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EPA

Galveston Bay 1993

Regional Environmental Monitoring and Assessment Program

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By

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The R-EMAP Galveston Bay Study is a follow-up study of the EMAP-Estuaries: Louisiana Province Studies. Several comparisons are made between data collected and analyzed in this report and that of the following citation:

Macauley J.M., J.K. Summers, V.D. Engle, P.T. Heitmuller, and A.M. Adams. 1995. Annual Statistical Summary: EMAP-Estuaries Louisianian Province - 1993. U.S. Environmental Protection Agency, Offices of Research and Development, Environmental Research Laboratory, Gulf Breeze, FL. EPA/620/R-96/003.

R-EMAP and EMAP data are available at http://www.epa.gov/emap

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Galveston Bay and Its Associated Small Bays and Marina Sites

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Executive Summary

The Regional Environmental Monitoring and Assessment Program (R-EMAP) Study of Galveston Bay, Texas addresses the ecological health of this estuary by identifying benthic community structure, measuring toxicity of sediments, and measuring concentrations of various pollutants in the sediments. The R-EMAP Study of Galveston Bay was proposed after the EPA's 1991 EMAP Study of the Louisianian Province estuaries identified Galveston Bay as an area of concern. The sampling design and ecological indicators employed for the R-EMAP Study of Galveston Bay are based on the EMAP concept (a locally intensified EMAP sampling grid was used), but they are limited to one sampling event.

The purpose of this study was to characterize the condition of Galveston Bay as a whole, characterize conditions of four small bays in the Galveston Bay Complex, and determine the impacts of marinas.

For comparison of the main body of Galveston Bay with other systems and the Louisianian Province as a whole, twenty-nine randomly selected sites were chosen to represent 1305 square kilometers of surface area of Galveston Bay. Random sites are located in Galveston Bay (GB), Trinity Bay (TB), East Bay (EGB), and West Bay (WGB). In addition, a random sample was taken for each of four important small bays associated with Galveston Bay: Clear Lake (CL), Dickenson Bay (DKL), Moses Lake/Dollar Bay (MLDL), and Offat's Bayou (OB). Also, five marina sites (MA) were chosen to determine local marina influences (see Map 1). This study does <u>not</u> include an analysis of conditions in the upper Houston Ship Channel, the Trinity River, or any other major tributaries. The Louisianian Province EMAP Study consisted of 96 sites which represented 25,725 square kilometers of estuarine area. The Louisianian Province extends along the Gulf Coast from Anclote Anchorage, Florida to the Rio Grande, Texas.

A comparison of the EMAP Study of the Louisianian Province with the R-EMAP Study of Galveston Bay did provide insight into the differences between Galveston Bay and its Small Bay & Marina Sites, and the entire Louisianian Province. These comparisons revealed that the EMAP results were useful as a screening tool to determine which systems had toxic pollutants or biological impairment and therefore, should be studied in more detail.

The Sediment Quality Triad approach was used in this study to differentiate between degraded sites and undegraded sites. The Sediment Quality Triad consists of three components: Benthic Community Structure, Sediment Chemistry, and Sediment Toxicity. For this study, a degraded site is defined as a site which has at least two of the Sediment Quality Triad Components indicating degradation.

Benthic Community Component

Several metrics were used to determine the benthic community health. The Benthic Index (Engle and Summers, in press), the Benthic Diversity Index (the Shannon-Weiner Index), number of species per site and abundance of amphipods at each site proved useful in demonstrating that communities living in contaminated sediments had a community structure indicating poor conditions. The proportions of the two indices and the number of species in the Galveston Bay area were higher or similar to the proportions reported for the Louisianian Province in the 1993 EMAP Study. In contrast, amphipod occurrence in Galveston Bay sediments was significantly lower than in the entire Louisianian Province sediments. Small Bay and Marina Sites in Galveston Bay had no amphipods present and had much lower index values relative to Galveston Bay and the Louisianian Province sites. A degraded Benthic Component was found at 7 of 29 sites in Galveston Bay, and 8 of 9 Small Bay & Marina Sites (see Table 13).

Sediment Toxicity Component

Ampelisca abdita (the tube dwelling amphipod), and *Mysidopsis bahia* (a mysid shrimp) were used as the lab organisms to test toxicity. Toxicity was not seen when using mysid shrimp as a test organism, but toxicity was reported when using amphipods. Sites with toxic sediments included: Offat's Bayou, Dickenson Lake, and West Galveston Bay near Swan Lake (see Table 13). Toxicity was present at 3.5% of Galveston Bay area and 22% of Small Bay and Marina sites. Toxicity could not be associated with any of the measured parameters including presence or absence of natural amphipod populations present at each site. The only apparent similarity between sites displaying toxicity is that all three sites are located in the same general area of the bay.

Toxicity results revealed a low occurrence of acute toxicity in Galveston Bay sediments.

Sediment Chemistry Component

Sediment contaminants analyzed included 44 individual Polynuclear Aromatic Hydrocarbons (PAHs), High Molecular Weight PAHs and Low Molecular Weight PAHs, 20 polychlorinated biphenyl congeners, 24 pesticides (including DDT and its derivatives), 15 heavy metals, and 3 forms of butyltin. Sediment grain size, percent silt-clay content, total organic carbon, and acid volatile sulfides also were measured.

The contaminants were compared to established criteria including NOEL, ERL, and ERM. The range-low (ERL) criteria was established using the lower 10^{th} percentile of effects data for the metal or chemical. Concentrations equal to or above the ERL, but below the ERM, represent a possible-effects range within which effects would occasionally occur. The range-high (ERM) criteria was established using the 50^{th} percentile of the effects data. The concentrations equal to or higher than the ERM value represent a probable-effects range within which effects would frequently occur (Long, et al., 1995). The concentrations equal to the NOEL value is the highest level at which observed effects occur (MacDonald, 1992). In addition, anthropogenic enrichment of metals was measured. Enrichment was determined using regression equations for each metal against aluminum concentrations in the sediments.

In Galveston Bay, arsenic, copper, lead, nickel, and zinc exceed the ERL but not the ERM criteria at one or more sites sampled (Tables 2 & 3, Figure 21). NOEL values, but not ERL values, are exceeded at one or more sites for arsenic, chromium, lead, mercury, and zinc (Table 4). Sites with the most metals contamination include Offat's Bayou, Clear Lake, Moses Lake/Dollar Bay, and two Marina sites (Table 2, Maps 5 and 6). All of these sites are Small Bay and Marina sites, which were chosen, not randomly selected, so they are not included in comparisons of Galveston Bay with the Louisianian Province 1993 EMAP sampling area. However, several of the randomly sampled sites in Galveston Bay did have exceedences for arsenic, chromium, nickel, and zinc. Exceedences of chromium, copper, lead, nickel, and zinc for each site were almost always found at sites where the above metal concentrations, when compared to aluminum concentrations, indicated anthropogenic inputs.

The Galveston Bay area (represented by the 29 randomly chosen sites) has high chromium and nickel values distributed across a larger area than would be expected when compared to the entire Louisianian Province area. The percent of area with exceeded values in Galveston Bay were compared to the percent of area with exceeded values in the entire Louisianian Province as reported in Macauley, et al., 1995. Arsenic distributions in Galveston Bay were lower than expected when compared to the Louisianian Province, while zinc distributions were similar. Copper values above ERL values were found only at marina sites and in Offat's Bayou, but not in the randomly sampled area representing Galveston Bay, nor in the entire Louisianian Province area.

Tributyltin (TBT) is toxic to marine animals and is used in anti-fouling paint for boats, buoys, and docks. TBT has been restricted for use in recent years to only larger boats in an effort to reduce the amount of TBT contamination in the marine environment. Values exceeding 1.0 ppb in the sediments are used as a screening criterion based on studies by Laughlin, et al. (1984). TBT concentrations are higher in Galveston Bay sediments than expected with values greater than 1.0 ppb occurring in 52% of the area, compared to 31% of the total Louisianian Province area. A significant relationship exists between butyltin concentrations in the sediments and butyltin concentrations in the water column.

Sites with high Dieldrin and Endrin concentrations in the sediments are located in upper Galveston Bay, Clear Lake and upper Trinity Bay.

For the Louisianian Province, Dieldrin and Endrin were found to exceed the ERL guidelines at 57% and 18%, respectively, of EMAP sites. Both Dieldrin and Endrin concentration exceedance by area are lower in Galveston Bay compared to the Louisianian Province. Dieldrin and Endrin ERL values were exceeded at 17% and 5% respectively in Galveston Bay, and 33% and 0% for the Small Bay and Marina sites. No other pesticides (including DDT and its associated metabolites) exceeded ERL values for either study.

Polynuclear Aromatic Hydrocarbons (PAHs) were examined for exceedance of NOEL, ERL, and ERM screening values. PAHs exceeding ERL values in Galveston Bay include only C3-fluorene at site TB5 in Trinity Bay where several active oil wells are located. PAHs exceeding NOEL, but not ERL, values in Galveston Bay include Acenaphthylene and High Molecular Weight PAHs only found at site TB5 in Trinity Bay. Distributions of Low Molecular Weight PAHs and High Molecular PAHs for Galveston Bay show that three sites have PAHs that are considerably higher than at the other sites in the Galveston Bay area.

C3-fluorene exceeded ERL criteria in 3% of Galveston Bay, which is similar to exceedences found in the entire area of the Louisianian Province. Also, the NOEL value for high Molecular Weight PAHs was exceeded at site TB5. In the Louisianian Province, only C3-fluorene ERL values and High Molecular Weight PAHs ERL values were exceeded.

Polychlorinated Biphenyl (PCB) concentrations in Galveston Bay did not exceed the sediment quality low-level ecological effects screening value of 22.7 ppb. In addition, only 1% of the Louisianian Province area had exceedences of PCBs in the sediments.

The major variables used to determine degraded sediment chemistry in Galveston Bay included metals, butyltins, PAHs, pesticides other than DDTs, and silt-clay content. These variables were compressed into one factor using Principal Components Analysis (PCA). Sites with the <u>highest</u> compressed significant environmental factor values for sediment chemistry include Offat's Bayou, Moses Lake/Dollar Bay, Clear Lake, four of the Marina sites, and two sites near large brine discharges in the Trinity Bay area (TB5 and GB6). Sites with the <u>lowest</u> significant environmental PCA factor values include GB5 and TB6 which are both areas with the highest percentages of sediment grain sizes representing sand. These sites could be areas of low deposition and/or high scour.

Site Degradation

For this study, a degraded site is defined as a site with at least two of the Sediment Quality Triad Components indicating degradation. A marginal site is defined as a site with a benthic index value from 4.0 to 5.1 (which represents a marginal benthic component) and with a degraded sediment chemistry component. Degraded and healthy site values were determined using Cluster Analysis. Heavy metal concentrations greatly influenced the determination of degraded sites for the Sediment Chemistry Component of the Triad.

The most degraded areas in the Galveston Bay Complex include seven Small Bay and Marina sites and five randomly chosen sites in the open bay: Offat's Bayou (OB), Clear Lake (CL) and its marina sites, Lafayette Landing and South Shore (MA3 and MA4), Upper Galveston Bay at the Houston Yacht Club (MA2), Upper Galveston Bay near the upper Houston Ship Channel (GB1), Upper Galveston Bay near Smith Point (GB7), Moses Lake/Dollar Bay (MLDL), Dickenson Lake (DKL), mid-Trinity Bay (TB5) and Trinity Bay near the river mouth (TB8, TB9), and mid-East Galveston Bay (EGB5).

INTRODUCTION

The Regional Environmental Monitoring and Assessment Program (R-EMAP) Study of Galveston Bay, Texas, addresses the ecological health of this estuary by identifying benthic community structure, measuring toxicity of sediments, and measuring concentrations of various pollutants in the sediments. The study was proposed after the EPA=s 1991 EMAP Study of the Louisianian Province estuaries identified Galveston Bay as an area of concern. The sampling design and ecological indicators employed are based on the EMAP concept (a locally intensified EMAP sampling grid is used), but they are limited to one sampling event. This study focuses on the main body of Galveston Bay. In addition, four small bays and five marinas located in the Galveston Bay System were sampled. This study does not include an analysis of the upper Houston Ship Channel, the Trinity River, or any other major tributaries.

The purpose of this study was to characterize the condition of the main body of Galveston Bay as a whole, characterize conditions of the four small bays, and determine the impacts of marinas.

The goals of this study were to:

- directly address the issues of toxic pollutants and biological impairment in Texas coastal waters,

- contribute data to characterize the extent and severity of potential waterbody-specific problems identified by the EMAP Study,

- provide management with the environmental data needed for making decisions for targeting toxic pollutants and specific geographic areas, and

- link the EMAP Study (Macauley etal., 1993) results with the 1993 R-EMAP Study results for comparison. This comparison can be used to evaluate the usefulness of coupling EMAP as a screening tool with R-EMAP as a follow-up tool and to test the utility of the EMAP approach to address waterbody-specific questions.

Galveston Bay is the most economically important estuary on the Texas coast. It contains the State=s largest seaport, houses the world=s largest industrial complex, and produces the largest shellfish catch on the Texas coast. It also contains sixty-three percent of the boat slips in Texas. Galveston Bay is adjacent to Houston, one of the most populated areas in Texas. Thirty percent of the total U.S. petroleum industry and nearly fifty percent of the total U.S. chemical production is located adjacent to Galveston Bay. From these and other sources, this estuary receives more industrial and municipal effluent than all the other Texas estuaries and their local watersheds combined (GBNEP 44, 1994).

Significant improvements have been made in the most polluted area of the bay system, the upper Houston Ship Channel. In the early 1970's, the Houston Ship Channel above Morgan=s Point was listed by the U.S. EPA as one of the ten most polluted bodies of water in the U.S. Starting in 1971, increasingly stringent discharge goals were established for point sources on the Houston Ship Channel (GBNEP 44, 1994). In a 1980 report, the EPA recognized the improvements made on the Houston Ship Channel as Athe most notable improvement, a truly remarkable feat@ (GBNEP 44, 1994).

In Galveston Bay, water and sediment quality problems generally occur along the western shoreline and western tributaries (including the Houston Ship Channel), where anthropogenic activities are highest. Water quality improvements in these areas over the last 20 years have been attributed to improved wastewater treatment and reduction by point source dischargers (GBNEP 44, 1994). The Houston Ship Channel and its tributaries are the receiving waters for approximately 400 permitted industrial and municipal discharges (TDWR, 1984). The Ship Channel is still impacted by these discharges; however, vast improvements have been made. A majority of the remaining pollution problems to be addressed involve nonpoint source pollution from urban areas and industrial sites (Ward and Armstrong, GBNEP 22, 1992).

METHODS

Sampling Design

The Louisianian Province EMAP Study used 96 sites which represented 25,725 square kilometers of estuarine area. The Louisianian Province extends along the Gulf Coast from Anclote Anchorage, Florida, to the Rio Grande, Texas.

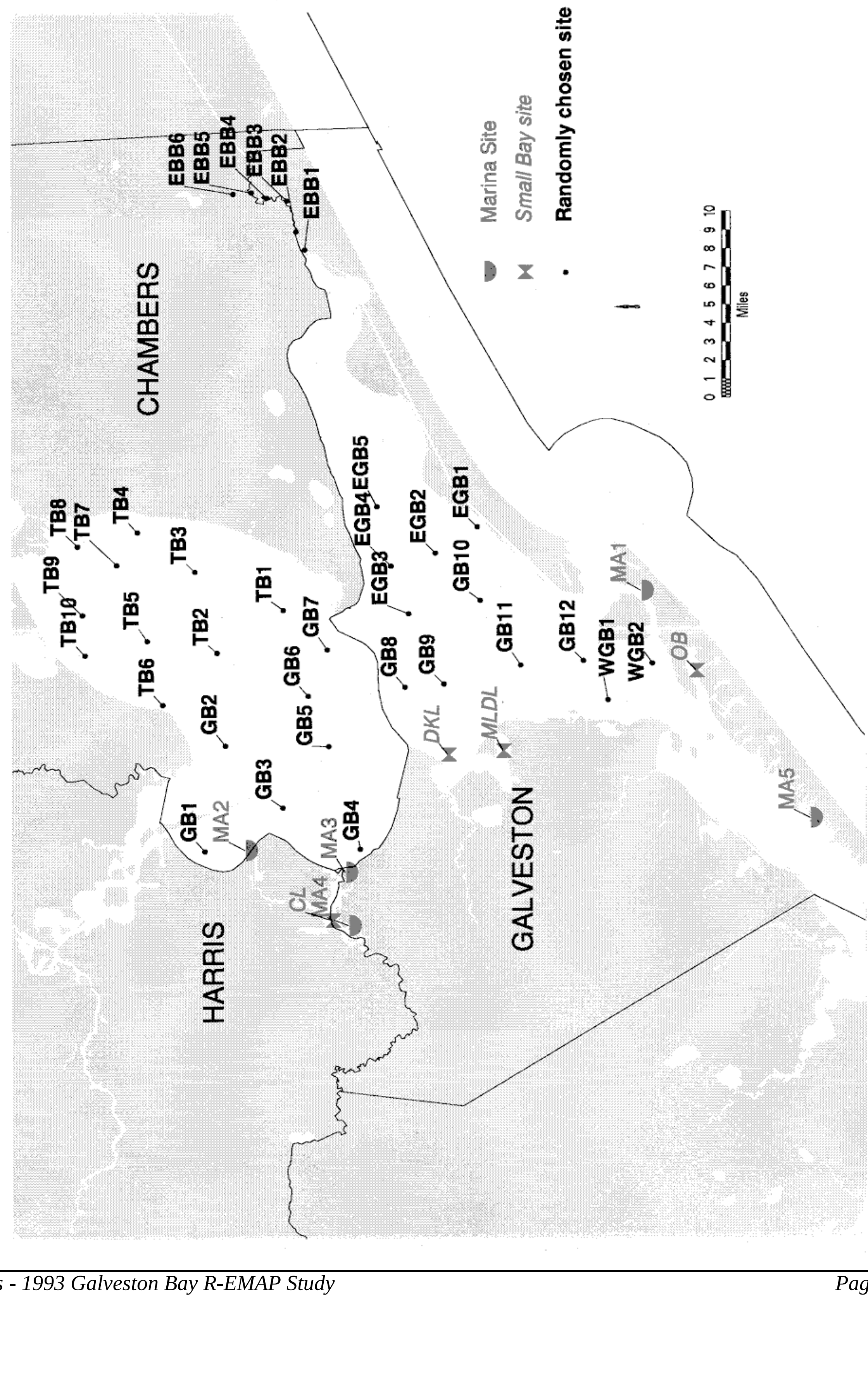
For comparison of Galveston Bay with other systems and the Louisianian Province as a whole, twenty-nine randomly selected sites were chosen to represent 1305 km^2 of surface area in Galveston Bay. Random sites are located in Galveston Bay (GB), Trinity Bay (TB), East Bay (EGB), and West Bay (WGB). In addition, a random sample was taken for each of four important small bays associated with Galveston Bay: Clear Lake (CL, 5.6 km^2), Dickenson Bay (DKL, 11.0 km^2), Moses Lake/Dollar Bay (MLDL, 7.7 km^2), and Offat=s Bayou (OB, 2.6 km^2). Also, five marina sites (MA) were chosen to determine local marina influences (see Map 1a). The tidal areas of major tributaries, including the Houston Ship Channel, were not sampled in this study.

The 1993 REMAP Study also includes six sites in East Bay Bayou, ten sites in the Arroyo Colorado, and three sites in the Rio Grande River (see Map 1b). These three small systems will be addressed in a separate report. Sites in East Bay Bayou (EBB 1-6) are shown in Map 1a because of their proximity to the Galveston Bay study area. East Bay Bayou, Arroyo Colorado, and the Rio Grande sites were selected by placing the first site at the mouth of the system and placing each additional site 2.5 km^2 upstream of the preceding site.

