^2) Van Veen grab. Samples for both toxicity/chemistry analyses and the benthic community analyses were collected at the same location.

Toxicological tests were conducted to measure: reduced survival of adult amphipods exposed to solid- phase sediments; impaired fertilization and development in gametes and embryos, respectively of sea urchins exposed to pore waters; reduced metabolic activity of a marine bioluminescent bacteria exposed to organic solvent extracts; and induction of a cytochrome P-450 human reporter gene system in exposures to solvent extracts of the sediments. Chemical analyses were performed on portions of each sample to quantify the concentrations of trace metals, polycyclic aromatic hydrocarbons, and chlorinated organic compounds.

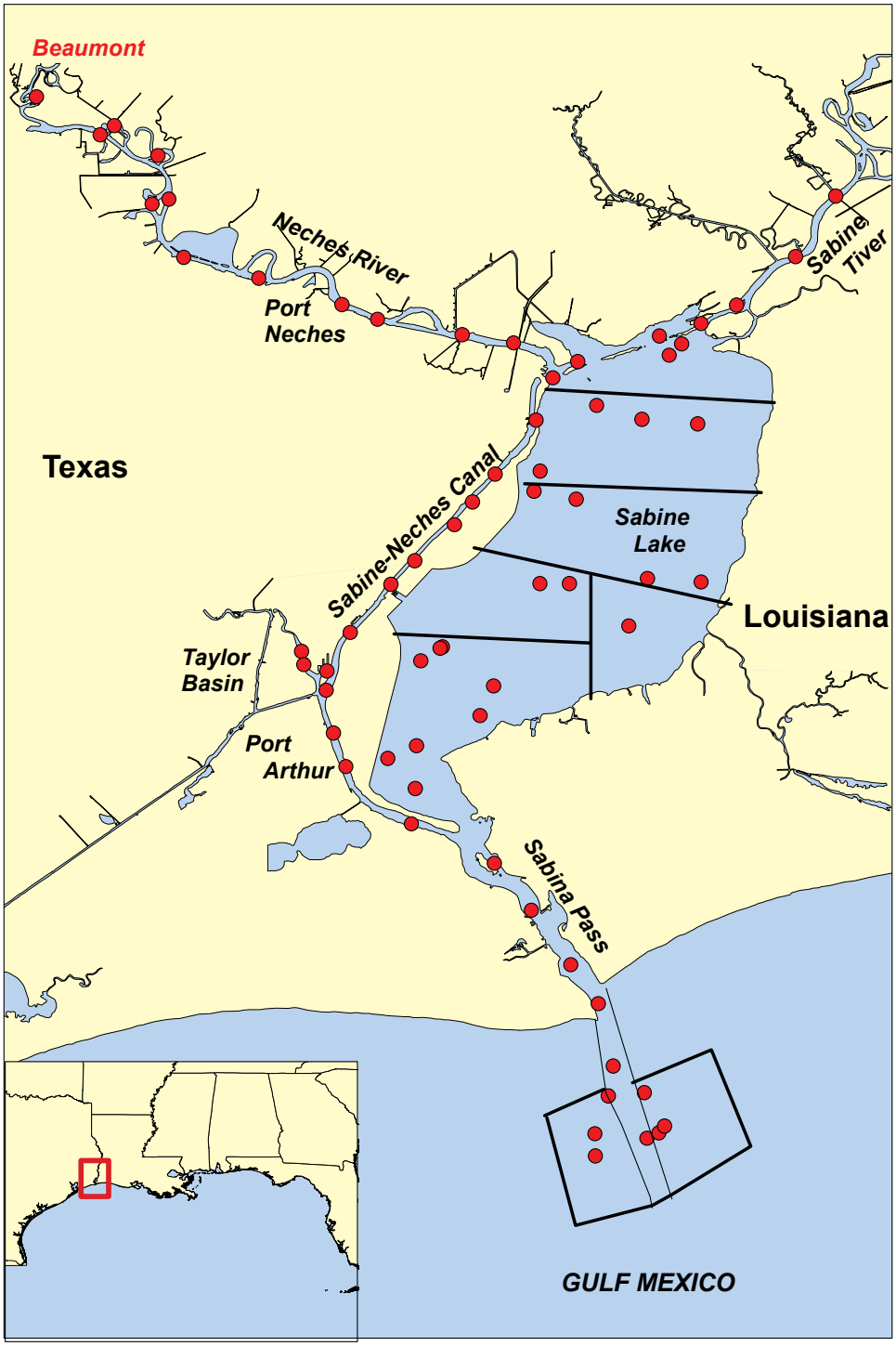


Figure 1. Sabine Lake and surrounding study area.

2. RESULTS

2.1 Important physical drivers

Sabine Lake (Figure 1) is a 364.2 km^2 estuary on the Texas/Louisiana border and is at the confluence of the Neches River and Sabine River, which supply freshwater to the Lake. The watershed of Sabine Lake is over 100,000 km^2. The tidal outlet (Sabine Pass) is approximately 8 km long, and empties into the Gulf of Mexico. Sabine Lake is also adjacent to a portion of the Intracoastal Waterway (ICW), which is composed

of several channels of the Neches and Sabine rivers. Average depth in Sabine Lake is approximately 2 m. Salinity in Sabine Lake averages 11ppt.

2.2 Contamination Results

Distinct spatial patterns in chemical concentrations did not appear to exist. The concentrations of the trace metaloid arsenic ranged from 0.3 to 15 µg/g, considerably below the ERM value of 70 µg/g. Arsenic concentrations were higher in the Sabine-Neches canal (stations 6-27) than in the adjacent basin of Sabine Lake. Arsenic concentrations also were relatively high offshore (stations 58-66) as compared to the Sabine Lake stations. Although arsenic concentrations exceeded the ERL value of 8.2 µg/g in many samples; none equaled or exceeded the ERM value of 70 µg/g. The pattern in the concentrations of total PAHs (sum of 13 compounds for which numerical guidelines have been derived) was clearer than that for arsenic. Total PAH concentrations were highest in samples from stations 2, 11, and 12 in the upper Neches River and from stations 28 – 30 in the Taylor Basin. As observed with arsenic, total PAH concentrations were somewhat higher in the canals than in the adjacent basin of Sabine Lake. However, unlike the pattern with arsenic, PAH concentrations decreased seaward and offshore. The spatial extent of chemical contamination was estimated for 25 substances and/or classes of compounds by weighting the data to the sizes of the sampling strata, similar to the methods used to calculate the spatial extent of toxicity.

ERL and ERM values from Long *et al*. (1995) were used as the critical values (Table 1). The data indicated that only one substance, acenaphthalene, equaled or exceeded an ERM value. The one sample in which the ERM value was exceeded represented 0.3 km^2, equivalent to 0.1% of the total study area. Concentrations of arsenic and nickel were elevated above the respective ERL values in about 17% and 9% of the study area, respectively. The spatial extent of contamination by all other substances was less than 1.0% of the area. Similarly, the samples in which the mean ERM quotients exceeded 0.1 represented less than 1% of the area (Table 1).

2.3 Toxicity Results

The results of the toxicity tests indicated that sediments in this survey area were not highly toxic (i.e., percent survival > 80% of controls) as measured with the acute amphipod survival tests. However, amphipod survival was significantly reduced in 13 samples and results of the sublethal tests performed with the sea urchin gametes and embryos were significant in additional samples. Sea urchin embryo development was significantly reduced in most samples. These data, collectively, suggest that sediments were slightly to moderately toxic, but not highly toxic, in parts of the study area. Results of the the Microtox^R and P450 tests performed with organic solvent extracts of the sediments showed that the potential for toxicity was highest in upper Neches River, Taylor Basin, and regions offshore beyond the entrance channel. Highly significant responses in these two tests, however, were neither pervasive nor widespread.

The spatial extent of toxicity is summarized in Table 2. Amphipod survival exceeded 80% of controls in all

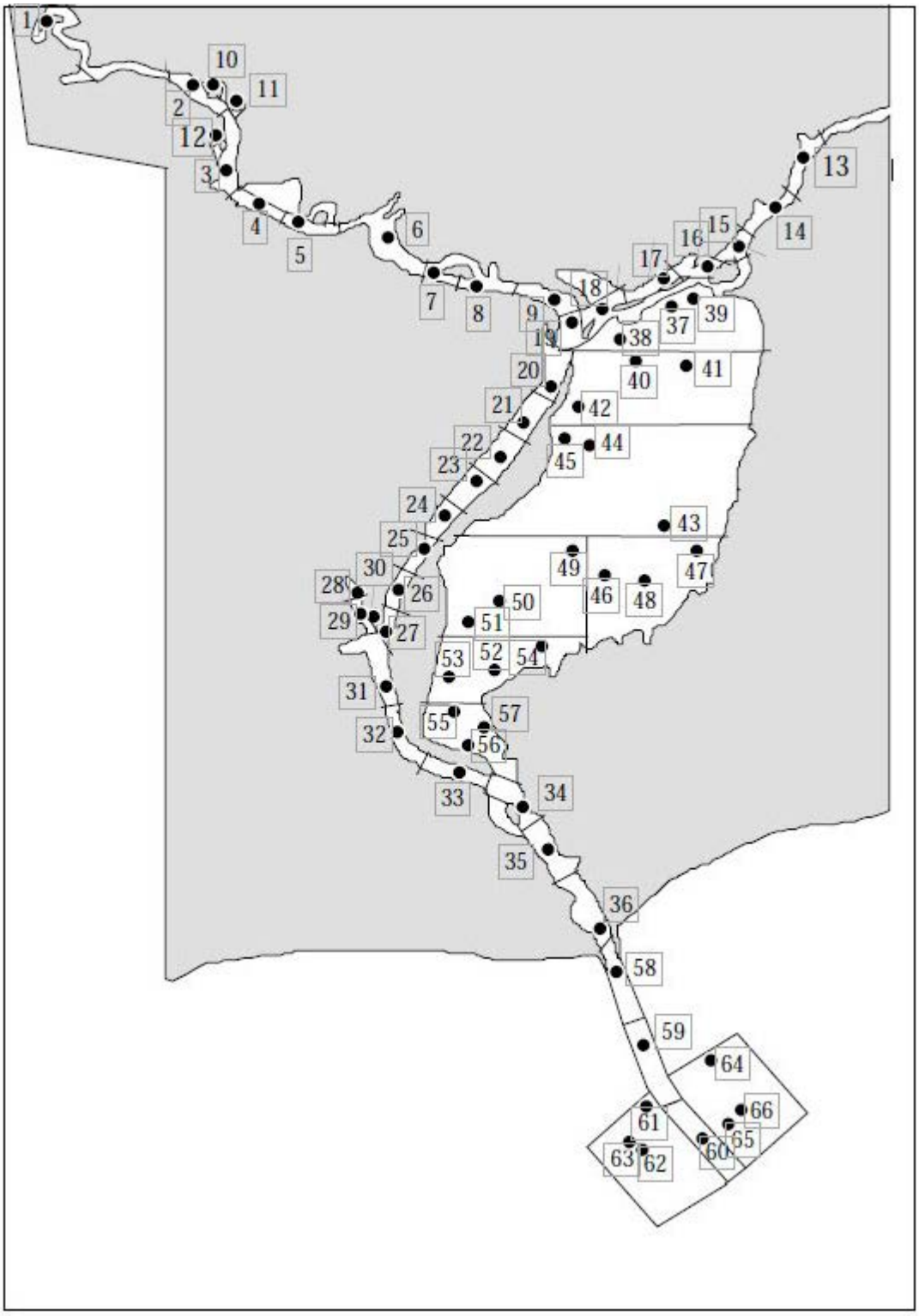


Figure 2. Locations of individual sampling stations within each stratum for Sabine Lake.

samples; therefore, the spatial extent of toxicity was estimated as 0% in that particular test. In the sea urchin tests of fertilization success, strata in which percent fertilization was less than 80% of controls represented 6%, 3%, and 0% of the area in tests of 100%, 50%, and 25% pore waters, respectively.

In the sea urchin embryo test, % development was less than 80% of controls in strata that represented 99%,

Table 1. Estimates of the spatial extent of chemical contamination relative to effects - based numerical guidelines (ERL and ERM) for Sabine Lake. Data are shown as km^2 and percentages of total study area.

Chemical or chemical class	>ERL km^2	>ERL Pct. of total	>ERM km^2	>ERM Pct. of total
arsenic	40.7	16.5	0	0
cadmium	0	0	0	0
chromium	0	0	0	0
copper	0	0	0	0
lead	0	0	0	0
mercury	0	0	0	0
nickel	22.2	9	0	0
silver	0	0	0	0
zinc	0	0	0	0
naphthalene	0	0	0	0
2-methyl napthalene	0.2	0.1	0	0
acenaphthylene	0	0	0	0
acenaphthene	1.7	0.7	0.3	0.1
fluorene	1.7	0.7	0	0
phenanthrene	0.3	0.1	0	0
anthracene	0.9	0.4	0	0
fluoranthene	0.9	0.4	0	0
pyrene	0.5	0.2	0	0
benzo(a)anthracene	1.1	0.4	0	0
chrysene	0	0	0	0
benzo(a)pyrene	0	0	0	0
dibenz(a,h)anthracene	0.4	0.2	0	0
sum low PAHs	0.9	0.4	0	0
sum hgih PAHs	0.9	0.4	0	0
total PAHs	0.5	0.2	0	0
p,p'-DDE	0	0	0	0
total DDTs	1	0.4	0	0
total PCBs	0.8	0.3	0	0
mean ERM quotient >0.1	0.1	0.4		

total area: 246 km^2

43%, and 0% of the area in the three pore water concentrations. Similarly, because of the large differences between the control means and sample means in the Microtox^R tests, the spatial extent of toxicity as defined as <80% of controls was 79%.

Two additional critical values were generated for the Microtox^R test results, both based upon statistical analyses of the existing data from NOAA surveys conducted at the time (n=1,013). The two critical values are <0.06 mg/ml and <0.51 mg/mL. The first value (0.06 mg/mL) represented the 90% lower prediction limit (LPL) of the entire data set. The probability that a future observation from this data distribution would be less toxic (i.e., have a greater EC50 value) than 0.06 mg/ml would be 90%. Therefore, a sample with an

Table 2. Estimates of the spatial extent of toxicity in sediments of Sabine Lake based upon results from five independent tests

Toxicity test	Criterion	Toxic area (Km^2)	Percent of total*
Percent amphipod survival			
	• <80% of control	0.0	0.0
Percent urchin fertilization			
	• <80% of control in 100% pore water	14.5	5.9
	• <80% of control in 50% pore water	7.3	2.9
	• <80% of control in 25% pore water	0.0	0.0
Percent normal urchin development			
	• <80% of control in 100% pore water	244.6[A]	99.4[A]
	• <80% of control in 50% pore water	107.6[B]	43.4[B]
	• <80% of control in 25% pore water	0.0	0.0
Microtox bioluminescence EC50			
	• <80% of control	194.2	78.9
	• <0.51 mg/ml	3.6	1.4
	• <0.06 mg/ml	0.0	0.0
Cytochrome p-450 induction			
	• >11.1 ug/g	6.7[C]	2.7[C]
	• >37.1 ug/g	1.7[D]	0.7[D]

* total area: 246 km^2

[A] Toxic area: 243.4 km^2 (99.4% of 244.8 km^2) accounting for second alternates at two stations

[B] Toxic area: 107.4 km^2 (43.7% of 245.8 km^2) accounting for second alternate at one station

[C] Toxic area: 6.5 km^2 (2.6% of 245.8 km^2) accounting for second alternate at one station

[D] Toxic area: 1.5 km^2 (0.6% of 245.8 km^2) accounting for second alternate at one station

EC50 less than 0.06 mg/mL would be considered to be extremely toxic in this test, but should occur rarely. The second value (0.51 mg/mL) represents the 80% LPL following removal of the lowest (most toxic) 10% of the data values from the database to eliminate the effects of these extremely toxic samples upon the distribution of the data. When defined as an EC50 response of <0.51 mg/mL and <0.06 mg/mL, 28 the estimates of the spatial extent of toxicity were 1.4% and 0%, respectively.

Two critical values were calculated and used to estimate spatial extent of toxicity from the Cytochrome P-450 HRGS tests. The first value, 37.1 ug/g benzo(a)pyrene equivalents, represented the upper 90% prediction limit (UPL) of the entire data set gathered at the time in all NOAA studies (n=530). This value agrees well with 32 *u*g/g, the HRGS induction level equivalent to the ERL value (Long et al., 1995) for high molecular weight PAHs determined in regression analyses of the existing data for this test. Therefore, this value is viewed as a concentration above which toxicologically significant effects may begin in sediments. The second value, 11.1 *u*g/g, was the 80% UPL of the data distribution following elimination of the data

above the 90th percentile of the entire data base. This value (11.1 *u*g/g) is viewed as the upper limit of background HRGS responses. Strata in which cytochrome p-450 HRGS responses exceeded 11.1 ug/g and 37.1 ug/g represented 3% and 1% of the total area, respectively.

2.4 Benthic Infaunal Results

Samples for benthic infaunal analysis were collected but not reported in NOAA Technical Memorandum NOS NCCOS CCMA 137.

2.5 Correlations

The relationships between results of laboratory toxicity tests and concentrations of chemical substances in the sediments were determined with correlation analyses (Spearman-rank). Initially, correlations were calculated for classes of chemicals normalized to their respective ERM values and expressed as mean chemical:ERM quotients (Table 3) to identify which groups of chemicals, if any, covaried with measures of toxicity.

Chemical classes were designated as nine trace metals, thirteen PAHs, three chlorinated organic hydrocarbons, and all 25 substances combined. None of the chemical classes showed significant relationships with either the amphipod survival or urchin fertilization tests. Microtox^{R} results were significantly correlated, but only at a significant level of 0.05, with the mean ERM quotients for all 25 substances.

Table 3. Spearman-rank correlation coefficients (Rho, corrected for ties) for toxicity test results and chemical concentrations normalized to ERM values in Sabine Lake sediments (n=66). (COHs – chlorinated organic hydrocarbons).

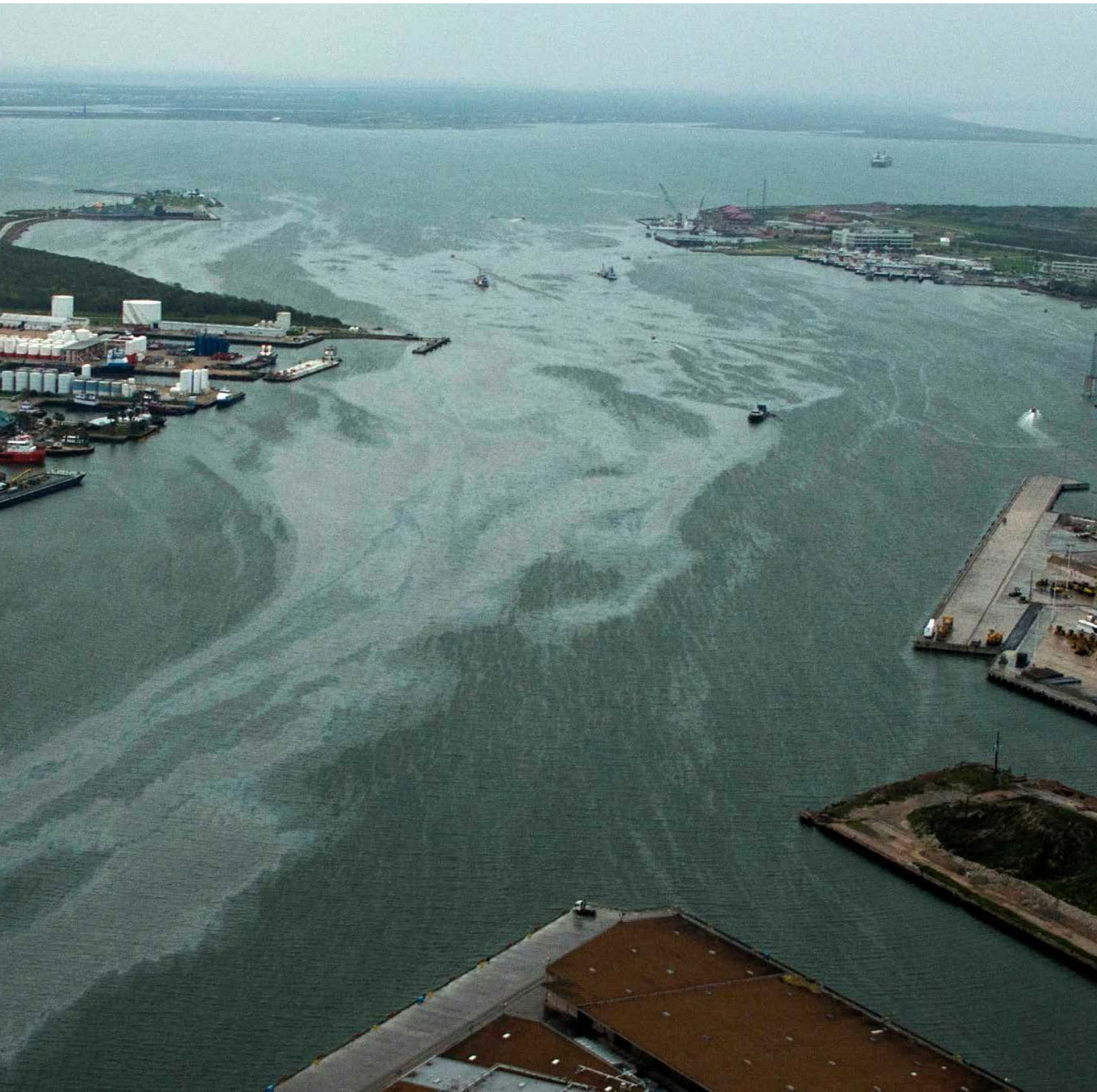
Chemical group	Percent amphipod survival	Percent urchin fertilization (100% pore water)	Percent urchin normal development (100% pore water)	Microtox EC50	Cytochrome P-450 RGS
mean ERM quotient: metals	0.012	-0.119	-0.698 ****	-0.19	-0.429 ***
mean ERM quotient: PAHs	-0.173	0.168	-0.408 ***	-0.13	0.827 ***
mean ERM quotient: COHs	0.080	0.126	-0.527 ****	-0.13	0.779 ***
mean ERM quotient: all	-0.040	-0.094	-0.677 ****	-0.28 *	0.662 ***
* p<0.05					
** p<0.01					
***p<0.001					
****p<0.0001					

In contrast, the concentrations for the chemical groups were highly correlated with the urchin development and P-450 HRGS test results. In the urchin development tests, the strongest correlations were with the trace metals. In the P-450 HRGS assays, the strongest relationships were with the PAHs and to a lesser degree the chlorinated organics. These correlations do not establish a causative relationship, but, rather a correlative association between a set of independent variables (chemical concentrations) and dependent variables (toxicity tests).

3. SUMMARY

Based upon the compilation of results from chemical analyses and toxicity tests, the quality of sediments in Sabine Lake and vicinity did not appear to be severely degraded. Chemical concentrations rarely exceeded effects-based numerical guidelines, suggesting that toxicant-induced effects would not be expected in most areas. None of the samples was highly toxic in acute amphipod survival tests, although 23% of samples were highly toxic in sublethal sea urchin fertilization tests. Toxic responses occurred frequently (94% of samples) in sea urchin embryo development tests performed with 100% pore waters, but toxicity diminished markedly in tests done with diluted pore waters. Microbial bioluminescent activity was not reduced to a great degree (no EC50 <0.06 mg/ml) and cytochrome P-450 activity was not highly induced (6 samples exceeded 37.1 ug/g benzo[a]pyrene equivalents) in tests done with organic solvent extracts. Sea urchin embryological development was highly correlated with concentrations of ammonia and many trace metals. Cytochrome P-450 induction was highly correlated with concentrations of a number of classes of organic compounds (including the polycyclic aromatic hydrocarbons and chlorinated compounds). Chemical concentrations often were below respective ERL values. A few chemical concentrations equaled or exceeded the ERL values and only one chemical in one sample exceeded an ERM value. The spatial extent of chemical contamination was restricted to a small percentage of the total survey area. Sediments from Taylor Basin and a side-channel bayou of the Neches River had higher chemical concentrations than those from other areas. Samples from the basin of Sabine Lake often were among the least contaminated. Concentrations of organic compounds such as the PAHs decreased seaward and offshore into the Gulf of Mexico; however, the concentrations of trace metals such as arsenic did not follow this pattern. Concentrations of arsenic in offshore samples were equivalent to those from inland locations.

Chapter 13
Galveston Bay



1. STUDY AREA DESCRIPTION

The project study area extended from the upper reaches of the Houston Ship Channel (HSC) in the north to beyond the jetties at the entrance to Galveston Bay, including West, East and Trinity Bays, and Clear Lake (Figure 1). The areas of study, as well as the dimensions of the sampling strata, were selected in consultation with state and local resource management. Galveston Bay has a surface area of 1,360 km^2, the drainage area of the bay is approximately 63,300 km^2.

Sampling Details

Seventy-five sites were sampled in Galveston Bay between 29 July and 16 August 1996. A stratified-random sampling design similar to those used in previous NOAA surveys (Long et al., 1996) was applied in Galveston Bay. The study area was subdivided into 22 irregular shaped strata (Figure 1). Large strata were established in the open waters of the bay where topographic features and oceanographic conditions were relatively uniform and toxicant concentrations were expected to be low. In contrast, relatively small strata were established in the upper and mid bay near suspected sources of contamination, or where environmental conditions were expected to be heterogeneous or transitional. The boundaries of the strata were also established to coincide with the dimensions of major basins, bayous, waterways, etc., in which hydrographic, bathymetric and sedimentological conditions were expected to be relatively homogeneous. The locations of individual sampling sites within each stratum were chosen randomly using a computer-based program applied to digitized nautical charts produced by NOAA's National Ocean Service. The program was used to select a primary site and three alternate sites. At least three sites were sampled within each stratum; four or five sites were sampled in larger strata.

2. RESULTS

2.1 Important physical drivers

The estuary receives most of its freshwater from the Trinity River, with much smaller contributions from the San Jacinto River (measured as spillover from Lake Houston Reservoir), HSC drainage (Buffalo Bayou and tributaries), and Chocolate Bayou. The average natural depth of the estuary is 2 m, with oyster reefs creating numerous shoal areas that divert the flow regime locally. Wind is the primary driving force for currents, with tides having a relatively minor, modifying influence. Relatively deep navigation channels, e.g., the 12 m deep HSC, and waterways that traverse the bay have created areas of higher salinity, altered flows and restricted water exchange. In addition, dredged material disposal sites, notably those in the vicinity of HSC, restrict water exchange and circulation across the channel.

The average near-surface salinity of Galveston Bay is approximately 15 ppt (Criner and Johnican, 2001), although there is considerable spatial and temporal variability. Surface salinity generally varies from nearly 30 ppt near the entrance to the Gulf of Mexico, to 3 ppt near major points of freshwater inflow, such as the Trinity River. Due to the shallowness of the bay, vertical stratification in salinity is either slight or nonexistent. Large fluctuations in salinity, ranging from 6 to 28, occurred during the sampling for the project, due to the influence of wind and tide.

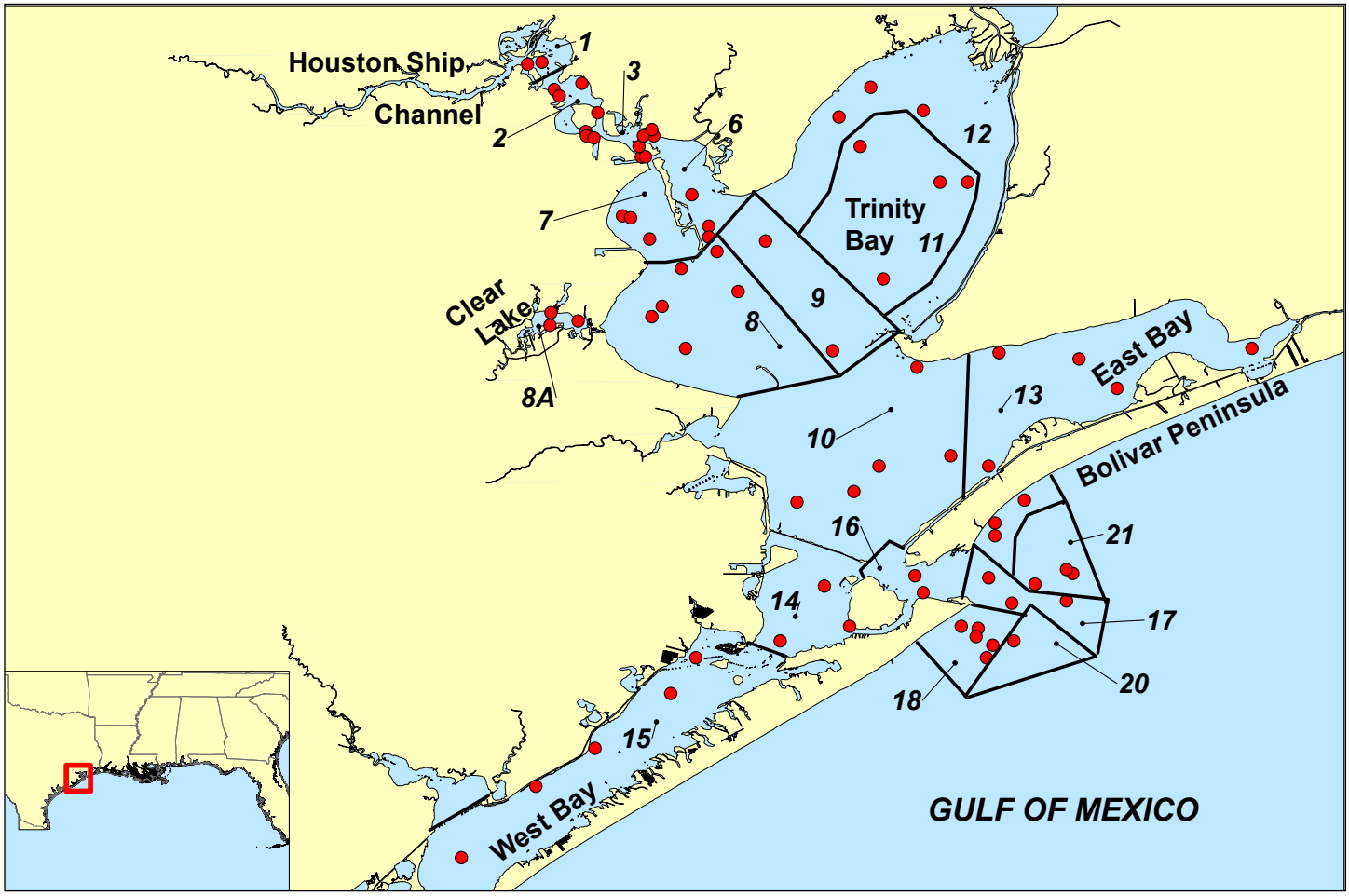


Figure 1. Sample strata (outlined type) and stations in Galveston Bay.

