CONTAMINANTS ASSESSMENT OF THE CORPUS CHRISTI BAY COMPLEX, TEXAS 1988-1989

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ABSTRACT

The U.S. Fish & Wildlife Service-Ecological Services, Corpus Christi Field Office conducted baseline contaminants assessments of sediments and biota from the Corpus Christi Bay Complex in 1988-1989. The approximately 900 sq km study area was comprised of Corpus Christi, Redfish, Nueces, Oso and Baffin Bays, the Upper Laguna Madre, the Nueces River and the Corpus Christi Inner Harbor. Two hundred and eighty-two sediment samples and 80 biota samples were collected. Biota included composite samples of shoalgrass (*Halodule wrightii*), eastern oysters (*Crassostrea virginica*), blue crabs (*Callinectes sapidus*), calico crabs (*Eriphia gonagra*), toadfish (*Opsanus beta*), and hardhead catfish (*Arius felis*). Samples were analyzed for polycyclic aromatic hydrocarbons (PAHs), organochlorines (OCs), polychlorinated biphenyls (PCBs), and twenty-three trace elements. Six biota samples were also analyzed for the dioxin 2,3,7,8 TCDD.

The results of organic analyses revealed levels of PAHs, OCs, and PCBs either below detection (lower limit of detection was 0.01 ppm wet weight) or at very low levels in sediments. All biota samples analyzed for dioxins were below detection (lower limit of detection ranged from 0.25 to 0.64 picograms per gram, or parts per trillion). OCs were below FDA levels of concern in all biota except for one Corpus Christi Bay hardhead catfish sample, which had 3.8 ppm PCBs (wet weight). However, an overall trend toward biomagnification of PCBs and p,p'-DDE was observed. Total PCBs were detected in 45% of the biota samples and DDE was detected in 86%.

Twenty-two out of 23 trace elements were above detection in sediments (ppm dry weight). Geometric means of the following trace elements were considered elevated above background levels: Cr (17.13 ppm), Cu (16.82 ppm), Pb (36.01 ppm), Hg (0.205 ppm), and Zn (179.5 ppm) from the Inner Harbor; Zn (55.59 ppm) from Nueces Bay; As (4.39 ppm) and Zn (56.8 ppm) from Corpus Christi Bay; and Cr (13.14 ppm), Cu (9.99 ppm), and Pb (17.84 ppm) from Baffin Bay. In addition, the following trace elements were also detected at elevated levels in individual sediment samples: Hg (0.43 ppm) from the Nueces River; As (27.8 ppm), B (343 ppm), Cr (31 ppm), Cu (52.2 ppm), Pb (79.8 ppm), Ni (18.5 ppm), and Zn (248 ppm) from the Laguna Madre, and Cr (38.5 ppm), Cu (53.1 ppm), Pb (87.3 ppm), and Ni (18.3 ppm) from Baffin Bay. Sediments from the Inner Harbor, Corpus Christi Bay and Nueces Bay have apparently been contaminated as a result of industrial discharges, dredging and dredge material disposal. The sources of elevated trace elements in Baffin Bay and Upper Laguna Madre sediments are unknown, but may be related to oil and gas production in the bays.

Trace element geometric means were also above levels of concern in some biota, particularly oysters. Oysters from Nueces Bay had elevated geometric means of As (5 ppm), Cd (12.3 ppm), Cu (280 ppm), Se (4.46 ppm), and Zn (6006 ppm). Residues of As (8.69 ppm), Cd (8.76 ppm), Cu (1330 ppm), Pb (3.5 ppm), Se (4.72 ppm), and Zn (11600 ppm) were also above levels of concern in Inner Harbor oysters. Cu and Zn were

of particular concern in oysters because of the alarmingly high residues. Elevated residues of trace metals, including Zn residues exceeding 100 ppm, were detected in blue crab samples from Corpus Christi Bay, Inner Harbor, Nueces River, and Baffin Bay. The geometric mean of As in Laguna Madre blue crabs (27.85 ppm) was elevated, as was the Hg residue in blue crabs from the Nueces River (0.411 ppm). Hardhead catfish from Baffin Bay had an elevated geometric mean of As (17.68 ppm), and Zn was elevated in hardhead catfish from Nueces Bay, the Nueces River, and the Inner Harbor. Five hardhead catfish samples from Corpus Christi Bay had mercury residues greater than 1 ppm Hg. Mercury is wide-spread in Corpus Christi Bay sediment at low levels and appears to be biomagnifying in biota within the study area. High sediment levels of copper and zinc were apparently caused by the historic contamination are the source for ongoing copper and zinc contamination of oysters in Nueces Bay and the Inner Harbor.