All samples were collected and analyzed using EMAP Protocols (Summers and Macauley, 1993. AStatistical Summary: EMAP - Estuaries Louisianian Province - 1991", Appendix A). Samples for analysis of benthic macroinvertebrate community structure, sediment toxicity, and sediment chemistry were collected for all 38 sites. Benthic macroinvertebrate samples for measures of species composition, abundance, and biomass were collected at all sampling sites. Samples were collected with a Young-modified Van Veen grab which samples a surface area of 440 cm^2. Three grabs were collected at each site. A small core was taken from each grab, and shipped on ice to the laboratory for sediment characterization (grain size, silt-clay content, acid volatile sulfides, and total organic carbon). The remaining sample was sieved through a 0.5 mm screen, with all organisms remaining on the sieve identified and counted.

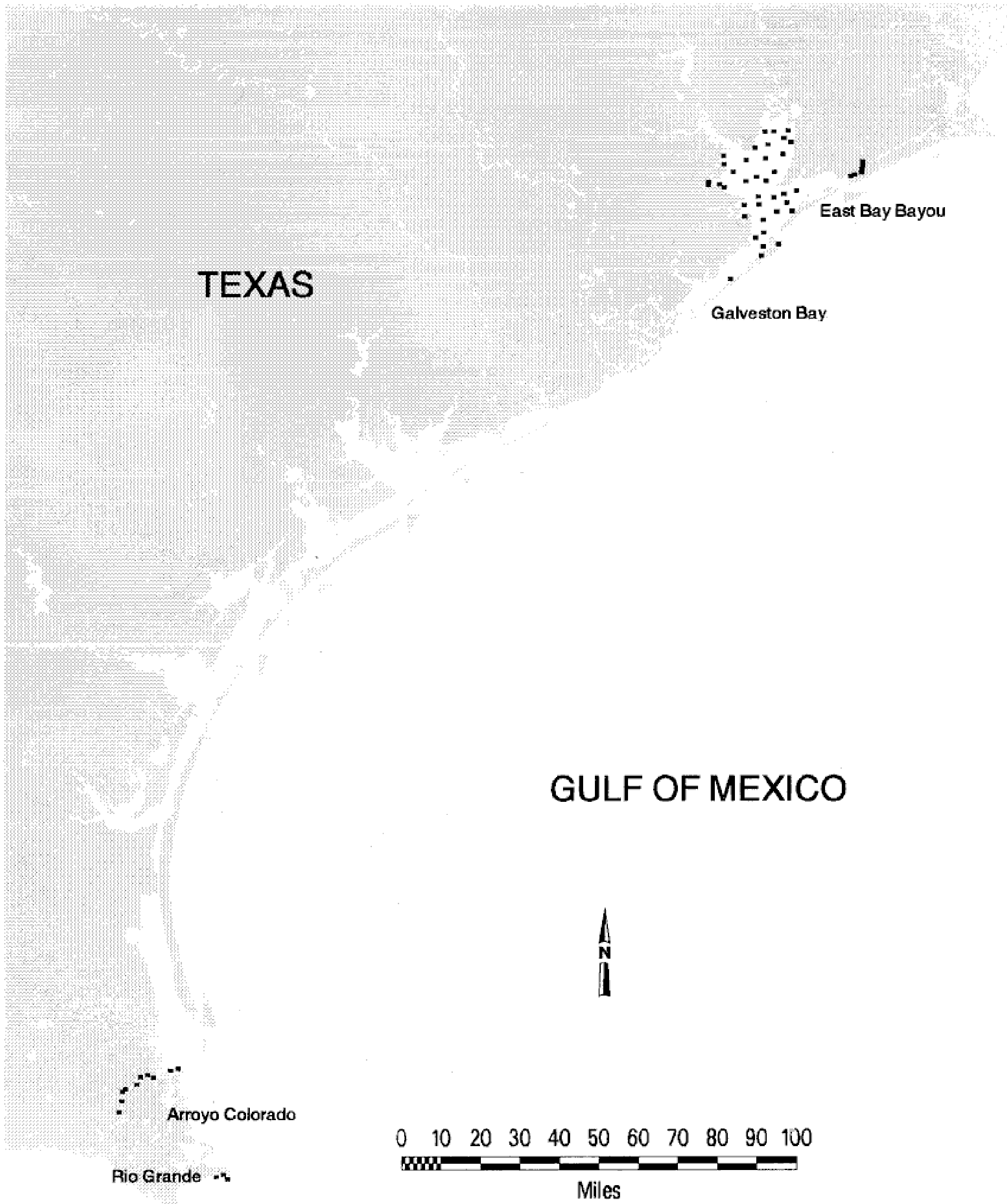
Sediment for the toxicity tests were collected using the Young-modified Van Veen grab. Sediments from the top 2 cm of 6 - 10 grabs were placed in a mixing bowl, homogenized, placed in containers, and stored on ice for transport. Sediment toxicity tests were performed using the standard 10-day acute test method and the tube-dwelling amphipod *Ampelisca abdita*. In addition, standard 4-day acute tests using the mysid, *Mysidopsis bahia*, were conducted.

Sediment samples for contaminant analysis were collected from a homogenate created during sampling by combining the top 2 cm of sediment from 6 - 10 sediment grabs. Sediments for organic analysis were placed in clean glass jars with foil lid liners, shipped on ice, and stored frozen in the laboratory prior to analysis. Sediment for metals analysis were placed in a plastic bag, shipped on ice, and stored in the laboratory prior to analysis. Sediment contaminants analyzed included 44 individual Polynuclear Aromatic Hydrocarbons (PAHs), High Molecular Weight PAHs, and Low Molecular Weight PAHs, 20 polychlorinated biphenyl congeners, 24 pesticides (including DDT and its metabolites), 15 heavy metals, and 3 butyltins.



Map 1a. Sampling Sites in the Galveston Bay Complex and the East Bay Bayou Area

Map 1b. Texas Estuaries Sampled during the 1993 R-EMAP Study



Measurements of water column temperature, dissolved oxygen, salinity, pH, water depth, and secchi depth were taken at all sites. Water samples were collected for mono-, di-, and tri- butyltin analysis at marina sites only.

Samples of fish tissue and fish community structure were not collected for the Galveston Bay R-EMAP Study.

Statistics

Variables that were not normally distributed and did not have acceptable homogeneity of variances were log-transformed to provide a normal distribution of the data. Many, but not all log-transformed variable distributions, were normal.

Spearman's Correlation Coefficients, Pearson's Correlation Coefficients, Linear Regressions, and 95% Confidence Intervals were determined using the Windows Version of the Statistical Program for the Social Sciences (SPSS). Cluster Analyses, Principal Component Analyses (PCA), and Bartlett's Test for Sphericity were determined using the Windows Version of Statistical Applications for the Sciences (SAS). The approach for the Sediment Quality Triad (SQT) data analysis using PCA was adapted from Green and Montagna (1996). Normally distributed data is preferred when using PCA. Sediment chemistry variables used in the principal components analysis which were not normally distributed after log-transformation included: aluminum, silt-clay content, nickel, lead, and the three forms of butyltin. Major variables in the sediment chemistry analysis had communality values of 0.8 or greater. The first set of factor scores were used to calculate the final Sediment Chemistry Component values, which accounted for 66% of the sediment chemistry variation and mainly represented heavy metals and silt-clay content.

RESULTS AND DISCUSSION

BENTHIC DISTRIBUTIONS: Biotic Habitat Indicators for Sediments

Several metrics were used to determine the benthic community health. Metrics calculated for each site include: abundance of benthic organisms, abundance of benthic organisms excluding polychaetes, the Benthic Index (Engle and Summers, in press), the Benthic Diversity Index (the Shannon-Weiner Index), number of species (species richness), and abundance of amphipods, gastropods, tubificids, and polychaetes. Other metrics calculated for this study for each site but not discussed in this report include: number of polychaete species, polychaete/amphipod ratio, and abundance of bivalves, decapods, and capitellids.

Abundance of Benthic Organisms

Abundance values represent the number of benthic macroinvertebrates found per grab at each site. The relative proportion of abundances of the 29 randomly selected sites in Galveston Bay were similar to abundances for the Louisianian Province. Selected small bay and marina sites in Galveston Bay have much lower relative abundances than the Galveston Bay and Louisianian Province sites (Tables 1 & 2, Figures 1 & 2).

Seven percent of Galveston Bay area and 22% of small bay/marina sites had abundances less than 10. Five percent of Louisianian Province area had abundances less than 10, indicating low benthic abundance. Twenty-eight percent of Galveston Bay area and 22% of small bay/marina sites had abundances from 10 to 25. Fifteen percent of Louisianian Province area had abundances from 10 and 25, indicating marginal benthic abundance.

Abundances in Galveston Bay ranged from 1 to 217 mean number of organisms per site per grab. Higher values generally contained large numbers of polychaetes. Site MA3 had low species richness, Benthic Index, and diversity index values, but it had 137 polychaetes and only 4 other organisms! Polychaetes can respond positively to high PAHs which could complicate the response of the total benthic abundance due to sediment contamination (Peterson et al., 1996). Removal of polychaete numbers from the total abundance clarified the relationship somewhat, but not completely. Abundance without polychaetes ranged from 0 to 81 mean number of organisms per site per grab.

Figure 1. Benthic Abundance Categories Compared by Percent of Area or Sites and 90% Confidence Intervals.

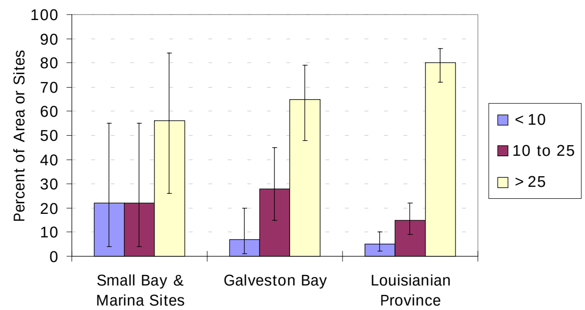
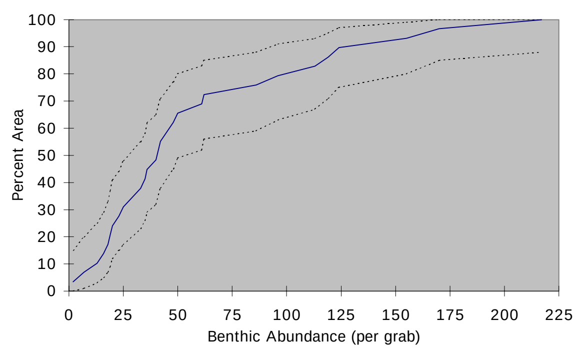


Figure 2. CDF of Benthic Abundance for Galveston Bay.



Benthic Index

Two sets of Benthic Index equations were developed for the Louisianian Province estuaries by Engle and Summers using EMAP data for the Louisianian Province (Engle, et al., 1994). The second set of equations was used for this study. The Benthic Index was developed to provide environmental managers with a simple tool to assess ecological conditions of benthic macro-invertebrate communities. The Benthic Index equation combines the Shannon-Wiener Diversity Index (adjusted for salinity), tubificid oligochaete abundance, percent capitellid polychaetes, percent bivalves, and percent amphipods:

Equation =
(1.5710 * Proportion of expected diversity) +
(-1.0335 * Mean abundance of tubificids) +
(-0.5607 * Percent capitellids) +
(-0.4470 * Percent bivalves) +
(0.5023 * Percent amphipods).

Benthic Index values less than 3.0 indicate a degraded benthic community; values between 3.0 and 5.0 indicate a marginal benthic community; and values greater than 5.0 indicate a healthy benthic community (Engle, pers com.).

The Benthic Index value proportions for the 29 randomly selected sites in Galveston Bay are higher than index values for the Louisianian Province. Small Bay and Marina sites in Galveston Bay had much lower index values relative to the Galveston Bay and Louisianian Province sites (Tables 1 & 2, Figures 3 & 4, Map 2).

Figure 3. Benthic Index Categories Compared by Percent of Area or Sites and 90% Confidence Intervals.

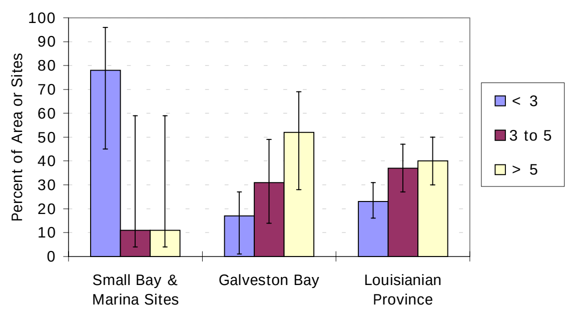
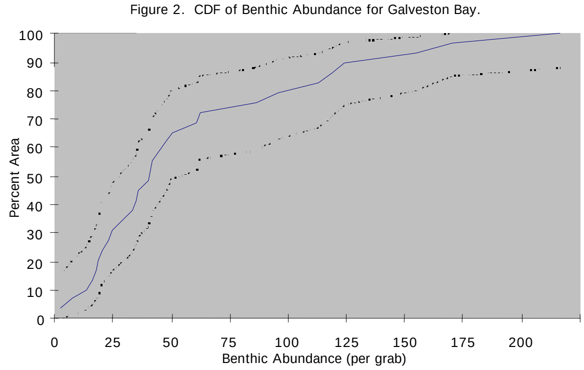


Figure 2. CDF of Benthic Abundance for Galveston Bay.



Fifty-two percent of the Galveston Bay area and 11% of small bay/marina sites had a Benthic Index value greater than 5.0, which indicated a healthy benthic community structure. (The Galveston Bay data actually has distinct separations points at 4.0 and 5.1.) Forty-five percent of the Galveston Bay area had Benthic Index values greater than 5.1. Forty percent of the Louisianian Province area had Benthic Index values greater than 5.0. Seventeen percent of the Galveston Bay area and 78% of small bay/marina sites had Benthic Index values less than 3.0, which indicated stressed or degraded benthic communities. Twenty-three percent of the Louisianian Province area had Benthic Index values less than 3.0.

The Benthic Index proved useful in demonstrating that communities living in contaminated sediments had a community structure indicating poor conditions. A significant negative relationship exists between sediments contaminated with heavy metals and low benthic index values ($R = -0.62$, $F=0.00$). These two factors, metal concentrations and benthic values indicate contamination. When comparing the benthic index with PAHs, a significant relationship does not exist ($R = -0.37$). Polychaetes responded positively or indifferently to PAH enrichment at some sites which could explain the non-significant value (Peterson et al., 1996).

Species Richness

Benthic species richness is a measure of the number of species found per grab at each site sampled. The benthic species richness proportions for the area represented by the 29 randomly selected sites in Galveston Bay were similar to species proportions for the Louisianian Province. Selected small bay and marina sites in Galveston Bay had much lower species richness overall than the Galveston Bay and Louisianian Province sites. Sites with total number of benthic species (mean species or species richness) less than or equal to five included 3 Galveston Bay sites (GB1,6,7), and 6 small bay/marina sites (OB, CL, MA2,3,4,5) (Table 1, Figures 5 & 6). Ten percent of Galveston Bay sites and 67% of small bay/marina sites had less than or equal to five species present. Fourteen percent of the Louisianian Province area had less than or equal to five species present. The poorest sites, with species richness equal to 1 or 2 include: GB7 (1), MA3 (2), MA4 (1), OB (1).

Map 2. Benthic Index Distributions

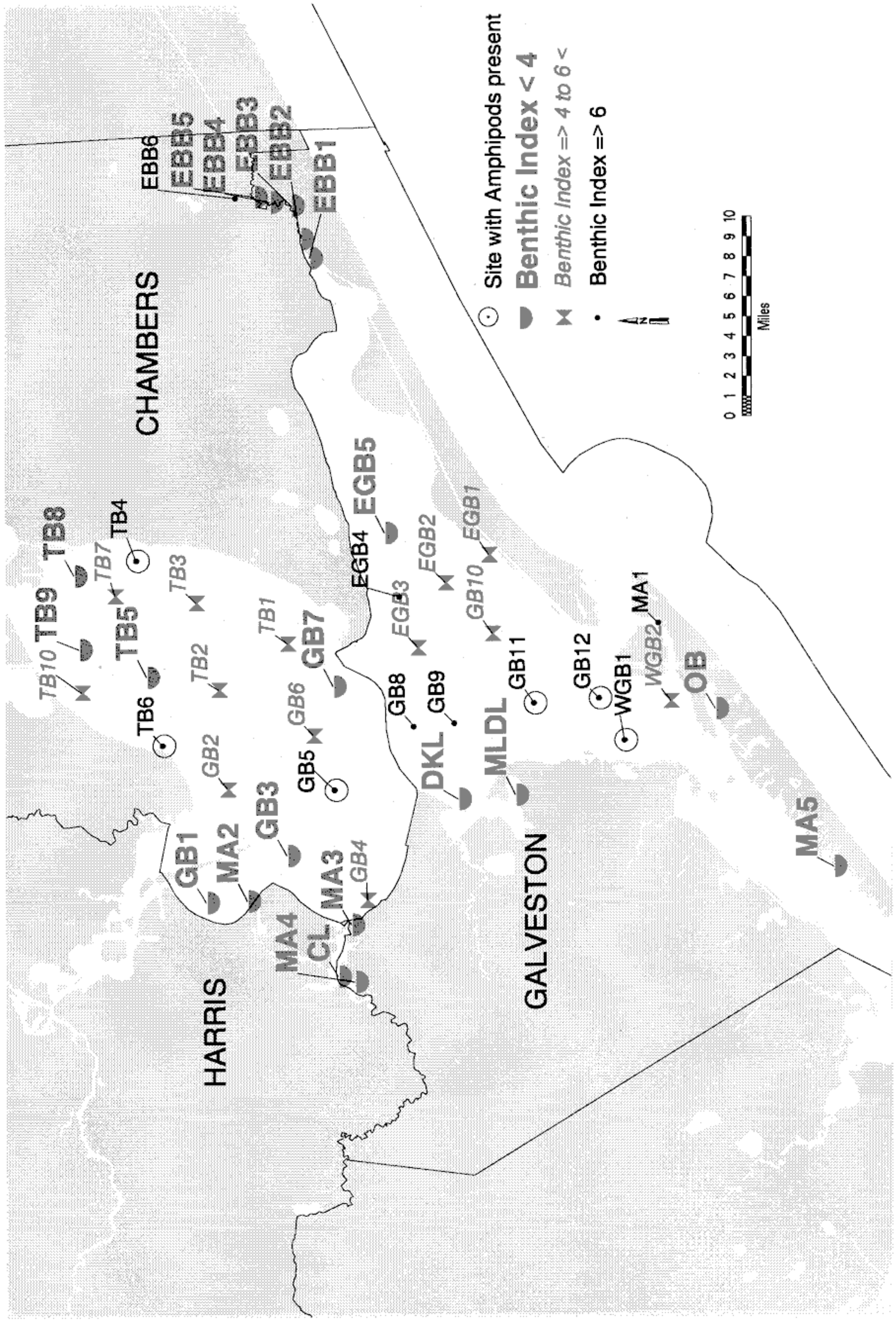


Figure 5. Benthic Species Richness Categories Compared by Percent of Area or Sites and 90% Confidence Intervals.

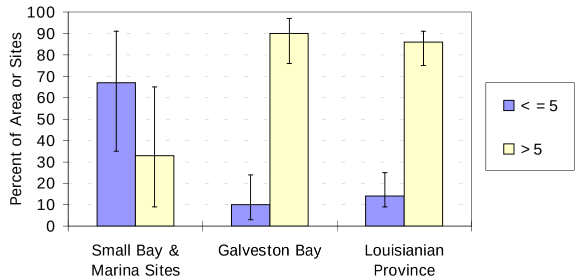
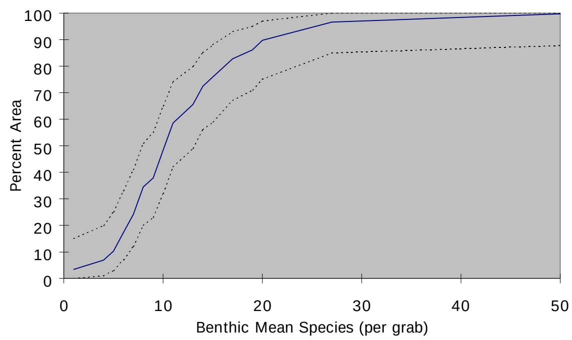


Figure 6. CDF of Benthic Species Richness for Galveston Bay.