Given the shallowness of the estuary, sediments are easily redistributed by currents and tides (GBNEP, 1992, 1994). Surficial sediment in Trinity Bay is composed primarily of mud; sandy sediment predominates in West Bay; while coarse-grained sand and shell material dominate the bay's entrance to the Gulf of Mexico, and in isolated reef areas throughout the bay.

2.2 Contamination Results

In general, trace elements were distributed relatively uniformly throughout the study area, with the exception of mercury, which was concentrated in the Houston Ship Channel. None of the trace element concentrations exceeded the ERM values at any of the 75 sites, although numerous sites exceeded the ERL values for arsenic, chromium, mercury, nickel and zinc. Arsenic concentrations exceeded the ERL value in 29% of the study area; nickel in 25% (Table 1) of the study area; while chromium, mercury and zinc ERL exceedances together totaled less than 1% of the study area.

The highest total PAH concentration was found in the middle of Galveston Bay, and exceeded the ERL value. ERL values for individual PAHs were exceeded in the middle of the bay and in the upper bay for compounds

such as acenapthene, anthracene, and fluorene. The calculated spatial extent of ERL exceedances for each PAH, as well as for total PAH, was 2% or less (Table 1). In general, measured pesticides and PCBs were uniformly low. However, the ERM guideline for total DDT was exceeded at two sites in the Houston Ship Channel. Total ERL exceedences for total DDT included 6% of the study area.

Table 1. Spatial extent of contaminants exceeding NOAA's sediment quality guidelines (SQG) in Galveston Bay.

Trace and major elements	>ER-L		>ER-M	
	Toxic area (km^2)	% of Total area (1,351 km^2)	Toxic area (km^2)	% of Total area (1,351 km^2)
Arsenic	386	29	0	0
Cadmium	0	0	0	0
Chromium	2	0.1	0	0
Copper	0	0	0	0
Lead	0	0	0	0
Mercury	3	0.2	0	0
Nickel	336	25	0	0
Silver	0	0	0	0
Zinc	2	0.1	0	0
Organic compounds	>ER-L		>ER-M	
	Toxic area (km^2)	% of Total area (1,351 km^2)	Toxic Area (km^2)	% of Total area (1,351 km^2)
Acenaphthene	32	2	0	0
Acenaphthylene	0	0	0	0
Anthracene	31	2	0	0
Fluorene	32	2	0	0
2-Methyl naphthalene	0	0	0	0
naphthalene	0	0	0	0
phenanthrene	31	2	0	0
Low-molecular wt. PAH	0	0	0	0
Benzo(a)anthracene	31	2	0	0
Benzo(a)pyrene	0	0	0	0
chrysene	0	0	0	0
dibenz(a,h)anthracene	0	0	0	0
Fluoranthene	0	0	0	0
pyrene	0	0	0	0
high molecular wt. PAH	0	0	0	0
total PAH	31	2	0	0
p,p'-DDE	0	0	0	0
total DDT	75	6	2	0.1
total PCBs	0	0	0	0
	Toxic area (km^2)	% of Total area (1,351 km^2)		
Mean ER-M quotient >0.1	64	4.7		

2.3 Toxicity Results

Results from the sediment toxicity tests were highly variable. No samples were found to be significantly toxic in the amphipod survival test (Table 2). Sea urchin fertilization as a percent of the control was significantly reduced at 53% of the sites (100% porewater test). Samples from the Houston Ship Channel, upper bay, Clear Lake, and east of the approach jetties to Galveston Bay, showed the lowest fertilization success. Sea urchin embryonic development results followed a pattern similar to fertilization. Low Microtox^{R} EC50 values were widely spread throughout the study area. Approximately 79% of the samples produced a value that was significantly lower than the control in the Microtox^{R} test. Thirty-five of these sites exhibited a significantly higher PSI (Phenol Spiked Index), indicating these sites produced a greater decrease in luminescence than the phenol-spiked (positive control) reference sediment. Results from the P450 HRGS indicated that only 9% of the sites exceeded a threshold toxicity value, while only one site exceeded a value indicative of toxicological significance.

Estimates of the spatial extent of sediment toxicity were also made. Using a criteria of less than 80% of the control values, none of the area was deemed toxic in terms of amphipod survival, 45% of the study area was toxic using sea urchin fertilization, 25% of the area was toxic to sea urchin development, and 87% of the Galveston Bay study area was toxic in terms of the Microtox^{R} test. Alternatively, none of the Microtox^{R} test results were lower than the 0.06 mg/ml or 0.51 mg/ ml Lower Prediction Limits (LPL) resulting from a nonparametric analyses of NOAA data (Long et al., 1999).

Table 2. Estimates of the spatial extent of sediment toxicity in Galveston Bay.

Toxicity Test	Criterion	Toxic Area (Km^2)	% of Total Area (1351 km^2)	Toxic Area (Km^2)[a]	% of Total Area[a] (1351 km^2)
Percent amphipod survival	<80% of control	0	0	NC[b]	NC
Percent urchin fertilization	<80% of control in 100% pore water	610	45	607	45
	<80% of control in 50% pore water	129	10	NC	NC
	<80% of control in 25% pore water	25	2	NC	NC
Percent normal urchin development	<80% of control in 100% pore water	340	25	337	25
	<80% of control in 50% pore water	72	5	70	5
	<80% of control in 25% pore water	23	2	21	1.5
Microtox bioluminescence EC50	<80% of control	1,178	87	1,175	87
Cytochrome p-450 induction	> 10 µg/g	64	5	NC	NC
	>32 µg/g	2	0.15	NC	NC

[a] recalculated to account for stations that were sampled as alternates
[b] NC - no change

For P450 HRGS, approximately 5% of the study area exceeded a moderate value of enzyme induction.

2.4 Benthic Infaunal Results

Two hundred and eleven taxa, with a total of 5,089 individuals, were identified from the 22 strata. The total number of taxa per stratum varied within the study area from a low of four in Clear Lake, to a high of 90 in West Bay, while the mean number of taxa per stratum ranged from 2.5 to 28 in Clear Lake and West Bay, respectively. Polychaetes comprised the most individuals (71%) of any taxa identified, followed distantly by bivalves (8.3%), gastropods (6.6%), and amphipods (3.6%).

The single most dominant and widely distributed genus was *Mediomastus*, most likely *Mediomastus ambiseta*). *Mediomastus* represented 29.1% of the total individuals and was found in 77% of the sites. The polychaete, *Paraprionospio pinnata*, the ribbon worms *Rhynchocoela* and *Tubulanus*, and the polychaete *Parandalia tricuspis,* were present in 61%, 55%, 46%, and 41% of the sites, respectively. The number of individuals ranged from 38 in Clear Lake, to 1,229 in West Bay. The mean density of individuals m^2 ranged from 342 in Upper Galveston Bay (Stratum 6), east of the dredge spoil islands, to 6,145 in West Bay (Stratum 15). The faunal diversity (H') followed a similar pattern, with the lowest diversity in Clear Lake (1.14), and the highest diversity in lower Galveston Bay (3.30).

2.5 Correlations

An analysis of the relationships between sediment contamination and the sediment toxicity tests revealed no correlations between sediment contaminants and the amphipod mortality or Microtox^R tests. The sea urchin fertilization test correlated positively with several PAHs, as did the sea urchin development test with total PAHs, a number of low molecular weight PAHs, and two PCBs (PCB 153/132 and PCB 138/160). The P450 HRGS assay correlated highly and positively with PAHs. Analysis of the ERM quotients followed a similar pattern, with no significant correlations being found between contaminants and the amphipod toxicity or Microtox^R, but strong correlations found between the HRGS P450 and the ERM quotients and a number of the contaminants/classes.

3. SUMMARY

The trace elements analyzed for this project were distributed relatively uniformly throughout the study area, and with the exception of mercury in the Houston Ship Channel, none of the trace element concentrations exceeded the ERM values, although numerous sites exceeded the ERL values for arsenic, chromium, mercury, nickel and zinc. The highest total PAH concentration was found in the middle of Galveston Bay, and exceeded the ERL value. For the most part, measured pesticides and PCBs were uniformly low. However, the ERM guideline for total DDT was exceeded at two sites on the Houston Ship Channel. Total ERL exceedances for DDT included 6% of the study area. The amphipod survival tests in this study do not indicate any areas of significant toxicity in Galveston Bay. Based on the sea urchin fertilization test and the Microtox® test, 45% and 87% of Galveston Bay showed toxic conditions, respectively. The results of the HRGS assay in Galveston Bay showed unexpectedly low induction of the cytochrome P450 enzyme system.

Chapter 15
San Diego Bay

1. STUDY AREA DESCRIPTION

NOAA teamed with state organizations to investigate the sediment quality conditions in the San Diego region including Mission Bay to the north and the Tijuana estuary to the south of San Diego Bay (Figure 1). These three water bodies receive inputs from a number of watersheds. Los Peñasquitos Watershed runs into Mission Bay. San Diego Bay receives water from three watersheds, Pueblo, Sweetwater and Otay. The Tijuana estu-ary is within California, but most of the watershed is in Mexico.

Figure 1. San Diego region sampling sites.

Prior to 1960, San Diego Bay received raw sewage and industrial discharges. There have been steady improvements to the water and benthic environments since regulations to prevent discharges were put in place in the early 1970's. As a component of the statewide bays and estuaries survey conducted under the California Bay Protection and Toxic Cleanup Program, NOAA and California State Water Resources Control Board (SWRCB) led an investigation of toxicity of sediments in the San Diego region beginning in 1992 (Fairey et al. 1996, Fairey et al., 1998).

Sampling Details

The sampling design consisted of both targeted and random sampling. One water body was selected each year between October 1992 and May 1994, with a total of 350 sediment samples collected in the region. The sampling design resulted in 229 samples from the targeted sampling and 121 samples from the stratified random sampling. Targeted sampling was used to evaluate specific areas of concern, while NOAA's standard stratified random sampling was designed to address spatial extent of regional toxicity and benthic community impact.

Amphipod bioassays were performed on all 350 sediment samples. Sea urchin bioassay tests were conducted using sediment pore water, extracted from 164 samples. Samples analyzed for chemistry were selected based on results of toxicity testing. Trace metals (16) and chlorinated synthetic organics (24 PCBs, 36 pesticides) and 24 polycyclic aromatic hydrocarbons (PAHs) were measured in 229 samples, as well as geological characterizations (grain size, total organic carbon, etc.).

2. RESULTS

2.1 Important Physical Drivers

San Diego Bay is a crescent-shaped estuary that is approximately 24 km in length and 0.4 km to 5.8 km in width. Depths in the Bay vary from 18 m near the mouth to less than 1 m in the southern part of the Bay. The Bay is much deeper and narrower than it was historically, due mainly to dredging of channels and filling of nearshore areas. Freshwater input into the bay has been greatly reduced over the years by diversion of rivers, dam construction, extensive ground water use, and limited rainfall. Freshwater input is now limited to periodic surface drainage from the metropolitan area and intermittent flow from several rivers and creeks during periods of rainfall. The tidal range is 1.6 meters. Tidal currents are strongest in the northern part of the Bay and are reduced considerably in the shallower central and south bay areas. Average tidal flushing for San Diego Bay is about 30% of the entire Bay water volume exchanged per tidal cycle. Tidal flushing rates differ drastically between the Bay entrance and South Bay. The latter requires seven to fourteen days, whereas, the entrance of the Bay may only require one to two days. San Diego Bay is a depositional environment with sand deposits found near the Bay's mouth and along western margins, while finer silt and clay deposits are located on the eastern margins and at the southern end of the Bay.

Mission Bay encompasses an area of 18.6 km^2. It was a natural estuary with salt marshes, tidal channels, and a shallow central bay. Major dredging within the Bay and modifications to the San Diego River flood control channel led to its present-day configuration as a highly modified lagoon which receives freshwater input only during infrequent, heavy rains. Tecolote Creek and Rose Inlet carry urban pollutants such as oil, grease, and fertilizers. Furthermore, sewer lines back up occasionally into the back bay. The lack of water circulation in the back bay allows these pollutants to accumulate and has resulted in quarantines for several months at a time.

The Tijuana River estuary has a relatively narrow ocean connection through a series of channels and is salt marsh wetland dominated where mudflats and sandflats occupy only a small fraction of the estuary. Long-term dumping and filling has altered most of the peripheral topography, while extensive damage to the southern half of the estuary from human activities is evident. Millions of gallons of sewage empty directly into the Tijuana River and estuary. An interceptor on the Tijuana River, completed in early October 1991, diverts approximately 15 million gallons of sewage a day to the San Diego wastewater facility. A sewage treatment plant is planned for the U.S. side of the border, and a new ocean outfall is under evaluation.

2.2 Contamination Results

Trace metal concentrations were elevated throughout the San Diego Bay region with copper, mercury and zinc most frequently exceeding their respective ERMs. Elevated levels of copper were generally found near small boat harbors, commercial, and naval shipping areas. This distribution pattern in shipping and boating areas was expected because of historical and present use of copper-based antifouling paints. The elevated levels of copper in the southern portion of the Bay were not in shipping areas and were perhaps linked with the copper ore loading facility in south San Diego Bay.

Mercury was also found at greater levels in several small boat harbors, near commercial shipping operations and particularly near naval shipyards in proximity to ship repair and dry dock facilities where sandblasting, painting, and other ship outfitting occur. Zinc exceeded the ERM guideline levels only in the central portion of San Diego Bay near naval shipyards. A potential source for elevated zinc concentrations may be zinc electrolytic sacrificial blocks, used by most commercial and recreational vessels. Zinc has been shown to cause damage to cell membranes, inhibit enzyme activity, and influence the toxicity of other heavy metals.

Concentrations of both low and high molecular weight polycyclic aromatic hydrocarbons (PAH) exceeded the ERM near commercial shipping operations and naval shipyard areas, as well as the submarine facility near the mouth of the harbor. Polycyclic aromatic hydrocarbons are also of concern in the region as they are components of crude and refined petroleum products and are byproducts of incomplete organic combustion. Some probable sources of PAHs are urban storm drains, groundwater flow toward San Diego Bay, from naval waste oil and drum disposal sites, various commercial or recreational shipping activities, and minor spills during fueling operations. For the majority of samples, incidental inspection of the PAH profiles suggests pyrogenic (combusted) rather than petrogenic (uncombusted) sources.

Elevated levels of total polychlorinated biphenyls (PCBs) were found in sediments along the naval shipyard waterfront. However, several locations along the downtown waterfront and small boat harbors also demonstrated total PCB values exceeding the ERM guidelines. PCB mixtures were used extensively in the U.S. prior to 1979 for industrial applications that required fluids with thermal stability, fire and oxidation resistance, and solubility in organic compounds.

Elevated levels of total chlordane were found along the north shore of San Diego Bay, the San Diego River, and the most northerly station in Mission Bay. Areas that receive storm runoff, such as Chollas Creek, Seventh St. Channel, and urban storm drains most often appeared to be contaminated with high levels of this pesticide. In comparison to other areas in the U.S., a number of San Diego Bay region samples contain chlordane concentrations at or near the upper limit of the range in the NS&T data base. For these reasons, chlordane was considered one of the major chemicals of concern for the region. The frequency of sediment quality guideline exceedances is illustrated in Figure 2.

2.3 Toxicity Results

Fifty-six percent of the area was toxic in the amphipod whole sediment bioassays. Toxicity was widespread throughout San Diego Bay and the Tijuana River, but toxicity was not observed in Mission Bay.

Embryo-larval development tests using the purple sea urchin *Strongylocentrotus purpuratus*, were performed on 164 samples. In 100% pore water, 121 samples (74%) in the purple sea urchin tests were determined to be toxic. In 50% pore water, 91 samples (55%) were determined to be toxic, and in 25% pore water, 53 (32%) samples were determined to be toxic. The majority of stations with samples toxic to all three concentrations of pore water (100, 50, and 25%) were located in central San Diego Bay, although a cluster of toxicity was also seen in the Mission Bay samples. Pore-water samples had sulfides exceeding tolerance limits in 5 of the 164 stations. In all five cases urchin development was abnormal in 100 and 50% pore-water concentrations. Unionized ammonia exceeded tolerance limits in 98 samples, of which 76% of those were determined to be toxic. Some of the greatest unionized ammonia concentrations (up to 0.4 mg/L) were measured in samples that demonstrated normal larval development; a perplexing result.

Concordance between amphipod and urchin larval toxicity tests was demonstrated for 49 samples. Caution should be used when interpreting these results, as these tests assess different media and animal life stages. However, agreement of the two bioassays suggests that presence of toxicants or lack of toxicants may affect an increased number of species or life stages in those samples.

The San Diego Bay region was among the areas in which toxicity was most pervasive when compared to toxicity in industrialized bays and coastal areas around the U.S.

2.4 Benthic Infaunal Results

The identification of benthic degraded and undegraded habitat (as determined by macro-benthic community structure) was conducted using a cumulative, weight-of-evidence approach. Tests were employed without prior knowledge or integration of results from laboratory exposures or chemical analyses. Analyses were performed to identify relationships between community structure within and between each station. This included diversity/evenness indices, analyses of habitat and species composition, construction of dissimilarity matrices for pattern testing, assessment of indicator species and development of a benthic index, cluster and ordination (multidimensional scaling) analyses. Initially, a correlation matrix was produced from species

density data from each station. From this matrix, several tests for association of variables were performed. In general, decreasing numbers of species, increasing numbers of individuals, and decreasing diversity values were common responses observed near polluted areas. One cautionary note is each of the benthic community and population condition tests are subject to effects of not only the pollutants measured in this study, but many other confounding natural factors, such as depth, salinity, sediment texture, and/or predation.

2.5 Correlations

Concordance of toxicity between the amphipod bioassay and urchin larval development bioassay (toxic to all three pore-water concentrations) occurred for 22 of 164 samples, most of which were located in central San Diego Bay. Lack of concordance was observed in 27 of 164 samples measured. There was little statistical correlation between toxicity results and chemical concentrations despite widespread contamination and observed toxicity. This was attributed to the presence of multiple pollutants, co-variation and possible synergistic effects within a group of multiple pollutants that confound the separation of effects to single pollutants. A single multiple regression or a variable selection technique may better describe the statistical relationship between toxicity and multiple chemicals, but these were not performed in this analysis.

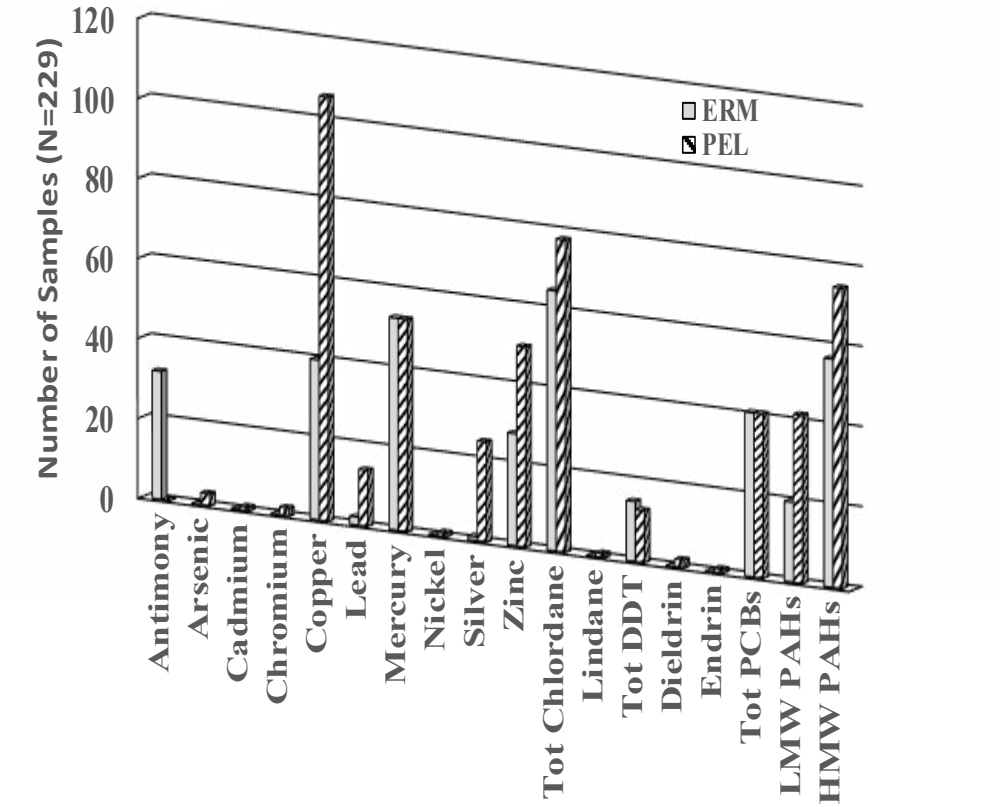


Figure 2. Number of stations that exceeded either the probable effects level (PEL) [40] or effects range median (ERM) [39] values (n = 229 stations) for selected chemicals.

3. SUMMARY

Stations requiring further investigation were prioritized based on combined evidence from toxicity, chemical and benthic community data, with a high, medium or low ranking. Seven stations were given a high priority ranking, 43 stations were given a moderate priority ranking, and 57 stations were given a low priority ranking. The seven stations receiving the high priority ranking were in the Seventh Street channel area, two naval shipyard areas near the Coronado Bridge, and the downtown anchorage area west of the airport. The majority of stations given moderate rankings were associated with commercial areas and naval shipyard areas in the vicinity of Coronado Bridge. Low priority stations were interspersed throughout the San Diego Bay Region.

Due to the large number of elevated chemicals at the majority of the prioritized sampling stations, toxic biological responses can only be associated with overall chemical pollution, rather than a particular chemical. Thus, overall no single chemical or chemical group had a dominant role in contributing to toxicity. The major chemical groups of concern in the San Diego Bay Region as determined by exceeding critical ERM values were copper, mercury, zinc, total chlordane, total PCBs, and PAHs. All stations with an ERM quotient greater than 0.85 had elevated levels of multiple chemicals.

Benthic community structure results found that of the 75 stations sampled, 23 had un-degraded stations, 43 were degraded and 9 were transitional.

Linear regression analyses failed to reveal strong correlations between amphipod survival and chemical concentration. It is suspected that instead of a linear response to chemical pollutants, most organisms are tolerant of pollutants until a threshold is exceeded. Comparisons to established sediment quality guideline thresholds demonstrate an increased incidence of toxicity for San Diego Bay Region samples with chemical concentrations exceeding the ERM values. It is further suspected that toxicity in urban bays is caused by exposure to complex mixtures of chemicals. Comparisons to ERM summary quotients (multiple chemical indicators) demonstrate that the highest incidence of toxicity (>78%) is found in samples with elevated ERM summary quotients (>0.85).

Chapter 16
Long Beach and San Pedro Bay

1. STUDY AREA DESCRIPTION

This study was the result of a cooperative effort between the State Water Resources Control Board's Bay Protection and Toxic Cleanup Program, the National Oceanic and Atmospheric Administration and the California Department of Fish and Game.

The port and harbors have been heavily modified over the course of more than one hundred years to include construction of breakwaters, landfills, slips and wharves, along with channelization of drainages, dredging of navigation channels, and reclamation of marshland. The area of study includes both the Los Angeles Harbor and Long Beach Harbor (Figure 1). Both harbors are considered to be one oceanographic unit, and have a common breakwater across the mouth of San Pedro Bay. The water masses, characterized as the inner harbors with estuarine characteristics with regards to aquatic life, while the outer harbors reflect the conditions of strong currents and rocky habitat typical of coastal marine waters of the Southern California Bight.

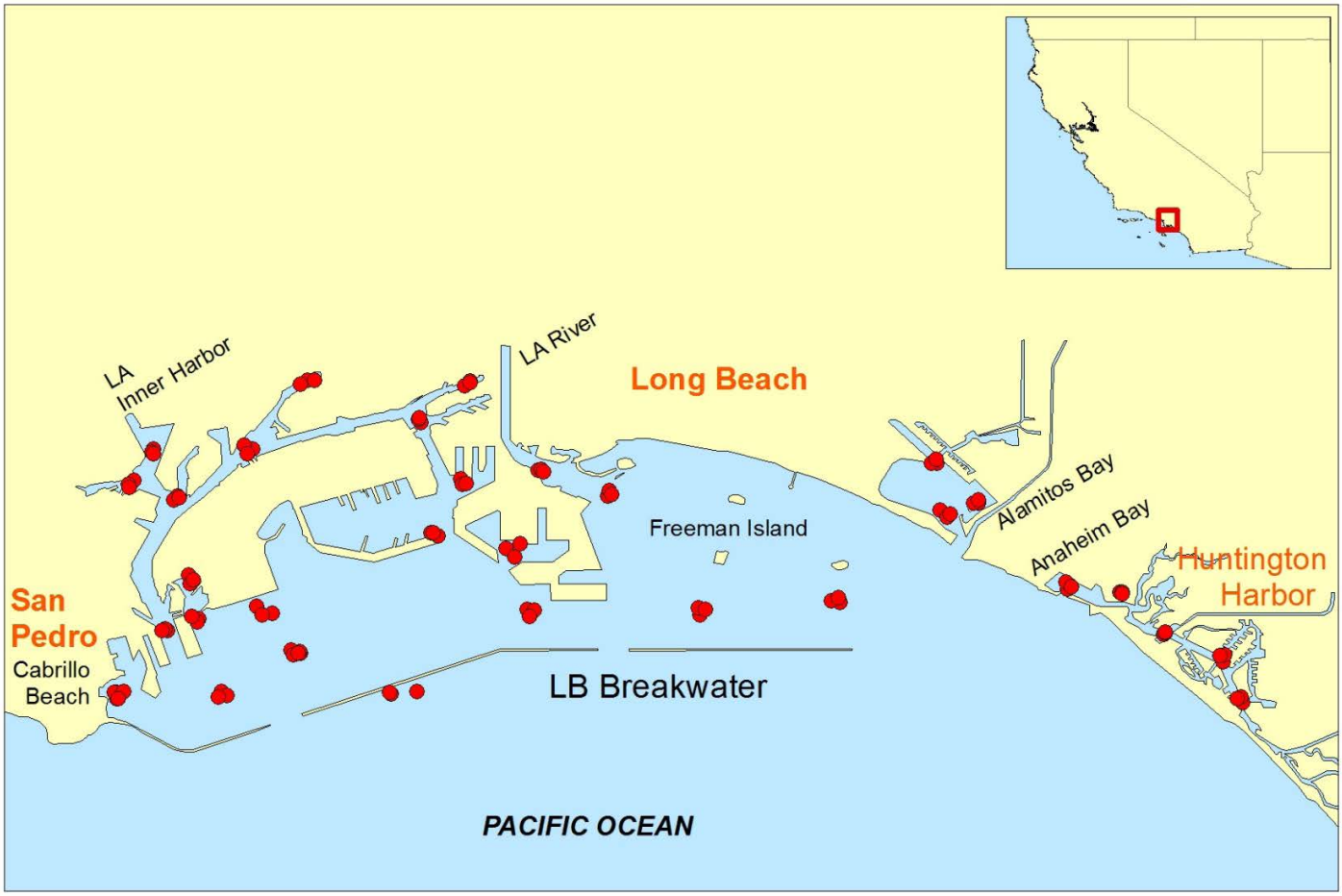


Figure 1. Overall San Pedro, Long Beach, Alamitos Bay, and Huntington Harbor study region.

Sampling Details

This study was one of the earliest Bioeffects studies, and was not designed as a stratified random project. Sites were selected using knowledge of the area and specific sites were targeted, so the spatial extent of toxicity

and chemical concentrations cannot be determined. Also, benthic community attributes were not included. In 1992, thirty-five sites were sampled in the area, including Los Angeles and Long Beach harbors, Anaheim Bay, and Huntington Harbor. Sites were sampled in triplicate (3 stations/site). Please refer to figures 2a, 2b and 2c for site locations. Two toxicity tests were performed; amphipod survival (*Rhepoxynius abronius*) using whole sediments, and red abalone (*Haliotis rufescens*), larval development using the using sediment pore water. Trace metals were analyzed from pore water from 21 stations, whereas both trace metals and organic toxicants were analyzed from sediments collected at 45 stations. The sampling sites were selected to provide a broad representation of conditions and general trends of pollution throughout the study area resulting from various sources, with known point sources of pollution avoided, and only areas having relatively fine-grained (greater than 30 percent fines) sediments included. Reference sites were far removed from the harbor, and one additional site was chosen outside the harbor for general comparative purposes.