Keywords: Corpus Christi Bay, Baffin Bay, Nueces Bay, Laguna Madre, Corpus Christi Inner Harbor, Redfish Bay, Gulf of Mexico, contaminants, sediments, blue crabs, eastern oysters, hardhead catfish, dioxins, PAHs, PCBs, OCs, trace elements, As, Cd, Cu, Hg, Zn.

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INTRODUCTION

The Texas coastal zone is a geographically large and diverse region consisting of seven major bay systems which have a combined total of over 2,375 km of bay shoreline (Texas Department Water Resources 1981). These highly productive and economically important estuaries have a total open-water surface area of 607,000 hectares, with an additional 445,000 hectares of adjacent marsh and tidal flats (Texas Department Water Resources 1981). Salinities range from nearly fresh at Sabine Lake to hypersaline in the Laguna Madre and Baffin Bay. An ecological gradient exists along the Texas coast, with higher rainfall amounts and greater freshwater inflows in the northern half of the coastal region giving rise to the establishment salt marshes dominated by smooth cordgrass (*Spartina alterniflora*). In the south, low annual rainfall and very little freshwater inflow result in the creation of vast areas of algal flats (wind-tidal flats) with little to no emergent salt marsh vegetation.

The Corpus Christi Bay Complex, positioned just south of the midway point on the Texas Gulf coast, serves as the ecotone between these two distinct habitat types. Stands of *Spartina alterniflora* become less common from Corpus Christi Bay south, and are replaced by algal flats, which become larger and more common. The resulting ecosytem provides essential nursery habitat for numerous commercially and recreationally important estuarine-dependent fish and shellfish species, as well as providing habitat for marine mammals, reptiles, resident birds, and wintering waterfowl, shorebirds, and other avian species.

Human-related activities and populations have increased dramatically along the Texas coast during the last several decades, placing severe pressures on fragile coastal habitats, including the bays and estuaries of the Corpus Christi area. The Port of Corpus Christi has become one of the nation's busiest seaports, supporting multi-billion dollar petrochemical and shipping industries. In addition to these economic interests, Corpus Christi Bay Complex estuaries are essential to multi-million dollar commercial and sport fisheries, and a growing tourist industry. The national importance of this estuary was underscored when the Corpus Christi Bay National Estuary, defined as the coastal waters from Mesquite Bay south to and including the Upper Laguna Madre, was designated for inclusion in the Environmental Protection Agency's National Estuary Program (Texas Water Commission 1992a).

The biological productivity of the Corpus Christi Bay system is potentially threatened by a myriad of human activities, including oil and gas production, petrochemical refining, industrial expansion, shipping, surface mining, agricultural development, reduction and redirection of freshwater inflows, shrimp trawling, navigation channel dredging, and urbanization. In addition to direct habitat loss associated with these activities, considerable quantities of environmental contaminants from the above point and non-point sources are discharged into the waters of this coastal area.

In 1984, the Environmental Contaminants Program from the Corpus Christi Ecological Services Field Office of the U.S. Fish & Wildlife Service (Service) initiated a comprehensive effort to assess the distribution and extent of chemical contamination in the sediments, flora, and fauna of the bays and estuaries of South Texas. Information documents have been produced for baseline studies from the Lower Rio Grande Valley-Lower Laguna Madre (Gamble et al. 1988) and the area from Matagorda Bay through Aransas Bay (Gamble et al. 1989). This report presents baseline data obtained from the bays and estuaries in and around Corpus Christi Bay, an area extending from Redfish Bay south to Baffin Bay, and including the Upper Laguna Madre. Knowledge of the occurrence and distribution of environmental contaminants in the Corpus Christi Bay Complex coastal ecosystem will ultimately provide policy makers, resource managers, and regulatory agencies with valuable information for making sound management decisions.