Benthic Diversity Index (Shannon-Wiener Diversity Index)

The Shannon-Wiener Diversity Index is a measure of both species richness and species evenness (which is the distribution of individuals among species). The Benthic Diversity Index refers to the measure of benthic macroinvertebrates using the Shannon-Wiener Index.

The Benthic Diversity Index proportions for the Galveston Bay area were similar to the diversity index proportions for the Louisianian Province. However, the area with diversity index values greater than 1.0 was only 17% for Galveston Bay compared to approximately 30% for the Louisianian Province. Selected small bay and marina sites in Galveston Bay had much lower diversity values overall than the Galveston Bay and Louisianian Province sites (Tables 1 & 2, Figures 7 & 8, Map 3). In the present study, Benthic Diversity Index values less than 0.4 indicate poor community structure; values between 0.4 and 0.7 indicate marginal community structure; and values greater than 0.7 indicate a healthy benthic community. The relationship between ten toxic heavy metals and the diversity index was significant (R = -0.61, F=0.00). The diversity index was not closely associated with aluminum, silt-clay content, or PAHs.

Figure 7. Benthic Diversity Index Categories Compared by Percent of Area or Sites and 90% Confidence Intervals.

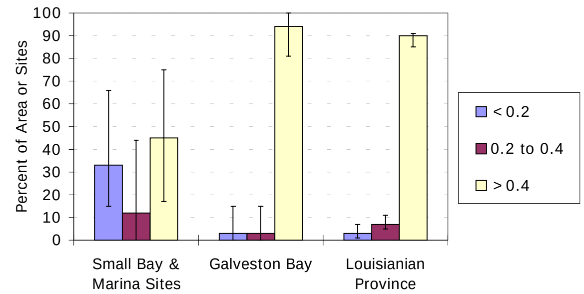
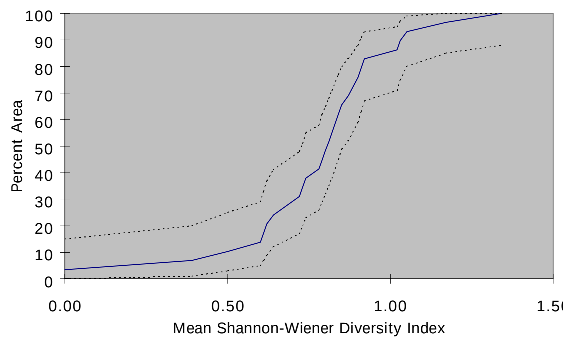


Figure 8. CDF of Benthic Diversity in Galveston Bay.



Abundances of Amphipods, Tubificids, Gastropods, and Polychaetes

Amphipods, tubificids, gastropods, and polychaetes are key groups of organisms. Abundance measurements of each provide a measure of benthic community structure. Amphipod occurrence in sediments of the area represented by the 29 randomly selected sites in Galveston Bay and the small bay/marina sites is significantly lower relative to the Louisianian Province (Table 3). Amphipods were found only at sites that had low metal concentrations, low combined pollution concentrations, low percentage of mud sediments, high benthic indices, and high benthic diversities (Map 2 & 3).

Their presence was used in this study as an indication of healthy benthic conditions (although they were not found at every site with high index values and low pollution values). Amphipod distributions were not limited to high or low salinity (Table 3, Figures 9 & 10). Amphipods were found at six sites: WGB1 (3), TB6 (1), TB4 (8), GB5 (17), GB11 (4), GB12 (8). Low occurrence of amphipods in Galveston Bay could be due to degradation.

Tubificids are a group of oligochaete worms that are considered opportunistic. Galveston Bay and the small bay & marina sites have a lower relative occurrence of tubificids than the Louisianian Province (Table 3, Figures 9 & 11).

Gastropods did not occur as frequently in Galveston Bay and its small bay & marina sites as in the Louisianian Province (Table 3, Figures 9 & 12).

Polychaetes were the dominant benthic class found in Galveston Bay sediment samples. Polychaete presence in samples were similar for all Galveston Bay sites and the Louisianian Province (Table 3). Only one Galveston Bay site (GB7, in upper Galveston Bay)(Figure 13), and only one small bay/marina site (OB, Offat=s Bayou) did not have polychaetes present. Very few sites in the Louisianian Province area did not have polychaetes present.

Figure 9. Percent of Area or Sites with Amphipods, Tubificids, Gastropods, or Polychaetes Present and 90% Confidence Intervals.

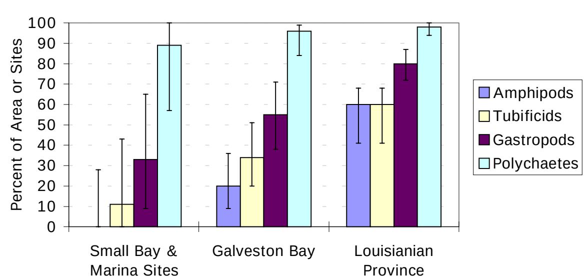


Figure 10. CDF of Amphipod Abundance in Galveston Bay.

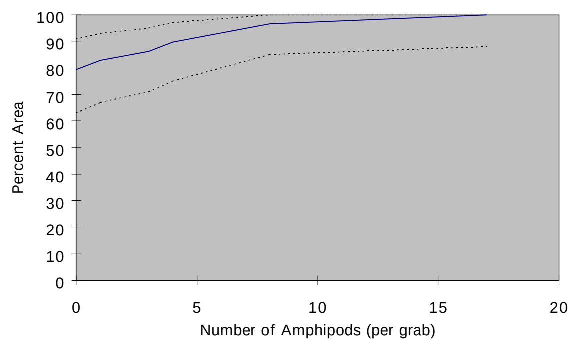


Figure 11. CDF for Mean Tubificid Abundance in Galveston Bay

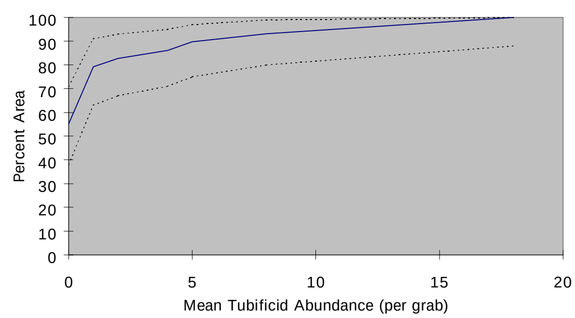


Figure 12. CDF of Gastropod Abundance in Galveston Bay.

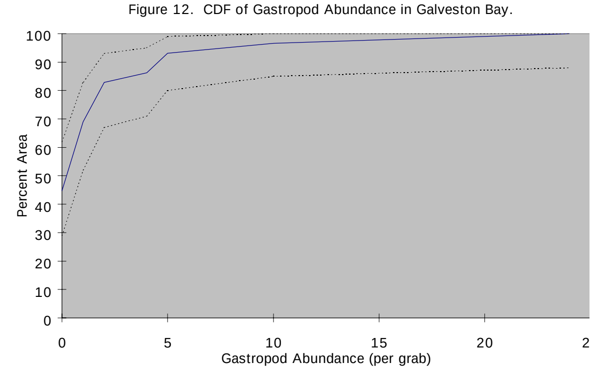
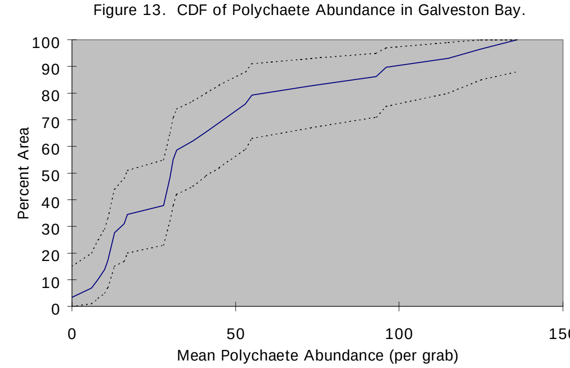


Figure 13. CDF of Polychaete Abundance in Galveston Bay.



Map 3. Benthic Diversity Index Distributions

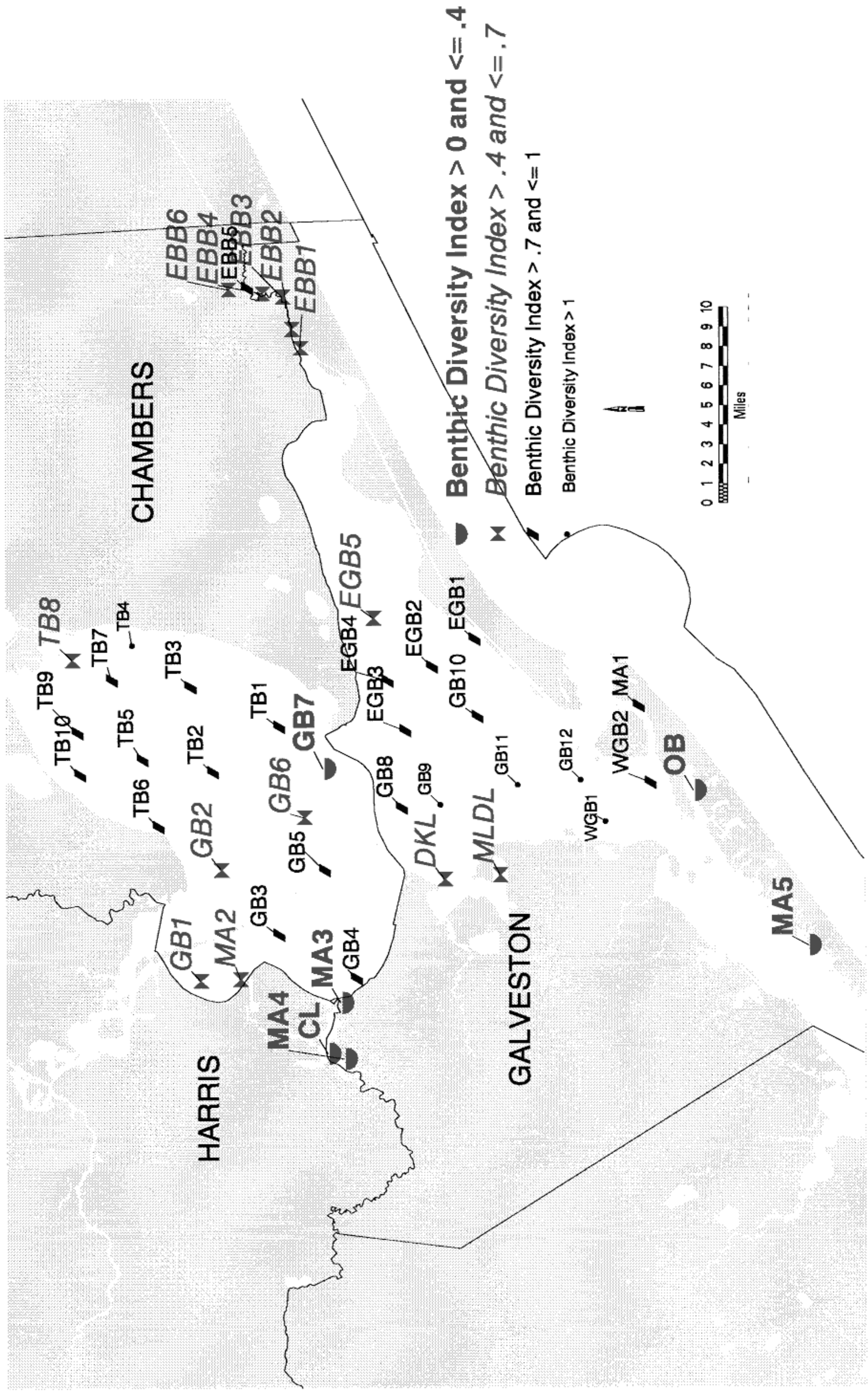


Table 1. Galveston Bay Benthic Community Values.

Station	Benthic Index	Mean Diversity	Mean Abundance	Mean Species
GB1	3.37	0.50	13	4
GB2	4.36	0.62	19	6
GB3	2.30	0.74	23	6
GB4	4.66	0.79	36	8
GB5	11.10	0.90	48	14
GB6	4.88	0.64	7	5
GB7	0.05	0.00	2	1
GB8	6.01	0.87	48	14
GB9	6.84	1.03	61	20
GB10	4.89	0.84	50	13
GB11	6.57	1.02	170	27
GB12	9.50	0.81	124	27
TB1	5.02	0.73	20	8
TB2	4.96	0.72	18	8
TB3	5.03	0.91	25	10
TB4	6.89	1.05	119	17
TB5	2.07	0.72	113	15
TB6	6.20	0.78	16	7
TB7	5.89	0.80	62	11
TB8	1.19	0.60	96	9
TB9	2.23	0.84	155	17
TB10	4.86	0.81	40	10
EGB1	5.49	0.85	42	13
EGB2	5.51	0.82	42	11
EGB3	4.03	0.74	23	10
EGB4	6.18	0.90	33	11
EGB5	3.42	0.61	35	7
WGB1	11.90	1.34	217	52
WGB2	5.74	0.92	86	19
OB	0.05	0.00	1	1
MLDL	2.86	0.53	26	6
DKL	2.95	0.57	47	8
CL	2.31	0.28	10	3
MA1	6.16	0.75	14	7
MA2	1.57	0.47	42	5
MA3	-0.34	0.05	137	2
MA4	0.05	0.00	2	1
MA5	3.00	0.27	49	4

* Benthic Index Range = -2.0 to +12.0. Shaded values indicate poor benthic community structure.

Table 2. Benthic Community Structure Group Comparisons by Percent of Area or Sites.

	MEAN ABUNDANCE			BENTHIC INDEX			BENTHIC DIVERSITY INDEX			MEAN SPECIES	
	<10	10 - 25	>25	<3	3 - 5	>5	<0.2	0.2- 0.4	>0.4	<=5	>5
GB Small Bays / Marinas	22%	22%	66%	78%	11%	11%	33%	12%	45%	67%	33%
Galveston Bay	7%	28%	65%	17%	31%	52%	3%	3%	94%	10%	90%
Louisiana Province	5%	15%	80%	23%	37%	40%	3%	7%	90%	14%	86%

Table 3. Presence of Amphipods, Tubificids, Gastropods, and Polychaetes Comparisons by Percent of Area or Sites.

	AMPHIPODS PRESENT	TUBIFICIDS PRESENT	GASTROPODS PRESENT	POLYCHAETES PRESENT
GB Small Bays/Marinas	0%	11%	33%	89%
Galveston Bay	20%	34%	55%	96%
Louisiana Province	60%	60%	80%	88%

TOXICITY

Ampelisca abdita (the tube dwelling amphipod), and *Mysidopsis bahia* (a mysid shrimp) were used as the lab organisms to test toxicity. Toxicity was not not found at any site when using mysid shrimp as a test organism, but toxicity was reported when using amphipods. Sites with toxic sediments, based on amphipod tests, included: Offat=s Bayou (OB) with 13% mortality, Dickinson Lake (DKL) with 13% mortality, and West Galveston Bay near Swan Lake (WGB1) with 14% mortality. Sites with sediments not considered toxic had amphipod mortality values of 3% to 8%. Only 3.5% of Galveston Bay sites and 22% of Small Bay and Marina sites had toxic sediments. Toxicity could not be associated with any of the parameters measured or with the presence or absence of natural amphipod populations present at each site. Site OB did not have any benthic organisms present, and site DKL had low benthic numbers and structure. In contrast, site WGB1 had amphipods present in the sediments and high benthic numbers and structure. The only apparent similarity is that all three sites are located in the same general location of the bay, although the general location probably is not a factor in toxicity.

Sediment toxicity tests using amphipods results indicated that acute toxicity due to contaminated sediments occurred infrequently in sediments sampled for Galveston Bay. Carr (1993) also reported very low occurrence of amphipod toxicity in Galveston Bay sediments. However, in contrast, he reported that significant toxicity was observed at a number of sites when sea urchin (*Arbacia punctulata*) fertilization and morphological development assays were used.

SEDIMENT COMPONENT DISTRIBUTIONS: Abiotic Habitat Indicators for Sediments

Total Organic Carbon

Total Organic Carbon (TOC) in Galveston Bay sediments ranged from 0.14% (at EGB5) to 2.43% (at EGB1). Proportions of TOC concentrations in sediments for the area represented by the 29 randomly selected sites in Galveston Bay were lower overall than the entire Louisianian Province area. Selected small bay and marina sites in Galveston Bay have similar distributions of sediment TOC concentrations as the Louisianian Province sites. Galveston Bay area consists of 62% low sediment organic content (<1% TOC), 34% slightly enriched (1-2% TOC), and 3% highly enriched (>2% TOC). Small Bay and Marina sites consist of 44% low TOC concentrations, 44% slightly enriched, and 12% highly enriched. The Louisianian Province area consists of 49% low organic content, 37% slightly enriched, and 14% highly enriched (Figures 14 & 15).

Sediment Composition (Silt-Clay Content in Sediments)

Proportions of Silt-Clay in sediments for the area represented by the 29 randomly selected sites in Galveston Bay are higher than Silt-Clay contents in sediments throughout the Louisianian Province (Figures 16 & 17). The Galveston Bay area consists of 48% mud, 45% muddy sand, and 7% sand. Small Bay and Marina sites consists of 67% mud, and 33% muddy sand. The Louisianian Province area consists of 35% mud (>80%), 44% muddy sand, and 21% sand (<20%).

Sediment texture is an important factor in determining which benthic organisms will be found in the estuarine environment. The texture of sediment is defined by the percentage of silt, clay, and sand in sediment. Higher Mean Amphipod Abundance and higher Benthic Index values are associated with lower Silt-Clay percentages in the sediments with correlations of -0.57 and -0.67, respectively.

Figure 14. Total Organic Carbon Distributions in the Sediments and 90% Confidence Intervals

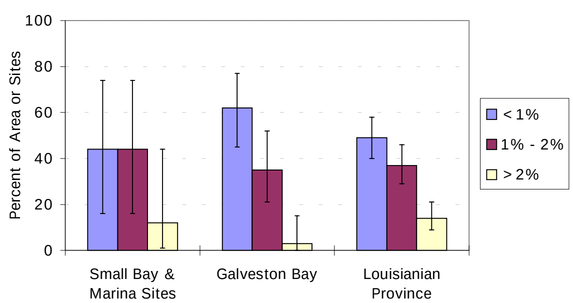


Figure 16. Sediment Composition Compared by Percent of Area or Sites and 90% Confidence Intervals

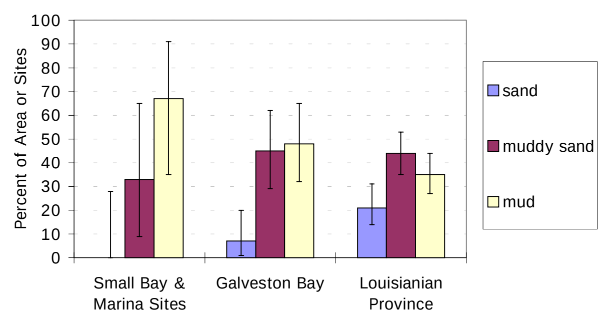


Figure 15. CDF of Total Organic Carbon in Galveston Bay Sediments.