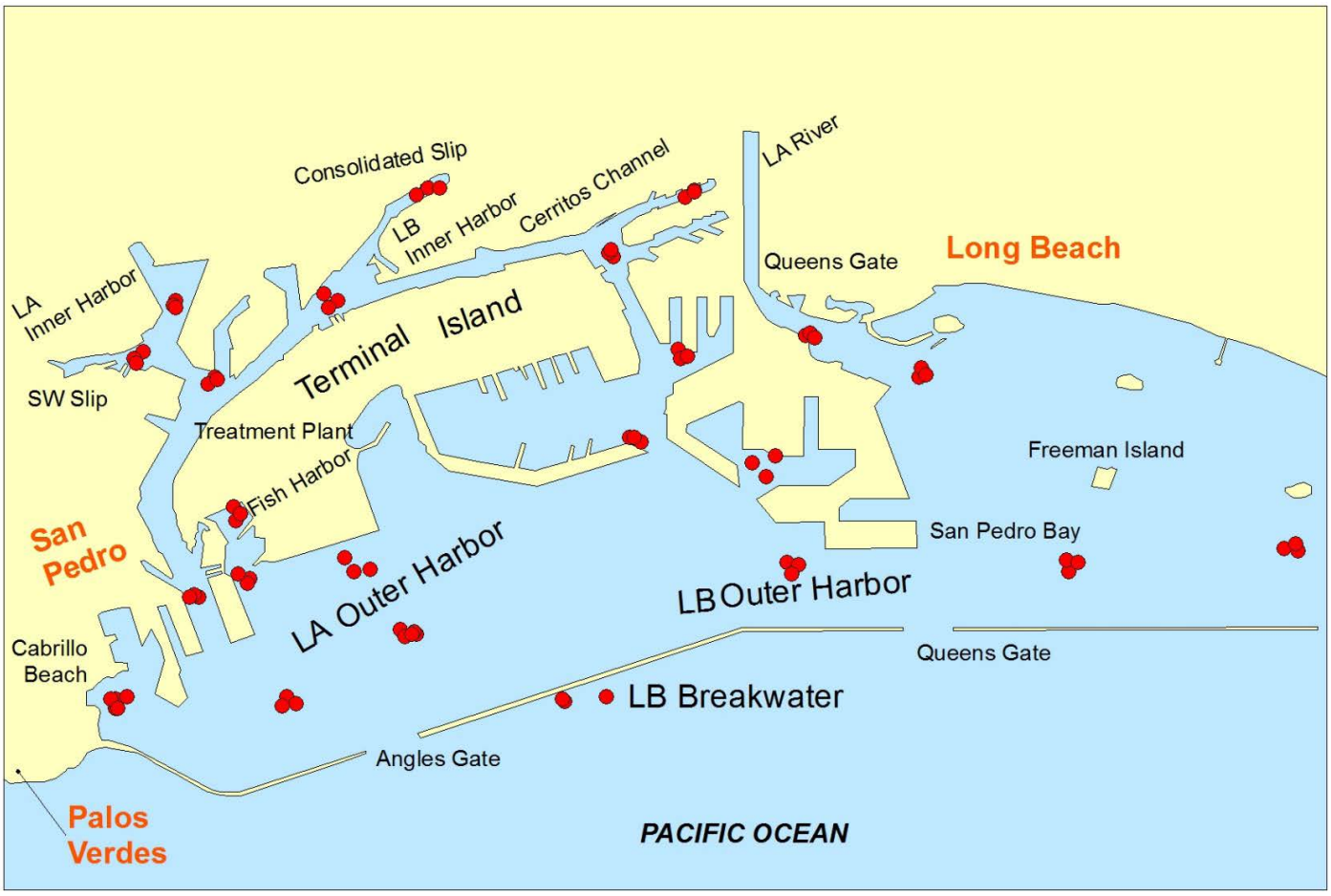


Figure 2a. Los Angeles, Long Beach sample sites.

2. RESULTS

2.1 Important Physical Drivers

The major surface drainages in the area include the Los Angeles River watershed, which drains parts of the San Fernando Valley into the bay at Long Beach. The Dominguez Channel watershed drains the intensely

urbanized area west of the Los Angeles River into the Consolidated Slip of the Los Angeles inner harbor, carrying with it mostly urban runoff. A major source of both freshwater and waste in the outer harbor is secondary effluent from the Terminal Island Treatment Plant. Circulation in the outer harbors result from tidal currents, with the general influx through Angels and Queens gates, and out flux at the east end of Long Beach Harbor (Figure 2a). Studies indicate the existence of a large clockwise circular current extending east from the Los Angeles Main Channel, and a counter clockwise eddy below at a depth of 20 feet. These and other minor eddy currents are considered to be partly responsible for relatively good quality water in the outer harbor. These patterns result in the greatest flushing rates due to tides occurring at the harbor entrances of Angels Gate, Queens Gate, and east of Freeman Island. The lowest flushing rates are in the channels around Terminal Island.

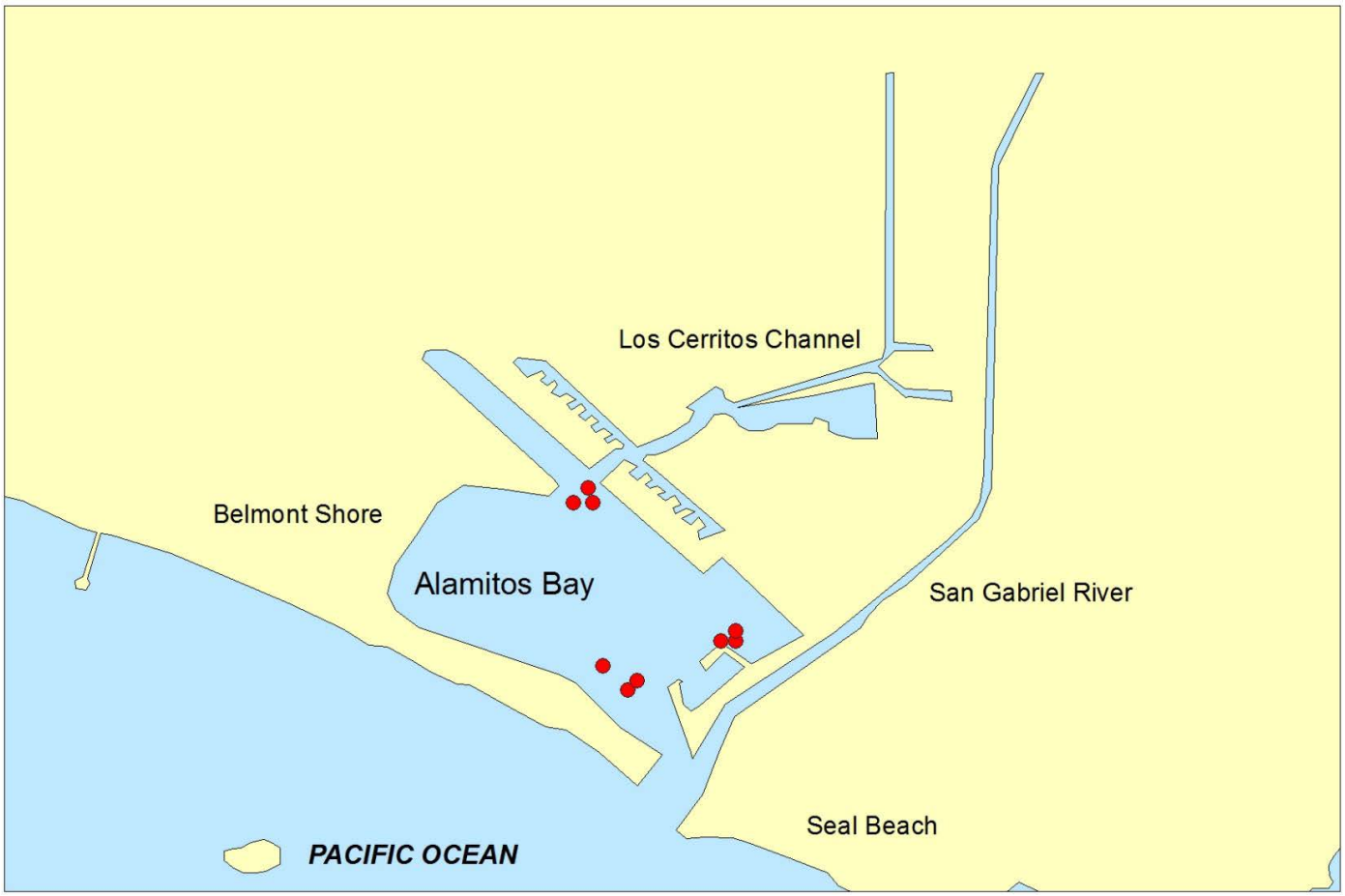


Figure 2b. Alamitos Bay sample sites.

The Anaheim Bay/Huntington Harbor on the Orange County coast consists of Anaheim Bay and Huntington Harbor (Figure 2c). Huntington Harbor receives very little tidal flushing so freshwater inputs have significant impacts on the water quality. Two major storm drains, the Bolsa Chica flood control channel and the East Garden Grove Wintersburg flood control channel, as well as their tributaries convey runoff from the northern portion of the heavily urbanized Orange County into Huntington Harbor.

2.2 Contamination Results

Virtually all contaminants had higher concentrations in the inner harbor areas (behind Terminal Island) than in the outer harbor sites. Total DDTs were found at elevated levels throughout the study area. Only two sediment sites had low molecular weight PAH concentrations above the ERM; Southwest Slip and Consolidated Slip. Four sites had high molecular weight PAH concentrations above the ERM including, Southwest Slip, Consolidated Slip, Long Beach Harbor Channel 2 and Inner Fish Harbor. Two sites, Consolidated Slip and Inner Fish Harbor had PCB concentrations above the ERM. Elevated levels of copper and zinc were scattered throughout the inner harbor region. Four stations had zinc concentrations above the ERM, Consolidated Slip, Long Beach Harbor Channel 2, Inner Fish Harbor, and the harbors of Long Beach and Los Angeles. Nickel was present at levels above the ERM at seven stations.

2.3 Toxicity Results

The amphipod bioassay toxicity tests identified Los Angeles Harbor, Long Beach Harbor, Huntington Harbor, West Basin, Consolidated Slip and portions of Alamitos Bay as toxic.

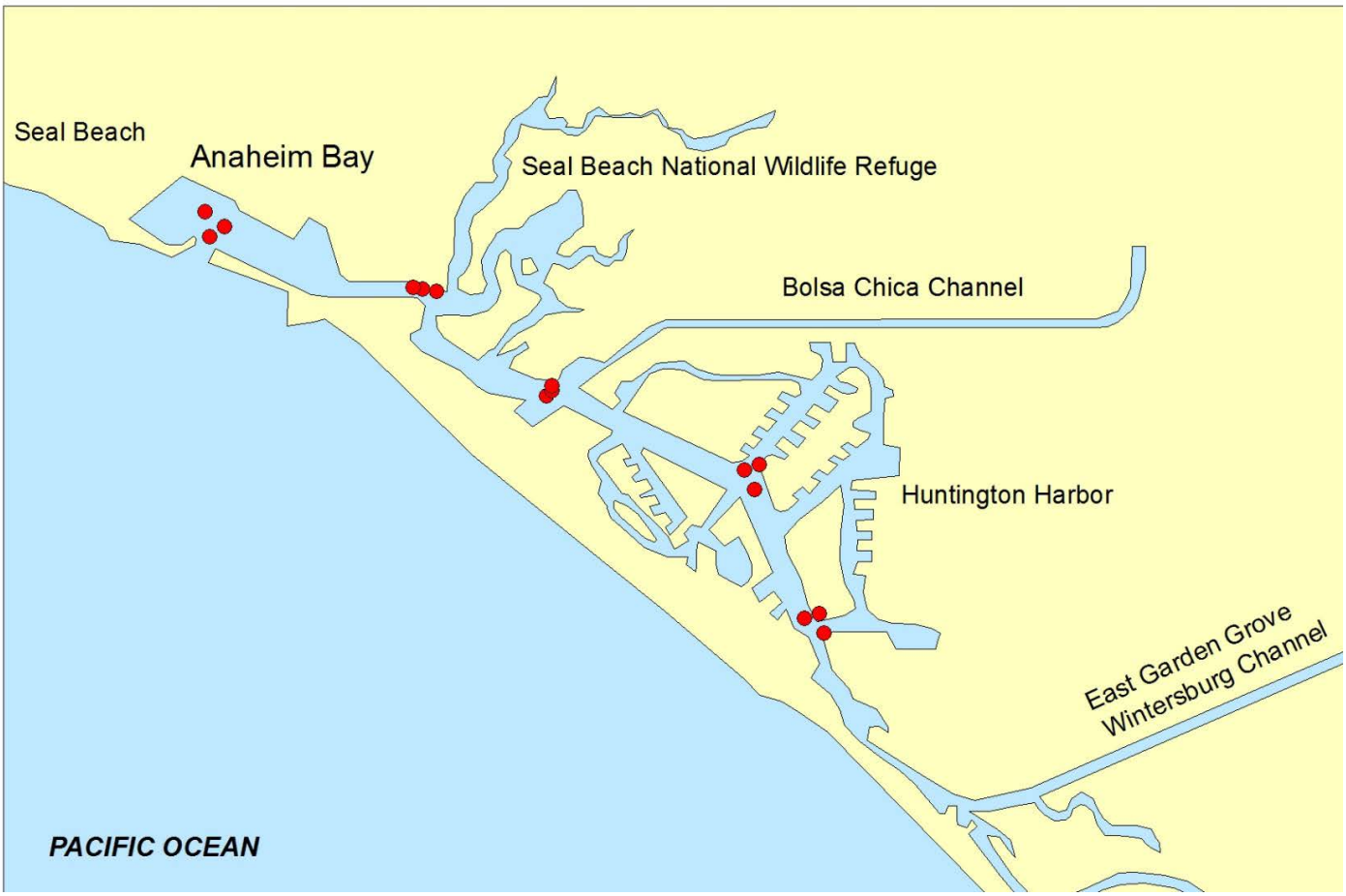


Figure 2c. Anaheim Bay to Huntington Harbor sample sites.

Los Angeles and Long Beach inner harbors had significant amphipod mortality, whereas most of the outer harbor site sediments were not lethal to amphipods. Significant negative correlations were found between amphipod survival and acenanaphthene, phenanthrene fluoranthene, copper, lead, zinc and total PAH.

Consolidated Slip receives drainage from the Dominguez Channel, a historical repository of pesticide wastes, and is near several petroleum-related companies and a small vessel marina. Consolidated Slip was the only site with three of three stations showing significant toxicity. Overall, significant toxicity was found in samples from the Los Angeles Harbor, Long Beach Harbor, the mouth of the Los Angeles River, and Huntington Harbor. Toxicity diminished into lower San Pedro Bay (toward Anaheim) and offshore beyond the San Pedro breakwater.

The abalone bioassays showed that at the 100 % porewater concentration, the results show 62 % of the sites (mean value of the stations in a site) had a response significant at $p<0.01$, with 15 % of the sites showing a response significant at $p<0.05$. All tested sites had one or more stations with a response significant at either the 95 or 99 % confidence levels. At 66 % of the sites, all stations had a response significant at $p<0.01$.

2.4 Benthic Infaunal Results

The study did not include sampling of sediment dwelling communities.

2.5 Correlations

Concentrations of Cu, Pb, Zn, Sb, Ni, Sn, low and high weight PAHs, total PAHs, total PCBs, and TBT were correlated with toxicity to the amphipods. Of interest is the lack of significant toxicity to amphipods relative to sediment total DDT. A study by Swartz et al. (1985) suggests that the lack of correlation between amphipod mortality and DDT may be related to the acute nature of the 10-day amphipod test, rather than to a lack of toxicity associated with this compound.

Lead and copper in sediment pore waters were positively correlated with inhibited abalone larvae development. Pore water was not analyzed for the organic constituents. The toxicity observed in the abalone larvae test was not strongly correlated with any of the pollutants analyzed in the sediments. Significant correlation was observed for sediment levels of tin and total pesticides, but the correlation coefficients were neither very large; nor were the correlations consistent for all dilutions of pore waters tested. These correlations appear to be heavily influenced by the values of only a few samples, resulting in the relatively weak correlations obtained. Abalone larvae development tests showed the most lethal sediment pore waters were from sites in Huntington Harbor and at Palos Verdes.

3. SUMMARY

Higher concentrations of PAHs were observed in samples from the Los Angeles and Long Beach Harbors than in samples from Los Alamitos Bay or Huntington Harbor. The highest levels of PAHs were observed in samples collected in the inner harbors of Los Angeles and Long Beach. Only Los Angeles inner harbor had high levels of PCBs. DDE and DDT concentrations were relatively high throughout the study area when compared to detection limits and non-detects. Cabrillo Beach, Fish Harbor, and Long Beach inner harbor had notably high concentrations of DDE. Concentrations of metals (Cu, Ni and Zn) were high in Fish Harbor and Long Beach inner harbor. However, the natural crustal concentrations of nickel along the west coast is noted for this element. Significant amphipod toxicity was observed at many stations in the Los Angeles and Long Beach inner harbors. Less toxicity was observed in the Los Angeles-Long Beach outer harbor. Most of the stations in Alamitos Bay, Anaheim Bay and Huntington Harbor showed toxicity to the amphipods. Undiluted pore water toxicity was observed throughout the study area. At the 50% dilution concentration most of the toxicity was observed in the Long Beach middle harbor, off Cabrillo Beach, in Alamitos Bay, and in Huntington Harbor. Collectively, the amphipod tests and the diluted pore water tests identified Huntington Harbor, West Basin, Consolidated Slip, and portions of Alamitos Bay as the most toxic locations in the study area.

Chapter 17
San Francisco Bay

1. STUDY AREA DESCRIPTION

San Francisco Bay is one of the two largest west coast estuaries. It encompasses roughly 4,144 km^2. and drains more than 40 percent of the state of California, including 4.5 million acres of farmland and ranchland. The population around the estuary exceeds 7 million people. More than 10 million tourists are estimated to visit the bay region annually. Virtually the entire shoreline of the South and Central Bays, and significant proportions of San Pablo and Suisun Bays are urbanized. In contrast, the Potomac River estuary in the Chesapeake Bay is roughly the same size but has only one major urbanized area (Washington, DC) with 2 million fewer people and most of the remaining shoreline is sparsely populated.

The San Francisco Bay system is one of the most heavily altered estuaries in the country. The Delta encompasses over 2,800 km^2. It is a maze of natural and man-made channels surrounded by marsh, riprapped levees, seasonal farmlands, and islands. The Delta was originally marshland; reclaimed by building levees. Once the rivers were confined to their riverbeds, the peat soil of the former tidal marsh was exposed to oxygen and decomposed, followed by profound subsidence. Now, most of the Delta is below sea level. Subsidence has rendered the Delta's 1,100-mile system of protective levees at risk. Levee failure and subsequent flooding is returning once-farmed lands into lakes partially exposed to tidal circulation. Located at the confluence of California's two major river systems, the Delta is the source of water for domestic and agricultural use outside the San Francisco Bay system via state and federal water export facilities. Approximately one quarter of the freshwater input to the Delta is diverted for agriculture in the central valley, and drinking water supply in southern California.

Since the days of hydraulic gold mining in the 1800s, sedimentation in San Francisco Bay has changed drastically. Hydraulic mining excavated and dislocated roughly 1.4 billion cubic yards of material from gold deposits. In the twenty-one years after the start of hydraulic mining in the Sierra foothills, massive quantities of sediment were washed down from the mountains to the Delta and San Francisco Bay. As hydraulic mining practices ceased, the amount of sediment deposited decreased. From 1867 until at least 1887, Suisun Bay was depositional and filled with hydraulic mining debris. After 1887, Suisun Bay was erosional due to the lack of sediment input from upstream, and the volume of material eroded has increased. More than 250 million cubic meters of sediment were subsequently deposited in San Pablo Bay. During the 1900's, San Pablo Bay also became erosional. In the latter half of the 20th century an increase in the implementation of flood control and water distribution projects in the Central Valley caused the Bay to be erosional due to the reduction of the frequency and duration of peak flow conditions, which in turn decreased sediment supply to the Bay. In the central bay strong tidal currents flow through the restricted entrance at the Golden Gate, sweeping away mud and fine sediment. The entire tidal prism from a 6 feet tide must pass through this channel. The sediments in the central bay are generally coarser in texture than the other bays. Tidal currents generate sand waves on the bottom that are as high as 10 feet. The northern bays and south bay have an average depth of 10 to 13 feet, with relatively deep tidal channels 30 to 65 feet. The central bay in contrast has

an average water depth of 36 feet. South San Francisco Bay has lost approximately 90 x 10^6 m^3 of sediment from 1858 to 1983; however, within this timeframe there have been periods of both deposition and erosion. During the most recent period, from 1956 to 1983, sediment loss approached 3 x 10^6 m^3/yr.

One of the most striking changes that occurred throughout the system from 1858 to 1983 was the conversion of more than 80% of the tidal marsh to salt ponds, agricultural, and urban areas. Tidal marshes occupied about 200,000 acres (209 km^2) along the bay's margins in the early 1800's. In addition, there has been a decline of approximately 40% in intertidal mud flat area. The California State Coastal Conservancy, the U.S. Fish and Wildlife Service and the California Department of Fish and Game are currently attempting to restore 15,000 acres (61 km^2) of salt pond to mixed wetland . If all 61 km^2 were to be successfully restored to tidal marsh, this would return the marsh to approximately 40% of its 1858 extent. Much of the waterfront from San Francisco down through Redwood City and Oakland are filled tidal marsh. This renders the areas more susceptible to earthquake damage due to soil liquefaction during the shaking.

Sampling Details

Sampling in San Francisco Bay was carried out in 2000 and 2001. The bay was divided into 47 strata with 179 sampling locations (Figure 1 a-d). Strata were not delineated to be uniform in size or shape, rather they

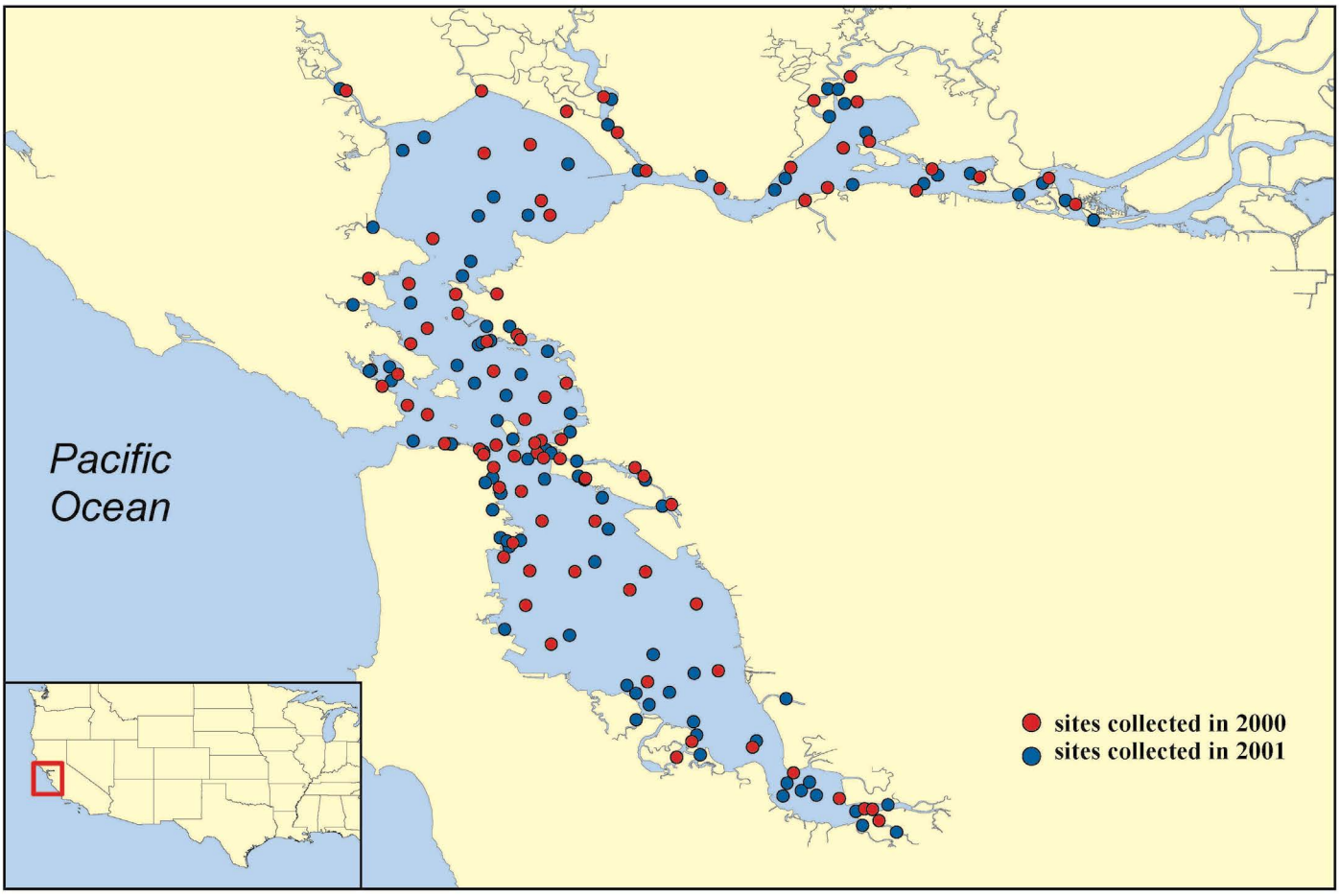


Figure 1a. Map of the San Francisco Bay showing all sampling points.

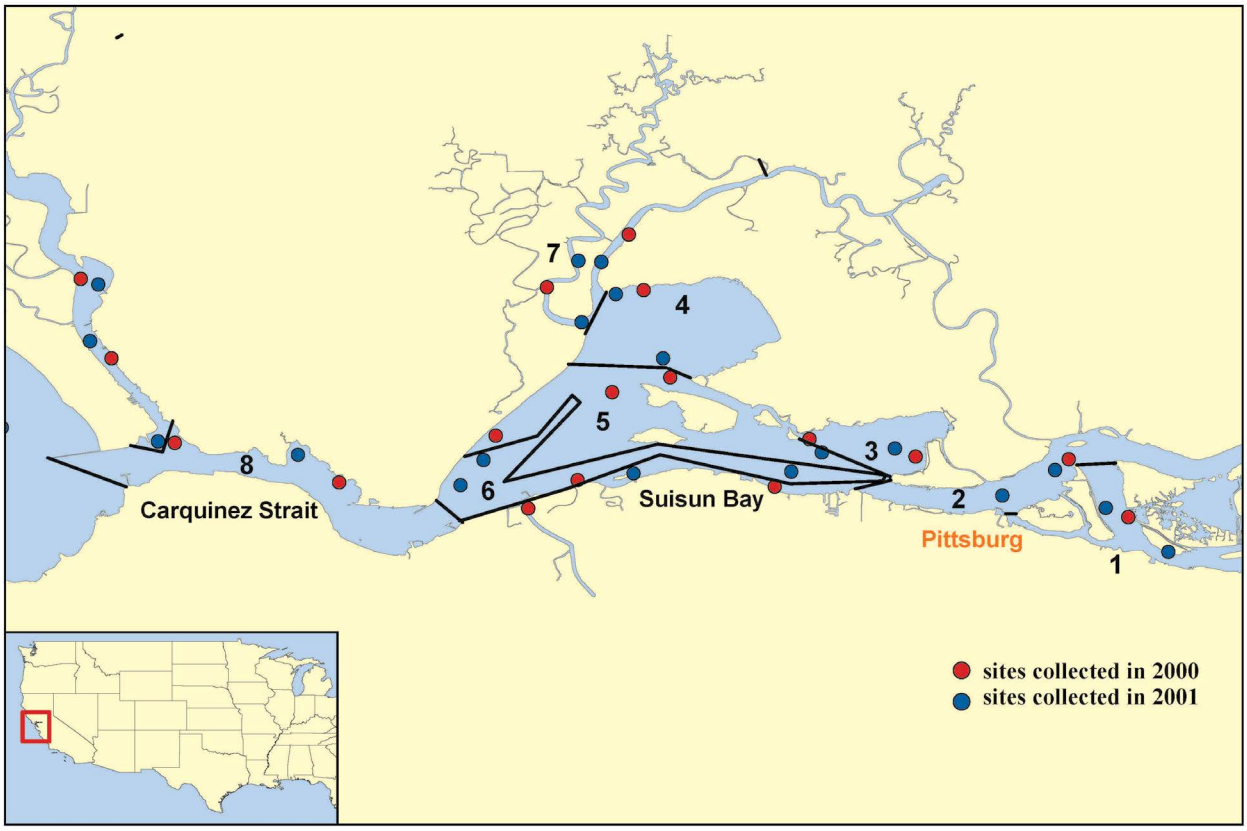


Figure 1b. Map of the upper Bay showing sampling strata boundaries.