STUDY SITE

The Corpus Christi Bay Complex covers more than 900 sq km (Texas Water Commission 1992b) of mixed estuarine habitat and includes Corpus Christi Bay, Nueces Bay, Redfish Bay, Oso Bay, the Upper Laguna Madre, and Baffin Bay, as well as the lower Nueces River, and the Corpus Christi Inner Harbor (Figure 1). Marine and estuarine habitat types include: riverine, estuarine, sand and mud flats, salt marsh, open bay-mud bottom, oyster reef, seagrass beds, and serpulid reefs. These habitats are essential to sport and commercially important species such as spotted sea trout (*Cynoscion nebulosus)*, red drum (*Sciaenops ocelatus)*, black drum (*Pogonias cromis*), blue crab (*Callinectes sapidus)*, and three species of penaeid shrimp. In addition, the Corpus Christi Bay Complex is important to a number of Federally listed endangered, threatened, and candidate species of reptiles, birds, and mammals that utilize this estuary for migratory, wintering, or resident habitat (Table 1).

The climate ranges from dry-subhumid in the Redfish Bay area, which has an average yearly rainfall of 89 cm, to semi-arid sub-tropical in the Laguna Madre-Baffin Bay area, with an average of 64 cm of rainfall a year (White et al. 1983 and 1989). Low precipitation rates coupled with high evaporation rates produce net precipitation deficits of 410 mm per year in the Corpus Christi area and 480-710 mm at the semi-arid Laguna Madre-Baffin Bay area. Salinities within the study area range from freshwater in the Nueces River to hypersaline (40-70 ppt), in Baffin Bay and the Upper Laguna Madre (White et al. 1983 and 1989). The major source of freshwater to the Corpus Christi Bay Complex is provided by the Nueces River; however, the amount of riverine flow to Nueces Bay has been severely reduced over the last twenty years as a result of the construction of Choke Canyon Reservoir and an increased urban and industrial demand