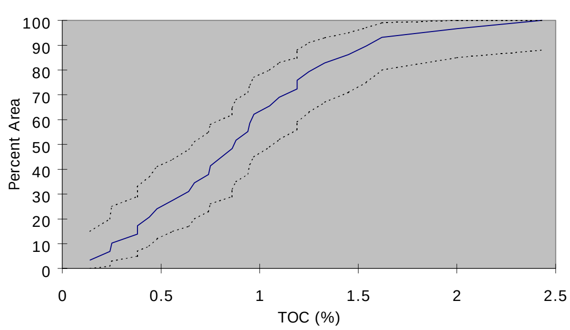
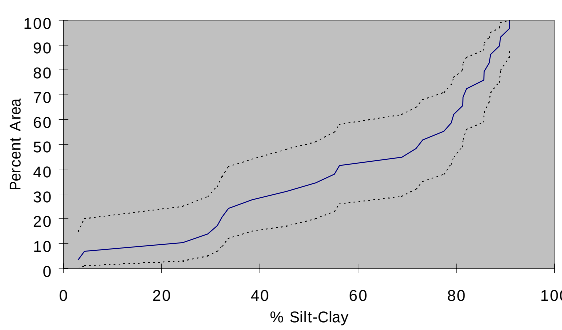


Figure 17. CDF of Percent of Silt-Clay in Galveston Bay Sediments.



Aluminum in Sediments

The earth=s crust is the source of most of the aluminum found in sediments. Aluminum does not have a significant anthropogenic source. For the Texas estuaries sampled in 1993, aluminum values covary with sediment texture and other heavy metal concentrations in the sediments.

In Galveston Bay and the small bays and marina areas sampled, a significant relationship exists between percent aluminum distribution and the percent silt-clay distribution (R = 0.84). A significant relationship (R = -0.44) does not exist between aluminum and the benthic index.

Aluminum concentrations in sediments at the Small Bay and Marina sites were high, indicating that all of these sites are in high depositional areas with aluminum concentrations greater than 3.6% (Table 4, Figures 18 & 19, Map 4).

Figure 18. Categories of Percent Aluminum in Sediments Compared by Percent of Area or Sites and 90% Confidence Intervals.

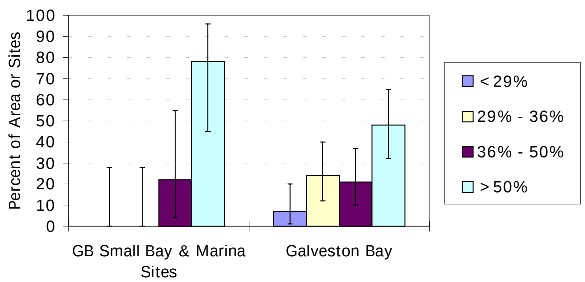
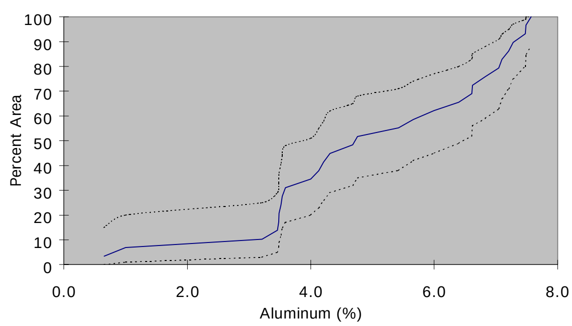


Figure 19. CDF of Aluminum Concentration in Galveston Bay Sediments.



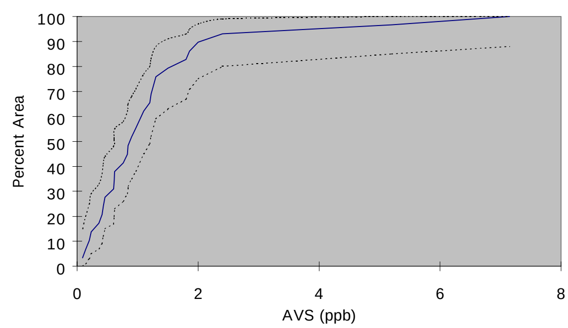
Acid Volatile Sulfides

Acid Volatile Sulfides (AVS) are important in controlling the bioavailability of metals under anoxic conditions (DiToro, et al., 1991). In the Louisianian Province sediments, the AVS concentration ranged from 1 - 20 umoles. Approximately 50% of the Louisianian Province area has an AVS concentration in the sediments of less than or equal to 1 umole/gram. Approximately 93% of the Louisianian Province estuarine area has 3 or less umoles/gram of AVS in the sediments.

The AVS concentration in Galveston Bay ranged from 0.2 to 7.2 umoles/gram. Galveston Bay has AVS sediment concentrations less than or equal to 1 umole at 66% of the area represented by the 29 randomly selected sites (Figure 20). Overall, the Galveston Bay area has lower AVS concentrations than the distribution throughout the Louisianian Province. In the Galveston Bay, 93% of the area had AVS concentrations less than 3 umoles/gram, which is the same as the distribution for the Louisianian Province.

AVS concentrations in the sediments of Small Bay and Marina sites ranged from 1.2 to 10.0 umoles/gram. AVS concentrations are higher than 3 umoles/gram at 7 of 9 sites or 78% of sites.

Figure 20. CDF of Acid Volatile Sulfides in Galveston Bay Sediments.



Map 4. Aluminum and Silt-Clay Distributions in Sediments Grouped Using Cluster Analysis

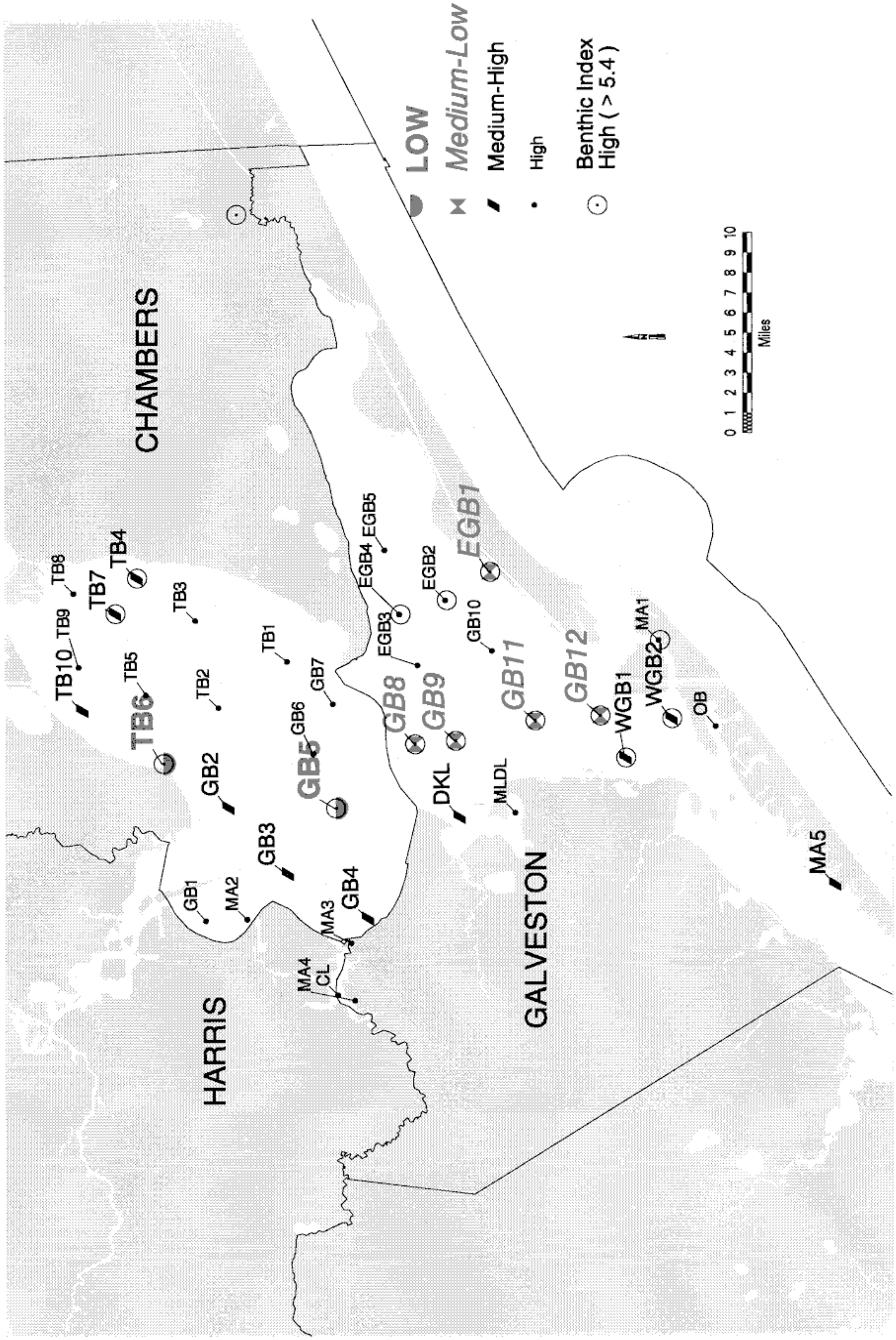


Table 4. Sediment Component Distributions.

System	% SILT-CLAY CONTENT			% ALUMINUM				% TOTAL ORGANIC CARBON		
	<20%	20 - 80	>80%	<2.9	2.9 - 3.6	3.6 - 5.0	>5.0	<1%	1 - 2	>2%
GB Small Bays/Marinas	0	33	67	0	0	22	78	44	44	12
Galveston Bay	7	45	48	7	24	21	48	62	35	3
Louisiana Province	21	44	35	?	?	?	?	49	37	14

Table 5. Acid Volatile Sulfides Distributions in Sediments.

System	ACID VOLATILE SULFIDES (UMOLES/GRAM)		
	<1	1 to 3	>3
GB Small Bays/Marinas	0	22	78
Galveston Bay	66	27	7
Louisiana Province	~50	~43	~7

Heavy Metal Distributions Identifying Areas with Exceedences and Contamination from Anthropogenic Sources

Concentrations for fifteen heavy metals in sediments of Galveston Bay were collected at 38 sites. Heavy metals were compared to established criteria and anthropogenic enrichment. The range-low (ERL) criteria was established using the lower 10^{th} percentile of effects data for each metal or chemical. Concentrations equal to or above the ERL, but below the ERM, represent a possible-effects range within which effects would occasionally occur. The range-high (ERM) criteria was established using the 50^{th} percentile of the effects data. The concentrations equal to or higher than the ERM value represent a probable-effects range within which effects would frequently occur (Long, et al., 1995). The concentrations equal to the NOEL value is the highest level at which Ano observed effects@ occur (MacDonald, 1992). Anthropogenic enrichment was determined using regression equations for each metal against aluminum concentrations in the sediments. Aluminum is used as a normalization factor because it is an abundant and relatively uniform crustal element, and it does not have a significant anthropogenic source (Summers, et al., 1996). Two sets of equations were used: 1) Hanson et al., 1993 and 2) Summers et al., 1996. Hanson=s equations were developed from data collected along the Atlantic and the Gulf of Mexico U.S. coasts. Summers= equations were developed from data collected during EMAP Studies for the Gulf of Mexico U.S. coastal area only.

Metals of greatest concern for monitoring include cadmium, chromium, mercury, lead, arsenic, selenium, and antimony because they are highly toxic to biota and they have few natural functions in biotic processes (Kennish, 1992). Copper, nickel, silver, tin, and zinc also are toxic to biota (Freedman, 1989). These 12 metals (except selenium) have the criteria threshold values, ERL, ERM, and NOEL, associated with them.

Agriculture is an important source of arsenic, lead, and copper pollution. Automobiles and boats are major sources of lead pollution, and they are also a source of cadmium, chromium, copper, nickel, and zinc pollution. Sewage sludge is a source for several heavy metal pollutants. Industry is a major source of nickel, copper, zinc, lead, cadmium, and other metal pollutants (Freedman, 1989).

Sources of metal contamination according to Cole et al. (1984) include the following:

Arsenic - fossil fuel combustion and industrial discharges.
Cadmium - corrosion of alloys and plated surfaces, electroplating wastes, exterior paints and stains, and industrial discharge.
Copper - corrosion of copper plumbing, anti-fouling paint, and electroplating wastes.
Lead - leaded gasoline, batteries, and exterior paints and stains.
Mercury - natural erosion and industrial discharges.
Zinc - tires, galvanized metal, and exterior paints and stains.

In Galveston Bay, arsenic, copper, lead, nickel, and zinc exceed the ERL but not the ERM criteria at one or more sites sampled (Tables 6 & 7, Figure 21). NOEL values, but not ERL values, are exceeded at one or more sites for arsenic, chromium, lead, mercury, and zinc (Table 8). Sites with the most metals contamination include Offat=s Bayou (OB), Clear Lake (CL), Moses Lake/Dollar Bay (MLDL), and two Marina sites (Table 8, Maps 5 and 6). The Small Bay and Marina sites were chosen, not randomly selected, so they are not included in the comparison of Galveston Bay with the entire Louisianian Province 1993 EMAP sampling area.

The Galveston Bay area (represented by the 29 randomly chosen sites) has chromium and nickel distributions that are higher than would be expected when compared to the entire Louisianian Province area (Table 9). However, chromium, lead, and nickel are also highly correlated with aluminum, which could indicate that these metals are in high concentrations due to crustal abundance.
Heavy metal concentrations are often normalized to aluminum concentrations to account for the metal concentration expected based on crustal abundance (Summers, et al., 1996). For this study, comparisons focus on the second set of equations developed from the 1993 EMAP data (Macauley et al., 1993). According to these equations, most nickel concentrations in the sediments are high due to anthropogenic sources. In addition, chromium, lead, mercury, silver, and zinc concentrations at several sites are high due to anthropogenic sources. Cadmium, arsenic, and copper concentrations are higher than expected due to natural deposition at a few sites (Table 10, Figure 22). Most sites with metal concentrations exceeding ERL or NOEL values are classified as having anthropogenic sources for these metals.

Figure 21. NOEL Exceedence for Five Metals Compared by Percent of Area or Sites and 90% Confidence Intervals

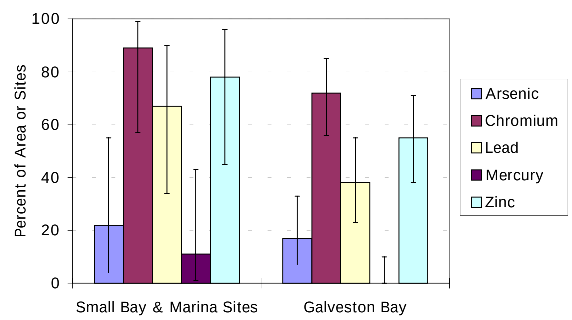
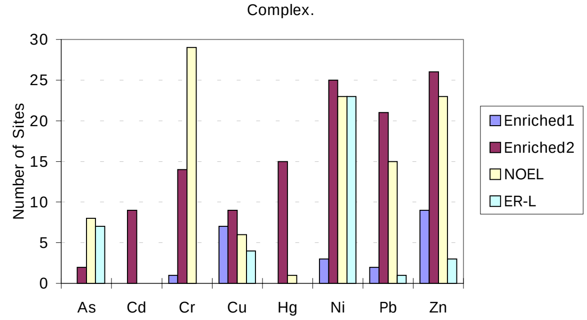


Figure 22. Comparison of Metal Concentration Classifications for Enrichment and Exceedance for 38 Sites in Galveston Bay Complex.



Map 5. Heavy Metals Distributions in Sediments Grouped Using Cluster Analysis

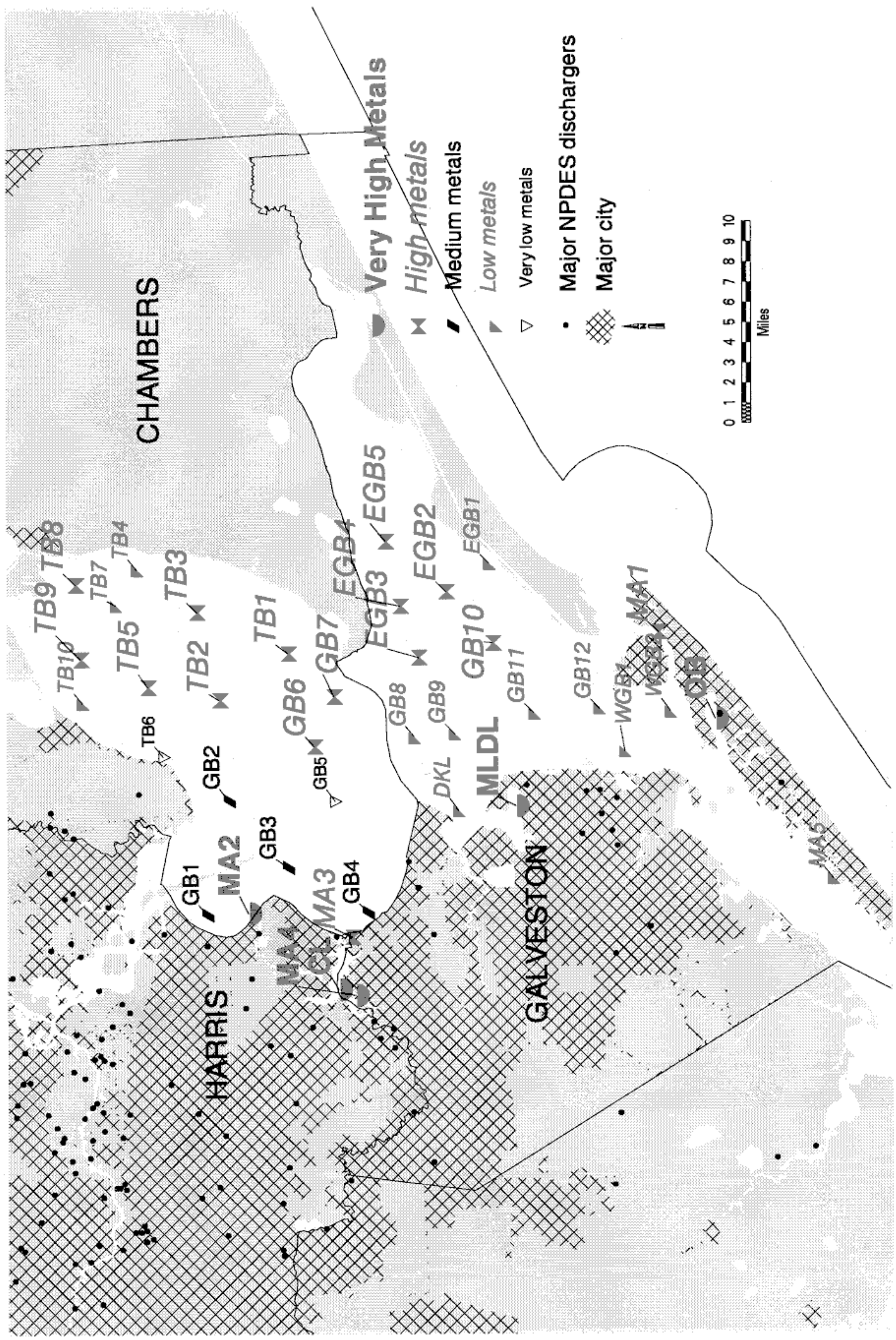


Table 6. Metal Concentration (ppm) Ranges, and ERL & ERM Exceeding in Sediments of Galveston Bay and Its Associated Small Bay & Marina Sites.