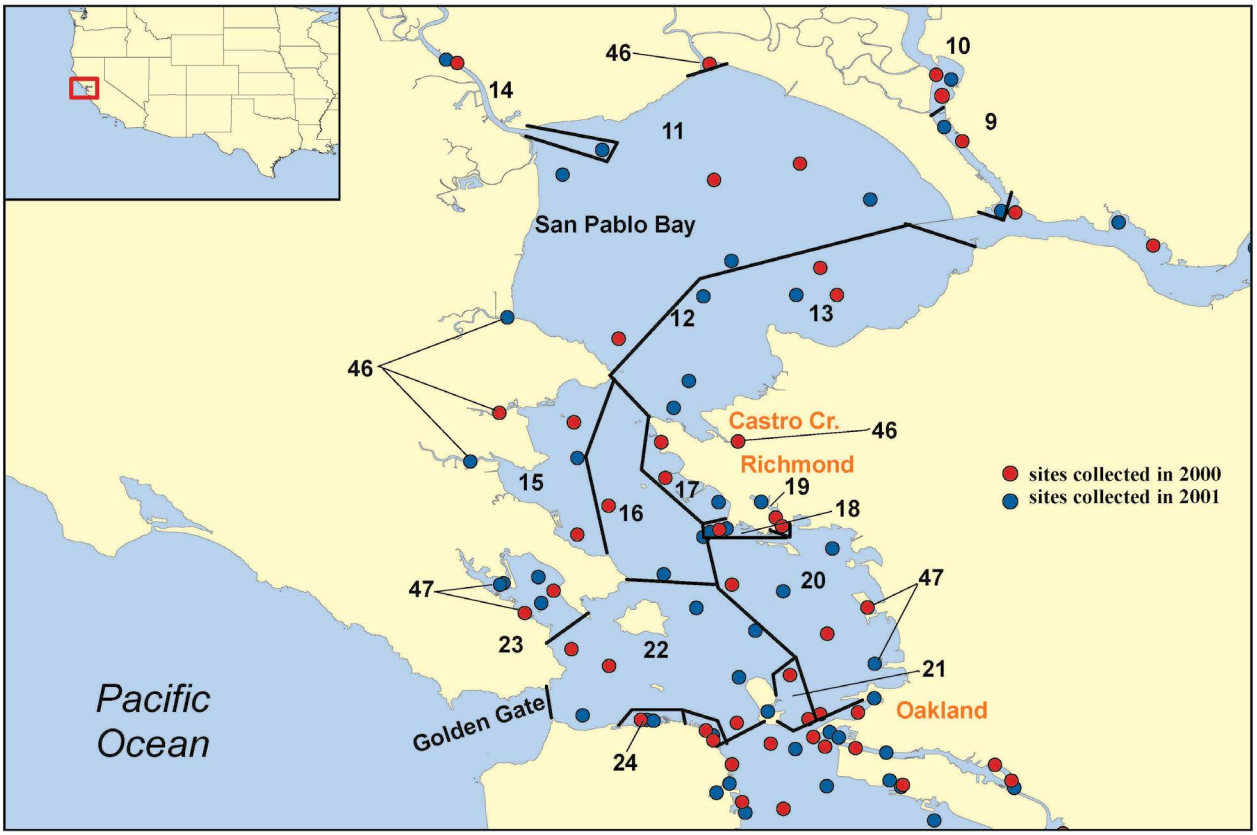


Figure 1c. Map of the central Bay showing sampling strata boundaries

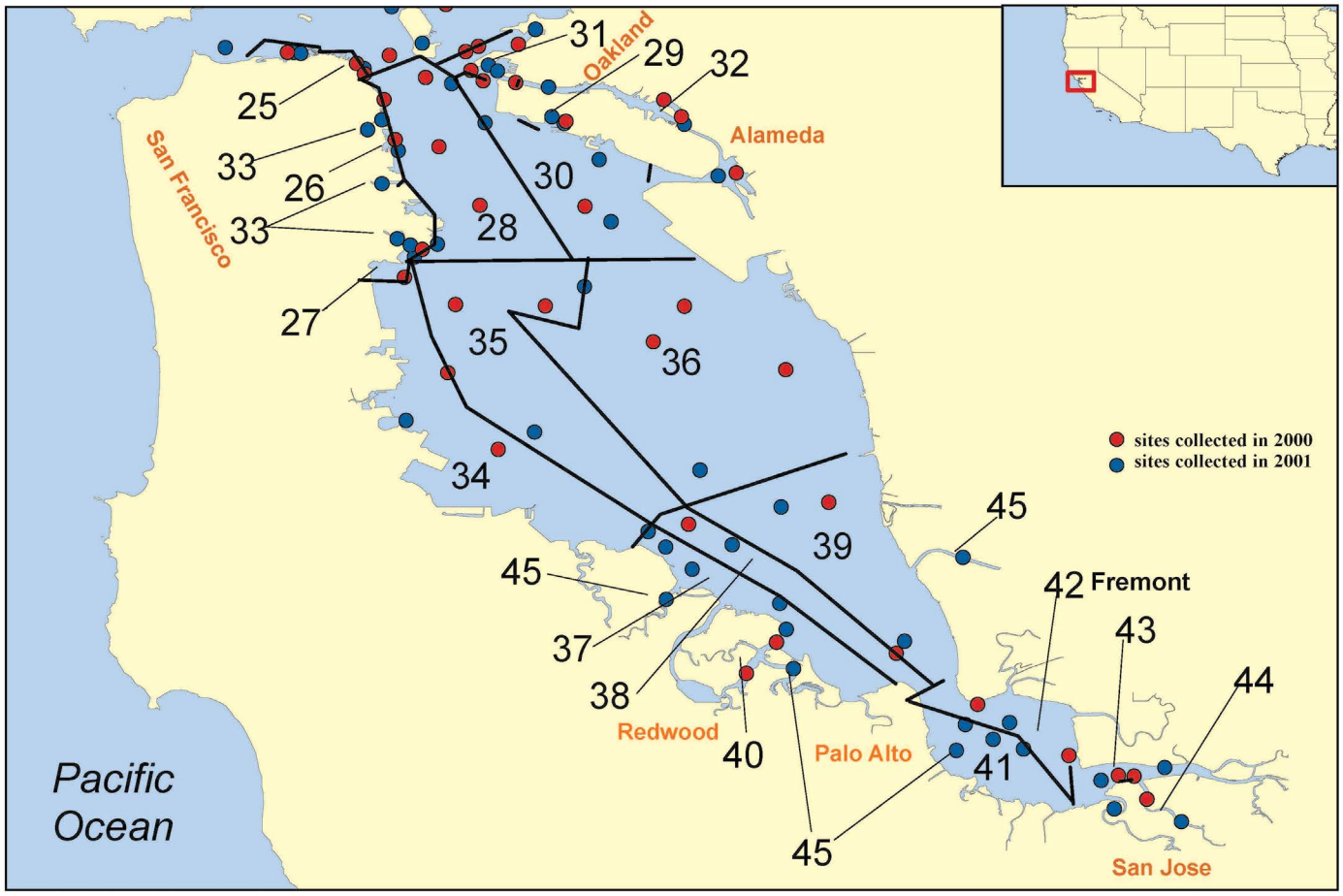


Figure 1d. Map of the south Bay showing sampling strata and boundaries.

were created to encompass specific habitat types (e.g. channels, tributaries, broad flats, etc.). A subset of sites in each stratum were sampled in each year, so all regions of the bay were sampled over both years, rather than in sections.

Sites ranged from the mouth of the Delta near Pittsburg, through the open bay and down into the creeks and sloughs at the tip of South Bay in San Jose and Fremont. In 2000, a subset of the stations were sampled in coordination with a US EPA monitoring program and the data were pooled. Five of the strata did not enclose contiguous areas, but were composed of tributary and marina sites in 1- Suisun Bay, 2- San Pablo Bay, 3- Central Bay, 4- urban streams in San Francisco, and 4- South Bay. Four additional sites were sampled in collaboration with the Regional Monitoring Program's annual sampling stations.

2. RESULTS

2.1 Important Physical Drivers

The estuary is composed of four distinct hydrographic regions, including the San Joaquin-Sacramento River Delta and Suisun Bay, San Pablo Bay, Central Bay, and the South Bay. San Pablo Bay and Suisun Bay are connected to each other by a deep, narrow channel, the Carquinez Strait. Suisun Bay is a shallow basin consisting of braided channels and shoals. San Pablo Bay is characterized by a deep channel surrounded by broad shoals and marshes. The Central Bay has a highly complex bathymetry. At the Golden Gate, the depth

is over 300 feet, while extensive intertidal mudflats are present at the eastern edge of the Central Bay in the vicinity of Richmond. South Bay is characterized by large areas of broad shallows surrounding a main channel 30 to 65 feet deep. It has similar bathymetry to San Pablo and Suisun Bays.

Freshwater input, tidal flows, and their interactions determine variations in the hydrology of the Bay, which in turn affect sediment dynamics, salinity patterns, and all species that live in the estuary. Ninety percent of the freshwater inflow to the Bay comes from the Delta and flows through the northern portion of the Bay, resulting in a partially to well-mixed estuary. Suisun and San Pablo Bays are hydrologically distinct from the Central and South Bays. The degree of mixing depends on seasonally varying river inflow, wind and tidal mixing. The timing and magnitude of the highly seasonal river inflow modulates estuarine circulation, which is largely maintained by salinity-controlled density differences between river and marine waters. Very little freshwater flows into the South Bay. It is a tidally oscillating, lagoon-type estuary, where salinity variations are determined by water exchange between the northern reaches and the South Bay. Water residence times are much longer in the South Bay than in the northern Bays.

2.2 Contamination Results

Chemical analyses indicate that contamination is widespread throughout the estuary. Elevated contaminant levels in tributaries and harbors/marinas were site specific with locally very high concentrations. Open water sites had marginally higher concentrations of contaminants in southern San Francisco Bay than in San Pablo or Suisun Bays. Metals were uniformly distributed throughout the Bay (Figure 2). PAHs and PCBs were found at higher levels in the Central and South Bays than in the northern bays. Chlorinated pesticides (primarily DDTs) were found throughout the system. The stations with the highest concentrations were concentrated in Richmond, Oakland/Alameda, San Francisco, and Castro Creek (Figure 2). These locations had vastly higher levels of DDTs and PCBs than the rest of the system. The spatial extent of ERL and ERM exceedances was highly dependent on which class of chemicals are assessed. Total DDTs and metals exceeded their respective ERLs in at least one station in every stratum but one, whereas few stations exceeded the ERL for PAHs and PCBs (Table 1). However, few locations exhibited ERM exceedances (Table 2). As noted above, these sites were localized, but did contain very high concentrations (e.g. > 370 ppb PCBs).

2.3 Toxicity Results

Paired amphipod bioassays were conducted with *Ampelisca abdita* and *Eohaustorius estuarius* for comparative purposes at the 49 sites that were sampled in coordination with EPA in 2000. The results did not correlate well with each other. Few stations demonstrated toxicity to *A. abdita*, whereas few stations were non-toxic to *E. estuarius*, indicating widespread low level toxicity for more sensitive species. Pore water bioassays with sea urchin (*Arbacia punctulata*) gametes demonstrated better correlation between fertilization and development, and development was a more sensitive endpoint, showing significant impacts at 77.52% of the sampling sites. Again this indicates widespread low level toxicity for more sensitive species. The P450 bioassay correlated primarily with PAH concentrations. Based on strata areas, the spatial extent of impaired habitat ranged from less than 1% to 77.5% depending on the selected bioassay (Table 3).

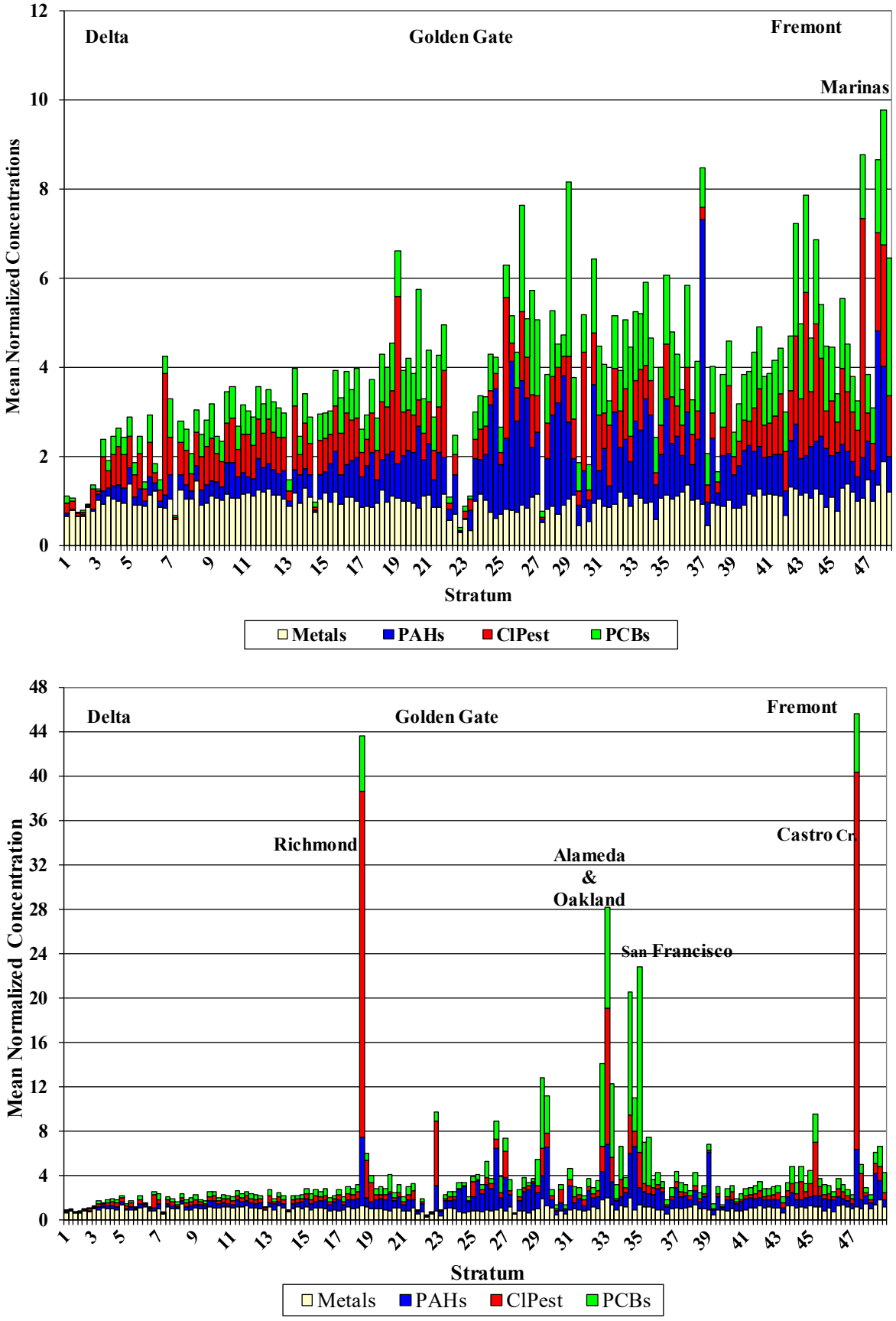


Figure 2. Mean-normalized concentrations of metals, PAHs, pesticides and PCBs in San Francisco Bay without (top) and with (below) the top 10th percentile of values. Stratum 47 consisted of marina sites.

Table 1 Spatial extent (km^2) of area where ERLs were exceeded in 47 strata in San Francisco Bay sediments.

Stratum	Total Area	area ERL PAH	area ERL PCB	area ERL DDT	area ERL Metals		Stratum	Total Area	area ERL PAH	area ERL PCB	area ERL DDT	area ERL Metals
1	6.5	0.0	0.0	0.0	2.2		25	0.6	0.6	0.0	0.6	0.2
2	15.2	0.0	0.0	5.1	5.1		26	1.6	1.6	1.1	1.6	0.5
3	9.6	0.0	0.0	6.4	3.2		27	3.4	1.1	3.4	3.4	1.1
4	22.4	0.0	0.0	22.4	7.5		28	38.5	23.1	0.0	30.8	7.7
5	34.0	0.0	0.0	34.0	6.8		29	1.9	1.9	1.9	1.9	0.6
6	21.7	0.0	0.0	14.5	3.6		30	38.3	0.0	0.0	28.7	9.6
7	3.9	0.0	0.0	1.4	0.2		31	3.3	1.1	0.0	3.3	0.6
8	19.8	0.0	0.0	19.8	6.6		32	3.2	1.6	2.7	3.2	0.5
9	2.0	0.0	0.0	2.0	0.7		33	0.7	1.1	0.9	1.1	0.2
10	3.2	0.0	0.0	3.2	1.1		34	54.8	41.1	13.7	54.8	13.7
11	151.1	0.0	0.0	151.1	25.2		35	61.8	15.4	0.0	61.8	15.4
12	36.7	0.0	0.0	24.5	12.2		36	120.9	30.2	30.2	120.9	30.2
13	41.3	0.0	0.0	27.5	13.8		37	13.1	4.4	0.0	13.1	4.4
14	3.0	0.0	0.0	3.0	1.0		38	15.2	0.0	0.0	10.2	5.1
15	19.3	0.0	0.0	19.3	6.4		39	45.0	0.0	0.0	45.0	15.0
16	38.7	0.0	0.0	38.7	12.9		40	0.6	0.0	0.0	0.6	0.2
17	6.5	0.0	0.0	6.5	2.2		41	6.7	0.0	0.0	6.7	2.2
18	0.8	0.0	0.0	0.8	0.3		42	5.2	0.0	0.0	5.2	1.7
19	0.7	0.2	0.2	0.7	0.2		43	1.1	0.0	1.1	1.1	0.4
20	52.8	8.8	8.8	52.8	8.8		44	1.4	0.0	0.9	1.4	0.5
21	3.5	0.0	0.0	3.5	1.2		45	4.0	0.0	0.0	2.9	0.6
22	60.7	10.1	0.0	30.3	10.1		46	2.1	0.2	0.2	1.0	0.2
23	8.1	0.0	0.0	8.1	2.7		47	3.2	2.1	2.1	5.3	1.1
24	0.8	0.6	0.0	0.8	0.3		**Total**	**988.9**	**145.4**	**67.3**	**880.9**	**245.8**
								%	**14.7**	**6.8**	**89.1**	**24.9**

Table 2 Spatial extent (km^2) of area where ERMs were exceeded in 47 strata in San Francisco Bay sediments.

Stratum	Total Area	area ERM PAH	area ERM PCB	area ERM DDT	area ERM metals		Stratum	Total Area	area ERM PAH	area ERM PCB	area ERM DDT	area ERM metals
1	6.5	0.0	0.0	0.0	0.0		25	0.6	0.0	0.0	0.0	0.0
2	15.2	0.0	0.0	0.0	0.0		26	1.6	0.0	0.0	0.0	0.0
3	9.6	0.0	0.0	0.0	0.0		27	3.4	1.1	0.0	1.1	0.0
4	22.4	0.0	0.0	0.0	0.0		28	38.5	0.0	0.0	0.0	0.0
5	34.0	0.0	0.0	0.0	0.0		29	1.9	0.0	0.0	0.0	0.6
6	21.7	0.0	0.0	0.0	0.0		30	38.3	0.0	0.0	0.0	0.0
7	3.9	0.0	0.0	0.0	0.0		31	3.3	0.0	0.0	0.0	0.0
8	19.8	0.0	0.0	0.0	0.0		32	3.2	0.5	0.5	0.5	2.1
9	2.0	0.0	0.0	0.0	0.0		33	0.7	0.4	0.4	0.0	0.2
10	3.2	0.0	0.0	0.0	0.0		34	54.8	0.0	0.0	0.0	0.0
11	151.1	0.0	0.0	0.0	0.0		35	61.8	0.0	0.0	0.0	15.4
12	36.7	0.0	0.0	0.0	0.0		36	120.9	0.0	0.0	0.0	0.0
13	41.3	0.0	0.0	0.0	0.0		37	13.1	0.0	0.0	0.0	0.0
14	3.0	0.0	0.0	0.0	0.0		38	15.2	0.0	0.0	0.0	0.0
15	19.3	0.0	0.0	0.0	6.4		39	45.0	0.0	0.0	0.0	0.0
16	38.7	0.0	0.0	0.0	0.0		40	0.6	0.0	0.0	0.0	0.0
17	6.5	0.0	0.0	0.0	0.0		41	6.7	0.0	0.0	0.0	0.0
18	0.8	0.0	0.0	0.0	0.0		42	5.2	0.0	0.0	0.0	0.0
19	0.7	0.4	0.0	0.4	0.2		43	1.1	0.0	0.0	0.0	0.4
20	52.8	0.0	0.0	0.0	0.0		44	1.4	0.5	0.0	0.5	0.9
21	3.5	0.0	0.0	0.0	0.0		45	4.0	0.0	0.0	0.0	0.0
22	60.7	10.1	0.0	10.1	0.0		46	2.1	0.2	0.0	0.2	0.0
23	8.1	0.0	0.0	0.0	0.0		47	3.2	0.0	0.0	0.0	1.1
24	0.8	0.0	0.0	0.0	0.0		**Total**	**988.9**	**13.3**	**0.9**	**12.9**	**27.4**
								%	**1.3**	**0.1**	**1.3**	**2.8**

Table 3. Spatial extent (km^2) of areas where bioassays demonstrated toxicity in 47 strata in San Francisco Bay sediments as estimated by laboratory bioassay tests.

Stratum	total area km^2	Amphipod Mortality	P450 B[a]P eq	Sea Urchin Fertilization	Sea Urchin Development		Stratum	total area km^2	Amphipod Mortality	P450 B[a]P eq	Sea Urchin Fertilization	Sea Urchin Development
1	6.5	0.0	0.0	0.0	0.0		25	0.6	0.0	0.0	0.2	0.6
2	15.2	0.0	0.0	0.0	0.0		26	1.6	0.0	0.54	0.0	1.6
3	9.6	0.0	0.0	0.0	6.4		27	3.4	1.1	0.0	2.3	3.4
4	22.4	0.0	0.0	0.0	7.5		28	38.5	0.0	0.0	7.7	30.8
5	34.0	0.0	0.0	13.6	20.4		29	1.9	0.0	0.0	0.0	1.9
6	21.7	0.0	0.0	7.2	14.5		30	38.3	9.6	0.0	19.2	38.3
7	3.9	0.0	0.0	1.2	1.4		31	3.3	1.1	0.0	1.7	2.2
8	19.8	0.0	0.0	0.0	13.2		32	3.2	0.0	0.53	0.5	3.2
9	2.0	0.0	0.0	0.7	2.0		33	0.7	0.2	0.0	0.2	1.1
10	3.2	0.0	0.0	2.1	3.2		34	54.8	0.0	0.0	27.4	54.8
11	151.1	25.2	0.0	0.0	125.9		35	61.8	0.0	0.0	15.4	46.3
12	36.7	12.2	0.0	12.2	36.7		36	120.9	0.0	0.0	60.5	120.9
13	41.3	13.8	0.0	13.8	27.5		37	13.1	0.0	0.0	0.0	8.7
14	3.0	1.0	0.0	1.0	3.0		38	15.2	0.0	0.0	5.1	15.2
15	19.3	0.0	0.0	0.0	19.3		39	45.0	0.0	0.0	15.0	15.0
16	38.7	0.0	0.0	0.0	25.8		40	0.6	0.0	0.0	0.2	0.6
17	6.5	2.2	0.0	2.2	6.5		41	6.7	2.2	0.0	0.0	6.7
18	0.8	0.3	0.0	0.0	0.8		42	5.2	0.0	0.0	3.5	5.2
19	0.7	0.0	0.22	0.2	0.7		43	1.1	0.0	0.0	0.8	1.1
20	52.8	0.0	0.0	8.8	35.2		44	1.4	0.0	0.0	0.9	1.4
21	3.5	1.2	0.0	1.2	3.5		45	4.0	0.0	0.0	1.8	2.3
22	60.7	0.0	0.0	0.0	40.5		46	2.1	0.2	0.0	0.4	0.8
23	8.1	0.0	0.0	0.0	5.4		47	3.2	1.1	0.0	0.0	4.2
24	0.8	0.0	0.0	0.0	0.8		**Total km**	**988.9**	**71.3**	**1.3**	**226.8**	**766.6**
							%		**7.21**	**0.13**	**22.93**	**77.52**

2.4 Benthic Infaunal Results

Annelid worms were the most numerous in terms of number of species. However, unlike most estuaries, arthropods (crabs, shrimp, amphipods) were the most numerous taxa (Figure 3). Mollusks in the upper bays and arthropods (primarily amphipods) in the Central and South Bays were numerically dominant at most stations. Diversity varied widely with high values even in some urbanized areas. The Delta area, Suisun and San Pablo Bays, and the sloughs and the extreme southern end of the system had lower diversity than the well flushed Central and open areas in South Bay. San Francisco Bay is one of the most heavily colonized bays by invasive species in the nation, due to international shipping. The proportion of introduced species exceeds that of native species throughout the system except in the vicinity of the Central Bay where marine species dominate (Figure 4). This makes interpretation of the distribution of benthic communities difficult, as species-species interactions are in a constant state of flux. A nodal analysis of the existing communities identified five distinct communities largely along a salinity gradient (Figure 5). The Delta, Suisun Bay, and shallow flats and tributaries throughout the system had very little species overlap. The central region of the system, including the harbors made up the fourth community, with overlapping species from the shallow flats. The final community was found in the high salinity region in the vicinity of the Golden Gate. These results are largely consistent with community assessments conducted by the Regional Monitoring Program (RMP) (Thompson et al. 2012).

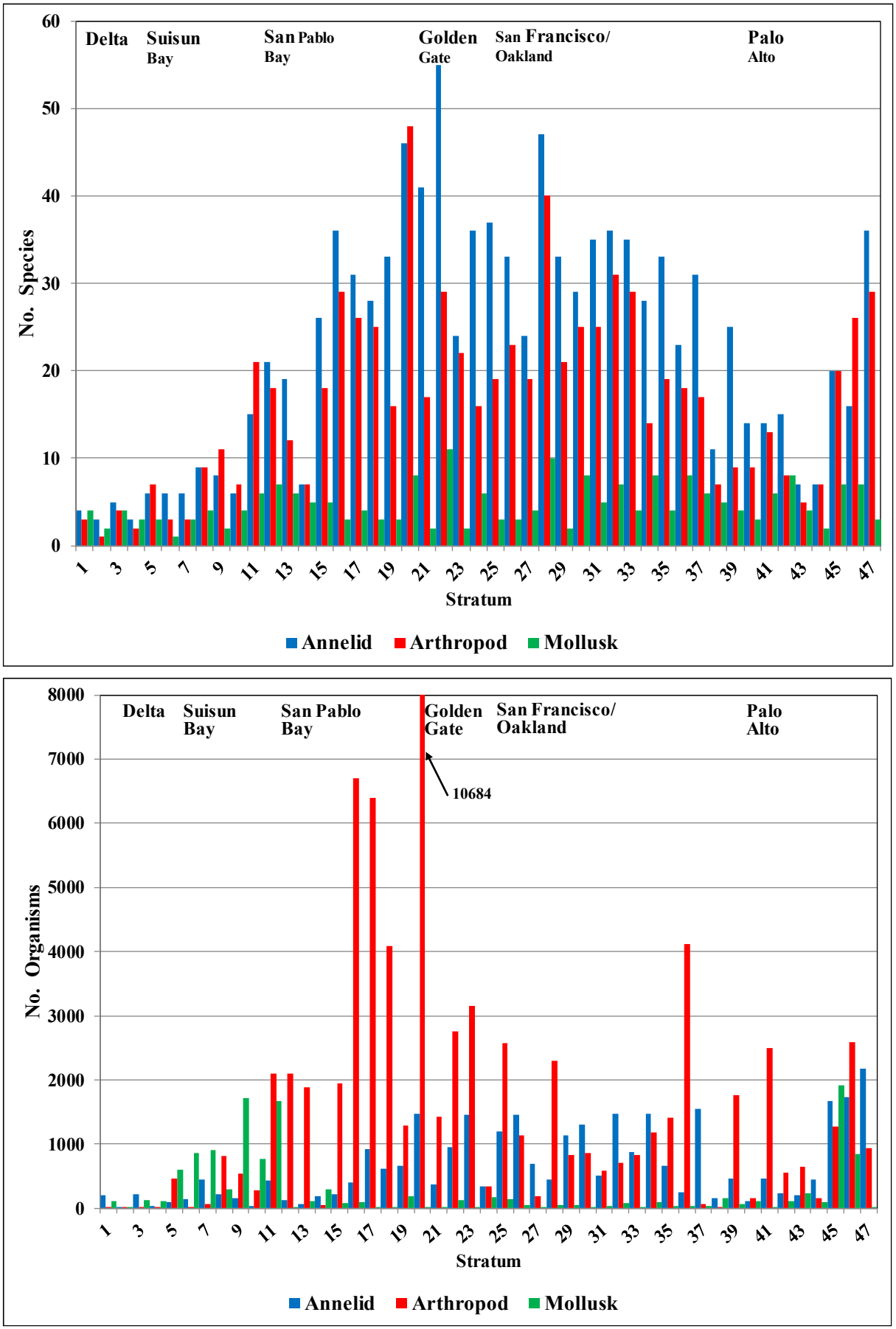


Figure 3. Number of species (top) and number of individuals (bottom) of the three dominant taxa at each station in San Francisco Bay.

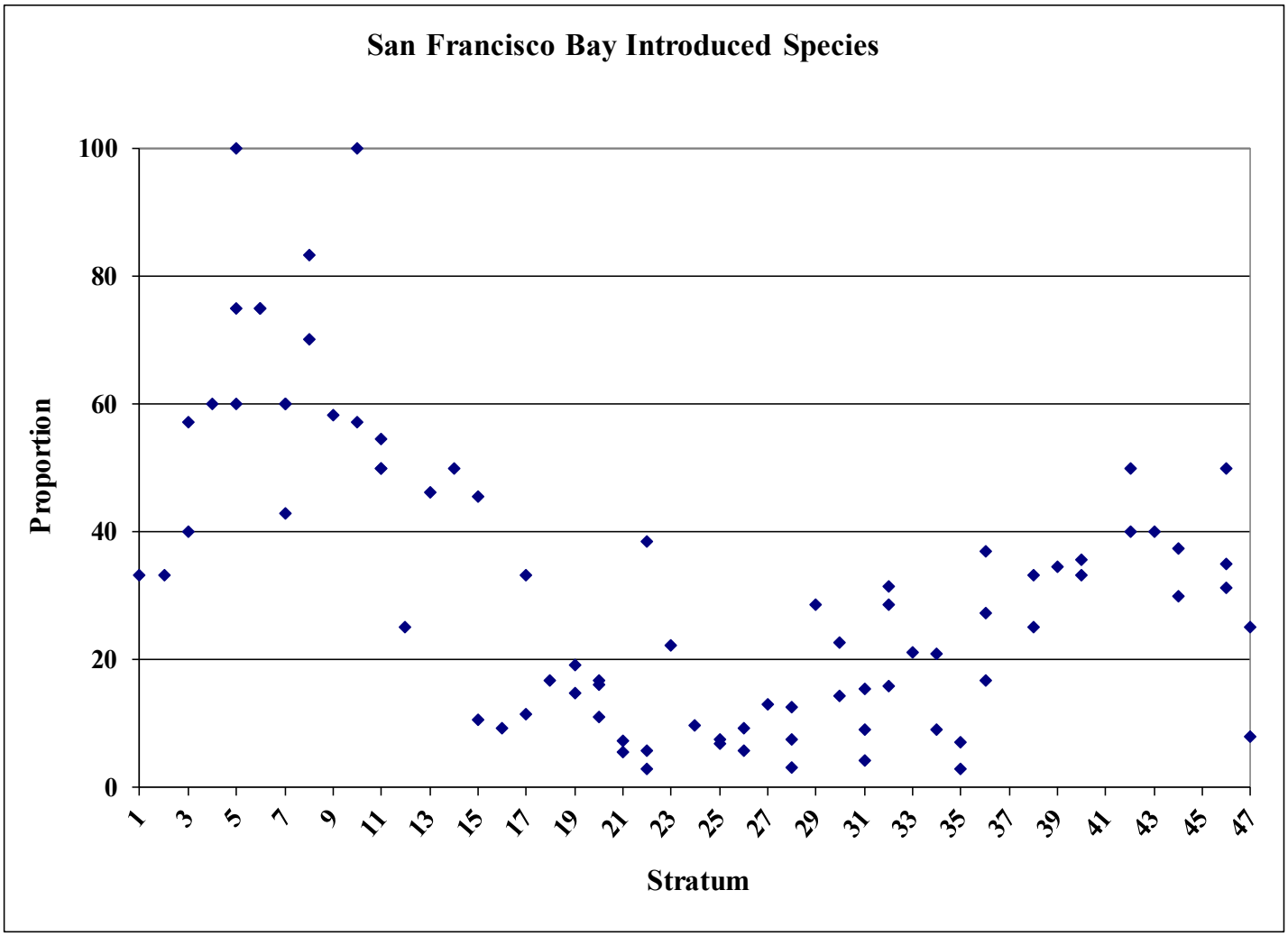


Figure 4. Proportion of introduced species in San Francisco Bay. Invasive species are more prominent in the northern and southern reaches of the Bay.

2.5 Correlations

The community attributes of species richness and diversity were significantly positively correlated with all but one of the organic contaminant groups and the P450 bioassay results. There was no correlation with metals levels. These results are a consequence of the distribution of species in response to the salinity and grain size gradients. Species richness and diversity were higher in the Central and South Bay areas, and lower in Suisun and San Pablo Bays. Contamination levels were higher in the urbanized areas of Central Bay and the muddy South Bay and lowest in Suisun and San Pablo Bays. Abundance showed a bimodal pattern with higher values in the northern Central Bay and southern South Bay and lower values in the central (urbanized) areas and Suisun and San Pablo Bays. Abundance was only correlated to log transformed PAH and negatively correlated with sea the urchin development bioassay results. Sea urchin development and the P450 bioassays were the most sensitive bioassays. The P450 assay results were positively correlated with all contaminant classes, including metals. Reduced embryo development was correlated with PAHs, PCBs, DDT and metals.