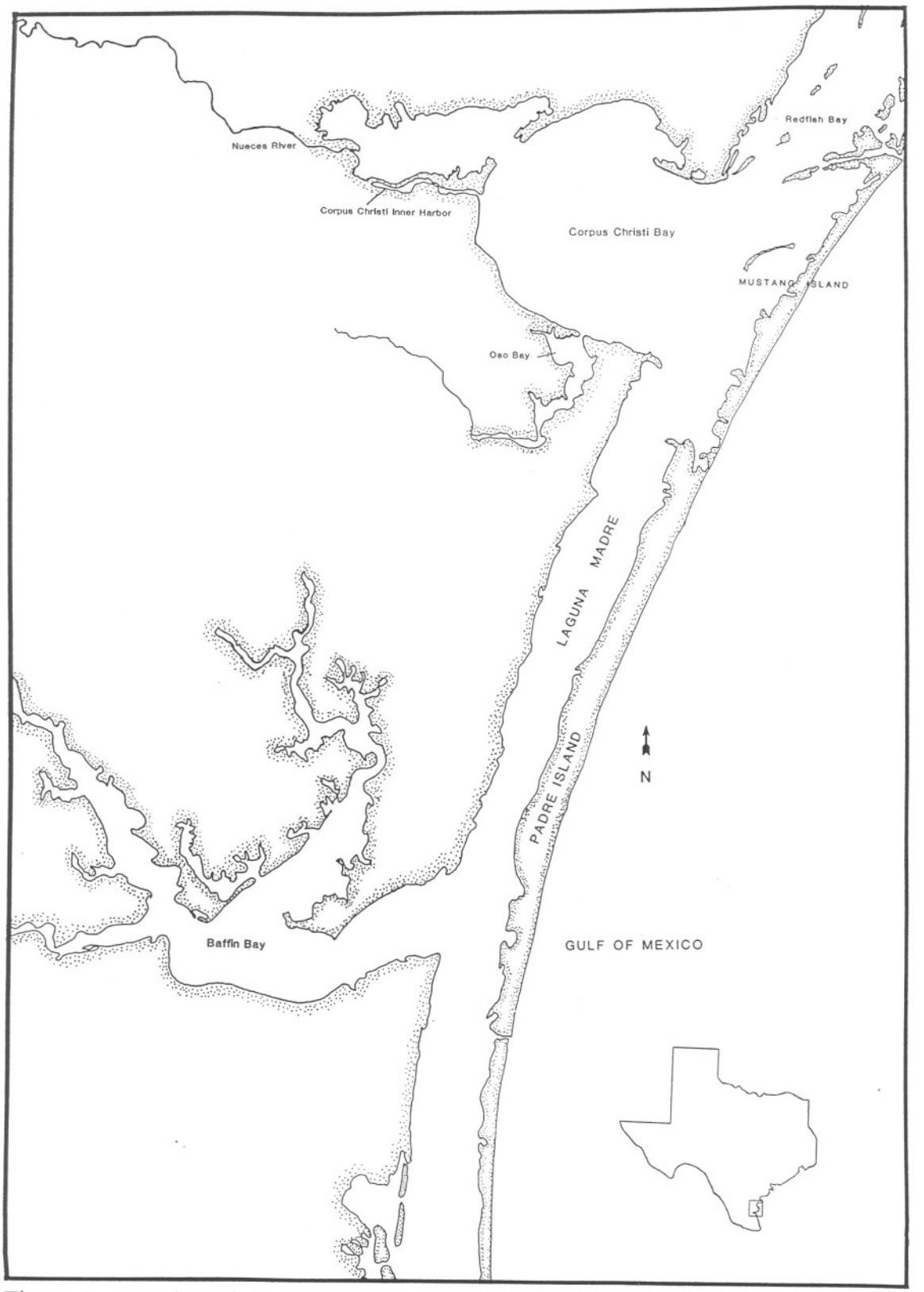


Figure 1. Location of the Corpus Christi Bay Complex.

Table 1. Federally listed species found within the coastal counties of the Corpus Christi Bay Complex (Aransas, San Patricio, Nueces, Kleberg and Kenedy Counties, Texas). Species are categorized as either endangered (E), threatened (T), proposed threatened (pT), or candidates (C1 or C2).

COMMON NAME	SCIENTIFIC NAME
American Peregrine Falcon E	*Falco peregrinus anatum*
Attwater's Prairie Chicken E	*Tympanuchus cupido attwateri*
Black Lace Cactus E	*Echinocereus reichenbachii* var. *albertii*
Brown Pelican E	*Pelecanus occidentalis*
Hawksbill Sea Turtle E	*Eretmochelys imbricata*
Jaguarundi E	*Felis yagouaroundi*
Kemp's Ridley Sea Turtle E	*Lepidochelys kempi*
Leatherback Sea Turtle E	*Dermochelys coriacea*
Northern Aplomado Falcon E	*Falco femoralis septentrionalis*
Ocelot E	*Felis pardalis*
Slender Rushpea	*Hoffmannseggia tenella*
Whooping Crane E	*Grus americana*
Arctic Peregrine Falcon T	*Falco peregrinus tundrius*
Bald Eagle T	*Haliaeetus leucocephalus*
Green Sea Turtle T	*Chelonia mydas*
Loggerhead Sea Turtle T	*Caretta caretta*
Piping Plover T	*Charadrius melodus*
Cactus Ferruginous Pygmy Owl pT	*Glaucidium brasilianum cactorum*
Gulf Coast Hog-nosed Skunk C1	*Conepatus leuconotus texensis*
South Texas Ambrosia C1	*Ambrosia cheiranthifolia*
Aransas Short-tailed Shrew C2	*Blarina hylophaga plumbea*
Audubon's Oriole C2	*Icterus graduacauda audubonii*
Bailey's Ballmoss C2	*Tillandsia baileyi*
Black-spotted Newt C2	*Notophthalmus meridionalis*
Black Tern C2	*Chilidonias niger*
Chandler Craig Lily or "lila de los llanos"	*Anthericum chandleri*
Coue's Rice Rat C2	*Oryzomys couesi aquaticus*
Ferruginous Hawk C2	*Buteo regalis*
Gulf Salt Marsh Snake C2	*Nerodia clarki*
Henslow's sparrow C2	*Ammodramus henslowii*
Loggerhead Shrike C2	*Lanius ludovicianus*
Mathis Spiderling C2	*Charadrius montanus*
Mountain Plover C2	*Boerhavia mathisiana*
Northern Gray Hawk C2	*Buteo nitidus maximus*
Reddish Egret C2	*Egretta rufescens*
Rio Grande Lesser Siren C2	*Siren intermedia texana*
Rough-seed Seed Purslane C2	*Sesuvium trianthemoides*
Sennett's Hooded Oriole	*Icterus cucullatus sennettii*
Texas Botteri's Sparrow C2	*Aimophila botterii texana*
Texas Diamondback Terrapin C2	*Malaclemys terrapin littoralis*
Texas Horned Lizard C2	*Phrynosoma cornutum*
Texas Olive Sparrow	*Arremonops rufivirgatus rufivirgatus*
Tropical Parula	*Parula pitiayumi nigrilora*
Welder Spine Aster C2	*Machaeranthera heterocarpa*
Western Snowy Plover C2	*Charadrius alexandrinus nivosus*
White-faced Ibis C2	*Plegadis chihi*