METAL	RANGE (PPM)		ERL	ERM	PERCENT EXCEEDED ERL	ERM
Aluminum	6510	75700	NA	NA	NA	NA
Antimony	0.03	0.86	2	25	0%	0%
Arsenic	1.62	11.09	8.2	85 (70)	18% (18%)	0%
Cadmium	0.1	0.78	1.2	9.6	0%	0%
Chromium	6.6	75.5	51 (81)	370	55% (0%)	0%
Copper	2.3	57.8	24 (34)	270	16% (10%)	0%
Iron	2073	40020	NA	NA	NA	NA
Lead	2.51	50.94	46.7	218	3%	0%
Manganese	40.0	1194	NA	NA	NA	NA
Mercury	0.014	0.096	0.15	0.71	0%	0%
Nickel	1.4	33.8	20.9	51.6	60%	0%
Selenium	0.06	0.69	NA	NA	NA	NA
Silver	0.09	0.35	3 (1)	3.7	0%	0%
Tin	0.2	3.4	NA	NA	NA	NA
Zinc	12.4	216.6	150	410	8%	0%

ERL and ERM exceeding values were taken from Long, et al. (1995).
ERL and ERM exceeding values in parentheses were taken from Long and Morgan (1990).

Table 7. Galveston Bay Sites With a Summary of Sediment Metal Concentrations Exceeding ERL or NOEL, and Higher Aluminum and Silt-Clay Content Values for Natural Concentration Comparison.

Stations	Aluminum	Silt-Clay	Arsenic	Chromium	Copper	Lead	Mercury	Nickel	Zinc
GB1	H	H		Cr^ >			>	Ni >	Zn >
GB2			>	Cr^ >	>		>	Ni >	Zn >
GB3				Cr >			>	>	>
GB4		H		Cr^ >	>			>	>
GB5						>			>
GB6*	H	H	As	Cr^ >		Pb >	>	Ni >	Zn >
GB7*	H	H	As	Cr^ >		Pb		Ni >	Zn >
GB8								>	>
GB9									
GB10 *	H	H		Cr^		Pb		Ni >	Zn >
GB11									
GB12							>	>	>
TB1 *	H	H		Cr^		Pb >		Ni	Zn
TB2 *	H	H		Cr^		Pb	>	Ni >	Zn
TB3 *	H			Cr				Ni >	Zn
TB4				Cr				>	
TB5 *	H		As >	Cr^			>	Ni >	Zn >
TB6						>		>	
TB7		H							
TB8 *	H	H		Cr^		Pb >		Ni	Zn
TB9 *	H	H		Cr^ >		Pb >		Ni	Zn
TB10				Cr		>			
EGB1						>		>	
EGB2 *	H	H	As	Cr^		Pb >		Ni	Zn
EGB3 *	H	H		Cr^ >		Pb >		Ni >	Zn
EGB4 *	H	H		Cr^		Pb >		Ni >	Zn
EGB5 *	H	H	As	Cr^ >		Pb >		Ni	Zn >
WGB1				Cr >		>	>	Ni >	Zn >
WGB2				Cr		>	>	>	>
OB *	H	H	As	Cr^ >	Cu >	Pb >	Hg >	Ni >	Zn >
MLDL *	H	H		Cr^	>	Pb >	>	Ni >	Zn >
DKL								>	>
CL *	H	H		Cr^ >	Cu >	Pb >	>	Ni	Zn >
MA1 *	H	H	As	Cr^ >	Cu >	Pb >		Ni >	Zn >
MA2 *	H	H	As	Cr^ >	Cu >	Pb >	>	Ni >	Zn >
MA3 *	H	H		Cr	Cu >			Ni >	Zn >
MA4 *	H	H		Cr^	Cu >	Pb >	>	Ni >	Zn >
MA5				Cr				>	>

* Cluster analysis indicates highest heavy metal concentrations (for 15 metals measured).
Plain type - values exceed NOEL; Shading - values exceed ERL
> - higher than natural abundance; H - high Aluminum or % Silt-Clay values; Cr^ - exceeds old ERL value of 51.

Table 8. Metal Concentration Ranges, and NOEL & ERL Exceeding in Sediments of Galveston Bay and Its Associated Small Bay & Marina Sites.

Heavy Metals	NOEL	ERL	Galveston Bay Percent Exceeded NOEL	Galveston Bay Percent Exceeded ERL	Small Bays/Marinas Percent Exceeded NOEL	Small Bays/Marinas Percent Exceeded ERL
Arsenic	8	8.2	17%	17%	33%	22%
Chromium	33	51.0 (81.0)	72%	52% (0%)	89%	78% (0%)
Copper	28	24.0 (34.0)	0%	0%	67%	67% (44%)
Lead	21	46.7	38%	0%	67%	11%
Mercury	0.1	0.15	0%	0%	11%	0%
Nickel	NA	20.9	NA	55%	NA	78%
Zinc	68	150.0	55%	4%	78%	22%

ERL and ERM exceeding values were taken from Long, et al. (1995).
ERL and ERM exceeding values in parentheses were taken from Long and Morgan (1990).

Table 9. Percent of Area With ERL Exceeded in Sediments of Galveston Bay (Represented by 29 Sites) and the Louisianian Province.

Metal	ERL	Percent ERL Exceeded in Galv. Bay Area	Percent ERL Exceeded in Louisianian Province Area
Antimony	2.0	0%	0%
Arsenic	8.2	17%	33%
Cadmium	1.2	0%	1%
Chromium	51.0 (81.0)	52% (0%)	9%
Copper	24.0 (34.0)	0%	0%
Lead	46.7	0%	0%
Mercury	0.15	0%	3%
Nickel	20.9	55%	35%
Silver	3.0	0%	0%
Zinc	150.0	4%	4%

ERL and ERM exceeding values were taken from Long, et al. (1995).
ERL and ERM exceeding values in parentheses were taken from Long and Morgan (1990).

Table 10. Comparison of Heavy Metal Concentrations with Regression Values for Metals in Uncontaminated Sediments using Aluminum Concentrations as a Standard.

1) by Hanson, et al. 1993, and 2) from Summers et al., 1996 and 1993 EMAP Study.

Metals	Sites with Metal Concentrations Higher than Uncontaminated Sediments
Arsenic	1) none 2) *GB2, TB5
Cadmium	1) none 2) OB, MA4, MA5, MLDL, GB2*, TB7, TB8, TB9, TB10
Chromium	1) *GB2 2) CL, OB, EGB3, EGB5, GB1, GB2*, GB3, GB4, GB6, GB7, MA1, MA2, TB9, WGB1
Copper	1) CL, MA1, MA2, MA3, MA4, MLDL, OB 2) CL, MA1, MA2, MA3, MA4, MLDL, OB, GB2*, GB4
Lead	1) CL, OB 2) CL, OB, MLDL, EGB1, EGB2, EGB3, EGB4, EGB5, GB5*, GB6, MA1, MA2, MA4, MA5, TB1, TB6, TB8, TB9, TB10, WGB1, WGB2
Mercury	1) none 2) CL, OB, MLDL, GB1, GB2*, GB3, GB6, GB12, MA1, MA2, MA4, TB2, TB5, WGB1, EGB2
Nickel	1) *GB2, GB7, MA1 2) OB, MLDL, EGB1, EGB3, EGB4, GB1, GB2*, GB3, GB4, GB6, GB7, GB8, GB10, GB12, MA1, MA2, MA3, MA4, MA5, TB2, TB3, TB5, TB6*, WGB1, WGB2
Silver	1) CL, MA2, MA4, OB, MLDL 2) CL, OB, MLDL, MA1, MA2, MA3, MA4, MA5, GB1, GB2*, GB3, GB4, GB5*, GB8, GB11, GB12, TB1, TB2, TB3, TB4, TB5, TB6*, TB8, TB9, TB10, WGB1, WGB2
Zinc	1) OB, CL, MA1, MA2, MA3, MA4, GB1, *GB2, GB6 2) CL, OB, MLDL, GB1, GB10, GB12, GB2*, GB3, GB4, GB6, GB7, GB8, MA1, MA2, MA3, MA4, MA5, TB5, WGB1, WGB2

*GB2 has a low Aluminum value. GB5 and TB6 have very low Aluminum values.

Identifying Areas with High Metal Concentrations in the Past and Present

Several historic datasets from Galveston Bay (1950's - 1980's) were analyzed by Ward and Armstrong (GBNEP 22, 1992) with the following general conclusions: 1) High concentrations of copper occur in mid-Trinity Bay and mid-East Bay, while high concentrations of lead and zinc occur in lower Galveston Bay inside the inlet. 2) Metals are elevated in general region of the lower bay and the Houston Ship Channel and both sides of the Texas City Dike. 3) They hypothesize that the principal sources of metals in Galveston Bay are from the Houston Ship Channel and Texas City areas, in turn originating from runoff from highly industrialized areas, waste discharges, and shipping activity.

Ward and Armstrong (GBNEP 22, 1992) reported high copper sediment values in mid-Trinity Bay, mid-East Bay and in lower Galveston Bay. The Texas City Industrial Area is the likely source of the copper contamination in lower Galveston Bay. In addition, high copper values were reported near and in Clear Lake area, which also are found in the present study. The Bureau of Economic Geology (BEG) Study (White et al., 1985) reported copper concentrations exceeding the ERL screening value in mid-Trinity Bay, western upper Galveston Bay, Galveston Channel, Clear Lake, and Offat=s Bayou. In the present study, copper concentrations exceed ERL criteria and natural deposition values at six Small Bay and Marina sites, including Clear Lake and Offat=s Bayou (Tables 7 & 8). A recent study by Guillien, et al. (1993) also reported high copper concentrations at the same marina sites. When comparing the results of the present and past studies, copper contamination appears to have decreased in the open areas of the Galveston Bay Complex. The source of copper contamination could be anti-fouling paint from boats or possibly urban nonpoint source pollution.

Chromium values are high due to anthropogenic sources at several sites throughout the Galveston Bay Complex (Tables 7 & 8). Results from the Bureau of Economic Geology Study also show chromium concentrations higher than ERL in most of upper Galveston Bay and Trinity Bay (except along bay margins), the northern half and upper portion of East Galveston Bay, in Galveston Channel, Clear Lake, and Offat=s Bayou. The findings of the present study are in agreement with the BEG=s reported locations of high chromium contamination.

In the present study, higher lead concentrations (above NOEL but not ERL values) are found on the east side of Trinity Bay, East Bay and in the small bays (OB, MLDL, & CL). Concentrations exceed the ERL value in Offat=s Bayou only, and are near exceedence in Clear Lake. Lead concentrations appear to be lower in the present study compared to results from the BEG study. In the BEG study, most lead concentrations are lower than the ERL values. A few isolated areas have values higher than the lead ERL including 1) south of Morgan=s Point and east of the Ship Channel (in the GB1 area), and 2) between Eagle Point and Smith Point near the Ship Channel, at the mouth of upper Galveston Bay.

Arsenic concentrations are highest at site TB5 in mid-Trinity Bay. Arsenic concentrations are above the ERL value at six other sites but they are not higher than expected based on normalization to aluminum.

High Nickel and Zinc concentrations (higher than ERL or NOEL) were reported by Ward and Armstrong (GBNEP 22, 1992) at the same areas as in the present study (Table 7). Also, nickel (above ERL) and zinc (above NOEL) concentrations are found at several sites throughout the bay. The BEG Study results are in agreement with the present study with nickel and zinc concentrations high throughout the bay. Nickel concentrations were found to be higher than the ERL in most of the open areas of upper Galveston Bay and Trinity Bay, north and upper East Bay, north of the Texas City Dike, Clear Lake, and Galveston Channel. In the BEG Study results, zinc concentrations are higher than the ERL in Offat=s Bayou, Clear Lake, between Eagle Point and Smith Point, Trinity Bay near Smith Point, and Cedar Bayou Channel. Zinc concentrations are higher than the NOEL but lower than the ERL in the open area of Trinity Bay and upper portion of East Bay, between Tiki Island and Offat=s Bayou in West Bay, near Flamingo Isle in West Bay, and two isolated areas of lower Galveston Bay.

Butyltin Compounds

Tributyltin (TBT) is toxic to marine animals and is used in anti-fouling paint for boats. TBT has been restricted for use in recent years to only larger boats in an effort to reduce the amount of TBT contamination in the marine environment. Values exceeding 1.0 ppb in the sediments are used as a screening criterion.

TBT values of 1 to 5 ppb occurred at 48% of Galveston Bay sites, and 22% of Small Bay and Marina sites. TBT values greater than 5 ppb occur at 3.4% of the Galveston Bay area (site GB1) , and 67% of Small Bay and Marina sites. Considerably higher TBT values (13.3 ppb to 40.7 ppb) occurred at four of five marina sites and in Offat=s Bayou (Tables 11 & 12, Map 7). Obviously, TBT concentrations in the sediments were higher in areas of higher boat traffic. Values were high in Offat=s Bayou due to the restricted nature of this small bay.

TBT concentrations were higher in Galveston Bay sediments than in Louisianian Province sediments overall. Values greater than 1 ppb occurred in 52% of the area, compared to 31% of the total Louisianian Province area. Louisianian Province TBT values of 1-5 ppb were found in 24% of the total area and >5 ppb were found in 7% of the total area (Figures 23 & 24).

High Dibutyltin (DBT) values occurred at 38% of the Galveston Bay area, and 89% of Small Bay and Marina sites chosen. DBT values greater than 5 ppb occurred at GB6, MA2, MA3, MA4.

Figure 23. TBT Concentrations Exceeding 1.0 ppb and 5.0 ppb Compared by Percent of Area or Sites and 90% Confidence Intervals.

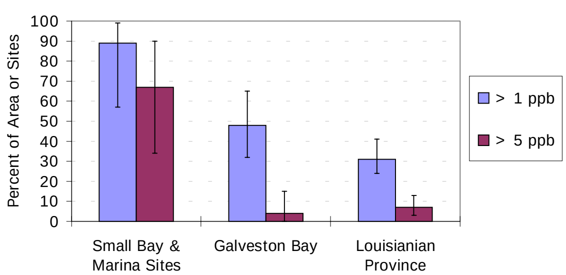
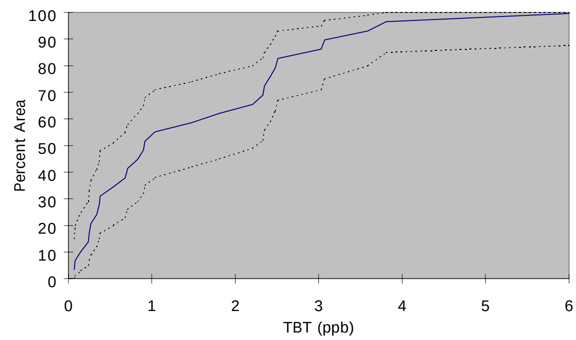


Figure 24. CDF of Tributyltin in Galveston Bay Sediments.



High Monobutyltin (MBT) values occurred at 34.5% of the Galveston Bay area, and 89% of Small Bay and Marina sites chosen. MBT values greater than 5 ppb occurred at MA1 and MA3.

Table 11. Percent of Area or Sites with Sediment TBT Concentrations Greater than or Equal to 1.0 ppb and 5.0 ppb.

System	TBT ≥ 1.0	TBT ≥ 5.0
Galveston Bay SB & MS	78%	67%
Galveston Bay	48%	3%
Louisianian Province	31%	7%

Map 6. Tributyltin Concentration Distributions in Sediments

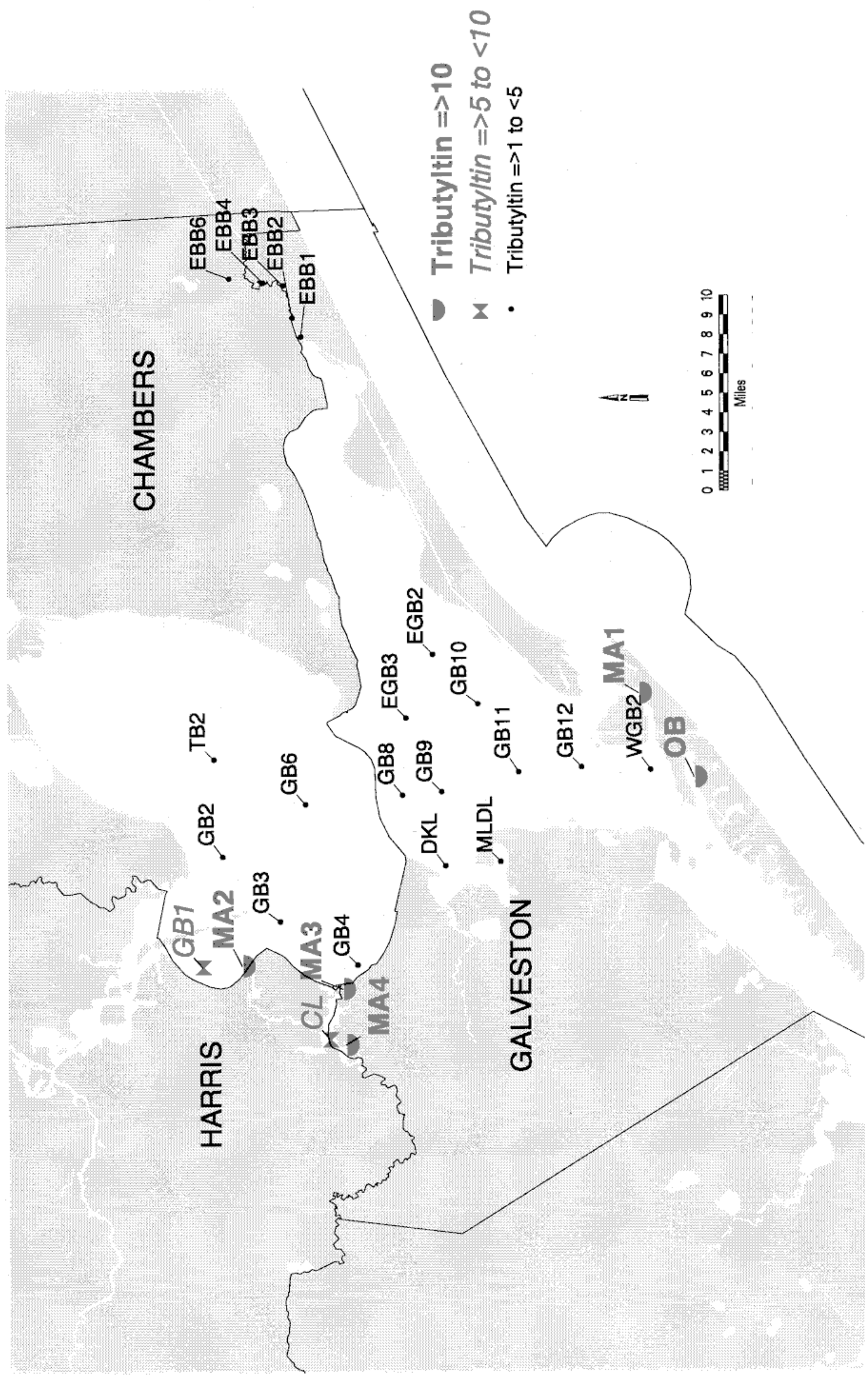


Table 12. Galveston Bay Sites with Butyltin Concentrations Exceeding the 1.0 ppb Criteria.

Stations	TBT	DBT	MBT	Total Butyltin
GB1	6.3	4.0	3.8	14.1
GB2	2.2	1.8	2.1	6.1
GB3	3.6	2.2	2.4	8.1
GB4	2.4	1.6	1.9	6.0
GB5				*0.7*
GB6	2.5	12.5	1.0	16.0
GB7				*0.7*
GB8	3.0	2.5	4.4	10.0
GB9	2.3	1.0		4.1
GB10	3.8	1.1		5.6
GB11	3.0	1.3	1.4	5.8
GB12	2.3	1.4	2.5	6.3
TB1	*0.9*			2.2
TB2	1.5	0.95	1.3	3.8
TB3				1.1
TB4				*0.8*
TB5			1.4	2.6
TB6				*0.2*
TB7				*0.7*
TB8				*0.8*
TB9				*2.8*
TB10				1.3
EGB1				1.2
EGB2	1.0			1.5
EGB3	1.8			3.1
EGB4				1.2
EGB5	*0.9*			1.5
WGB1				2.2
WGB2	2.5	1.8	1.4	5.7
OB	17.7	4.5	3.4	25.6
MLDL	1.7	2.5	2.3	6.6
DKL	1.2	2.3	2.3	5.7
CL	8.5	3.3	1.8	13.6
MA1	19.4	4.0	5.0	28.3
MA2	13.3	5.0	4.6	22.9
MA3	40.7	10.3	14.5	65.6
MA4	24.5	11.2	4.4	40.1
MA5				1.9

TBT, DBT, & MBT Values less than 1.0 ppb not shown. All values shown for Total Butyltin.
All sites had detectable TBT, DBT, & MBT concentrations.