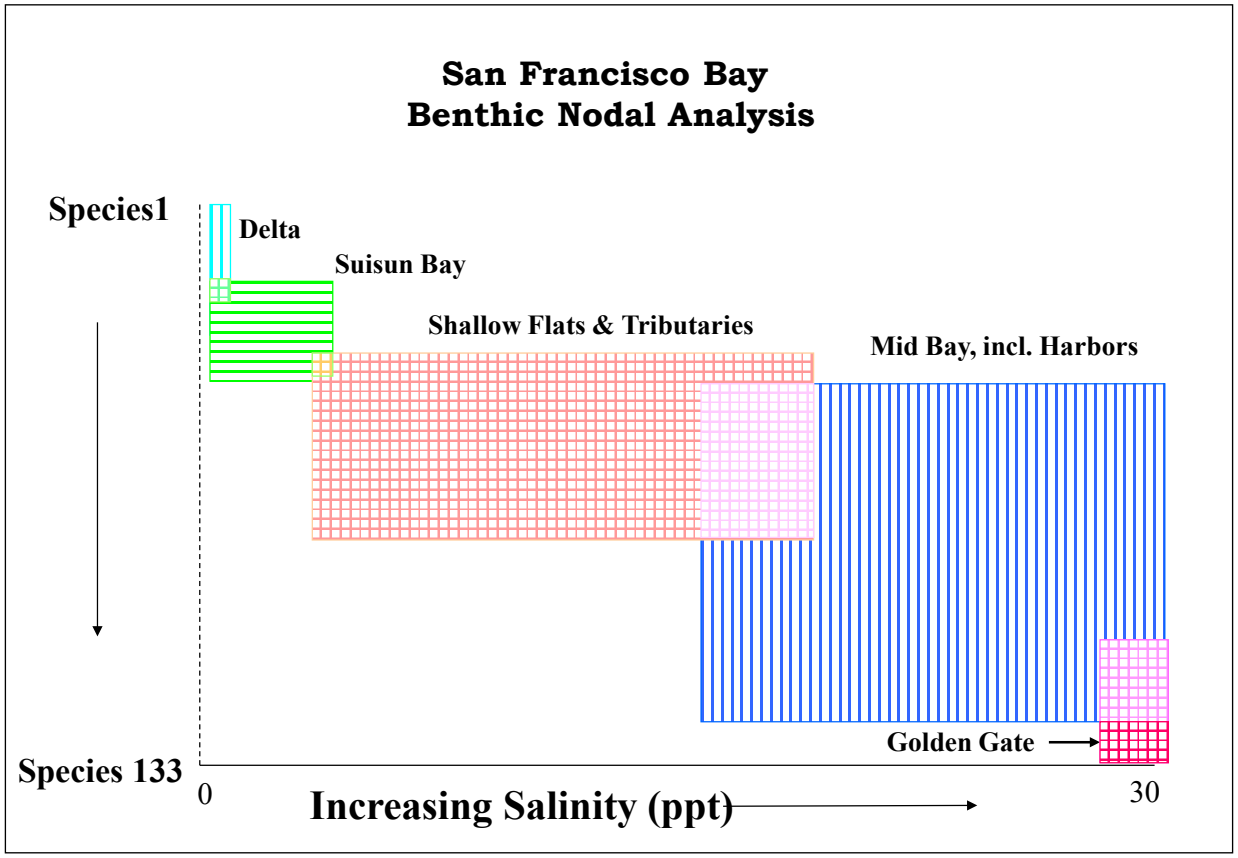


Figure 5. Five distinct communities in San Francisco Bay, with little species overlap are distributed largely along the salinity gradient.

3. SUMMARY

San Francisco Bay is one of the most heavily modified estuaries in the country. Most of the shoreline is developed. Sediment dynamics and freshwater input have gone through radical changes due to anthropogenic activities in the watershed that span over 100 years. Up to 50% of the species in the system are introduced invasive species. Low level contamination by DDT and selected metals were pervasive, but not PAHs or PCBs. However, locations with extreme values of these latter contaminants were found in specific urbanized and industrial areas. Because salinity appears to be the dominant factor in the distribution of benthic species, correlations of community attributes with contamination patterns were not statistically evident. The more sensitive bioassays do show statistical correlations with contaminant levels. According to the RMP, mercury, selenium, PCBs, and PAHs, concentrations remain of concern. Input of mercury and PCBs have declined, but large reservoirs remain in the sediments. In addition PBDEs (polybrominated diphenyl ether) and nonylphenols constitute more recent chemicals of concern and are being monitored.

Chapter 18
Puget Sound

1. STUDY AREA DESCRIPTION

Puget Sound is bounded by three major mountain ranges: the Olympics to the west, the mountains of Vancouver Island and the Coast Mountains to the northwest, and the Cascade Range to the east. The northern end of Puget Sound is open to the Strait of Juan de Fuca and the Strait of Georgia, connecting it with the Pacific Ocean. The Puget Sound Basin is glacially scoured, with depths to approximately 300 meters. It has a surface area of 2,600 km^2 and a volume of 169 km^3 (Kennish, 1998). The human population in the watershed is over four million, nearly half of which live in coastal urban centers. The catchement area of the watershed is 31,440 km^2. The Puget Sound estuary is a highly complex, biologically important ecosystem with numerous commercial and recreational uses. The Sound is surrounded by both rural and urban areas. The major urban centers include the cities of Bellingham, Everett, Seattle, Bremerton, Tacoma, and Olympia. For more than a century, Puget Sound has been a major repository of various types of wastes derived from municipal and industrial wastewater discharges, combined sewer overflows, storm drains, dumping operations, chemical spills, and urban and agricultural runoff. These wastes, which include heavy metals, PAHs, and chlorinated hydrocarbons enter Puget Sound in both dissolved and particulate phases from both direct and indirect sources from the Strait of Juan de Fuca, rivers, streams, runoff and rainwater. Freshwater enters the Puget Sound estuary via precipitation, surface runoff, groundwater inflow and various rivers.

Sampling details

Sediments from 300 locations in Puget Sound were tested to determine their relative chemical and toxicological characteristics, and benthic infauna during 1997-1999 (Figure 1). One hundred sediment samples were collected each from northern, central and southern Puget Sound in sequential sampling years. Information available for southern Strait of Georgia, the San Juan Islands, Rosario Strait, Haro Strait, Deception Pass, and eastern Strait of Juan de Fuca indicated they were not likely to be contaminated or they were not depositional areas. Therefore, they were excluded from the study area. A battery of four toxicity tests was performed on all samples. These included an acute bioassay of marine amphipods exposed to solid phase sediments. The toxicity of sediment pore waters was determined with a test of sea urchin fertilization success. A microbial bioluminescence test of metabolic activity and a cytochrome P450 HRGS activity test were conducted in organic solvent extracts of the sediment. Resident benthic infauna were collected to determine the relative abundance, taxa richness, taxa composition, and other characteristics of the invertebrate assemblages present in the sediments at each site.

2. RESULTS

2.1 Important Physical Drivers

Circulation patterns in Puget Sound are driven largely by freshwater inputs (e.g. Fraser River), tides, oceanic processes, and winds. The water circulation of Puget Sound is primarily tidal. The outflow of Puget Sound is primarily river fed surface fresh water, with the inflow of oceanic saltwater along the bottom. Puget Sound is characterized by a two layered estuarine system with marine waters entering the Sound through the Strait

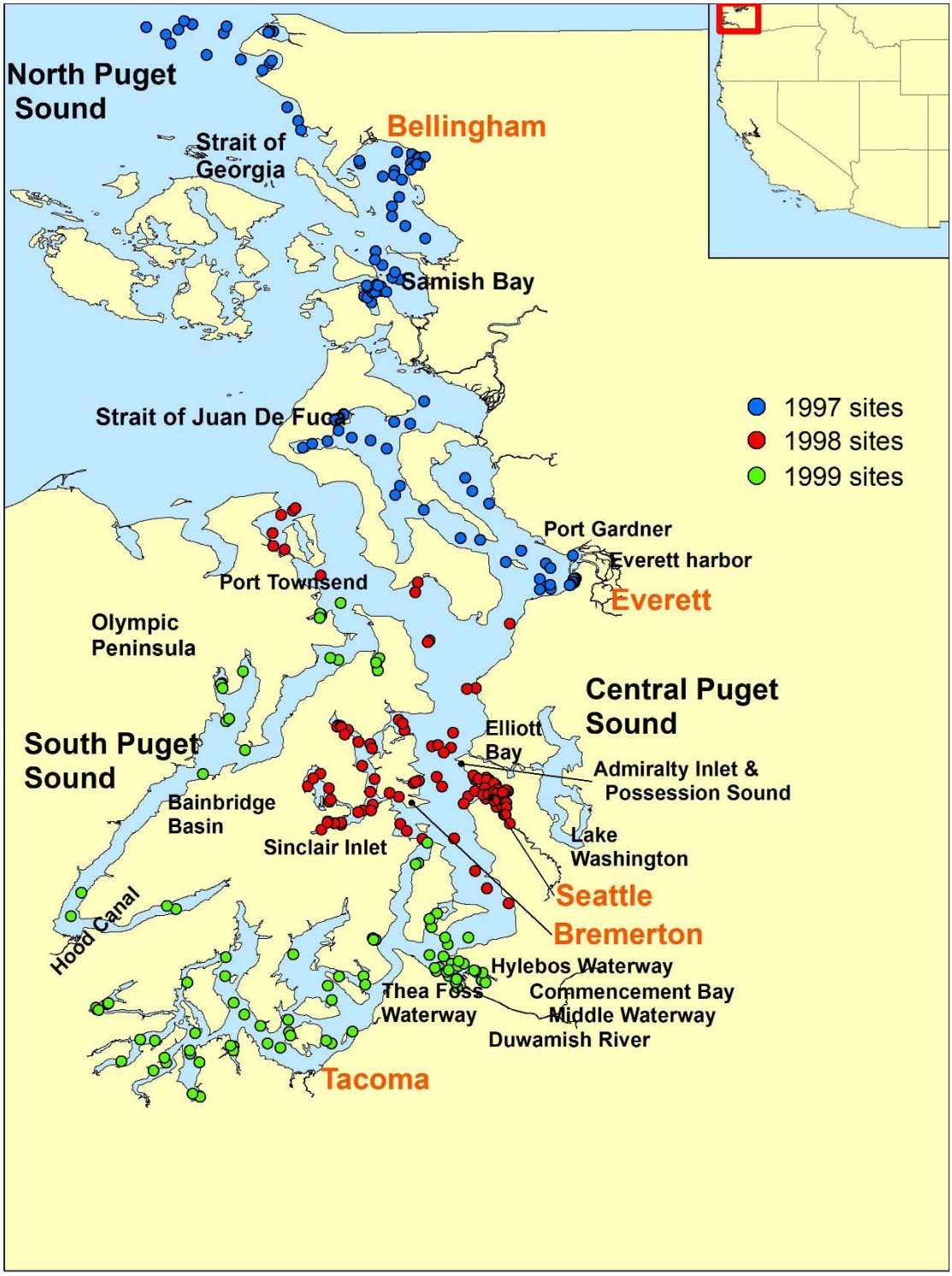


Figure 1. Map of sampling locations per year. First year blue, second year red, and third year green dots.

of Juan de Fuca at depths of 100 to 200 m with net surface outflow of fresher water. The mean residence time for water in the central basin is approximately 120-140 days, but is much longer in isolated inlets and in restricted, deep basins (Kennish, 1998). The bottom sediments of Puget Sound are composed primarily of compact, glacially formed clay layers and relict glacial tills. Greater than 80% of the sites from northern Puget Sound had silt-clay sediments, whereas 32% of the central Sound and 24% of the southern sampling regions had silt-clay sediments.

Values for TOC in the northern Sound ranged between 0.13% - 9.91%, with a mean of 1.90%. The central Sound had a range 0.1% to 4.2% and a mean of 1.4%. The southern Sound had a range of 0.06% to 7.9% with a mean of 1.8%. Salinity values from the northern sites ranged between 14 - 32 ppt, with a mean of 25.2 ppt. The Central Sound salinity varied between 25-34 ppt, with a mean of 30.5ppt and the south Sound ranged from 23-32ppt, with a mean of 29.1ppt.

2.2 Contamination Results

The surficial area in which chemical concentrations exceeded numerical guidelines (Long et al., 1995) for the northern portion of the study area, was very small for most substances. Central Puget Sound had the highest chemical contaminant concentrations in samples collected in the urbanized bays, namely Elliott Bay (Seattle) and Sinclair Inlet (Bremerton). Often, these samples contained chemicals at concentrations previously observed to be associated with acute toxicity and other biological effects. Concentrations generally decreased steadily away from these two bays and were lowest in Admiralty Inlet, Possession Sound, Rich Passage, Bainbridge Basin, and most of the central basin.

In Southern Puget Sound twenty of the 100 samples collected had one or more chemical concentrations that exceeded applicable NOAA guidelines and/or Washington state criteria. Among these samples, chemical contamination was highest in eight samples collected in or near the industrialized waterways of Commencement Bay (Tacoma). Samples from the Thea Foss and Middle Waterways were primarily contaminated with a mixture of PAHs and trace metals, whereas those from Hylebos Waterway were contaminated with chlorinated organic hydrocarbons. The remaining 12 samples with elevated chemical concentrations had high levels of other chemicals, including bis(2-ethylhexyl) phthalate, benzoic acid, benzyl alcohol, and phenol. There was a distinct spatial pattern in contamination in Commencement Bay (i.e. high concentrations in the waterways that diminished rapidly into the outer reaches of the bay).

2.3 Toxicity Results

Cytochrome P450 HRGS assay results for northern Puget Sound indicated a clear pattern of highest toxic response in sediments from Everett Harbor. Enzyme induction was highly correlated with the presence of mixtures of organic substances, primarily PAHs. However, there was evidence in samples from Everett Harbor of the presence of dioxins and furans.

In the central bay, highly significant toxic responses in the sea urchin, Microtox^{R} and cytochrome P450 HRGS tests were observed in the inner strata of Elliott Bay and the lower Duwamish River. Toxicity in these tests decreased considerably westward into the outer and deeper regions of the bay. Many of the samples from the Liberty Bay and Bainbridge basin area were toxic in the Microtox^{R} and cytochrome P450 HRGS assays. The degree of toxicity decreased steadily southward down the Bainbridge basin to Rich Passage, where the sediments were among the least toxic. Samples from two stations located in a small inlet off Port Washington Narrows in Bremerton were among the most toxic in two or more tests. Several samples from stations scattered within Sinclair Inlet indicated moderately toxic conditions; toxicity diminished steadily eastward into Rich

Passage. Finally, samples from Port Townsend, southern Admiralty Inlet, and much of the central main basin were among the least toxic. However, there was significant variability in some of the apparent correlations, including samples in which chemical concentrations were elevated and no toxicity was observed. Therefore, it is most likely that the chemical mixtures causing toxicity differed among the different toxicity tests and among the regions of the survey area.

Most obvious toxicity for the Southern Puget Sound were in some of the industrialized waterways of Commencement Bay at Tacoma. The responses in the samples analyzed by the human reporter gene system (cytochrome P450) from Thea Foss Waterway, was the highest found (356 ug/g to 1,995 ug/g BaP eq.), where Middle Waterway and Hylebos Waterway were also found to be very toxic, with all Cytochrome P450 analyses exceeding 37.1 ug/g BaP eq. Significant responses were also observed in both the amphipod and sea urchin tests in one of the samples.

The causes of toxicity were not determined in this study. However, the weight of evidence strongly suggests that the samples from Everett Harbor had the highest chemical concentrations and the highest degree of toxicity, and, therefore, contributed substantially to the overall chemical/toxicological associations that were observed.

2.4 Benthic Infaunal Results

The northern Puget Sound stations had a wide range of infaunal parameters that could be attributed to naturally occurring environmental variables, suggesting strong evidence against pollution-induced degradation at most stations. Total abundance of benthic infauna ranged over two to four orders of magnitude among stations and taxa. However, sediments from Everett Harbor stations often were devoid of mollusks and/or echinoderms, had low species richness, and were dominated by polychaete worms, suggestive of pollution impacts.

Indices of the relative abundance and diversity of the benthic infauna for Central Puget Sound had very wide ranges in results attributed to large differences in depth, sediment texture, organic carbon content, proximity to rivers, and other natural habitat-related factors. Also, the relationships between measures of benthic structure and chemical concentrations were similarly variable.

Southern Puget Sound infaunal results were similar to those from the north and central Puget Sound, varying widely in different locations and habitat types. Polychaetes were typically the most abundant taxa group followed by arthropods, mollusks, and echinoderms. In general, many of the small embayments and inlets throughout the study area had infaunal assemblages with relatively low total abundance, taxa richness, evenness, and dominance values. Two samples collected in the Port of Olympia near a superfund cleanup site had no living organisms in them. In some of the small urban/industrial embayments, however, cases were found where total abundance values were very high, typically due to high abundance of opportunistic species. The majority of the samples collected from passages, outer embayments, and larger bodies of water tended to have infaunal assemblages with high total abundance, taxa richness, evenness, and dominance values.

2.5 Correlations

Northern Puget Sound. Correlation analyses between infaunal indices, sediment toxicity and chemistry indicated inverse relationships between taxa richness and mollusk abundance and percent fines, percent TOC, and chemical concentrations. There was no single chemical or group that was uniquely correlated with the benthic indices. Rather, the concentrations of many trace metals, PAHs, PCBs, appeared to co-vary with each other and with the benthic indices. These observations were similar to those made with the correlations between measures of toxicity and chemical concentrations; that is, indicative of the presence of complex mixtures of chemicals in samples that were toxic. Only a small portion (18 out of 100) of the stations sampled displayed significant results from both the toxicity and chemistry analyses, and of these, only the nine Everett Harbor stations also displayed infaunal community characteristics that suggested strong evidence for pollution-induced degradation. In contrast, 16 of the 100 stations, scattered throughout the study area, had neither significant toxicity nor elevated chemical concentrations.

Central Puget Sound. Chemical analyses, toxicity tests, and benthic community analyses, indicated that of the 100 stations sampled, 36 had sediments with toxicity and elevated chemical contamination. Of these, 18 stations appeared to have benthic communities that were possibly affected by chemical contaminants in the sediments. They included stations in Sinclair Inlet, Dyes Inlet, Elliott Bay and the Duwamish River. In the region around Bremerton and Bainbridge Island, Dyes Inlet, Port Washington Narrows, Sinclair Inlet, Rich Passage and Liberty Bay typically had moderate to very high total abundance, including high numbers of pollution-tolerant species, moderate to high taxa richness, low evenness, and low Swartz's Dominance Index values. Pollution-sensitive species such as arthropods and echinoderms were low in abundance or absent from these stations. Twenty-five stations were identified with no indications of significant sediment toxicity or chemical contamination, and with abundant and diverse populations of benthic infauna. The remaining thirty-nine stations displayed either signs of significant chemical contamination but no toxicity, or significant toxicity, but no chemical contamination, and for the majority, the benthic populations were abundant and diverse.

Southern Puget Sound. Because there was no mortality in the amphipod tests, correlations between survival and benthic indices were not significant. The abundance of arthropods and taxa were weakly correlated with sea urchin fertilization, indicating a slight pattern of declining abundance as fertilization success decreased. Both Microtox^{R} and HRGS assays, showed strong correlations with indices of evenness and dominance that were highly significant. Eleven stations were found to have elevated sediment toxicity, chemical contamination, and degraded benthic community. Typically, these stations were shallow, represented a small area, were primarily located in major urban areas, with relatively fine grain sediment and high TOC values. Infaunal assemblages typically had higher total abundance (usually due to one or two opportunistic species), moderate taxa richness and evenness, and were dominated by annelids, followed by mollusks, arthropods, echinoderms, and miscellaneous taxa. The number of stations displaying degraded sediments based upon the sediment quality triad was slightly greater in the central Puget Sound than in the northern and southern Puget Sound study areas.

In summary, sediments from inner Everett Harbor and Bellingham Bay were generally the most toxic. A sediment quality index category (Table 1) was produced from the chemistry, toxicity, and benthic infauna parameters. High quality sediments were defined as having acceptable results of all three parameters. Intermediate high quality sediments were defined as having one parameter outside of the acceptable range. Intermediate degraded sediments were those with two unacceptable parameters. Sediments considered poor quality (e.g. degraded) were those with all three parameters unacceptable.

3. SUMMARY

While the spatial extent of contamination varied considerably among chemicals, less than 2% of the area of Puget Sound was considered "contaminated" for most substances. Collectively, the data from the chemical analyses, toxicity tests, and benthic analyses indicated that sediment quality outside of urbanized areas was very good. Most indices of sediment quality indicated that less than 5% of the area was either highly toxic or contaminated.

Table 1. Sediment quality index.

Sediment Quality Index Category (number of parameters impaired /station)	No. (%) of stations		km^2	(%) of total study area
1997 Northern Puget Sound	**100**	**(100.0)**	**773.9**	**(100.0)**
High (0)	26	(26.0)	211.9	(27.4)
Intermediate/High (1)	52	(52.0)	516.2	(66.7)
Intermediate/Degraded (2)	12	(12.0)	35.5	(4.6)
Degraded (3)	10	(10.0)	10.3	(1.3)
1998 Central Puget Sound	**100**	**(100.0)**	**731.7**	**(100.0)**
High (0)	2	(2.0)	59.5	(8.1)
Intermediate/High (1)	38	(38.0)	436.1	(59.6)
Intermediate/Degraded (2)	39	(39.0)	215.7	(29.5)
Degraded (3)	21	(21.0)	20.4	(2.8)
1999 Southern Puget Sound	**100**	**(100.0)**	**857.7**	**(100.0)**
High (0)	36	(36.0)	493.5	(57.5)
Intermediate/High (1)	35	(35.0)	274.1	(32.0)
Intermediate/Degraded (2)	18	(18.0)	85.7	(10.0)
Degraded (3)	11	(11.0)	4.4	(0.5)
Total Study Area	**300**	**(100.0)**	**2363.3**	**(100.0)**
High (0)	64	(21.3)	764.9	(32.4)
Intermediate/High (1)	125	(41.7)	1226.4	(51.9)
Intermediate/Degraded (2)	69	(23.0)	336.8	(14.3)
Degraded (3)	42	(14.0)	35.1	(1.5)

High - (no parameter impaired)
Intermediate/High - (one parameter impaired chemistry, toxicity, or benthos)
Intermediate/Degraded - (two parameters impaired chemistry, toxicity, or benthos)
Degraded - (three parameters impaired chemistry, toxicity, or benthos)

The chemistry-toxicity relationships were also most apparent among the samples from Everett Harbor. Samples from Everett Harbor that indicated highest toxicity in the Cytochrome P450 HRGS, Microtox^{R} and sea urchin tests also had high concentrations of PAHs, other organics, and several trace metals. The infauna in sediments from Everett Harbor stations often were devoid of mollusks and/or echinoderms, had lower species richness compared to other samples, and were dominated by annelids. It was apparent that the statistical associations observed throughout the study area were driven in large part by the data from Everett Harbor.

The geographical focus of previous studies was primarily in central Puget Sound. These historic studies were to determine if potentially toxic substances occurred in Puget Sound, to identify where they occurred, and to measure their adverse biological effects. The sediments from Everett Harbor demonstrated greater toxicity than those from Bellingham Bay, and samples from Samish Bay were the least toxic. A study conducted in 1986 by PTI for the U.S. EPA focused on Everett Harbor (PTI, 1989). This study found that the benthic communities at the inner harbor stations had significantly lower total abundance, species richness, and a higher incidence of pollution-tolerant species than the outer harbor and control stations. Washington's Department of Ecology, Puget Sound Ecology Sediment Management Unit has compiled a database that includes sediment data from over 400 Puget Sound sediment surveys of various sizes and scopes. The Sediment Quality Information Management System (SEDQUAL), studies (Striplin Environmental Associates, 2003) showed that elevated concentrations of contaminants usually occurred near population centers, urban areas and ports such as Bellingham, Everett, and Port Gardner. The majority of the sediment samples in which toxicant concentrations exceeded Washington State Sediment Quality Standards (SQS) in northern Puget Sound were collected in Bellingham Bay and Everett Harbor and Samish Bay as well as areas near Anacortes. Trace elements such as arsenic, copper, mercury and lead, as well as PAHs, were among the toxic chemicals found in higher concentrations in the SEDQUAL database for Bellingham Bay. Concentrations of mercury, cadmium, copper, low and high molecular weight PAHs, and dibenzofuran have often exceeded the Washington State SQS values in previous studies.

Chapter 19
Kachemak Bay

1. STUDY AREA DESCRIPTION

Kachemak Bay is a 64 km long glacial fjord on the east side of lower Cook Inlet, located in south central Alaska. At the mouth, Kachemak Bay is nearly 40 km wide, but narrows to 10-11 km at Homer Spit, which cuts the Bay into inner and outer portions. The inner portion of the Bay, behind the spit, is approximately 32 km long. The north shore of inner Kachemak Bay is mostly tidal flats below sandy bluffs, with numerous coal seams. The south shore has numerous smaller fjords and embayments cut into steep terrain that rises to glaciated valleys and mountain peaks on the Kenai Peninsula. Except for the Jakolof Trench running along its southern edge, inner Kachemak Bay has a relatively flat bottom and averages 46 m in depth. Glaciers have covered and retreated from Kachemak Bay repeatedly over the past 25,000 years. Homer Spit, and the Archimandritof Shoals to the west, may be the remnants of terminal glacial moraines.

Kachemak Bay has a complex water circulation pattern, fueled by the intrusion of saline water from the Gulf of Alaska. Freshwater input from rivers, glacial melt water, and precipitation, maintain a slightly brackish water mass. The large tides (6 m) and wind mix the fresh and salty waters and create one or two circular counterclockwise currents that tend to deposit sediment in the northern portion of the bay. This circulation pattern, coupled with the tidal exchange, help create diverse habitats, such as tidal flats, kelp beds, marshes, and eelgrass beds. The middle and south portion of the bay are relatively deep. These habitats, and the brackish water, make the bay an excellent spawning ground for marine organisms.

This nutrient rich estuarine environment sustains diverse and economically important marine life, such as fish, shrimp, crabs, and clams. Additionally, hundreds of plant and animal species inhabit the bay proper and its watershed, including thriving populations of sea otters, bald eagles, moose, black bears, salmon, Pacific halibut, and a large number of other marine organisms. The bay supports significant subsistence and commercial fishery resources and, although stocks have been declining in recent years, it is still considered one of the most productive bays in the U.S. Commercial harvests of herring, coonstripe shrimp, and king, Dungeness, and tanner crabs have been closed due to depressed stock. Studies point to impacts of natural changes and anthropogenic activities that cause pollution as the overriding causes of the depressed stock. The human population in the area is less than 10,000, including peripheral communities, such as Anchor Point and Port Graham. Through history, there have been sporadic episodes of coal and hard rock metals mining in the watershed, and large scale seafood canning operations along the shore. Some oil and contaminated hulls related to the Exxon Valdez oil spill did enter Kachemak Bay. However, the area remains remote from major sources of pollution.

Sampling Details

The study site was divided into five areas of relatively uniform habitats: Homer Harbor (HH), intertidal western mudflats (WF), and subtidal zones of Coal Bay (WS), to a depth of 10 fathoms; and intertidal eastern mudflats (EF), and subtidal zones (ES) east of Coal Bay to Chugachik Island (Figure 1). Three sites

were located in Homer Harbor, six sites were located in each stratum in Coal Bay, and seven in both of the strata between Coal Bay and Chugachik Island. In addition, three sites in the vicinity of the Native Village of Port Graham were sampled to assess that area and as a contrast to the Homer harbor area (Figure 2). Two species of amphipods were used for toxicity testing (*Eohaustorius estuarius* and *Ampelisca abdita*). Analysis of 120 organic and metalic caontaminants were conducted on each sample. Benthic infaunal were collected at each site.

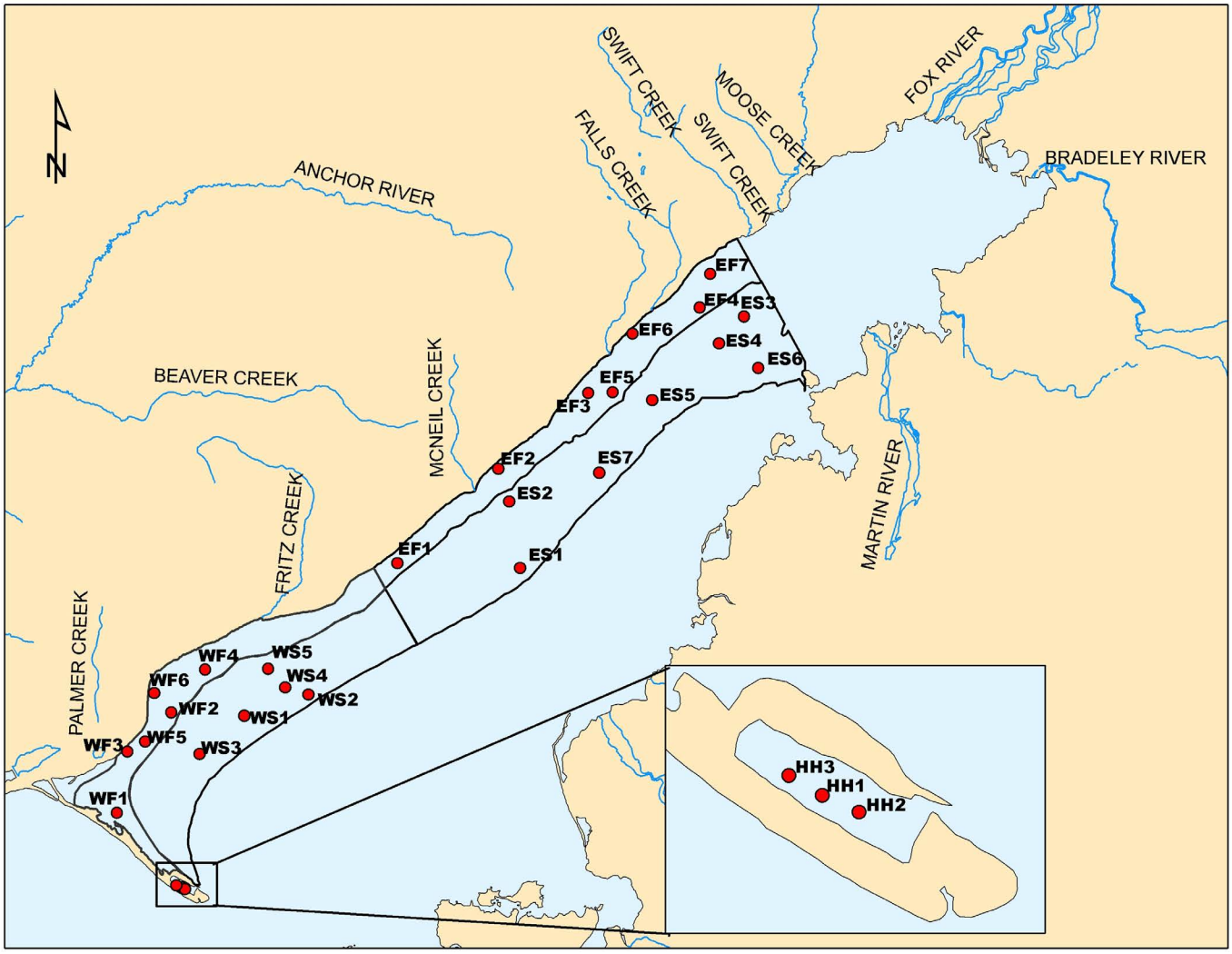


Figure 1. Sampling points in east and west strata plus Homer Harbor (inset).