for freshwater (Freund and Nicolau 1994). The bays receive additional freshwater from the discharges of 114 industrial and municipal outfalls permitted by the Texas Natural Resource Conservation Commission (TNRCC), (Texas Water Commission 1992b).

Aransas Pass at Port Aransas, Texas, is the only open connection with the Gulf of Mexico in the study area. The Corpus Christi Ship Channel (13.7 m deep at mean low tide), the Gulf Intracoastal Waterway (GIWW) (3.7 m deep), and numerous smaller channels cross the study area. A salinity gradient exists within these channels; denser, more saline waters sink and move along the bottom while lower salinity waters remain closer to the surface. Water movement throughout the bays is influenced by tides, currents, waves, freshwater inflows, and winds, with winds playing the most important role in creating circulation patterns (Texas Dept. Water Resources 1981, Britton and Morton 1989). Bay and estuarine tides are small in magnitude, less than 25 cm (Shew et al. 1981) and characteristically mixed in nature (Britton and Morton 1989).

The area-wide human population is currently over one-half million and is projected to more than double by the year 2040 (HDR 1991). Much of the surrounding uplands have been converted to urban and suburban centers, agricultural operations (both for cultivated cropland and livestock grazing), and industrial facilities. Cotton and grain sorghum are the two major agricultural crops and cattle are the principal livestock raised in the area. Oil and gas production, petrochemical refining, and shipping are the most significant local industries, representing 14% of the petrochemical refining production and 8.7% of the chemical production in Texas (HDR 1991). In 1992, 65 million tons of petroleum products were shipped through the Port of Corpus Christi, the sixth largest port in the nation (Port of Corpus Christi 1993).

REDFISH BAY

Redfish Bay covers 74.6 sq km, receives negligible riverine input, has an average salinity of 27 ppt, and receives the discharge of 14 TNRCC permitted outfalls (Texas Water Commission 1992b). The TNRCC designated uses of Redfish Bay are: contact recreation, exceptional quality aquatic habitat and shellfish waters (Texas Water Commission 1992b). Bay depths range to 1.2 m and support dense sea grass meadows composed of shoal grass (*Halodule wrightii*), widgeon grass (*Ruppia maritima*), and turtle grass (*Thalassia testudinum*). These seagrass beds and the adjacent tidal flats provide habitat for the most diverse estuarine faunal species assemblage on the Texas coast (Shew et al. 1981). The largest Brown Pelican (*Pelecanus occidentalis*) rookery in Texas is found on Pelican Island Spoil in Redfish Bay (Wagner and Lange 1992), with 1126 successful nesting pairs documented for the 1994 breeding and nesting season (Blacklock pers. comm.). Redfish Bay also provides important wintering habitat for redhead ducks, which are found there in significant numbers during the fall and winter (Gamble and Woodin 1993). Additionally, the bay is important to bottle-nosed dolphins (*Tursiops truncatus*), which use the bay waters and nearby channels extensively, as do recreational fishermen and waterfowl hunters. Ninety percent of the shipping traffic involves

petroleum products, and the surrounding petrochemical industries pose the greatest potential for environmental concerns. Analyses were obtained for ten sediment and seven biota samples collected from this bay.