Comparison of Butyltin Concentrations in the Sediments and Water Column.

Water samples were collected at the Marina sites only and analyzed for mono-, di-, and tri- butyltin. A significant relationship was found between butyltin concentrations in the sediments and butyltin concentrations in the water column.

The butyltin concentrations in the sediment and the butyltin concentrations in the water column were found to be closely associated, which indicated that the sediments may be a continuous source of butyltin to the water column (Table 13).

Table 13. Spearman Correlation Coefficients for Butyltin Compounds at Marina Sites.

	TBT in Sediments	DBT in Sediments	MBT in Sediments
TBT in Water	0.68*	0.30	0.98*
DBT in Water	0.62	0.37	0.91*
MBT in Water	0.60	0.40	0.89*
TBT in Sediments	---	0.80*	0.70*
DBT in Sediments	---	---	0.30

*indicates significance at $p<0.05$.

Pesticides

DDT and its associated compounds individually did not exceed the ERL values for Galveston Bay and its associated small bay and marina areas. DDE, DDD, and DDT ranged from non-detectable to 0.9 ug/Kg for all 38 sites. However, Total DDT concentrations exceeded ERL values in Offat=s Bayou sediments.

Dieldrin and Endrin ERL values were exceeded at 17% and 5% respectively, in Galveston Bay, and 33% and 0% for both Galveston Bay and the Small Bay and Marina sites (Tables 14 & 15, Figure 25). Sites with high Dieldrin and Endrin concentrations in the sediments are located in upper Galveston Bay (GB1, GB2, GB3, GB4, MA2), Clear Lake (CL, MA3, MA4), and upper Trinity Bay (TB8, TB10). These distributions appear to be related to the proximity of these sites to the San Jacinto River, the Trinity River, and Clear Creek. Low benthic values at these sites could be related to the presence of Dieldrin and Endrin in the sediments.

Dieldrin concentration distributions were much lower in Galveston Bay than in the Louisianian Province. Endrin concentration exceedence by area were lower in Galveston Bay compared to the Louisianian Province. For the Louisianian Province, Dieldrin and Endrin both were found in exceedence of the ERL guidelines at 57% and 18% respectively, of EMAP sites (Table 14). No other pesticides exceeded ERL values for both studies (although, many pesticides do not have exceedence criteria established).

Figure 25. Percent of Area or Sites with ERL Exceedence of Pesticides and 90% Confidence Intervals.

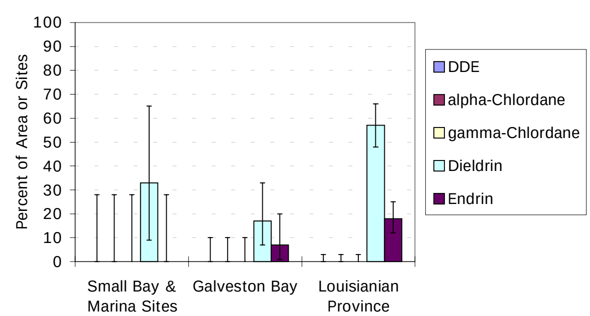


Table 14. Pesticide Concentrations in Galveston Bay Sediments at 38 Sites.

Pesticide	Range (ppb)		ERL	ERM	Percent Exceeded 10%	50%
2,4 DDD	0	0.2	2.0	20	0	0
4,4 DDD	0	0.6	2.0	20	0	0
2,4 DDE	0	0.1	2.0	15	0	0
4,4 DDE	0	0.9	2.2	15	0	0
2,4 DDT	0	0.1	1.0	7	0	0
4,4 DDT	0	0.4	1.0	7	0	0
Total DDT	0.2	**2.0**	1.58	46.1	**3 (0)**	0
Aldrin	0	0	NA	NA	NA	NA
alpha-BHC	0	0.6	NA	NA	NA	NA
beta- BHC	0	0	NA	NA	NA	NA
delta-BHC	0	0	NA	NA	NA	NA
alpha-Chlordane	0	0.4	0.5	6	0	0
gamma-Chlordane	0	0.3	0.5	68	0	0
Dieldrin	0	0.2	0.02	45	**21 (17)**	0
Endrin	0	0.1	0.02	NA	**7 (5)**	0
Hexachlorobenzene	0	0.9	NA	NA	NA	NA
Heptachlor	0	0	NA	NA	NA	NA
Heptachlor Epoxide	0	0.7	NA	NA	NA	NA
Mirex	0	0	NA	NA	NA	NA
cis-Nonachlor	0	0.6	NA	NA	NA	NA
trans-Nonachlor	0	0.4	NA	NA	NA	NA
Oxychlordane	0	0	NA	NA	NA	NA
Lindane	0	0.4	NA	NA	NA	NA

Values in parentheses represent percentage of the 29 randomly sampled sites with ERL exceedences.
ERL and ERM exceedence values from Long and Morgan (1990).

Table 15. Galveston Bay Stations with Sediment Pesticide and PAH Concentrations Exceeding NOEL or ERL Values.

Stations	Dieldrin	Endrin	PAHs
GB1	Dieldrin		
GB2		Endrin	
GB3	Dieldrin		
GB4	Dieldrin		
GB5			
GB6			
GB7			
GB8	Dieldrin		
GB9			
GB10			
GB11			
GB12			
TB1			
TB2			
TB3			
TB4			
TB5			C3 Fluorene, *Acenapthene, *HM PAHs P
TB6			
TB7			
TB8	Dieldrin		
TB9			
TB10		Endrin	
EGB1			
EGB2			
EGB3			
EGB4			
EGB5			
WGB1			
WGB2			
OB			
MLDL			
DKL			
CL			
MA1			
MA2	Dieldrin		
MA3	Dieldrin		
MA4	Dieldrin		
MA5			

*Contaminant values exceed the NOEL values but not the ERL values.

Polynuclear Aromatic Hydrocarbons (PAHs)

Forty-four PAHs were analyzed in sediment samples taken at the 38 sites in Galveston Bay. PAHs were examined for exceedence of NOEL, ERL, and ERM criteria (Table 16). PAHs exceeding ERL values in Galveston Bay included only C3-fluorene at site TB5 in Trinity Bay where several active oil wells are located. PAHs exceeding NOEL, but not ERL values in Galveston Bay included Acenaphthylene and High Molecular Weight PAHs only found at site TB5 in Trinity Bay (Tables 16 & 17). Distributions of Low Molecular Weight PAHs and High Molecular PAHs for Galveston Bay showed that three randomly chosen sites (TB5, WGB1, WGB2) have PAHs that were considerably higher than at the other sites in the Galveston Bay area (Figures 26 & 27, Map 7).

Figure 26. CDF of High Molecular Weight PAH's in Galveston Bay Sediments.

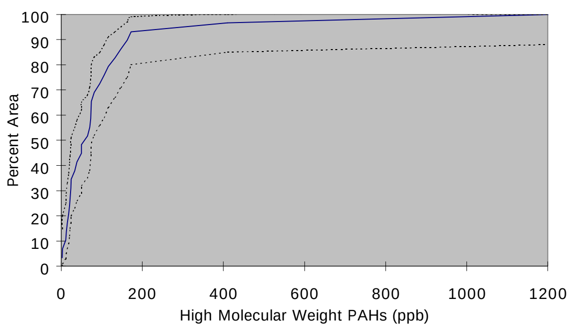
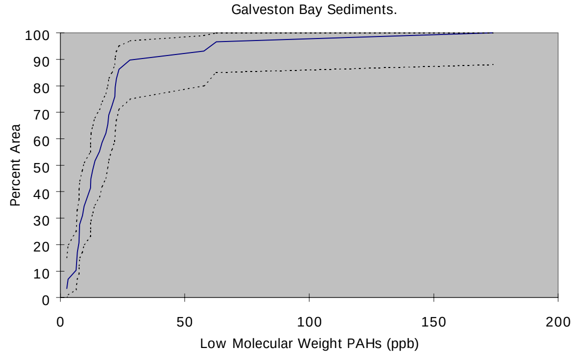


Figure 27. CDF of Low Molecular Weight PAHs in Galveston Bay Sediments.



ERL criteria for C3-fluorene were exceeded in 3% of Galveston Bay (site TB5), which were similar to exceedences found in the entire area of the Louisianian Province. In the Louisianian Province, C3-fluorene ERL values were exceeded at 5% of the area, and High Molecular Weight PAHs ERL values were exceeded at 1% of the area. These were the only individual PAHs with ERL values exceeded in the Louisianian Province.

Major sources of PAHs to Galveston Bay include spilled or released petroleum products, and combustion products found in urban runoff (GBNEP 44, 1994). Ward and Armstrong (GBNEP 36, 1993) reported that 65.8% of the Oil & Grease loading to Galveston Bay comes from non-point source pollution, 31.1% comes from Municipal WWTP, and 3.1% comes from industry wastewater discharges. PAH concentrations exceeding ERL and/or NOEL criteria occurred only in mid-Trinity Bay (site TB5), where several oil platforms are located (Map 7). Ward and Armstrong (GBNEP 22, 1992) and Carr (GBNEP 30, 1993) reported very high Oil & Grease values in mid-Trinity Bay, where four large brine discharges totaling 2,000 MG/yr are located in Trinity Bay. Trinity Bay and Tabbs Bay (400 MG/yr) appear to receive the bulk of brine discharge in the Galveston Bay Complex. Of the 51 brine discharges in this system, 16 are located in Trinity Bay and 10 are located in Tabbs Bay (Armstrong and Ward, GBNEP 36, 1993).

Ward and Armstrong (GBNEP 22, 1992) also report high Oil & Grease values (although not as high as in mid-Trinity Bay) in the Houston Ship Channel, in and around the Clear Lake area, north of the Texas City Dike, and in far West Bay. In the present study, high PAH values (that do not exceed NOEL criteria) also are found in Clear Lake, four of five Marina sites, and Moses Lake/Dollar Bay. And, unlike the GBNEP 22 Study, the present study also found high PAHs in West Bay south of the Texas City Dike which may be influenced by the petroleum industry in Texas City . In contrast, two sites on the Galveston Island shoreline that did not have PAHs present in the sediments include Offat=s Bayou and the Marina site (MA1) in Galveston Channel. However, Qian et al. (1999) reported detecting elevated PAH concentrations in samples collected from these areas.

Cluster analysis results of PAH distributions are shown on Map 7. High PAHs were found on the western shoreline in Galveston Bay and near the Galveston Island shoreline. These locations are near areas of high human activity, such as urban areas, industry, and shipping.

East Bay Bayou on the Intracoastal Waterway (ICWW) was another area associated with Galveston Bay that had PAH concentrations higher than ERL values. (Map 7). Sediment concentrations in the ICWW exceeded ERL criteria for C2 & C3 Fluorene and C3 Phenanthrene. Nearby oil fields are a possible continuous source of PAHs in this area. The watershed in this area is sparsely populated with very little human activity. The East Bay Bayou area will be discussed in detail in a separate report.

Table 16. Percent of Area or Sites Exceeding Polynuclear Aromatic Hydrocarbon ERL Values.

System	C2-Fluorene	C3-Fluorene	C3-Phenanthrene
East Bay Bayou	50%	83%	33%
Galveston Bay SB&MS	0%	0%	0%
Galveston Bay	0%	3%	0%
Louisianian Province	0%	5%	0%

Map 7. Polynuclear Aromatic Hydrocarbon Distributions in Sediments Using Cluster Analysis

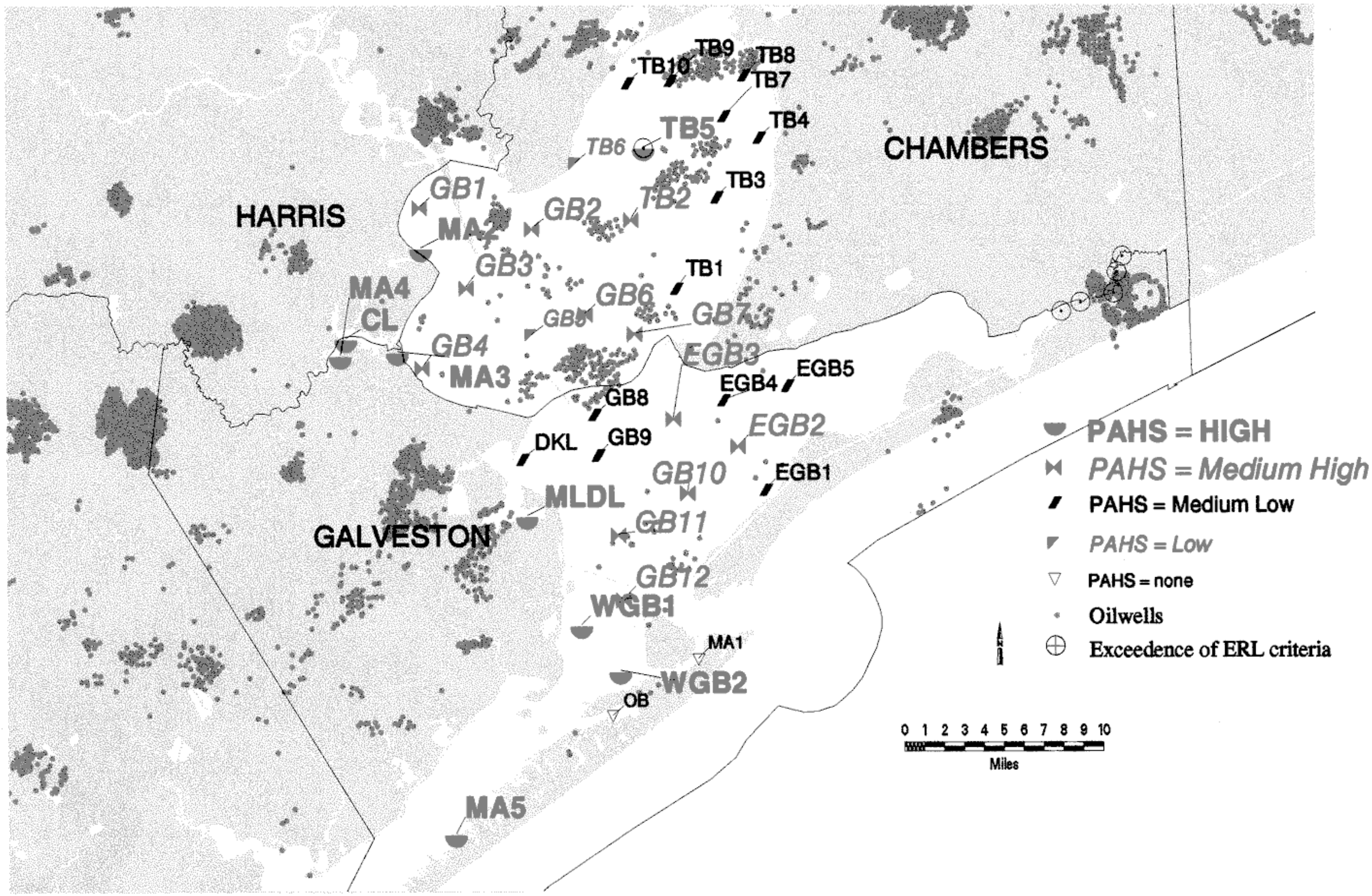


Table 17. Polynuclear Aromatic Hydrocarbon Concentrations in Galveston Bay Sediments for 38 Sites.

PAH	Range (ppb)		ERL	ERM	Percent Exceeded 10%	50%
Acenaphthene (L)	0.1	3.5	16.0	500	0	0
Acenaphthylene (L)	0.1	40.7	44.0	640	0	0
Anthracene (H)	0.1	56.2	85.3	1100	0	0
Benzo(a)anthracene (H)	0.2	105	261	1600	0	0
Benzo(a)pyrene (H)	0.2	122	430	1600	0	0
Benzo(b)fluoranthene (H)	0.2	127.6	NA	NA	NA	NA
Benzo(e)pyrene (H)	0.2	88.4	430	1600	0	0
Benzo(g,h,i)perylene (H)	0.3	56.4	NA	NA	NA	NA
Benzo(k)fluoranthene (H)	0.2	135.3	NA	NA	NA	NA
Biphenyl (L)	0.2	1.9	NA	NA	NA	NA
Chrysene (H)	0.2	164.4	384	2800	0	0
C1-chrysene (H)	0	81.4	384	2800	0	0
C2-chrysene (H)	0	36.7	384	2800	0	0
C3-chrysene (H)	0	5.15	63.4	2800	0	0
C4-chrysene (H)	0	9.0	63.4	2800	0	0
Dibenzo(a,h)anthracene (H)	0.1	16.1	63.4	260	0	0
Dibenzothio (H)	0	1.8	NA	NA	NA	NA
C1-dibenzothio (H)	0	1.9	NA	NA	NA	NA
C2-dibenzothio (H)	0	8.6	NA	NA	NA	NA
C3-dibenzothio (H)	0	12.5	NA	NA	NA	NA
Fluoranthene (H)	0.3	119.1	600	5100	0	0
C1-fluoranthpyrene (H)	0	140.6	NA	NA	NA	NA
Fluorene (L)	0.1	6.2	19.0	540	0	0
C1-fluorene (L)	0	4.0	19.0	540	0	0
C2-fluorene (L)	0	14.0	19.0	540	0	0
C3-fluorene (L)	0	27.6	19.0	540	**3**	0
Naphthalene (L)	0.7	4.1	160	2100	0	0
C1-naphthalene (L)	0.4	11.3	160	2100	0	0
C2-naphthalene (L)	0	8.3	160	2100	0	0
C3-naphthalene (L)	0	11.4	160	2100	0	0
C4-naphthalene (L)	0	12.3	160	2100	0	0
Perylene (H)	0.3	45.2	NA	NA	NA	NA
Phenanthrene (H)	0.3	45.9	240	1500	0	0
C1-phenanthrene (H)	0	34.3	240	1580	0	0
C2-phenanthrene (H)	0	38.7	240	1580	0	0
C3-phenanthrene (H)	0	48.2	240	1580	0	0
C4-phenanthrene (H)	0	31.8	240	1580	0	0
Pyrene (H)	0.4	154.1	665	2600	0	0
(i)1,2,3-c,d-pyrene (H)	0.1	68.1	NA	NA	NA	NA
1-methylnaphthalene (L)	0.2	2.9	NA	NA	NA	NA
2-methylnaphthalene (L)	0.1	9.2	70.0	670	0	0
2,3,5-trimethylnaphthalene (L)	0.2	2.4	NA	NA	NA	NA
2,6-dimethylnaphthalene (L)	0.1	2.6	NA	NA	NA	NA
1-methylphenanthrene (H)	0.1	7.1	NA	NA	NA	NA
High Molecular Weight PAHs	3.1	1201.7	1700	9600	0	0
Low Molecular Weight PAHs	2.6	173.7	552	3160	0	0
Total PAHs	6.1	1884.9	4022	44792	0	0

Polyclorinated Biphenyls

Total PCBs ranged from 0.0 to 6.1 ppb in Galveston Bay and its associated Small Bay and Marina Sites. None of the measured PCB concentrations exceeded the criterion for low-level ecological effects which is 22.7 ppb. PCB congeners 128 and 138 were found in greatest concentration among all PCB forms at 7.7 and 4.4 ppb, respectively (Table 18).

The Louisianian Province Total PCBs range was 0.0 to 73.3 ppb, with less than 1% of the Louisianian Province area having PCB levels exceeding the criterion.