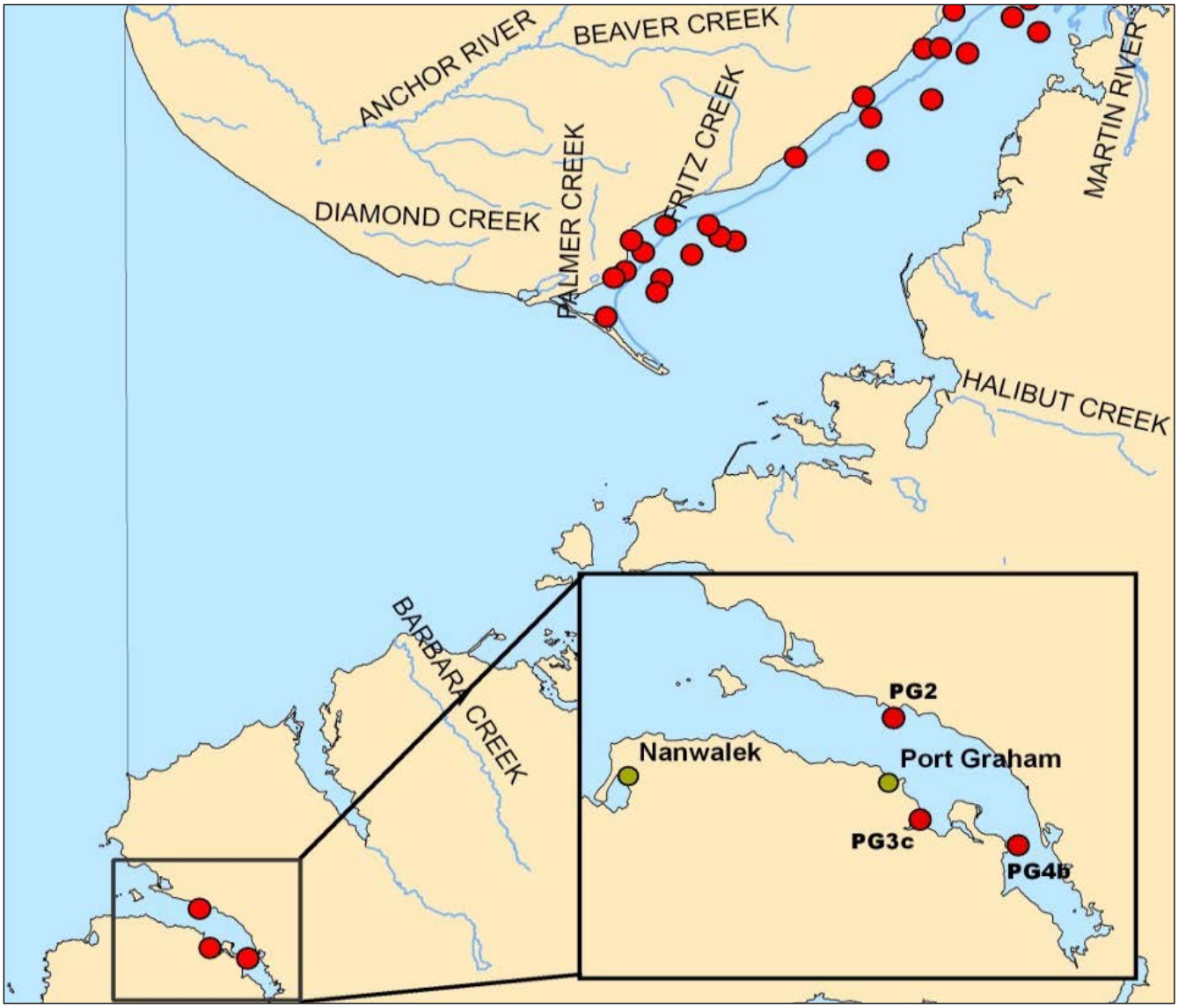


Figure 2. Relative location of Port Graham and Kachemak Bay, and Port Graham sampling points (inset).

2. RESULTS

2.1 Important physical drivers

The study area is relatively flat, with depth varying from 2.6 – 11.2 m at high tide. Past the mouth of the Fox River delta, the shelf drops directly into deep water (greater than 30 m). The water column is fairly well mixed. Only small differences in salinity, temperature, and dissolved oxygen (DO) were observed between the surface and bottom. Water clarity showed a distinct increasing gradient from east to west in the bay, reflecting the turbid inflow of glacial till transported by the Fox and Bradley Rivers (Figure 3). Data was grouped into categories using the Jenks natural breaks classification method, which clusters data into different classes that represent the minimum variation within each class and the maximum variation between classes. Both eastern and western subtidal areas have similar sediment textures of sand to sandy mud. Sediment composition in the intertidal mudflats varied from sandy silt to clayey silt in the eastern flat, and

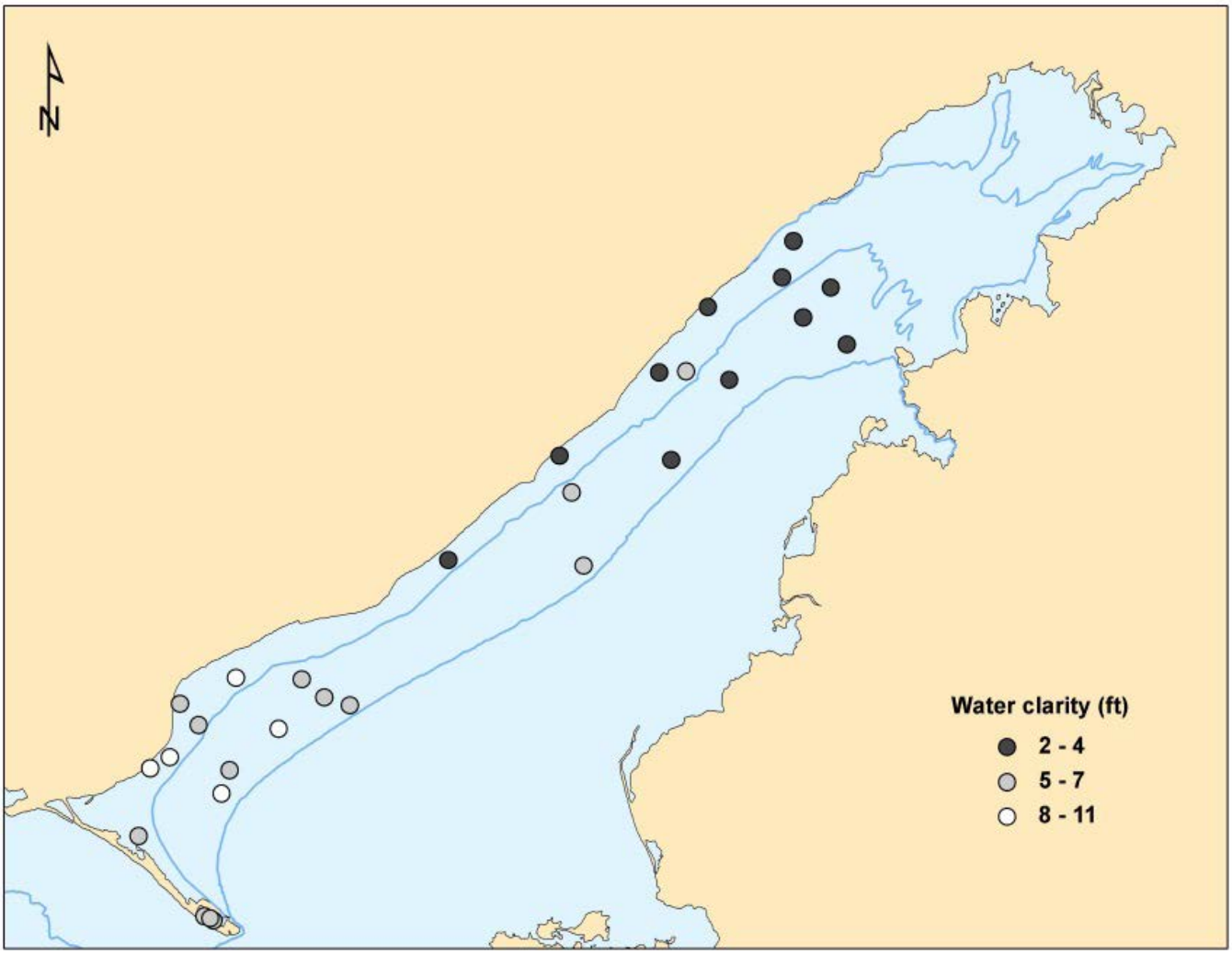


Figure 3. Spatial distribution of water clarity in Kachemak Bay as measured by Secchi disk.

from sandy mud to silty sand in the western flat (Figure 4). In the Homer Harbor area, the bottom sediment was mainly composed of fine grained mud. Total organic carbon (TOC) content demonstrated a distinctive gradient between the eastern and western areas of the study area. Sediment at Port Graham varied widely by specific location from coarse sand to very fine mud.

2.2. Contamination results

In general, trace element concentrations in Homer Harbor were elevated relative to other areas. One site in the eastern flats area showed spikes in the concentration of silver, chromium, copper, nickel, mercury, selenium, antimony, and zinc. Excluding Homer Harbor, trace elements were found to be significantly elevated in the eastern areas of the bay compared to the western areas, except for mercury. Grain size (% fine) was found to be strongly correlated with metals. Metal concentrations are elevated in finer grained sediment due to adsorption onto particle surfaces. Most of the trace element concentrations were below the ERL and ERM sediment quality guidelines. Sediment concentrations of arsenic, chromium, copper, and zinc were above the ERL in at least one area (Table 1). Mercury, and selenium were elevated 4-6 times above the Kachemak Bay average concentrations near the village of Port Graham. Chromium, selenium, and cadmium were

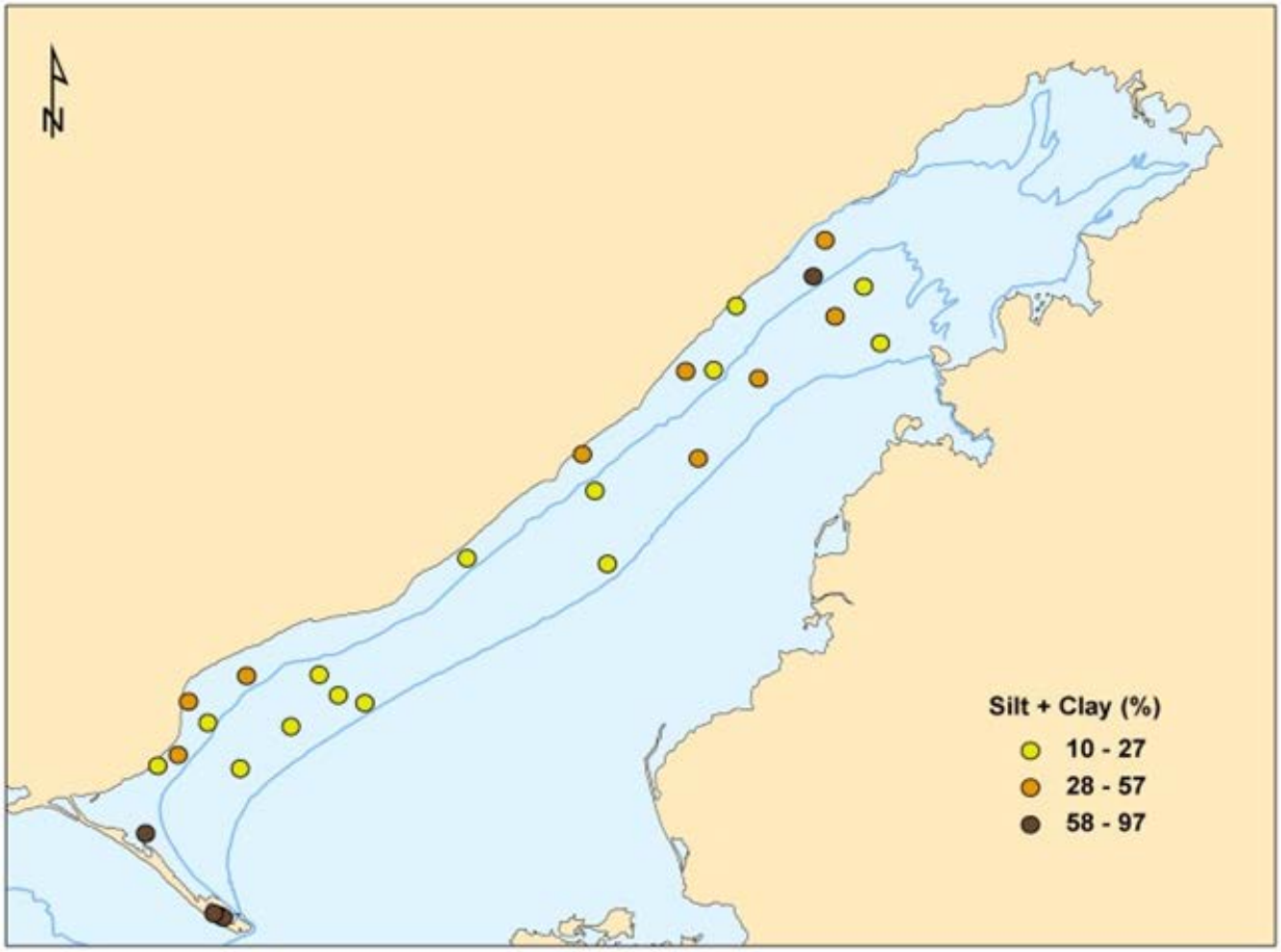


Figure 4a. Proportion of fine grained material and TOC in the sediments of Kachemak Bay.

elevated at a station located toward the head of the bay. Conversely, arsenic, antimony, and lead at all three Port Graham sites were approximately half the concentrations seen in Kachemak Bay. These differences are likely due to local geological characteristics. Nickel exceeded the ERM in one site. Every site in the study exceeded the ERL for arsenic, except one location in Port Graham. This appears to be a consequence of natural background geology, as has been observed in other regions. Copper concentrations in Homer Harbor were twice the Bay average. Metals concentrations in greater Kachemak Bay and Port Graham Bay sediments were quite different. Cadmium, and organic contami-nants were found at low levels throughout the study area.

Most of the organic compounds were nearly ten times higher in Homer Harbor relative to other areas. However, neither the ERMs nor the ERLs were exceeded in any location for any organic contaminant. In Kachemak Bay, the dominant PAH was perylene, usually accounting for 40-60% of the total PAHs. Perylene is a natural product from old plant material, as opposed to petroleum, coal, or pyrogenic pollution sources. In the harbor, elevated concentrations of pyrene and other unsubstituted high molecular weight compounds, with lower concentrations of alkylated compounds, are indicative of pyrogenic sources (burned fuel). One

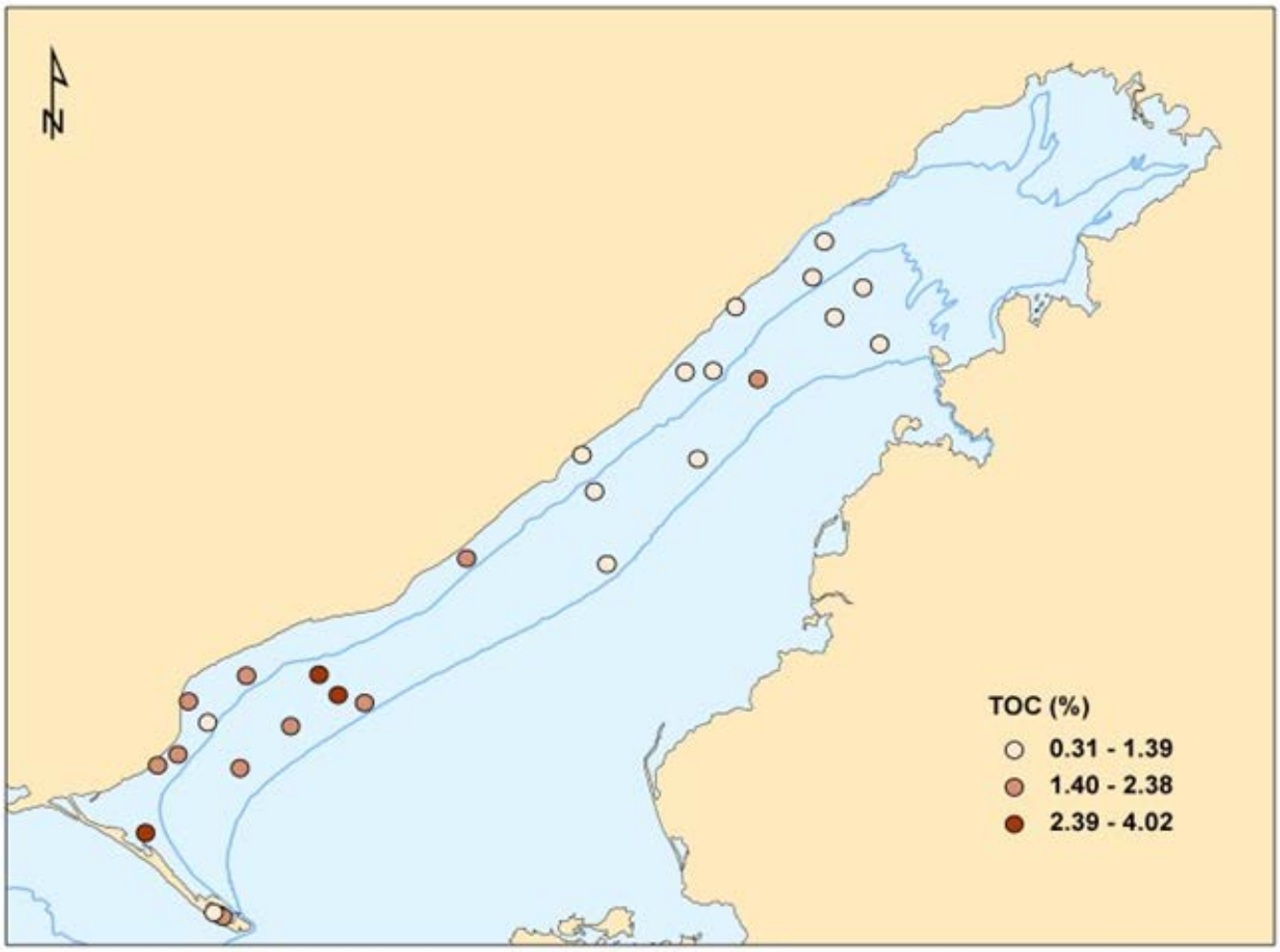


Figure 4b. Percent TOC in the sediments of Kachemak Bay.

station near the village of Port Graham had a similar distribution of PAHs as was found in Homer Harbor, with indications of contributions from fuel and combustion by-products. The single station in Port Graham where PAHs were elevated also had elevated PCBs relative to the other stations, but was below the levels in Homer Harbor. Hexachlorocyclohexanes (HCHs), which were present in subtidal and mudflat areas, were not detected in the Harbor. Homer Harbor and Millers Landing had elevated PCB concentrations relative to the rest of the Bay. Overall, PCB concentrations in the study area are very low, and even in Homer Harbor they are well below sediment quality guidelines. Chlorinated insecticides were also found at most sites in the study area, but concentrations were very low. Concentrations of DDTs were primarily composed of DDT metabolites, indicating old material, transported in from distant sources. The distribution of total DDTs was similar to that of the PAHs, and was significantly correlated with high sediment TOC. Total DDTs were well below the NOAA ERL value. Butyltins were above detection limits only in Homer Harbor.

2.3 Toxicity Results

In general, no highly significant toxicity was observed in any of the areas, including Homer Harbor. Bioassays with the more sensitive amphipod species (*Eohaustorius estuarius*) demonstrated significant toxicity at one station near the Fox River (Table 2). The site had extremely fine grained muddy sediment, but also

elevated metals concentrations. The other species demonstrated significantly reduced survival at only one station in Coal Bay. While survival was statistically reduced relative to controls, it was above 80% and is therefore considered to be an indicator of only marginal effect. Sediment toxicity tests at Port Graham showed significant toxicity results only with *Ampelisca abdita*, at station PG3c. Survival was reduced to 68.8%. All the other tests resulted in survival rates of 90% or more.

Table 1 Spatial extent (km^2) of area where ERL or ERMs were exceeded in 6 strata in Kachemak Bay sediments.

Stratum	Total Area	ERL area	ERM area
Eastern Subtidal	41	41	0
Western Subtidal	21	21	0
Eastern Flats	15	15	2.1
Western Flats	14	14	0
Homer Harbor	0.25	0.25	0
Port Graham	8	8	0
Total km^2	**99.25**	**99.25**	**2.1**
%		**100.0**	**2.2**

2.4 Benthic Infaunal Results

Polychaete worms had the highest number of taxa at every station, and were the most numerous at all but four stations. Clams were the next most abundant taxa. Snails and crustaceans were more numerous and diverse in the western stations. Benthic community analysis indicates the primary influences on community distributions are depth and proximity to the outflow from the Fox and Bradley Rivers. Stressed sites were characterized by low diversity and abundance. There were stressed sites on the shoreline that were exposed for many more hours per day than they were submerged (Figure 5). There were stressed sites in the east end of the bay and one in Homer Harbor. The sites in the east were impacted by the high sediment loads from glacial melt water. The Homer Harbor site had very fine grained mud which was dominated by one species. The remaining intertidal and subtidal habitats each contained distinct species assemblages that segregate themselves into turbid and clear water habitats. All sites were characterized by the presence of a small number of dominant species, and a much larger number of less numerous taxa. This study did not assess deeper areas of Kachemak Bay. Beyond the 10 fathom isobaths, the bottom drops off to a deeper basin.

Table 2 Spatial extent (km^2) of areas where bioassays demonstrated toxicity in 6 strata in Kachemak Bay sediments, as estimated by laboratory bioassay tests.

Stratum	Total Area	*A. abdita* Mortality	*E. estuarius* Mortality
Eastern Subtidal	41	0	0
Western Subtidal	21	0	0
Eastern Flats	15	0	2.1
Western Flats	14	0	0
Homer Harbor	0.25	0	0
Port Graham	8	2.7	0
Total km^2	**99.25**	**2.7**	**2.1**
%		**2.7**	**2.2**

Samples taken in deeper water in a separate study in 2008 revealed a more diverse community than what was found on the shelf, but with little species overlap between the two habitats. Sampling in 2009 on the south shore yielded a much more diverse assemblage in the bays and fjords, but again showed little species overlap with the deep central or shallow north side of the bay. Of the 239 total taxa found in Kachemak Bay, 79 were also found in Port Graham. However, 45 taxa were identified in Port Graham that were not seen in the larger bay. None of the Port Graham

stations were intertidal, so that portion of the community was largely missing. In addition, the species in deep sandy habitats found in the larger bay were absent in Port Graham. Port Graham station PG3c was particularly depauperate in diversity. The sediments were organically enriched and anoxic. Samples were also taken at Port Graham to assess the presence of *Clostridium perfringens* in the sediment, as an indicator of possible sewage contamination. *C. perfringens* counts were elevated at station PG3c relative to the other stations. Sediment quality guidelines for *C. perfringens* do not currently exist. While the value at station PG3c is well below what might be expected in the proximity of a sewage outfall, it is elevated relative to the other stations, indicating that conditions favor propagation of pathogenic bacteria.

2.5 Correlations

The biological community attributes showed no significant correlations with any of the contaminant indices except for DDT. Number of species, diversity, and abundance were all positively correlated with DDT, indicating a spurious relationship confounded by organisms' response to TOC. The Homer Harbor sites were all positively correlated with all the contaminants. Community attributes were generally negatively correlated with the eastern strata, and positively correlated with the western strata, which reflects the stressful influence of the glacial runoff in the east.

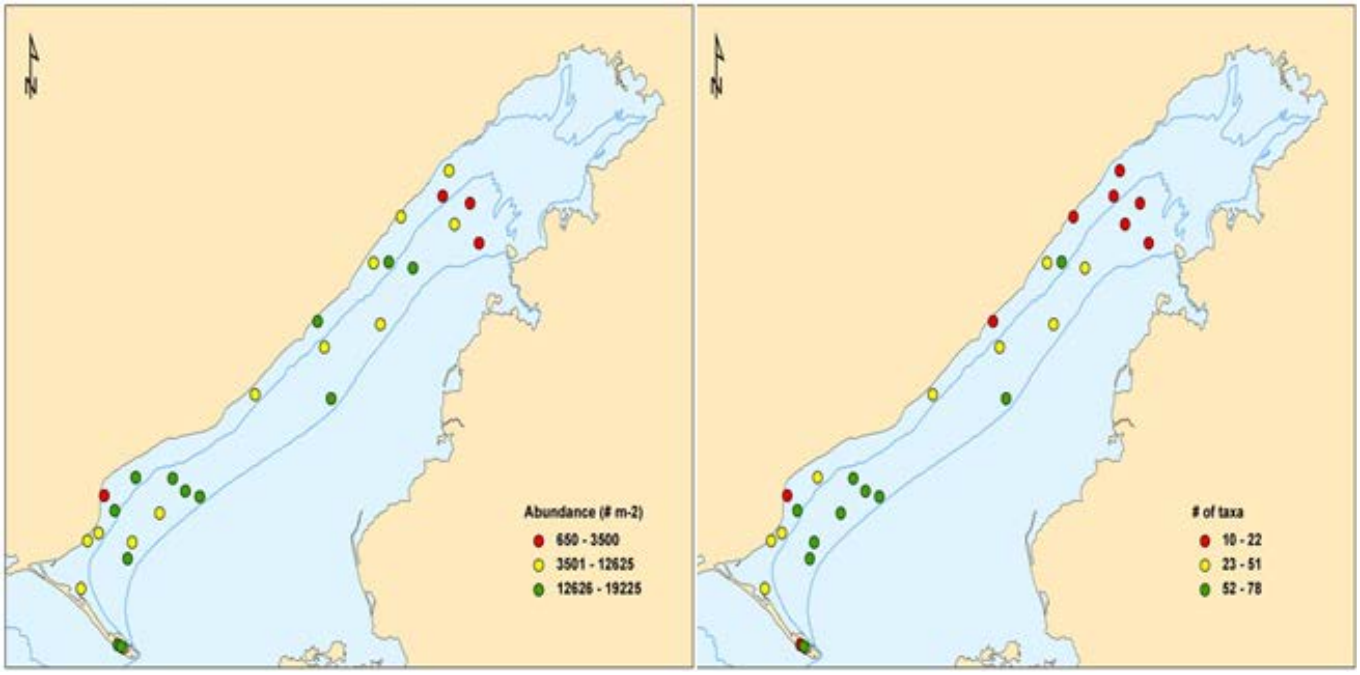


Figure 5. Abundance of animals and number of taxa living in the sediments in Kachemak Bay.

3. SUMMARY

Sediments were mostly mixed silt and sand, with pockets of muddy zones. Organic compounds (PAHs, DDTs, PCBs, chlorinated pesticides) were detected throughout the bay, but at relatively low concentrations. With some exceptions, metals concentrations were relatively low and probably reflect the input of glacial

runoff. Homer Harbor had elevated concentrations of metallic and organic contaminants that were five to ten times higher than in the open bay sites. This indicates that point and non-point controls would be useful in the immediate vicinity, while concentrations are still relatively low. Tributyltin was detected in trace amounts only in Homer Harbor. There was no evidence of residual PAHs attributable to historic oil spills, outside of local input in the confines of the harbor. The benthic community is very diverse. Specific community assemblages were distributed based on depth and water clarity. Species richness and diversity was lower in the eastern end of the bay in the vicinity of the Fox River input. Abundance was also generally lower in the eastern portion of the study area, and in the intertidal areas near Homer. The eastern portions of the bay are stressed by the sediment load from glacial meltwater. Significant toxicity was virtually absent. The benthic fauna at Port Graham contained a significant number of species not found in Kachemak Bay. Selected metal concentrations were different (higher or lower) at Port Graham relative to Kachemak Bay, probably due to local geology. Organic contaminants were elevated at one site south of the village. These results agree with the previous EMAP findings. Data published by Saupe *et al*. (2005) also indicated that concentrations of antimony, arsenic, chromium, copper, mercury and zinc were relatively elevated in the inner Kachemak Bay.

Compared to the 1995-1997 Mussel Watch sediment data from Prince William Sound, the concentrations of metals in Kachemak Bay had similar ranges, with the exception of mercury, which was relatively elevated in Kachemak Bay. In Kachemak Bay, the source of mercury may be linked to both geological and anthropogenic sources. The Cook Inlet basin that encompasses Kachemak Bay and its watershed lies on top of large coal deposits. Coal has been mined for export and burned for electricity in the Homer region. Coal-fired power plants emit mercury, but its presence in Kachemak Bay sediments may be of an atmospheric and/or geological source.

The presence of butyltins in the harbor is due to the use of antifouling paint applied to boat hulls. The sloughing paint chips from hulls, and the slow release from the paint into the water from cleaning boat hulls, and uncontrolled runoff from power washing hulls that falls directly into the harbor, increases ambient environmental levels (Figure 6).

Figure 6. Grids used for boat hull cleaning and maintenance operations in Homer Harbor.