CORPUS CHRISTI BAY

Corpus Christi Bay covers approximately 320 sq km of open water (Texas Water Commission 1992b), has an average bay depth of approximately 4 m (White et al. 1983), and an average salinity of 30 ppt (Shew et al. 1981). Freshwater is provided to the bay by the Nueces River (via Nueces Bay) and by 21 TNRCC permitted outfalls which discharge into the bay. The TNRCC designated uses for Corpus Christi Bay waters are: contact recreation, exceptional quality aquatic habitat, and shellfish waters (Texas Water Commission 1992b). Corpus Christi Bay is nearly surrounded by urban and industrial development. The only extensive stretch of undeveloped shoreline remains on the bay side of Mustang Island, where algal and sand flats provide important habitat for shorebirds, including threatened and candidate species such as Piping (*Charadrius melodus*) and Snowy Plovers (*Charadrius alexandrinus nivosus*). Shipping, petrochemical production, industrial discharges, urban and agricultural runoff, commercial fishing, and recreational uses pose the greatest potential environmental concerns threatening this bay (Shew et al. 1981).

A total of 26 biota samples and 111 sediment samples were collected from Corpus Christi Bay. Specific sites offshore of Naval Air Station Corpus Christi were chosen for the collection of biota and sediment because of concerns related to the historical discharge and/or dumping of toxic metals and/or organic compounds from the Corpus Christi Naval Air Station and the Corpus Christi Army Depot.

NUECES BAY

Nueces Bay has a surface area of 74.9 sq km, depths ranging to 1.2 m, and salinities ranging from 15-30 ppt (Texas Water Commission 1992b and White et al. 1983). A number of estuarine-dependent species, such as brown (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*), spot (*Leiostomus xanthurus*), bay anchovy (*Anchoa mitchilli*), spotted sea trout, and striped mullet (*Mugil cephalus*) utilize Nueces Bay as essential nursery and foraging habitat. From 1941-1976 the Nueces River supplied an average freshwater flow of over 70,000,000 m^3 per year to Nueces Bay (Freund and Nicolau 1994). The current flow over the Calallen Dam (average for 1978-1993) has been reduced to approximately 22,000,000 m^3 per year (Freund and Nicolau 1994). Nueces Bay receives additional inflow from the discharges of three TNRCC permitted outfalls (Texas Water Commission 1992b). Potential environmental threats to the bay are further reductions of freshwater inflow, brine discharges and spills from local oil and gas production operations and pipelines, dredging, and dredge material disposal. Nine biota samples and 18 sediment samples were collected from Nueces Bay and submitted for chemical analyses.

INNER HARBOR

The Corpus Christi Inner Harbor covers approximately 2 sq km of surface area and receives the discharges of one municipal and 44 industrial permitted outfalls (Texas Water Commission 1992b). Historically, discharges from chemical and petrochemical facilities, as well as spills from shipping transfer activities, have been sources for the deposition of heavy metals and organic pollutants in sediments of the Inner Harbor. One notable example was the pollution of the Inner Harbor with zinc as a result of the operation of a smelting facility for thirty-five years. Several billion tons of zinc were processed during that time and Inner Harbor waters and sediments still remain heavily contaminated (Holmes et al. 1974). Additionally, cadmium and lead have also been found at levels of concern in Inner Harbor sediments (Holmes et al. 1974). In 1987, the project to deepen the Corpus Christi Inner Harbor to 15 meters was begun and heavily contaminated sediments were excavated and deposited on a nearby upland site (Nicolau and Adams 1993), resusupending contaminated sediments in the water column. Chemical analyses were obtained for three biota samples and seven sediment samples collected from the Inner Harbor.

NUECES RIVER

The Nueces River is the source for the municipal water supply of over one-half million people. Two upstream reservoirs, Choke Canyon and Lake Corpus Christi, and other diversions account for over a 50% reduction in the amount of river water flowing into the Nueces River Delta and Nueces Bay (Nicolau and Adams 1993). Two biota samples and one sediment sample were collected from the tidally influenced portion of the Nueces River and submitted for chemical analyses.