Table 18. Polychlorinated Biphenyl (PCB) Concentrations in Galveston Bay Sediments.

PCB (Congener)	**Range (ppb)**
8 (CL2)	0 - 1.0
18 (CL3)	0 - 0
28 (CL3)	0 - 0.6
44 (CL3)	0 - 0.2
52 (CL4)	0 - 0.5
66 (CL4)	0 - 0.7
101 (CL5)	0 - 0.6
105 (CL5)	0 - 0.4
110/77 (CL5/4)	0 - 0.7
118/108/149 (CL5/5/6)	0 - 0.8
126 (CL5)	0 - 0.7
128 (CL6)	0 - 7.7
138 (CL6)	0 - 4.4
153 (CL6)	0 - 1.7
170 (CL7)	0 - 4.1
180 (CL7)	0 - 0.5
187/182/159 (CL7/7/6)	0 - 1.5
195 (CL8)	0 - 0.1
206 (CL9)	0 - 0.2
209 (CL10)	0 - 0.5
TOTAL PCBs	**0.0 - 8.2**

Sites Near Dredging Activities.

A consistent pattern between dredging activities and the Sediment Quality Triad Components did not appear to exist when comparisons were made throughout the bay. However, past dredging activity was responsible for poor conditions in Offat=s Bayou, and may have affected other sites individually rather than affecting all sites in the same manner. High cumulative 404-permitted dredged areas (>200 acres), which are distributed by GBNEP hydrographic area, are located near sites DKL, WGB2, and CL (GBNEP 28, 1993). Sites CL and DKL have a degraded benthic community structure, which may or may not be caused by dredging activities. Note that these sites are chosen sites, not randomly selected sites.

Randomly Sampled Sites with Dredging Activities:

1. GB8 and GB9 are located near the main channel in lower Galveston Bay. Both sites have healthy benthic community structure and good sediment quality.
2. TB3 is located near the channel entering Double Bayou. Site TB3 has a marginal benthic community structure and degraded sediment chemistry.
3. TB8 is located on spoil areas of Anahuac Channel in upper Trinity Bay. Site TB8 has both a degraded benthic community structure and degraded sediment chemistry.
4. WGB2 is located on spoil areas of the ICWW entering Galveston Channel. Site WBG2 has a healthy benthic community structure and good sediment chemistry.

Small Bay Sites with Dredging Activities:

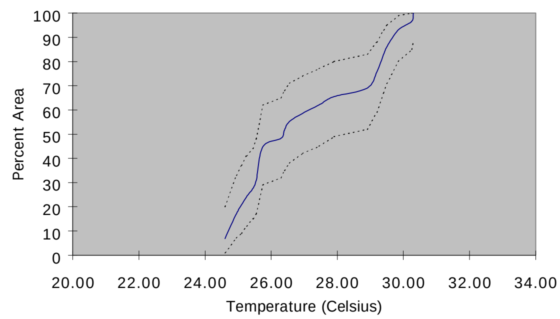
1. Site CL is located on a spoil area in Clear Lake. Site CL has both a degraded benthic community structure and degraded sediment chemistry.
2. Site OB is located in the dredged area of Offat=s Bayou. Site OB is degraded for all three Sediment Quality Triad Components.
3. Site DKL has a degraded benthic community structure and toxic sediments.

All Marina Sites have been exposed to dredging activities and do display poor benthic community structure and/or degraded sediment chemistry. In addition, they are poorly flushed areas.

Water Quality Measurements

Surface temperatures during R-EMAP sampling in Galveston Bay ranged from 24.50 C to 30.45 C. Bottom temperatures ranged from 24.6 C to 30.3 C (Table 19, Figure 28). Bottom temperatures during EMAP sampling in the Louisianian Province ranged from 24 C to 34 C.

Figure 28. CDF of Bottom Water Temperature in Galveston Bay.



Water depth ranged from 3.3 feet to 11.8 feet at the Galveston Bay sites and the Small Bay & Marina sites (with the exception of 19.2 feet in Offat=s Bayou) (Table 19). 21% of the Galveston Bay area and 22% of Small Bay and Marina sites had depths greater than 3 meters. Galveston Bay is shallow in a larger percentage of its area (79%) than in the Louisianian Province (65%). In the Louisianian Province area depth exceeded 3 to 4 meters mainly in dredged channels or the Mississippi River: Depths greater than 3-4 meters occurred in 42 % and 12%, respectively, for large and small estuaries.

Salinity ranged from 11.15 ppt to 32.25 ppt in surface waters (Table 19, Map 8, Figure 29). Salinities of 20 - 25 ppt extended into upper Galveston Bay and into Trinity Bay during this sampling period (August 1993). Average salinity conditions for August in these areas are 10 - 15 ppt, based on measurements collected over several years, see GBNEP 44, 1994).

Map 8. Surface Salinity (ppt) Gradient During R-EMAP Sampling

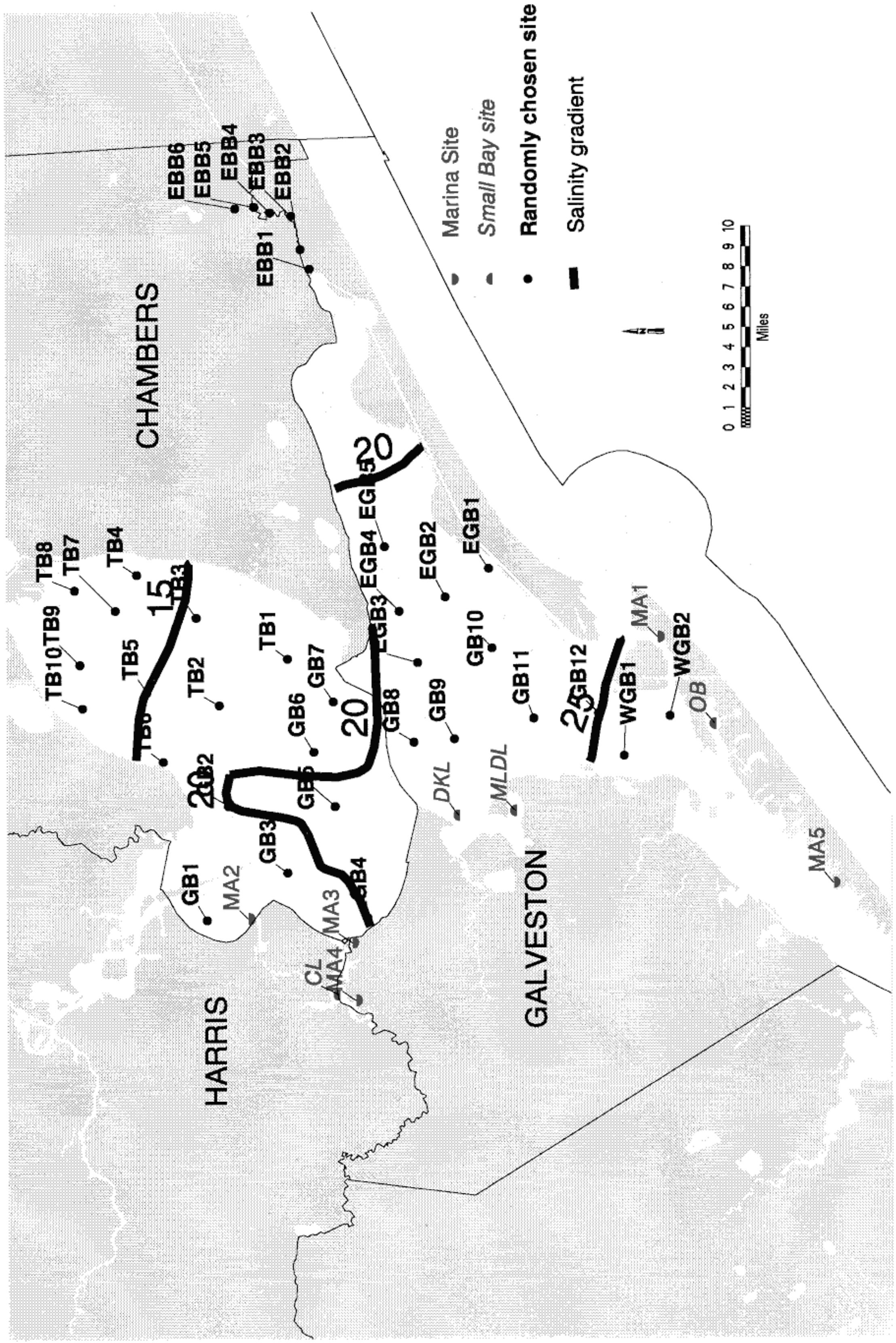


Figure 29. CDF of Salinity in Surface Waters of Galveston Bay.

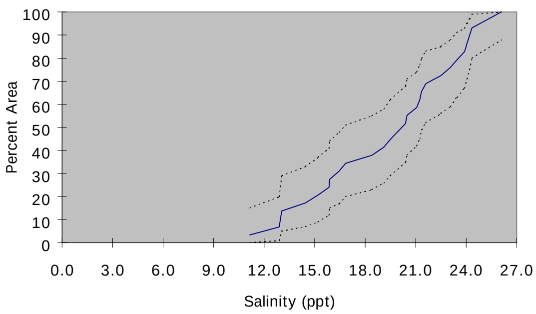
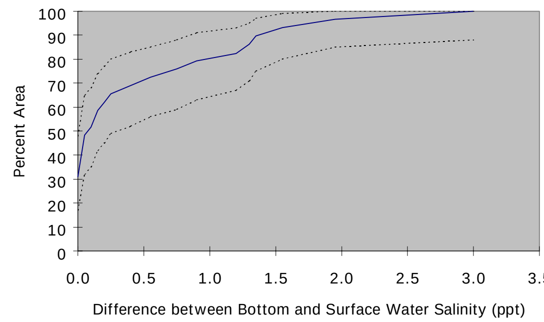
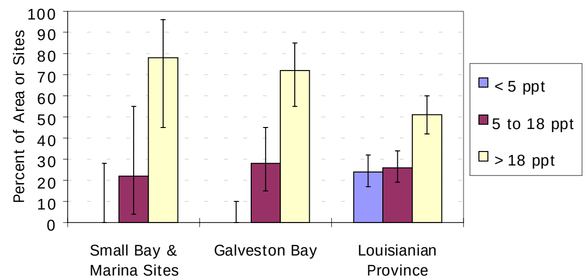


Figure 31. CDF of Salinity Stratification in Galveston Bay Waters.



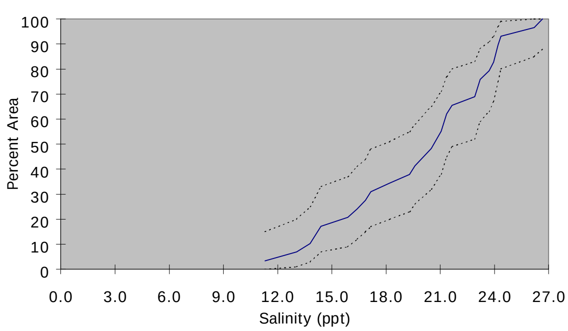
Salinity ranged from 11.3 ppt to 32.3 ppt in bottom waters (Table 19, Figure 30). Significant water column stratification was seen in upper Galveston Bay and in Trinity Bay where freshwater inflows enter the bay from the Houston Ship Channel, the San Jacinto River and the Trinity River (Figure 31). 31% of the Galveston Bay area and 22% the Small Bay and Marina sites had bottom water salinities ranging from 11 ppt to 18 ppt. 69% of the Galveston Bay area and 78% of Small Bay and Marina sites had bottom water salinities greater than 18 ppt. None of the Galveston Bay Complex sites had salinities less than 11 ppt (Tables 19 & 20, Figure 32).

Figure 32. Bottom Water Salinity Compared by Percent of Area or Sites and 90% Confidence Intervals.



Dissolved Oxygen (DO) concentrations in the water column of Galveston Bay are good, especially for August when the warmer water temperatures lead to lower dissolved oxygen levels in water. Surface water dissolved oxygen concentrations ranged from 6.15 and 11.70 mg/l in Galveston Bay (Figure 46), and from 4.65 to 10.10 mg/l at the Small Bay and Marina sites. Bottom water Dissolved Oxygen concentrations ranged from 6.00 to 9.40 mg/l in Galveston Bay (Figures 33 & 34), and from 3.70 to 10.20 mg/l at the Small Bay and Marina sites.

Figure 30. CDF of Salinity of Bottom Waters in Galveston Bay.



In the Louisianian Province, 51% of estuarine area had bottom water salinities greater than 18 ppt, and 26% of estuarine area had bottom water salinities between 5 and 18 ppt. Galveston Bay had higher salinities than those reported for the entire Louisianian Province (Figure 32). These higher salinities are not unexpected, because Texas estuaries generally have lower freshwater inflow per unit area than the remainder of the Louisianian Province.

Galveston Bay surface and bottom water DO concentrations were above 5 mg/l in 100% of the area represented by the 29 randomly selected sites. Surface water DO concentrations were similar for Galveston Bay and the Louisianian Province. Galveston Bay bottom water DO concentrations were higher overall than DO concentrations throughout the entire Louisianian Province. In the Louisianian Province, 96% of the surface water and only 67% of the bottom water area had DO concentrations greater than 5 mg/l.

Sites with bottom water dissolved oxygen concentrations lower than 5.0 mg/l included Offat's Bayou, Lafayette Landing Marina, and South Shore Marina (sites OB, MA3, MA4). The effects of the bathymetry and the high deposition rate at Offat's Bayou, likely caused the bottom water concentrations to be low at Offat's Bayou. Sites MA3 and MA4 are both located in Clear Lake. The heavy use of these marinas, and the constricted nature of the marinas, as well as Clear Lake, could be the cause for these lower bottom water concentrations. In contrast, the dissolved oxygen measurements at the Clear Lake site (CL) were high at 10.10 mg/l. These high DO levels probably were caused by high photosynthetic rates in the water column, which could be due to high inputs of nutrients from the local watershed.

Surface and bottom water pH levels were within acceptable ranges. Surface water pH levels ranged from 7.25 to 8.45 for all 38 sites. Bottom water pH levels ranged from 7.10 to 8.55 for all 38 sites.

Water clarity, measured as secchi depth, ranged from 0.5 m to 2.5 m. These values indicate that all 38 sites had measurements of acceptable water clarity. Generally, water clarity is not a good indicator of degradation for Texas estuaries, because these systems are naturally turbid. High turbidity predominates in Texas estuaries due to wind suspending sediments from the shallow depths.

Figure 33. CDF of DO in Surface Waters of Galveston Bay.

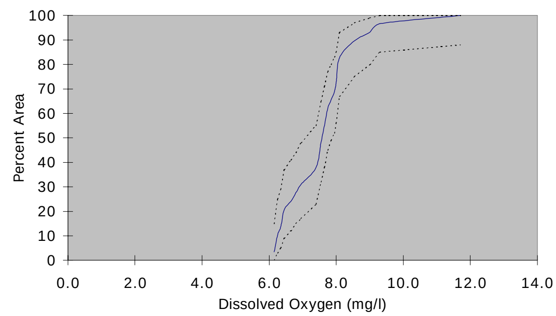


Figure 34. CDF of DO in Bottom Waters of Galveston Bay.

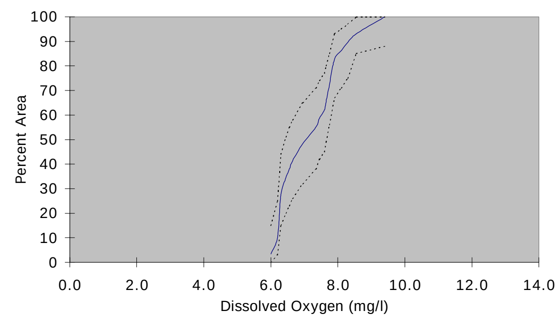


Table 19. Galveston Bay Water Column Physical and Chemical Measurements.

	Dissolved Oxygen		Salinity (ppt)		Temperature (C)		Secchi Depth	
Station	Surface	Bottom	Surface	Bottom	Surface	Bottom	Depth	(feet)
GB1	11.7	6.2	18.4	19.6	26.8	26.4	1.0	9.7
GB2	6.8	6.65	21.05	21.0	25.7	25.7	1.0	9.2
GB3	7.85	6.45	20.4	20.5	26.2	25.7	1.0	10.6
GB4	7.5	6.55	20.5	21.25	26.5	25.75	0.5	9.2
GB5	6.25	6.3	21.35	21.35	27.0	27.45	0.5	6.1
GB6	6.95	6.9	19.5	21.05	29.5	29.5	0.5	9.8
GB7	6.65	6.3	16.85	16.85	26.25	26.3	0.5	8.2
GB8*	6.35	6.3	22.5	22.9	29.4	29.4	1.0	11.6
GB9*	6.4	6.4	23.05	23.2	29.2	29.2	1.0	11.8
GB10	7.75	7.7	24.05	24.1	30.45	30.25	1.0	8.2
GB11	7.65	7.3	24.2	24.2	29.6	29.4	2.0	11.2
GB12	6.25	6.15	24.35	24.35	27.85	27.9	1.0	6.5
TB1	7.5	7.33	15.9	15.87	24.7	24.6	1.0	7.4
TB2	7.55	6.95	19.1	19.3	25.9	25.25	1.0	9.2
TB3*	7.4	7.45	15.85	17.15	24.55	24.9	2.5	8.2
TB4	8.1	7.9	13.0	13.05	25.1	25.1	2.0	6.2
TB5	7.95	7.6	15.2	18.2	24.5	25.45	2.0	8.1
TB6	7.75	7.65	16.45	16.4	24.6	24.6	1.0	2.8
TB7*	8.55	7.75	12.9	13.8	25.7	25.55	1.5	6.1
TB8*	8.55	8.3	11.15	11.3	25.75	25.7	0.5	3.3
TB9	9.0	9.4	13.05	14.4	25.75	24.9	1.5	6.7
TB10	9.3	9.4	14.45	14.4	25.2	24.95	1.0	6.6
EGB1	8.05	7.85	23.9	23.95	29.9	29.85	0.5	4.5
EGB2	7.9	7.2	23.45	23.7	29.85	29.85	1.0	7.2
EGB3	7.4	6.3	21.25	23.2	29.55	29.2	0.5	8.1
EGB4	7.65	8.55	21.6	21.65	30.3	30.3	1.0	6.9
EGB5	8.1	8.1	20.35	20.4	28.85	28.9	0.5	7.5
WGB1	6.15	6.0	26.1	26.65	27.0	26.95	0.5	7.9
WGB2*	6.45	6.25	26.1	26.1	26.6	26.55	0.5	5.9
OB*	5.45	4.4	30.3	30.5	27.6	27.8	1.0	19.2
MLDL	6.9	6.85	21.15	21.15	30.0	29.9	0.5	4.2
DKL*	7.7	6.95	17.9	22.9	29.7	29.65	1.0	6.5
CL*	10.1	10.2	16.1	16.15	27.05	27.1	0.5	4.8
MA1	5.15	5.05	24.55	24.7	27.8	27.9	1.0	9.5
MA2	5.95	5.5	18.3	18.4	26.4	26.4	0.5	6.1
MA3	4.65	3.7	18.6	18.7	27.3	26.6	1.0	11.2
MA4	6.35	4.25	15.55	15.6	27.85	26.9	0.5	8.6
MA5	6.5	6.5	32.25	32.3	25.35	25.15	0.5	4.1

***Dredging activity at site or nearby.**

Table 20. Percent of Area or Sites Compared by Salinity Categories.

Bottom Water Salinity	Galveston Bay Area	Small Bay and Marina Sites
>18 ppt	69%	78%
11 to 18 ppt	31%	22%
<11 ppt	0%	0%
Surface Water Salinity	**Galveston Bay Area**	**Small Bay and Marina Sites**
<18 ppt	65%	78%
11 to 18 ppt	35%	22%
<11 ppt	0%	0%

Comparisons of Benthic Distributions with Sediment Chemistry

Data from all 38 sites were used to make statistical comparisons of benthic distributions with sediment chemistry. Significant correlations exist between the Benthic Index, Benthic Diversity, Amphipod Abundance, and a combination of heavy metals, pesticides, butyltins, and natural sediment characteristics. Benthic responses in this study are not associated with water quality measurements of temperature, dissolved oxygen, pH, salinity, or light penetration.