Chapter 9
Bristol Bay

1. STUDY AREA DESCRIPTION

Bristol Bay is the site of one of the most productive fisheries in the U.S. Its biologically diverse marine wildlife supports important subsistence and commercial fisheries. The sockeye salmon fishery in the bay is the largest in the world, as well as strong runs of chum, coho, pink and king salmon, and herring. Two of the most productive salmon rivers flow into Nushagak and Kvichak Bays (Figure 1). The fishery resources and the commercial fishing and seafood processing industries are the backbone of the regional economy and integral to many residents' livelihoods and way of life in outlying villages. The population in the three boroughs surrounding the bay is approximately 7,000 people. Half live in the vicinity of Dillingham, Naknek and King Salmon. The rest are spread out over 40,000 square miles in small villages. Winter conditions last about seven to nine months out of the year. During the summer fishing season, the human population in the region swells by thousands for recreational and commercial fishing. Access to the region is only by air or water as there are no roads that lead to the outside world from either Dillingham or Naknek.

Significant features of the Nushagak and Kvichak Bays that impact habitat patterns include multiple deep channels, multiple tributaries, an extreme tidal range of 20+ feet, freshwater inflow from rivers, and saltwater inflow from the Bering Sea from the south. Large fresh water flows from the tributaries render the estuaries to be low salinity systems. Counterclockwise circulation within Bristol Bay also delivers seawater diluted by the Egegik and Ugashik rivers further south. The upper portions of Nushagak and Kvichak Bays are highly turbid from eroding cliffs of loess soil deposits in the tidal areas, which suppresses benthic diversity.

The land area draining to Nushagak and Kvichak Bays consists of four major watersheds, the Wood, Nushagak, Kvichak, and Naknek, The Nushagak and Kvichak watersheds encompass approximately 50% of the total watersheds. The watersheds are bordered to the west by the Ahklun Mountains and to the east and south by the Alaska and Aleutian Ranges. There are active volcanoes on the Alaska Peninsula and the Aleutian archipelago to the southwest. These periodically contribute volcanic ash to the system, and have produced tsunamis that impact the region. These watersheds contain over 54,000 km of streams (Johnson and Blanche 2012). Lakes cover a relatively high proportion of the watershed area. With very few exceptions, all major lakes in the watershed are accessible to anadromous salmon (EPA, 2014).

There are no known industrial point source discharges in Nushagak or Kvichak Bays. However, there are a variety of permitted waste discharges from fish processing plants at Dillingham, Ekuk, and Naknek, plus Egegik just south of the study area. In addition, floating fish processing plants anchor outside of Naknek and in the Nushagak at Clarks Point during the salmon run. These plants operate seasonally producing large volume effluents containing fish waste and process water. Other sources of pollution to Nushagak and Kvichak Bay may include leaking septic tanks, marine activities associated with commercial and recreational fishing, commercial shipping, stormwater runoff, and long-range atmospheric transport. There are no sewage pumpout facilities for vessels anywhere in the region.

Despite its fishery and ecological importance, the bay and its watersheds are threatened by increasing anthropogenic activities. The projected Pebble Mine Project and other proposed mining operations in the headwaters of tributaries of the Kvichak and Nushagak Rivers constitute the most significant pollution threats to water and habitat quality in the bay. Baseline data will be essential for monitoring pollution control effectiveness in the watershed.

Figure 1. Map of the Bristol Bay area showing the towns of Dillingham, King Salmon, and Naknek, in Alaska (inset).

Sampling Details

The study area was divided into upper and lower reaches of Nushagak and Kvichak Bays, plus Dillingham Harbor and the mouth of the Naknek R. in the vicinity of the town of Naknek and the fish packing industries (Figure 2). Four sampling sites were located on a random basis within each Bay stratum and three in the much smaller strata at Dillingham and Naknek.

Field work was initiated in September 2013 but sampling was suspended due to poor weather conditions. In July 2014, sampling resumed. A total of 23 sites were sampled for sediment chemistry, benthic infauna, fecal coliform and *Clostridium perfringens* measurements. Bioassay samples were collected in Dillingham Harbor, at Naknek, and at a subset of randomly chosen sites in the open portions of Nushagak and Kvichak Bays. Bioassays included the sea urchin fertilization test and the Microtox^{R} response test. Fish were collected by trawl at Dillingham and Naknek and at 1-3 locations in two of the open-bay strata using a 3 m otter trawl. Rainbow smelt and two size classes of starry flounders were retained for body burden analyses and histological examination.

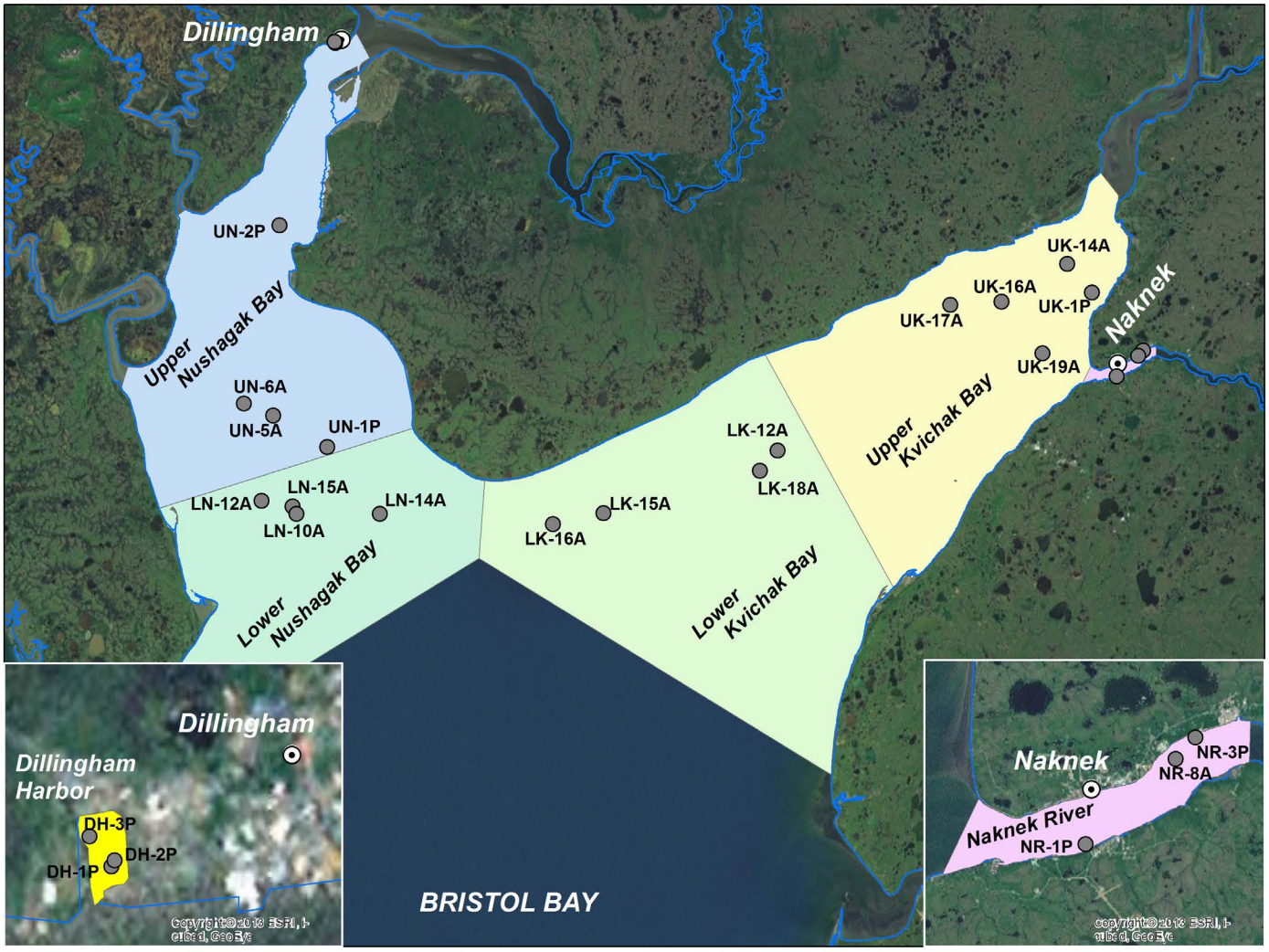


Figure 2. Map of the Bristol Bay study area showing strata and sampling site locations. The strata are DH (Dillingham Harbor), UN and LN (Upper and Lower Nushagak, respectively), UK and LK (Upper and Lower Kvichak, respectively), and NR (Naknek River). P (primary site) or A (alternate site).

2. RESULTS

2.1 Important Physical Drivers

Water clarity was uniformly low in the study area. The tidal areas are bordered by eroding cliffs of loess soil deposits. The constant input of eroded materials into the system and the extreme tidal range that continuously scours the bottom and mixes the water column keeps the turbidity high. The combination of the highly murky water and the constant erosion and deposition of silt material on the bottom of the bay system may suppress sensitive benthic species to where only tolerant communities can survive. Due to the extreme tidal range, the water column was very well mixed with measurements at the bottom and surface showing no significant differences in salinity, temperature or dissolved oxygen. The tidal stage resulted in large temporal variations in the upper portions of the tributaries where salinity increased for example, from zero to 8-10 ppt at Naknek at high tide. Salinity was more variable than other water column measures depending on tidal stage at the time of sampling. Sediment texture was mainly gravel and sand, with pockets of mud in Dillingham Harbor and in the upper stratum at the head of the Kvichak Bay. The organic carbon content in the sediment was very low. TOC values exceeded 1% at only four stations with fine grained sediment in Dillingham Harbor and at the mouth of the Kvichak River. One location in the vicinity of a fish processing plant at Naknek had slightly higher TOC than the rest of that stratum.

Figure 3. Illustration of sediment collection using stainless steel, 0.1 m2 Smith-Macintyre sediment grab sampler. (Note water turbidity.)

2.2 Contamination Results

PAHs were at higher concentrations in Dillingham Harbor than the open bays, but at very low concentrations overall, and were dominated in all samples by perylene, a natural degradation by- product from decaying vegetation. The same was true for the mouth of the Kvichak and Naknek Rivers. Differences in PAH levels between locations are likely a by-product of site specific watershed characteristics. No sample site had indications of spilled fuel, combustion by-products, or oil. For those chemicals with ERLs and ERMs, the concentrations of organic contaminants were at least an order of magnitude below the ERL levels. When considered individually or together, organic contaminants are unlikely to cause any toxic effects in the sediment.

Chlorinated pesticides, PCBs, and butyltins were either below detection limits or were found only at trace levels, and in widely separated locations. Except for Dillingham Harbor, there was only one instance where a single PCB congener was above the method detection limit (0.04 ppb). In Dillingham Harbor, the sediment contained higher levels of PCBs than other places, but still were only at trace concentrations. All concentrations, even summed concentrations, were below the one part per billion range. There was no evidence of residual PCBs from a 2011 spill of PCB contaminated soil from a clean-up site at Port Heiden. Total PCB concentrations were more than two orders of magnitude below the ERL.

Concentrations of major and trace elements in sediment from the study area were generally low except for arsenic. Relative to the other strata, most of the metals in Dillingham Harbor were elevated although some spikes were recorded at isolated sites in the Upper Kvichak and Nushagak strata due to the prevalence of fine-grained sediment. Dillingham Harbor is a depositional environment with a high percentage of fine grain sediments. It is also a center of vessel activity and maintenance, which undoubtedly is a source of metals. In the rest of the system, metal concentrations were evenly distributed in sediment due to the strong influence of tidal mixing. In general, trace element concentrations in the study area were lower than concentrations reported by other studies in the coastal regions of the central and southcentral Alaska. None of the toxic trace elements exceeded any ERL or ERM, except arsenic. Arsenic was present at virtually all stations at or above the ERL level, and appears to be related to naturally occurring background concentrations in the watersheds.

2.3 Toxicity Results

The toxicity bioassays did not indicate acute toxicity due to anthropogenic contamination. The Microtox^{R} bioassays did not result in negative responses at any location. The sea urchin fertilization results indicated toxicity at two adjacent stations in the Lower Kvichak stratum. The development endpoint is generally a more sensitive indicator than the fertilization endpoint. That test indicated significant impacts at those same two sites and also in the Naknek River and Lower Nushagak strata. The impacts appear to be related, in part, to unionized ammonia concentrations in the pore water. These sites were located below where the fleet of factory ships are required to anchor and/or land-based fish packing plants.

Some uncertainty exists as to the cause of developmental effects, but it is clear that some sublethal impacts are occurring in specific locations due to either natural or anthropogenic causes. Over forty three million pounds of shredded fish waste were dumped into Nushagak and Kvichak Bays in 2014, mostly in the Kvichak. This huge influx of organic matter introduced over a relatively short period must affect the habitat. Whether the net effect is harmful (e.g. ammonia toxicity, local hypoxia) or beneficial (e.g. food resource) needs investigation.

2.4 Benthic Infaunal Results

Total number of taxa, abundance per m^2 and diversity at each station and stratum are listed in Table 1. Benthic community condition was highly variable, with pockets of diverse communities throughout the study

area, but with no obvious gradients or spatial patterns. Diversity and species richness were correlated with higher salinity and Secchi depth and negatively correlated with latitude. This would indicate that there is increasing diversity away from the river mouths, but all three parameters are confounded. In addition, this statistical result is driven by the extremely low diversity at Dillingham and Naknek (all less than 1.0). Station NR-3P near the fish packing plant within the Naknek River stratum had only 1 taxon (Oligochaete sp.). Diversity and species richness did not show consistently increasing gradients going down the estuaries. Previous reports state that the upper Nushagak Bay has a benthic community Shannon Diversity (H') value of 1.54, ranking it below similar subarctic estuaries (Radenbaugh and Pederson 2011) which is consistent with the current data. Sampling data from the lower bays is virtually non-existent. The nodal analysis did not identify any discernable pattern or gradient of locations beyond grouping those stations with relatively high numbers of taxa vs low numbers. Similar results were obtained in 2010 by a USGS survey of the western side of Kvichak Bay to assess benthic food resources for migratory birds (unpublished data). They identified a total of 98 taxa. The number of taxa per station ranged from zero to 26, with a median of six.

2.5 Fecal coliform and Clostridium perfringens Results

Statistical tests indicated that both *C. perfringens* and fecal coliform bacteria were positively correlated with the % fines fraction of the sediment, and negatively correlated with the coarse fractions. The highest levels of *C. perfringens* were found in the sediments in Upper Kvichak Bay, at Site UK-14A and at Site UK-1P with colony forming units of 1,450 CFU/g and 1,095 CFU/g respectively. *C. perfringens* occurs in the intestines of animals, including birds. Kvichak Bay is an important stopover area for migrating waterfowl such as king eiders and black scoters. In addition, Kvichak Bay is used by seasonally resident plovers, yellowlegs and dunlin. Kvichak Bay also receives terrestrial runoff. *C. perfringens* in this part of the Bay would not appear to be derived from human sources, however, as the nearest town (Levelock) is nearly 38 km upstream. The NS&T Program has monitored levels in *C. perfringens* as part of its regular monitoring of contaminants throughout the coastal US. Values range as high as 41,000 CFU/g in polluted urban harbors. The 90th percentile is 588 CFU/g and the median value is 11. The median from the sediment samples taken in Bristol Bay was 18 CFU g-1, comparable to the NS&T median value, although four sites from Bristol Bay were above the NS&T 90th percentile. *C. perfringens* also has the capability of forming spores which can persist in soils and sediments.

The highest levels of fecal coliform (230 MPN/g) were found in Dillingham Harbor (Site DH-3P), and downstream from Dillingham Harbor (UN-2P) in Upper Nushagak Bay, which may indicate human influences. The third highest level (170 MPN g-1) was also found in Dillingham Harbor (DH-2P), with the fourth highest level being found at Site NR-3P (130 MPN/g), near the town of Naknek. Like *C. perfringens*, sources of fecal coliform bacteria can be human as well as wildlife.

2.6 Fish Condition Results

Contaminant body burdens in fish were relatively low. Only strongly lipophilic contaminants (organic compounds and methyl-mercury) were consistently detected at or above instrument detection limits. Rainbow

Table 1. Total number of taxa and abundance (# /m^2) for stations in the Bristol Bay study area.

Station	Location	# TAXA	Abundance #/m^2	Ln Diversity
DH-1P	Dillingham Harbor	3	3,475	0.26
DH-2P	Dillingham Harbor	4	2,725	0.47
DH-3P	Dillingham Harbor	4	1,225	0.76
UN-2P	Upper Nushagak Bay	0	0	
UN-1P	Upper Nushagak Bay	32	2200	2.94
UN-5A	Upper Nushagak Bay	31	1580	2.59
UN-6A-2013	Upper Nushagak Bay	2	80	0.56
UN-6A-2014	Upper Nushagak Bay	8	400	1.88
LN-10A	Lower Nushagak Bay	7	140	1.73
LN-12A	Lower Nushagak Bay	5	80	1.49
LN-14A	Lower Nushagak Bay	9	410	1.71
LN-15A	Lower Nushagak Bay	6	180	1.45
NR-1P	Naknek River	5	14280	0.5
NR-3P	Naknek River	1	30	0
NR-8A	Naknek River	3	140	1.08
UK-14A	Upper Kvichak Bay	7	440	1.04
UK-1P	Upper Kvichak Bay	4	460	0.75
UK-16A	Upper Kvichak Bay	5	430	0.91
UK-17A	Upper Kvichak Bay	16	1170	2.07
UK-19A	Upper Kvichak Bay	15	890	1.57
LK-12A	Lower Kvichak Bay	36	1800	3.2
LK-15A	Lower Kvichak Bay	9	410	1.05
LK-16A	Lower Kvichak Bay	9	1280	0.74
LK-18A	Lower Kvichak Bay	32	1100	2.89

smelt accumulated relatively higher levels of mercury, PCBs and chlorinated pesticides than young starry flounder in Dillingham Harbor, due in part to higher lipid contents. The fish from Dillingham and Naknek had higher lipid levels than fish from the open bays. Whether or not the fish waste dumped at those areas is a contributing factor is unknown. Larger (older) flounder had accumulated higher levels of mercury than younger fish. Given the relatively uniform spatial distributions of mercury, location is unlikely to have affected this. The number of PCB congeners in fish tissues was much larger than that seen in the sediments and is very similar in fish from separate locations, indicating that the source(s) are probably not local but due to long-range water and/or atmospheric dispersal. However, body burdens were higher in fish from Dillingham and Naknek than in the open bays. Overall, all tissue concentrations are in the same range as those reported by the Alaska Fish Monitoring Program (AFMP, 2011) in a variety of species from around the state.

Externally, all fish appeared normal with two exceptions. A single flounder with a papilloma extending from the dorsal side, maxillary region of the mouth. Tumors in Pacific flatfish are fairly common, and well documented (McArn et al., 1968). A single smelt had an unusual growth extending from the opercular cavity on the right side of the fish. The operculum was moderately deformed to accommodate this growth, which appeared grayish white, with liver-like consistency. Tissue sections of skin, muscle, spleen, kidney, heart,

liver, and intestine were assessed for pathological conditions. No pathologies that could be separated from preservation artifacts were noted.

2.7 Correlations

Most of the chemical analytes were found at such low concentrations that correlation statistics are meaningless. Some parameters such as % fine grain sediment and %TOC content in sediment were strongly correlated, but this was predictable, and driven by extreme values. Similarly, fecal coliform and *C. perfringens* levels were correlated. There were significant differences between concentrations of some of the metals between strata, but they were element specific and showed no consistent pattern, beyond Dillingham Harbor usually having higher concentrations. Arsenic was elevated in all strata.

3. SUMMARY

A baseline environmental characterization of the eastern reaches of Bristol Bay, Alaska was conducted using the sediment quality triad approach, along with measures of contaminant body burdens and the characterization of parasites and disease in starry flounder and rainbow smelt. The study area was subdivided into six strata based on geophysical and hydrodynamic patterns Within each stratum, a stratified random sampling approach was used to select sampling sites for surficial sediment. Concentrations of over 150 organic contaminants and metals were analyzed. Ambient toxicity was assessed using two bioassays. Water quality conditions were also measured. Polycyclic aromatic hydrocarbons, were low relative to NOAA's sediment quality guidelines (SQG). Tributyltin was detected at trace levels only in Dillingham Harbor. The physical characteristics of the harbor sediment probably account for the chemical results.

Polychlorinated biphenyls and other chlorinated organic contaminants were detected only in trace amounts in the sediment. Sediment metal concentrations were very low; all values were below NOAA SQGs except for arsenic. Benthic communities were relatively sparse at most locations due to harsh physical conditions. Species richness and diversity had no correlation to grain size, TOC, depth, or location when outliers were removed. Very strong tidal currents result in highly turbid water, physical scouring and large salinity changes, particularly toward the heads of the bays and the tributaries. Significant chemical toxicity was virtually absent except for high pore-water ammonia levels at selected locations, possibly associated with fish processing waste streams. Contaminant body burdens and histopathological lesions were very low in the fish tested. Older fish had accumulated higher levels as expected. Fish from Naknek and Dillingham tended to have higher lipid levels, possibly related to food availability in the vicinity of fish processing plants.

Chapter 20
Summary

Photo credit: Dave Dewitt, University of Maryland IAN

Summary

The following tables illustrate the use of sediment toxicity results and chemical analysis from a variety of locations. These comparisons were tabulated on a study area-by-study area basis to examine national patterns (Table 1), or on stratum-by-stratum basis within a study area to contrast regional conditions (Table 2). Table 1 illustrates the variability between results from different bioassays on a national scale. Biological systems are inherently variable, especially when contrasting different levels of biological organization (e.g. whole organisms vs biochemical reactions). The amphipod bioassays are generally the least sensitive bioassay. Thus, when this bioassay shows a significant response, it probably indicates a genuine contamination problem. However, amphipods do not survive well in coarse grained sediment, so not all results are absolute. Conversely, the other assays are more sensitive and may be better indicators of low level effects, but may also result in false positives. It is also possible that toxicity is the result of contaminants that are not on the analytical list (e.g. current use pesticides). This is why the Bioeffects studies use three different indicators of contamination (toxicity, chemical analyses, benthic community). All must be considered. It is also important to note that most of the study sites were in developed areas or were large systems that encompassed large urbanized areas. There are vast stretches of US coastline that have never been tested and where only background concentrations of contaminants would be expected to be found.

Table 2 illustrates the areal extent of ERL exceedances for San Francisco Bay. The strata were laid out to run from the delta in the north, down through the Bay and to the sloughs in San Jose. Elevated PAH and PCB concentrations are not as widespread as other contaminants, but with extremely high concentrations in specific locations in urban streams and the harbors in Richmond, Oakland and south San Francisco. The pesticide DDT is a ubiquitous contaminant, with ERL exceedances throughout the Bay. Elevated metals are commonly seen throughout the bay, with harbors and urban streams showing high levels of cadmium, copper and lead. Mercury is also elevated, but especially in the South Bay area where there are multiple ERM exceedances.

The ERMq is also a useful data transformation because it allows for comparison of the entire suite of measured chemicals, for which there are sediment quality guidelines, all on the same normalized scale. Figure 1 illustrates the relative contamination conditions for a variety of harbors and open water bodies throughout the U.S. Note also, that the open water bodies away from even the most contaminated harbors are relatively clean. For example, the open reaches of Delaware and Massachusetts Bays are relatively uncontaminated despite the condition of Philadelphia and Boston.

The database can also be used to examine regional trends in contamination or the biological parameters (e.g. toxicity, species richness). Figure 2a is a plot of total PAHs in sediment from harbors and heavily urbanized

areas on the East Coast. The harbors in the New England and Mid-Atlantic regions are contaminated with much higher levels of PAHs than what is seen in most of the southeast. Indeed, St Lucie Inlet for example, is heavily urbanized but is not an industrial port, and does not contain the same level of pollution as seen in other areas on the East Coast. In contrast, a plot of the PAH concentrations found in non-urban areas along the east coast reveals that most estuarine areas away from cities are well below the total PAH ERL level (Figure 2b). Similar associations can be seen for PCB concentrations.

National scale distributions of selected contaminants can also be identified using the data base. Concentrations of DDT for the Atlantic and Pacific coasts are shown in Figure 3a and b. Virtually all of the high concentrations in the Hudson River/Newark Bay area are from the Arthur Kill between Staten Isl. and New Jersey. Similarly, all of the elevated values in Delaware Bay are in the Delaware River between Philadelphia, PA and Wilmington, NJ. All of the elevated values in Biscayne Bay are found in the Miami River. On the Pacific coast, the highest concentrations in the Long Beach area are spread throughout the harbor, not just in the vicinity of the well documented dump site at Palos Verdes. Monterey Bay has low level but widespread DDT concentrations that previous studies have shown to come from the Salinas River (Hartwell, 2007). San Francisco Bay also has widespread low level DDT concentrations with well documented hot spots in Richmond, San Francisco, and Oakland. DDTs are barely detectable in Alaska. Finally, patterns of heavy metals distributions can also be examined on regional scales. Figure 4 shows chromium concentrations on the west coast. The data suggest that the watersheds of San Francisco and Puget Sound are, respectively, high and low sources of chromium simply due to the regional geology (outside of contaminated industrial areas). The spike in Kachemak Bay is from a single isolated fjord at Port Graham. The adjacent fjords do not show high chromium levels.

Correlations

To be valid and useful to managers, the SQT parameters must be demonstrated to be predictive of adverse effects in the field. Do high concentrations of contaminants result in measurable impacts? Figure 5 illustrates the relationship between the mean ERMq and a combined bioassay toxicity ranking score (Hartwell, 1997) in three very different systems, Chesapeake Bay, Delaware Bay, and San Francisco Bay. Not only do the toxicity response scores cluster together at the same ERMq values, there is a clear gradient of increasing toxicity response with increasing ERMq. Equally important is the relationship between contamination and biological impacts observable in the environment. This is difficult in many cases because biological systems respond to many variables both natural and anthropogenic. One of the most important variables for benthic organisms is sediment grain size, which in turn is determined by a variety of factors such as location, depth, current speed, etc. By normalizing species richness data for grain size (# taxa ÷ % fine grained sediment) for example, it is possible to contrast species richness with ERMq without the confounding influence of sediment type. Figure 6 illustrates the grain size-normalized species richness values vs the mean ERMq for 204 sites in Chesapeake Bay. Thus, the Bioeffects studies approach can show clear relationships between environmental contamination and biological effects in real world settings.

Table 1. National data showing the area impacted as measured by each toxicity test in various regions.

NS&T Studies	Total number of samples	Total Area (km^2)	Area with reduced Amphipod survival (km^2)	Percentage of total area	Area with reduced Microtox response (km^2)	Percentage of total area	Area with reduced Sea Urchin fertilization (km^2)	Percentage of total area	Area with reduced Sea Urchin development (km^2)	Percentage of total area	Area with increased P450 response (km^2)	Percentage of total area
Apalachicola Bay	9	187.6	0	0.0%	186.84	99.6%	63.6	33.9%	157.5	84.0%	ND	
Biscayne Bay	226	484.2	62.3	12.9%	248.4	51.3%	229.5	47.4%	408	84.3%	8.8	33.0%
Boston Harbor	55	56.1	5.7	10.0%	25.8	44.9%	3.8	6.6%	56.8	100.0%	ND	
California coastal lagoons	30	5.0	2.9	57.9%	nd		2.1	42.7%	ND		2.30	46.8%
Charleston Harbor	63	41.1	0	0.0%	17.6	42.9%	12.5	30.4%	ND		ND	
Chesapeake Bay	210	9119.5	0.0	0.0%	525.6	5.8%	2964.7	32.51%	ND		256.8	2.8%
Choctawhatchee Bay	37	254.5	0	0.0%	254.47	100.0%	113.14	44.4%	116.1	45.4%	ND	
Delaware Bay	73	2346.8	145.4	6.2%	114	4.9%	247.5	10.5%	ND		145.2	62.0%
Galveston Bay	75	1351.1	0.0	0.0%	1143.7	84.6%	432.0	32.0%	314.8	23.3%	56.7	42.0%
Hudson-Raritan Estuary	117	350.0	133.3	38.1%	136.1	38.9%	ND		ND		ND	
Kachemak Bay	33	93.6	0.0	0.0%	ND		ND		ND		ND	
Leadenwah Creek	9	1.7	0	0.0%	0.34	20.1%	0	0.0%	ND		ND	
Long Island Sound	60	71.9	36.3	50.5%	48.8	67.9%	ND		ND		ND	
Los Angeles Harbor	105	53.8	7.8	14.5%	ND		52.6	97.7%	ND		ND	
Mission Bay	11	6.1	0.0	0.0%	ND		4.0	65.9%	ND		ND	
Newark Bay	57	12.7	10.8	85.0%	ND		ND		ND		ND	
Pensacola Bay	40	272.6	0.04	0.0%	262.8	96.4%	14.4	5.3%	5.41	2.0%	ND	
Puget Sound	300	2369.0	1.0	0.0%	19.2	0.8%	93.5	3.90%	ND		586.4	24.8%
Sabine Lake	66	245.9	0.0	0.0%	194.2	79.0%	14.0	5.7%	ND		6.7	27.0%
San Diego Bay	117	40.2	26.3	65.8%	ND		25.8	75.9%	ND		ND	
San Diego River	2	0.5	0.0	0.0%	ND		0.26	52.0%	ND		ND	
San Francisco Bay	179	988.9	71.3	7.2%	ND		226.8	22.9%	766.6	77.5%	ND	
Savannah River	60	13.1	0.16	1.2%	7.49	57.1%	2.42	18.4%	ND		ND	
St. Andrews Bay	31	127.2	0	0.0%	127	100.0%	2.28	1.8%	7.17	5.6%	ND	
St. Simons Sound	20	24.6	0.10	0.4%	11.42	46.4%	0.65	2.6%	ND		ND	
St Thomas V.I. STEER	24	6.0	1.9	3.2%	ND		1.2	20.2%	ND		0.2	33.0%
Tampa Bay	165	550.0	0.5	0.1%	0.6	0.1%	463.6	84.3%	ND		ND	
Tijuana River	6	0.3	0.18	56.2%	ND		0.18	56.2%	ND		ND	
Winyah Bay	9	7.3	0	0.0%	5.1	70.0%	3.1	42.2%	ND		ND	
Total area tested		19081.2	219.6		798.9		3286.2		823.4		1063.1	
Average				14.1%		53.2%		33.4%		52.8%		33.9%
Minimum				0.0%		0.1%		0.0%		2.0%		2.8%
Maximum				85.0%		100.0%		97.7%		100.0%		62.0%

Table 2 San Francisco Bay data showing the area impacted, expressed as the % area in which ERL exceedances for specific contaminant groups were seen.