OSO BAY

Oso Bay covers 20.5 sq km, has depths ranging to 1.2 m, an average salinity of 20 ppt, and receives the discharge of Oso Creek and 8 TNRCC permitted outfalls (Texas Water Commission 1992b and White et al. 1983). Oso Bay seagrass beds have expanded since 1975, the year Central Power and Light Company's Barney Davis Power Plant in Corpus Christi, Texas, went on-line. The facility discharges approximately 1.9 billion liters per day of hypersaline water into Oso Bay. The discharge water is derived from the Laguna Madre where the power plant's intake channel is located (HDR 1991). Ecologically, Oso Bay serves as nursery habitat for white shrimp, blue crabs, and other commercially important species. The bay also supports a large and diverse avifauna due to a unique combination of natural and artificial environmental features. The Blind Oso, an area of approximately 200 hectares, provides some of the most important avian habitat in the Corpus Christi Bay area. Large expanses of mud and algal flats lie adjacent to a well-developed salt and brackish marsh formed, in part, by industrial and municipal discharges. The whole area supports tens of thousands of birds of over 100 species (Barrera unpublished data). Three biota and three sediment samples collected from Oso Bay were

submitted for chemical analysis.

LAGUNA MADRE

The Upper Laguna Madre encompasses approximately 300 sq km of hypersaline lagoon, has depths to 1.4 m, and an average salinity of 40 ppt. Prevailing winds are from the southeast and serve as the driving circulation factor in the system. The average tidal range is 15 cm and there is no significant freshwater inflow (White et al. 1989 and Shew et. al 1981). The Upper Laguna Madre is separated from the Lower Laguna Madre by a land bridge of wind tidal flats called the Land Cut, which is traversed by the Gulf Intracoastal Waterway. Hundreds of thousands of waterfowl, including the majority of the North American population of Redhead Ducks (*Aythya americana*) (Woodin 1994), as well as hundreds of Federally listed threatened Piping Plovers winter in and around the Laguna Madre. Additionally, the endangered American Peregrine Falcon and the recently delisted Arctic Peregrine Falcon (which is still protected due to similarity of appearance to the endangered subspecies) utilize the flats as staging areas in both fall and spring. This unique environment is part of the largest hypersaline lagoon in the world and supports the most productive recreational fishing waters on the Texas coast, especially for red drum and spotted seatrout (Diener 1975 and Gunter 1945).

Under normal conditions, turbidity is minimal and seagrass meadows are extensive in the Laguna Madre. However, a brown tide bloom has persisted since the spring of 1990 causing serious problems to the sea grass beds of both the Laguna Madre and surrounding bays. The brown tide organism, a one-celled Chrysophyte (Montagna pers. comm.), has been responsible for a dramatic increase in the amount of total suspended solids which, in turn, has caused a reduction in the amount of light reaching submerged aquatic vegetation (Dunton pers. comm.). Seagrasses, including *Halodule wrightii*, the principal food for wintering Redhead Ducks, require clear water. Their growth is directly related to the amount of photosynthectically active radiation (PAR) reaching the leaf blades (Onuf 1994). Since the brown tide bloom began, seagrass biomass has been reduced as much as fifty percent, especially at depths greater than one meter, and the associated macrobenthic fauna has declined as well (Chris Onuf pers. comm.).

Other potential environmental threats to the Laguna Madre include GIWW barge traffic, GIWW maintenance dredging and spoil disposal, channelization, housing developments, and problems associated with recreational use. A residential canal development built on North Padre Island during the early- to mid-1970's called Padre Isles, has a current population of approximately 4300 people. The canals are supplied with water from the Laguna Madre and have been plagued with water quality problems, including poor water circulation and eutrophication. The resulting low levels of dissolved oxygen have been responsible for a number of fish kills over the years, especially in summer months. In 1974, the City of Corpus Christi completed construction and began operation of a sewage treatment plant to service the development. The plant discharges on average over 3,000,000 liters of treated wastewater per day, 80% of which is used by a nearby golf

course during the summer months. The remaining discharge eventually flows into the Upper Laguna Madre (Bhaskar Patel pers. comm.). The outfall of this wastewater treatment plant was specifically selected as a site for sampling because of concerns related to contaminants in the discharge. Seventy-three sediment samples and 15 biota samples were collected in the Upper Laguna Madre and submitted for chemical analyses.