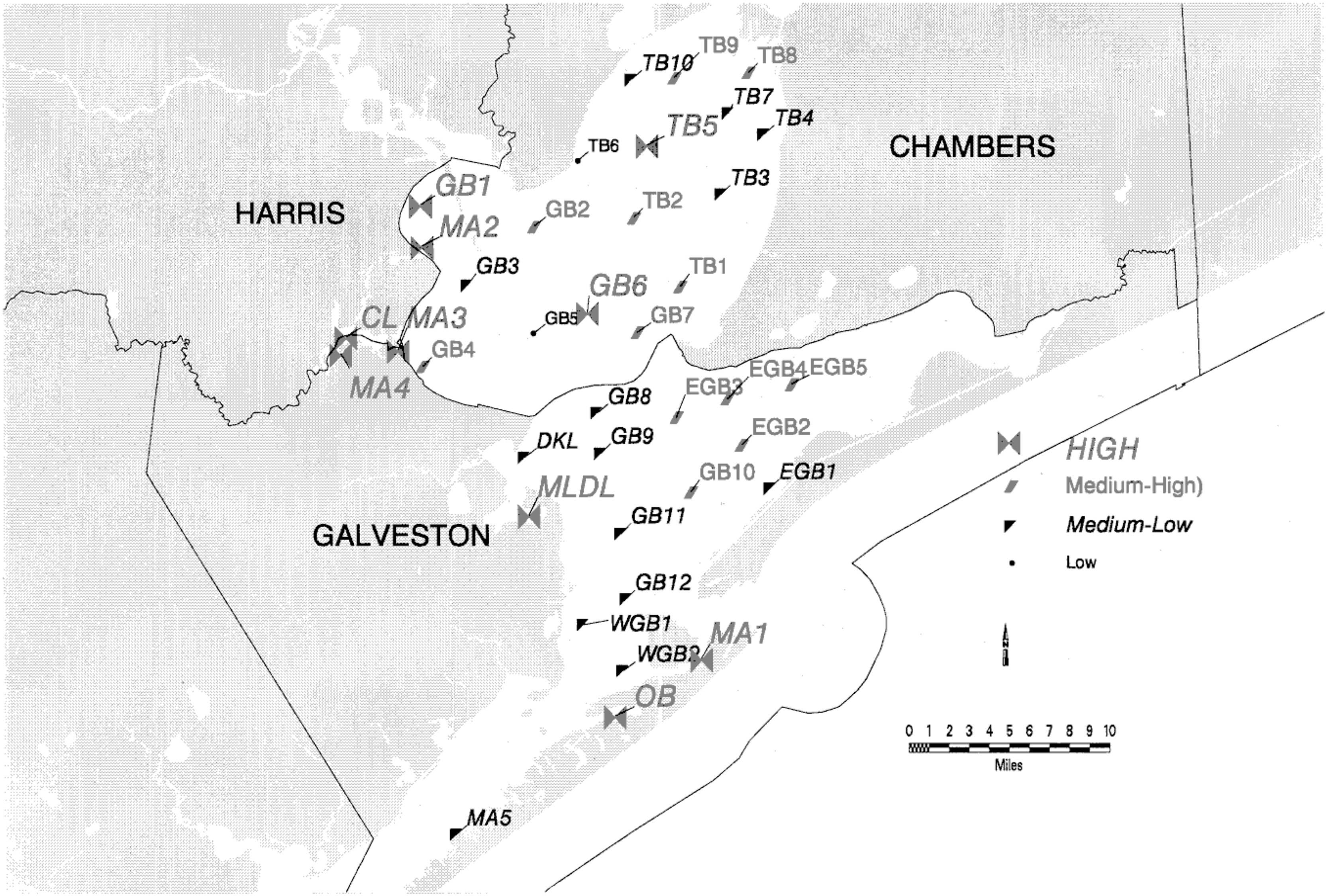
When the Benthic Index is regressed against the ten toxic heavy metals (compressed factor using PCA, normally distributed) listed in Table 5, a significant negative relationship is found (R = -0.60, F=0.00). When the Benthic Index is regressed against heavy metal values that have been compressed into two sets of numbers using Principal Components Analysis (PCA), a significant relationship is found (R = -0.74, F=0.00). When the Benthic Index is regressed against chromium, copper, lead, nickel, and zinc (compressed using PCA), a significant relationship is not found (R = -0.49, F=0.00).

When the Benthic Diversity Index is regressed against the ten toxic heavy metals (compressed factor using PCA, normally distributed) listed in Table 5, a significant negative relationship is found (R= -0.61, F=0.00). When the Benthic Diversity Index is regressed against heavy metal values that have been compressed into two sets of numbers using PCA, a significant relationship is not found (R = -0.52, F=0.00). When the Benthic Diversity Index is regressed against chromium, copper, lead, nickel, and zinc (compressed factor using PCA, normally distributed), a significant negative relationship is found (R = -0.61, F=0.00).

Significant correlations exist between the combined set of important environmental factors in the sediments and benthic distributions. Significant correlations also exist, when compared separately, for the benthic values and metals, and benthic values and pesticides other than DDT. Significant correlations do not exist for benthic distributions and TBT, PAHs, or PCBs in this study. Heavy metals in the sediments are the most important anthropogenic factor affecting benthic distributions.

When the Benthic Index was regressed against the compressed significant environmental factors, a significant negative relationship is found (R= -0.63, F=0.00). Sites with the highest sediment PCA factor values included Offat's Bayou, Moses Lake/Dollar Bay, Clear Lake, four of the Marina sites, and two sites near large brine discharges (TB5 and GB6). Sites with the lowest significant sediment factor values included GB5 and TB6 which are both areas with sandy sediments (Map 9).

Map 9. Significant Environmental Factor Distributions Groupings Using Principal Components Analysis

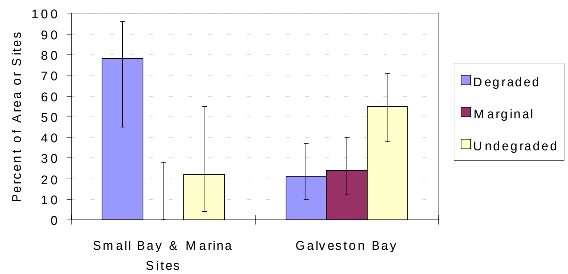


The goal of the PCA analysis was to condense the results and to statistically determine the significance of the results of the Sediment Quality Triad Approach, by compressing the sediment variables of importance into one factor. PCA determines the variables of importance for the compressed factor and what weights should be given to each variable in the equation that defines the Sediment Chemistry Component. Variables of importance include metals (aluminum, arsenic, copper, chromium, iron, nickel, selenium, tin, zinc), sediment grain size (percent of silt & clay), Butyltins (mono-, di-, and tri-), PAHs (represented by high molecular weight and low molecular weight PAHs), and pesticides other than DDT and DDT metabolites. The PCA analysis determined that the Sediment Chemistry Component was influenced most by the heavy metals listed above and sediment grain size. Seven of eight of the metals above were significantly correlated with the deposition rate and sediment grain size. In the final step, the Sediment Chemistry Component (using the significant environmental factor values) was compared with the Toxicity Component, and the Benthic Component (the benthic index) using a correlation matrix and Bartlett's Test of Sphericity (as described by Green and Montagna, 1996).

Bartlett's Test of Sphericity indicates significance ($p = 0.005$) when the correlation matrix of the Benthic Index, Toxicity, and the compressed set of significant environmental factors were compared. A significant negative relationship exists between the Benthic Index and Sediment Chemistry ($R = -0.63$). The correlations involving the Toxicity Factor reveal no relationship with Benthic or Sediment Factors (with Benthic Index $|R| = 0.05$ and with sediment factors $|R| = 0.03$). As stated earlier, toxicity was not found at most sites.

Despite the low occurrence of toxicity in sediments, benthic distributions and sediment chemistry support each other in defining degraded sites (Table 21). For this study, a degraded site is defined as a site with at least two of the Sediment Quality Triad Components indicating degradation. A marginal site is defined as a site with a benthic index value from 4.0 to 5.1, which represents a marginal benthic component, and a degraded sediment chemistry component (Table 21, Map 10).

Figure 35. Degradation Status Compared by Percent of Area or Sites and 90% Confidence Intervals.



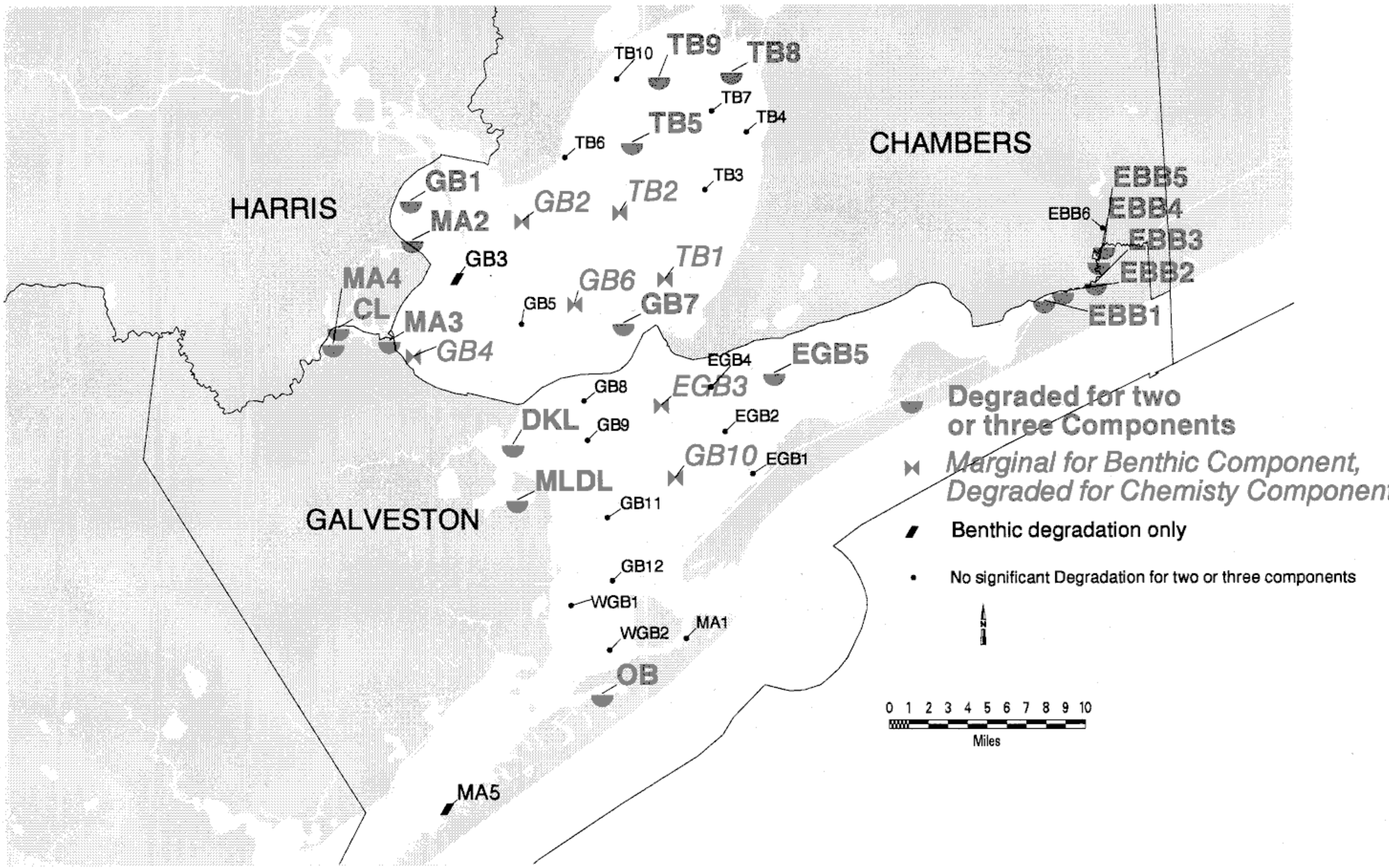
Twenty-one percent (21%) of the Galveston Bay Area is degraded, 27% is marginal, 52% is undegraded. 4% (Site GB3) of the undegraded area in Galveston Bay has a poor benthic value but a good sediment chemistry component value. 78% of the Small Bay & Marina Sites are degraded. Of the remaining two small bay and marina sites, one has poor benthic values, and the other has poor sediment chemistry values (Figure 35).

Comparisons of general degradation between Galveston Bay and Louisianian Province could not be made because some measurements of degradation used in the 1993 EMAP Study were not measured in the R-EMAP Study.

The most degraded areas in the Galveston Bay Complex include:

1) Offat=s Bayou (OB),
2) Clear Lake (CL) and its marina sites, Lafayette Landing and South Shore (MA3 and MA4),
3) Upper Galveston Bay in the Houston Yacht Club Marina (MA2),
4) Upper Galveston Bay near the Upper Houston Ship Channel (GB1),
5) Upper Galveston Bay near Smith Point (GB7),
6) Moses Lake/Dollar Bay (MLDL),
7) Dickinson Lake (DKL),
8) mid-Trinity Bay (TB5) and Trinity Bay near the river mouth (TB8, TB9), and
9) mid-East Galveston Bay (EGB5).

Map 10. Degradation Status at Each Site Using Sediment Quality Triad Components



Carr (GBNEP 30, 1993) employed the Sediment Quality Triad approach and used species richness values of less than 10 to indicate stressed benthic communities. He reported stressed communities in Trinity Bay near the river mouth and mid-East Galveston Bay, which is in agreement with the present study. Carr also reported stressed conditions in East Galveston Bay near Rollover Pass, which could be associated with poor conditions found in the 1993 R-EMAP Study of East Bay Bayou (Map 10). In addition, the GBNEP 30 Study (Carr, 1993) reported stressed benthic communities, poor sediment chemistry, and toxic sediments for sites in the Houston Ship Channel.

The 1993 EMAP Study defines stressed benthic communities as having Benthic Index values of 4.0 or less. In this study, cluster analysis of benthic communities revealed five distinct groups. A possible marginally stressed group falls in the lower portion of the moderate category. These values could indicate areas with marginal conditions when coupled with the high Sediment Chemistry Component values (marginal sites include: TB1, TB2, GB2, GB6, GB10, and EGB3) (Table 21). Other sites of interest, because of a marginal or degraded Benthic Component but not a high Sediment Chemistry Component, include sites TB3, GB3, and GB4.

Table 21. Degradation at Each Site Indicated by the Sediment Quality Triad Components.

Station	Benthic Index	Sediment Chemistry	Sediment Toxicity
GB1	X	X	
GB2	x	X	
GB3	X		
GB4	x	X	
GB5			
GB6	x	X	
GB7	X	X	
GB8			
GB9			
GB10	x	X	
GB11			
GB12			
TB1	x	X	
TB2	x	X	
TB3	x		
TB4			
TB5	X	X	
TB6			
TB7			
TB8	X	X	
TB9	X	X	
TB10	x		
EGB1			
EGB2		X	
EGB3	x	X	
EGB4		X	
EGB5	X	X	
WGB1			X
WGB2			
OB	X	X	X
MLDL	X	X	
DKL	X		X
CL	X	X	
MA1		X	
MA2	X	X	
MA3	X	X	
MA4	X	X	
MA5	X		

X = Values indicate degradation (Benthic Index Values less than 4.0),
x = Benthic Index Values between 4.0 and 5.1.

CONCLUSIONS

1. A comparison of the EMAP Study of the Louisianian Province with the R-EMAP Study of Galveston Bay did provide insight into the differences between Galveston Bay and its Small Bay & Marina Sites, and the entire Louisianian Province. These comparisons revealed that the EMAP results were useful as a screening tool to determine which systems had toxic pollutants or biological impairment and, therefore, should be studied in more detail.

2. The Benthic Index, Benthic Diversity Index, number of species per site, and number of Amphipods per site proved useful in demonstrating that communities living in contaminated sediments had a community structure indicating poor conditions. The proportions of the two indices and the number of species in the Galveston Bay area were similar to the proportions reported for the Louisianian Province in the 1993 EMAP Study. In contrast, amphipod occurrence in Galveston Bay sediments was significantly lower than in the entire Louisianian Province sediments.

3. In Galveston Bay, arsenic, copper, chromium, lead, nickel, and zinc exceed the ERL but not the ERM sediment quality screening values at one or more sites sampled. NOEL values, but not ERL values, are exceeded at one or more sites for arsenic, chromium, lead, mercury, and zinc. Sites with the most metals contamination include Offat=s Bayou (OB), Clear Lake (CL), Moses Lake/Dollar Bay (MLDL), and two Marina sites. All of these sites are Small Bay and Marina sites, which were chosen, not randomly selected, so they are not included in comparisons of Galveston Bay with the Louisianian Province 1993 EMAP sampling area. However, several of the randomly sampled sites in Galveston Bay did have exceedences for arsenic, chromium, nickel, zinc. Exceedences of chromium, copper, lead, nickel, and zinc for each site were almost always due to anthropogenic inputs and not natural deposition rates.

4. The Galveston Bay area (represented by randomly chosen sites) has chromium and nickel values that are higher than would be expected when compared to the entire Louisianian Province area. Arsenic distributions in Galveston Bay were lower than expected when compared to the Louisianian Province, while zinc distributions were similar. Copper values above ERL values were not found in the randomly sampled area representing Galveston Bay, nor in the entire Louisianian Province area.

5. TBT concentrations are higher in Galveston Bay sediments than expected with values greater than 1 ppb occurring in 52% of the area, compared to 31% of the total Louisianian Province area. A significant relationship exists between butyltin concentrations in the sediments and butyltin concentrations in the water column in the marina sites.

6. Dieldrin concentration distributions are much lower in Galveston Bay than in the Louisianian Province. Endrin concentration exceedence by area are lower in Galveston Bay compared to the Louisianian Province. Total DDT concentrations exceeded ERL guidelines in Offat=s Bayou. No other pesticides exceeded ERL values for both studies.

7. C3-fluorene exceeded ERL criteria in 3% of Galveston Bay (site TB5), which is similar to exceedences found in the entire area of the Louisianian Province. Also, the NOEL value for high Molecular Weight PAHs was exceeded at site TB5. In the Louisianian Province, only C3-fluorene ERL values and High Molecular Weight PAHs ERL values were exceeded.

8. PCB concentrations in Galveston Bay did not exceed sediment quality screening values. Only 1% of the Louisianian Province area had exceedences of PCBs in the sediments.

9. The major variables used to determine degraded sediment chemistry in Galveston Bay include metals, butyltins, PAHs, pesticides other than DDTs, and silt-clay content. These variables were compressed into one factor using Principal Components Analysis. Generally, sites with the highest significant environmental PCA factor values and sites with the most degradation were located near the shoreline and near areas of high anthropogenic activities.

10. Heavy metal concentrations greatly influenced the determination of degraded sites.

11. Toxicity results reveal a low occurrence of acute toxicity in Galveston Bay sediments.

12. The most degraded areas in the Galveston Bay Complex include: Offat=s Bayou (OB), Clear Lake (CL) and its marina sites, Lafayette Landing and South Shore (MA3 and MA4), Upper Galveston Bay at the Houston Yacht Club (MA2), Upper Galveston Bay near the upper Houston Ship Channel (GB1), Upper Galveston Bay near Smith Point (GB7), Moses Lake/Dollar Bay (MLDL), Dickenson Lake (DKL), mid-Trinity Bay (TB5) and Trinity Bay near the river mouth (TB8, TB9), and mid-East Galveston Bay (EGB5).

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