Stratum	Total Area (km^2)		PAH	PCB	DDT	Metals
1	6.5		0.0	0.0	0.0	33.3
2	15.2		0.0	0.0	33.3	33.3
3	9.6		0.0	0.0	66.7	33.3
4	22.4		0.0	0.0	100.0	33.3
5	34.0		0.0	0.0	100.0	20.0
6	21.7		0.0	0.0	66.7	16.7
7	3.9		0.0	0.0	34.7	5.8
8	19.8		0.0	0.0	100.1	33.4
9	2.0		0.0	0.0	100.0	33.3
10	3.2		0.0	0.0	99.7	33.2
11	151.1		0.0	0.0	100.0	16.7
12	36.7		0.0	0.0	66.7	33.3
13	41.3		0.0	0.0	66.7	33.3
14	3.0		0.0	0.0	100.0	33.3
15	19.3		0.0	0.0	100.0	33.3
16	38.7		0.0	0.0	100.0	33.3
17	6.5		0.0	0.0	100.0	33.3
18	0.8		0.0	0.0	100.0	33.3
19	0.7		33.3	33.3	100.0	33.3
20	52.8		16.7	16.7	100.0	16.7
21	3.5		0.0	0.0	100.0	33.3
22	60.7		16.7	0.0	50.0	16.7
23	8.1		0.0	0.0	100.0	33.3
24	0.8		66.7	0.0	100.0	33.3
25	0.6		100.0	0.0	100.0	33.3
26	1.6		100.0	66.7	100.0	33.3
27	3.4		33.3	100.0	100.0	33.3
28	38.5		60.0	0.0	80.0	20.0
29	1.9		100.0	100.0	100.0	33.3
30	38.3		0.0	0.0	75.0	25.0
31	3.3		33.3	0.0	100.0	16.7
32	3.2		50.0	83.3	100.0	16.7
33	0.7		69.8	58.2	69.8	11.6
34	54.8		75.0	25.0	100.0	25.0
35	61.8		25.0	0.0	100.0	25.0
36	120.9		25.0	25.0	100.0	25.0
37	13.1		33.3	0.0	100.0	33.3
38	15.2		0.0	0.0	66.7	33.3
39	45.0		0.0	0.0	100.0	33.3
40	0.6		0.0	0.0	100.0	33.3
41	6.7		0.0	0.0	100.0	33.3
42	5.2		0.0	0.0	100.0	33.3
43	1.1		0.0	100.0	100.0	33.3
44	1.4		0.0	66.7	100.0	33.3
45	4.0		0.0	0.0	72.0	14.4
46	2.1		9.5	9.5	47.6	9.5
47	3.2		66.7	66.7	100.9	33.3
Total	**988.9**		14.7	6.8	88.8	24.8

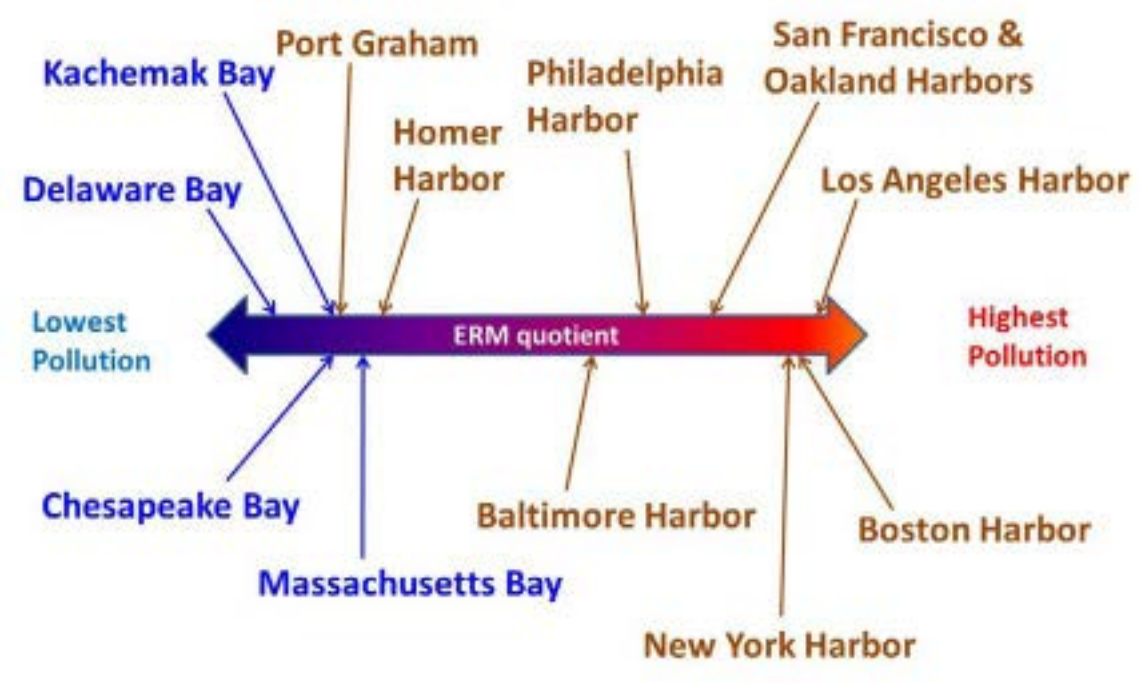


Figure 1. Relative contamination levels of various ports and water bodies expressed as the ERMq and transformed to a scale of 1 (cleanest) to 100 (most contaminated).

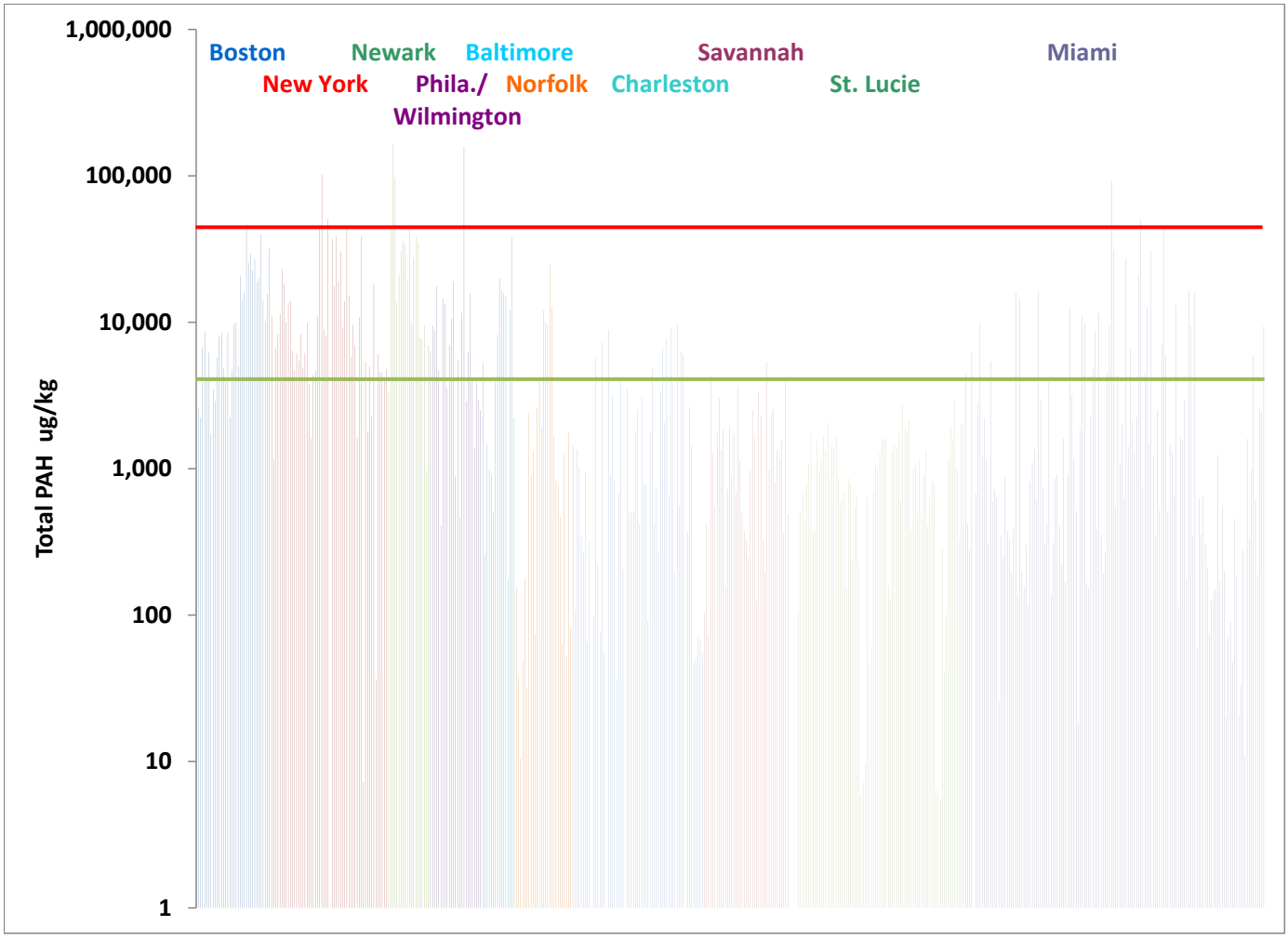


Figure 2a. Plot of total PAHs in harbor and urban areas on the US east coast. (Red line = ERM, Green line = ERL)

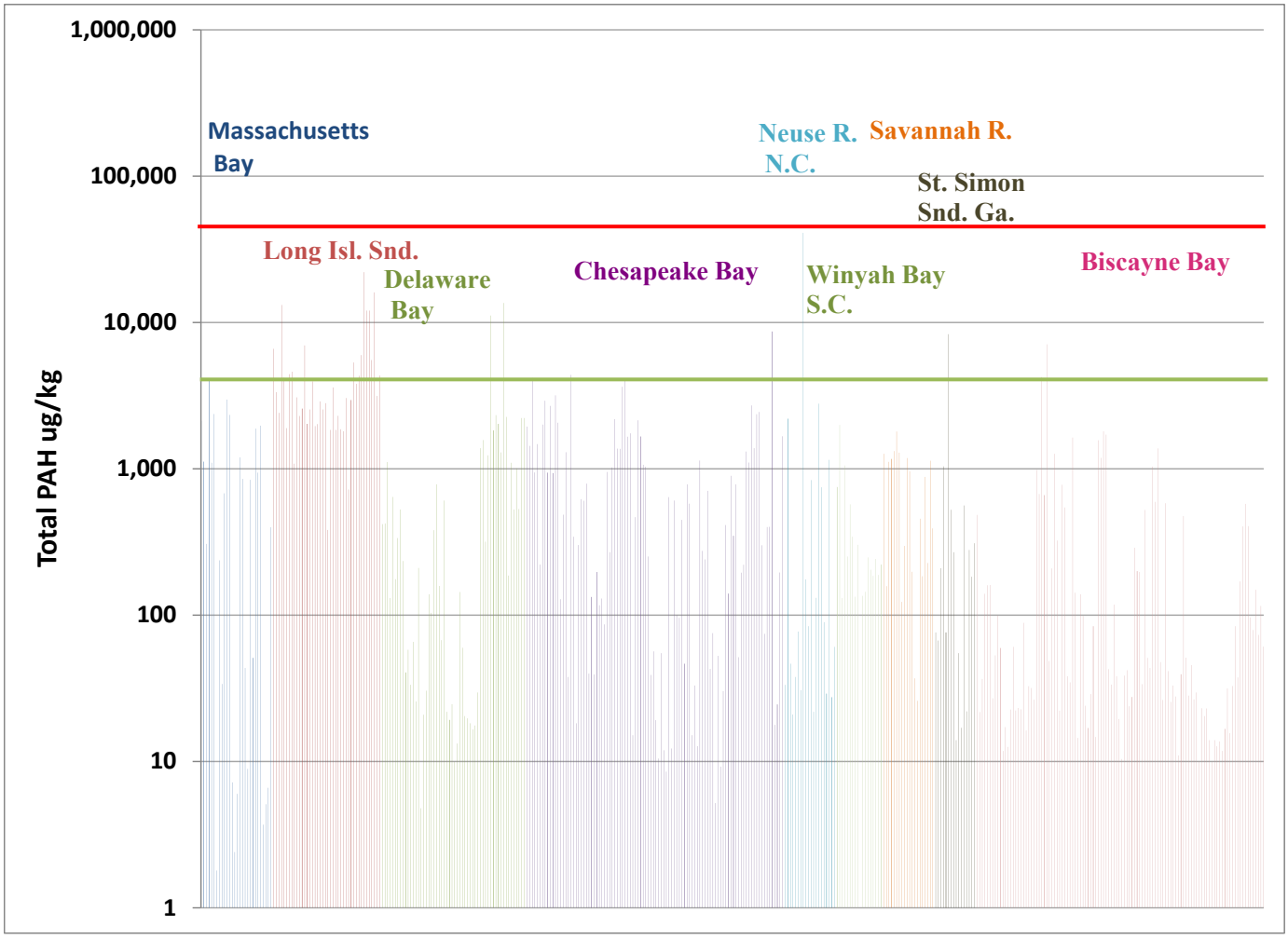


Figure 2b. Plot of total PAHs in non-urban locations on the US east coast. (Red line = ERM, Green line = ERL).

The data base is publicly available at https://products.coastalscience.noaa.gov/nsandt_data/data.aspx and data can be downloaded in large or small files which can in turn be converted into spreadsheets or entered into statistical packages. Data are applicable to environmental risk assessments, damage assessments, cleanup targets, and for planning future resource management and restoration activities. Utilization of consistent methods over the life of the program allows for comparison of the magnitude and extent of contaminant effects relative to other locations throughout the US, and over time. All data were generated following strict performance-based quality control and quality assurance protocols. Ongoing efforts include developing additional techniques to analyze statistical relationships between contaminant concentrations and histopathological lesions in resident organisms, and to identify and assess emerging chemicals of concern for the environment and for human health, such as flame retardants, stain repellants, pharmaceuticals, and for other site specific assessments.

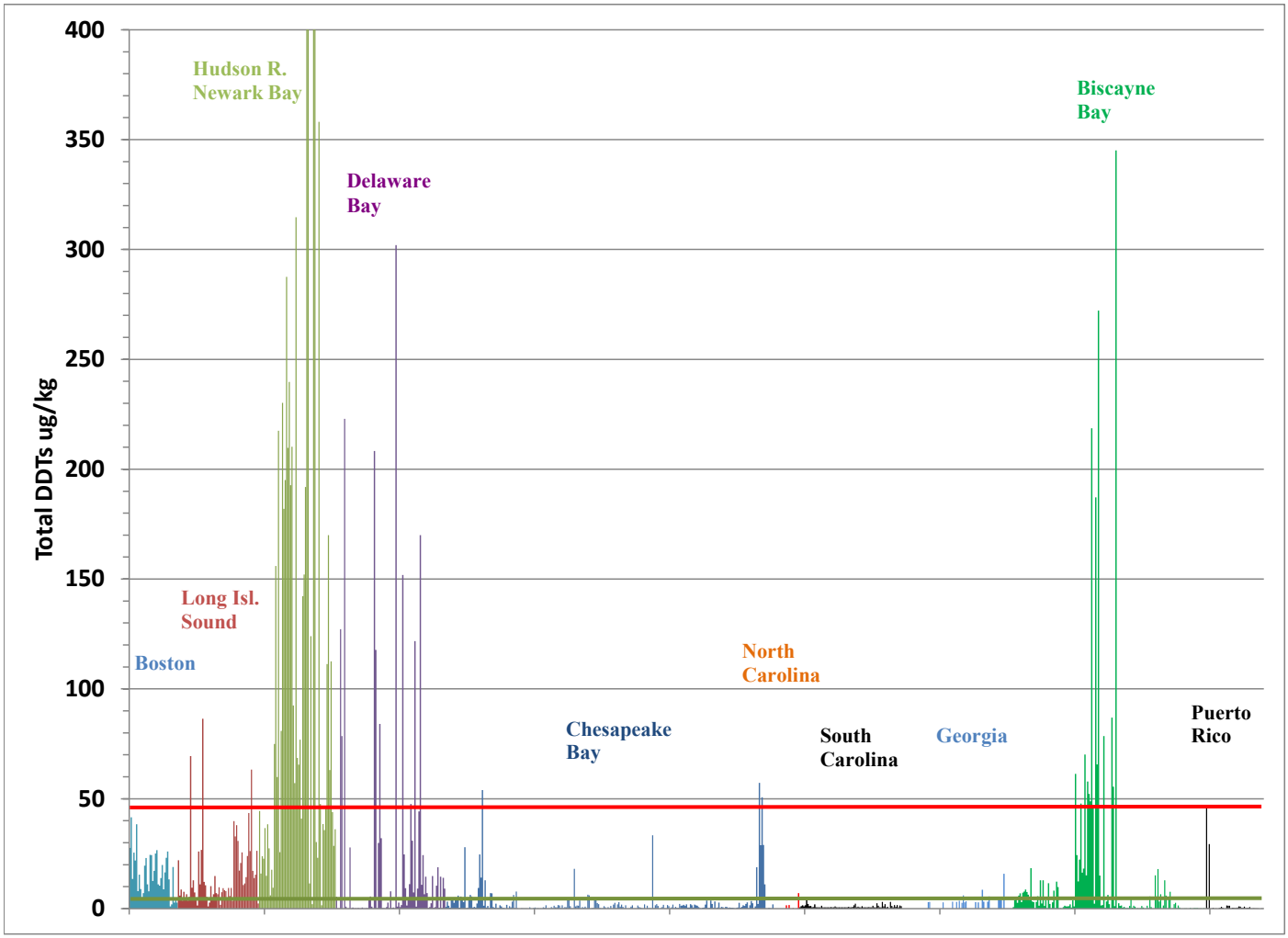


Figure 3a. Plot of total DDTs on the US east coast. (Red line = ERM, Green line = ERL)

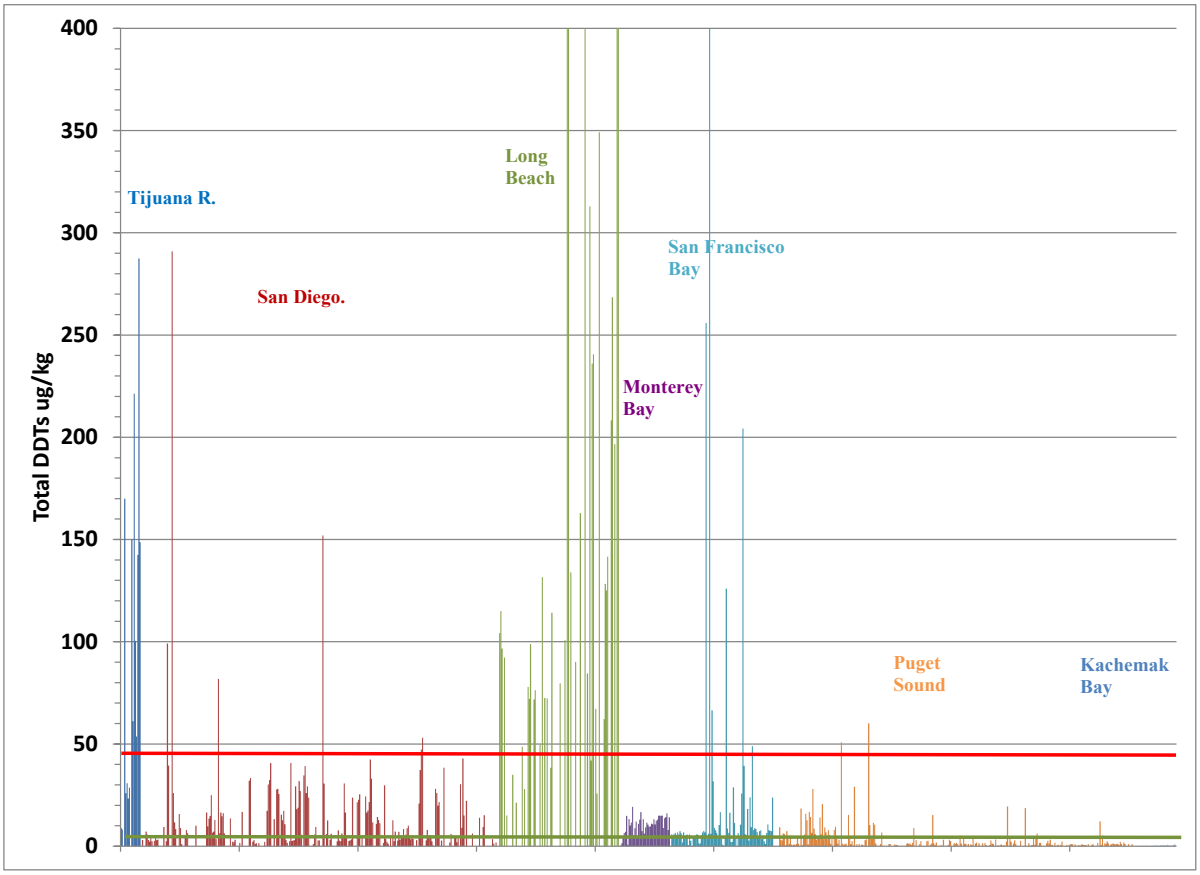


Figure 3b. Plot of total DDTs on the US west coast. (Red line = ERM, Green line = ERL)

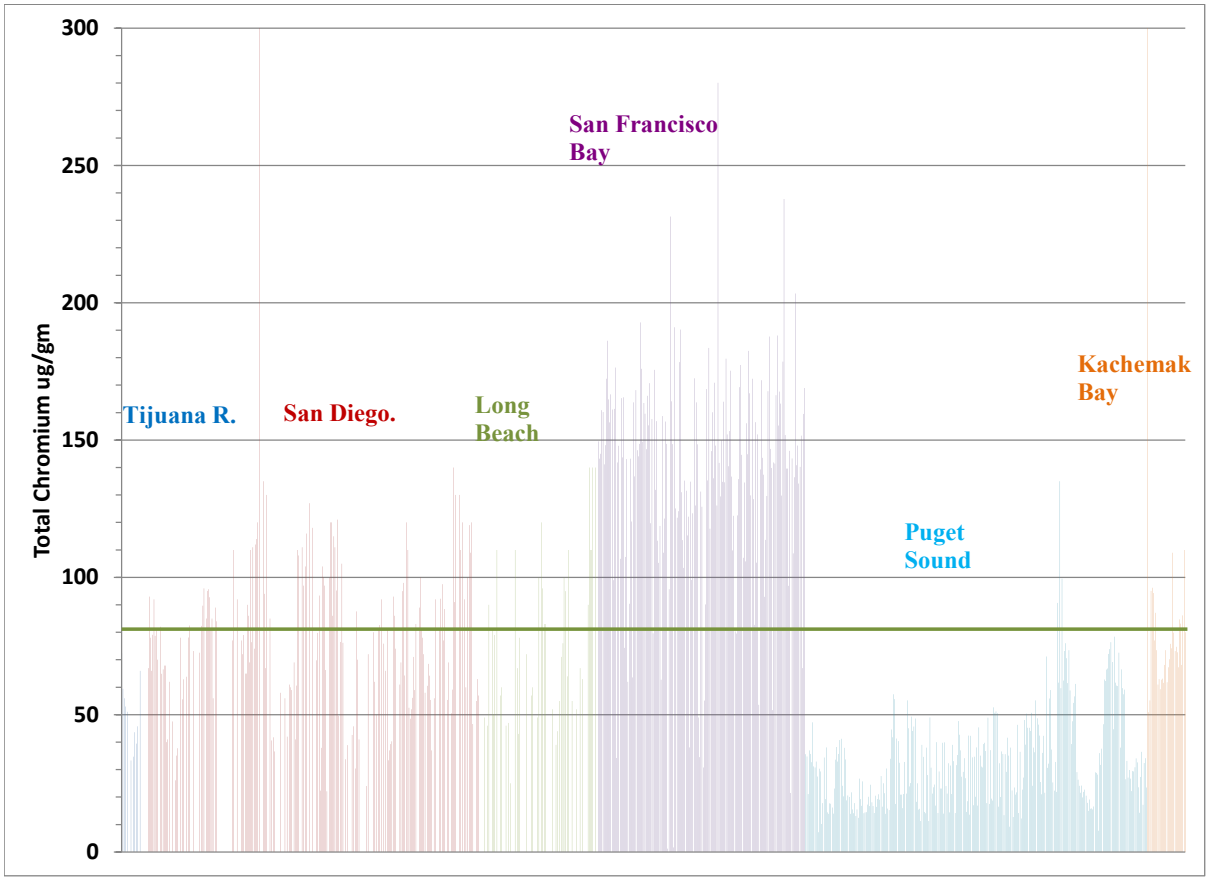


Figure 4. Plot of total chromium on the US west coast. (Green line = ERL, ERM=370)

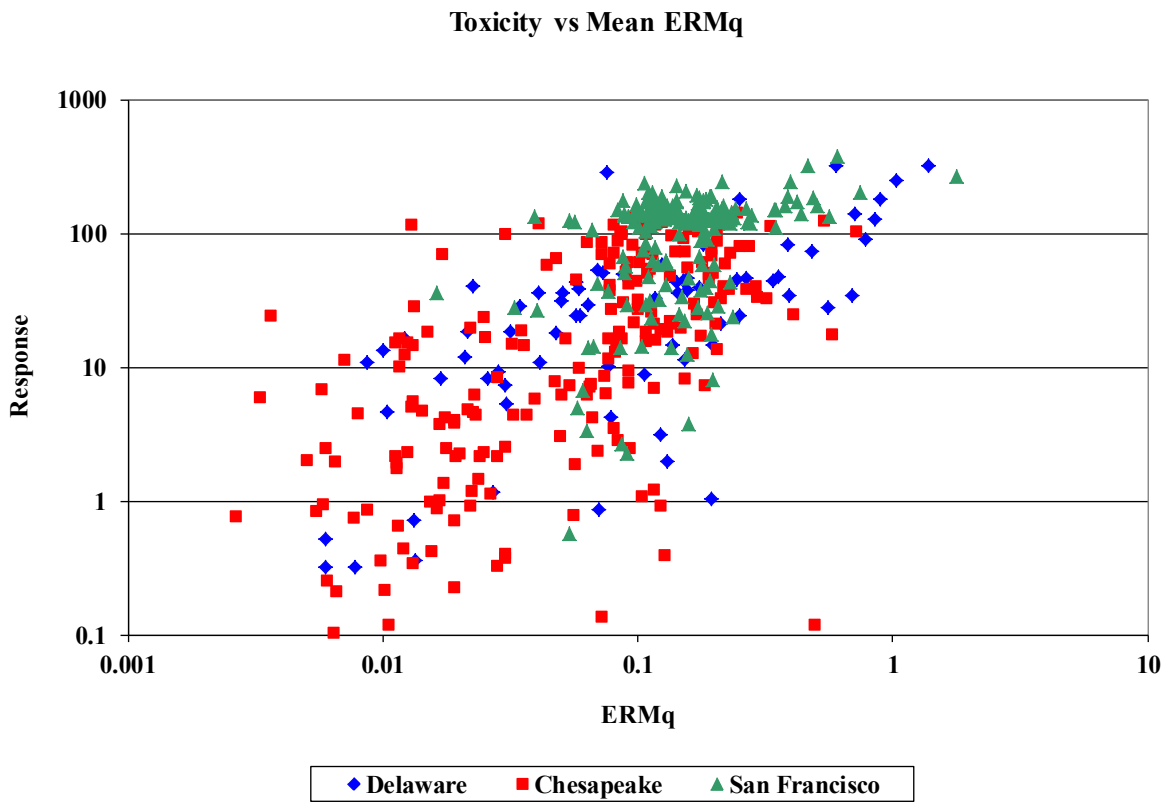


Figure 5. Plot of an integrated bioassay toxicity response score vs the ERM quotient from three different NS&T Bioeffects projects.

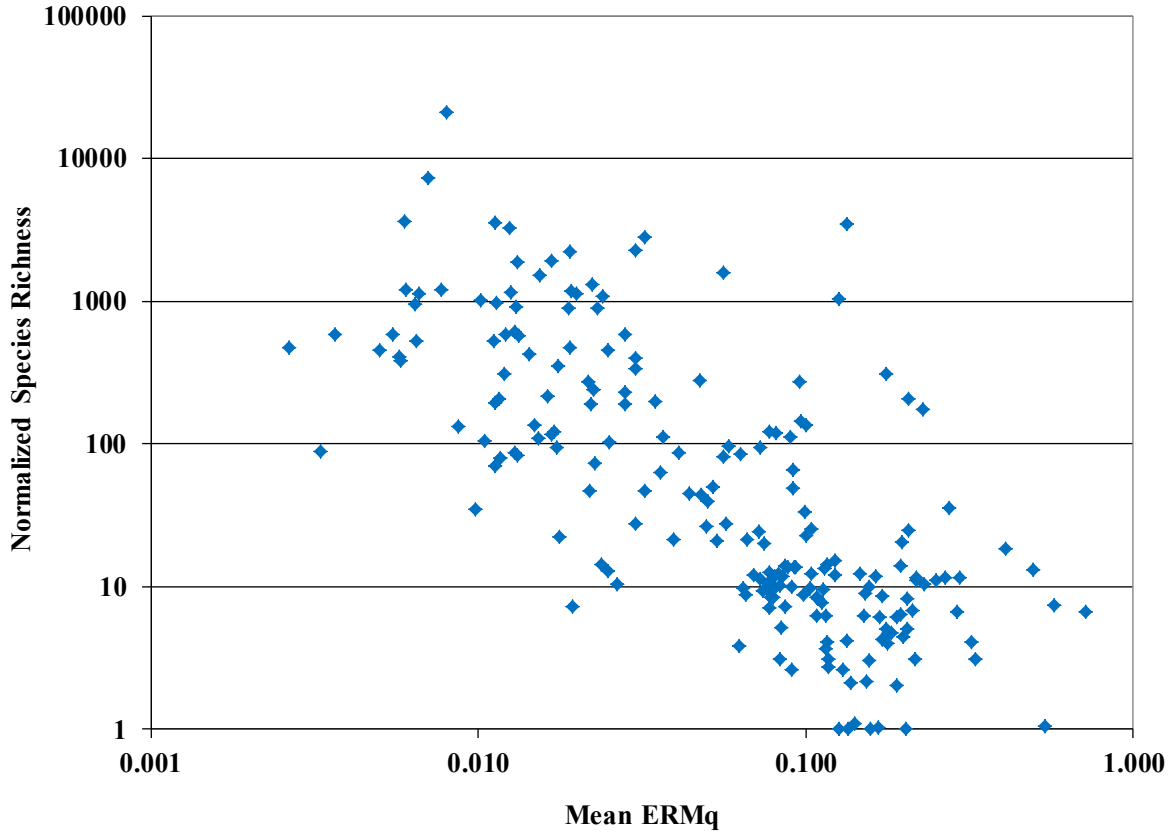


Figure 6. Plot of species richness (number of taxa) normalized for grain size vs the mean ERMq in Chesapeake Bay.

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