BAFFIN BAY

Baffin Bay and its associated tertiary bays, Alazan Bay, Cayo del Grullo and Laguna Salada, encompass 129 sq km of bay waters. The only significant freshwater Baffin Bay receives, other than runoff, is derived from Los Olmos Creek and the discharge of 22 TNRCC permitted outfalls (Texas Water Commission 1992b). The average bay depth is 2.7 m and the salinities range from 40 ppt on average to extreme hypersaline levels, such as 60-70 ppt and higher, during the summer months and times of drought. Unique features of this bay include fossilized serpulid reefs and the Point of Rocks, the only naturally occurring rocky bay habitat in the study area. The bay waters are generally more turbid than the Laguna Madre and depaupurate in numbers of species when compared to other area bays (Breuer 1957). However, Baffin Bay does support very high numbers of certain species, such as striped mullet, black drum, and red drum (Breuer 1957).

Potential environmental threats to the bay involve oil and gas production and spillage, channelization and dredge material disposal, and upland agricultural practices. Over fifty thousand hectares of upland brush adjacent to Baffin Bay have been converted to crop land within the past five years. Concerns have been raised that non-point source runoff from these converted lands may contain residues of ammonia-based fertilizers, which in turn may have contributed, at least in part, to the brown tide bloom. The brown tide organism is dependent on ammonia-based nutrients and is also believed to have originated in Alazan Bay, the drainage basin for the land conversion area (Edwards 1995). Fifty-nine sediment samples and fifteen biota samples were collected from this bay and submitted for chemical analyses.

MATERIALS AND METHODS

SEDIMENT

Sediments were collected at 282 locations within the Corpus Christi Bay Complex from May to July, 1988 (Figures 2-5). Sampling locations were established using a one-mile grid system aligned to magnetic north with collection sites located at approximately one mile intervals. Locations were determined in the field by traveling at a known speed along a compass reading for the amount of time needed to travel one mile. Triangulation using channel markers, islands, oyster reefs, drilling platforms and other fixed objects

aided in locating sites. Where gridded sites occurred on oyster reefs, islands, or shorelines, their locations were moved to the nearest areas where sediments were found. Additional sites were established in areas of known or suspected contamination, such as the Corpus Christi Inner Harbor, brine discharge outfalls, and outlets of storm drains.

Composite sediment samples were taken from each site by using either a stainless steel Ekman dredge or a stainless steel Ponar dredge. Sample sediments were collected from the top 15 cm only. At each sampling location, the dredged sediments were placed in a deep stainless steel pan and homogenized with a stainless steel spoon. An aliquot of 300-500 grams was placed in two separate 1000 ml glass jars with teflon lid liners for organic analyses or in 250 ml Whirl Paks® for trace metal analyses. Jars and teflon lid liners were chemically cleaned with acid and organic solvents according to Environmental Protection Agency (EPA) procedures (EPA 1982).

Oil and grease concentrations were determined for all 282 samples (Mississippi State Chemical Laboratory). Fifty samples were selected for analysis of polycyclic aromatic hydrocarbons (PAHs) and organochlorine residues (Mississippi State Chemical Laboratory). Results for organic analyses were verified with gas chromatography/mass spectrometry (GC/MS), and are reported in parts per million (ppm) wet weight (ww). All organic compounds are listed in Table 2. Analytical laboratories, analyses obtained, and the lower limits of detection (LLD) are reported in Appendix A.

A total of twenty-three trace elements (Table 2) were determined for all 282 sediment samples (Environmental Trace Substance Center and Hazelton Laboratory, Inc.). Results are reported in ppm dry weight (dw). Inductively coupled plasma emission spectroscopy was used to determine residues of all the trace elements except arsenic, selenium, and mercury. Arsenic and selenium residues were determined by hydride generation and atomic absorption. Cold vapor reduction was used for the mercury analysis. Blanks, duplicates, spiked samples, and standards were used for quality control and quality assurance, and were monitored by the National Biological Service's Patuxent Analytical Control Facility. Analytical laboratories, trace elements, and LLD are reported in Appendix A.

BIOTA

Biota collections were made at 37 sites throughout the Corpus Christi Bay Complex from July to November 1989 (Figures 2-5). Organic and trace metal analyses were obtained for a total of 80 samples, including hardhead catfish (*Arius felis*), toadfish (*Opsanus beta*), calico crab (*Eriphia gonagra*), blue crab, eastern oyster (*Crassostrea virginica*), and shoal grass. Sampling sites for biota were selected to cover all types of estuarine habitats, such as open bay, salt marsh, seagrass beds, oyster reefs, and the tidally influenced portion of the Nueces River. As with sediment sampling, specific areas of known or suspected

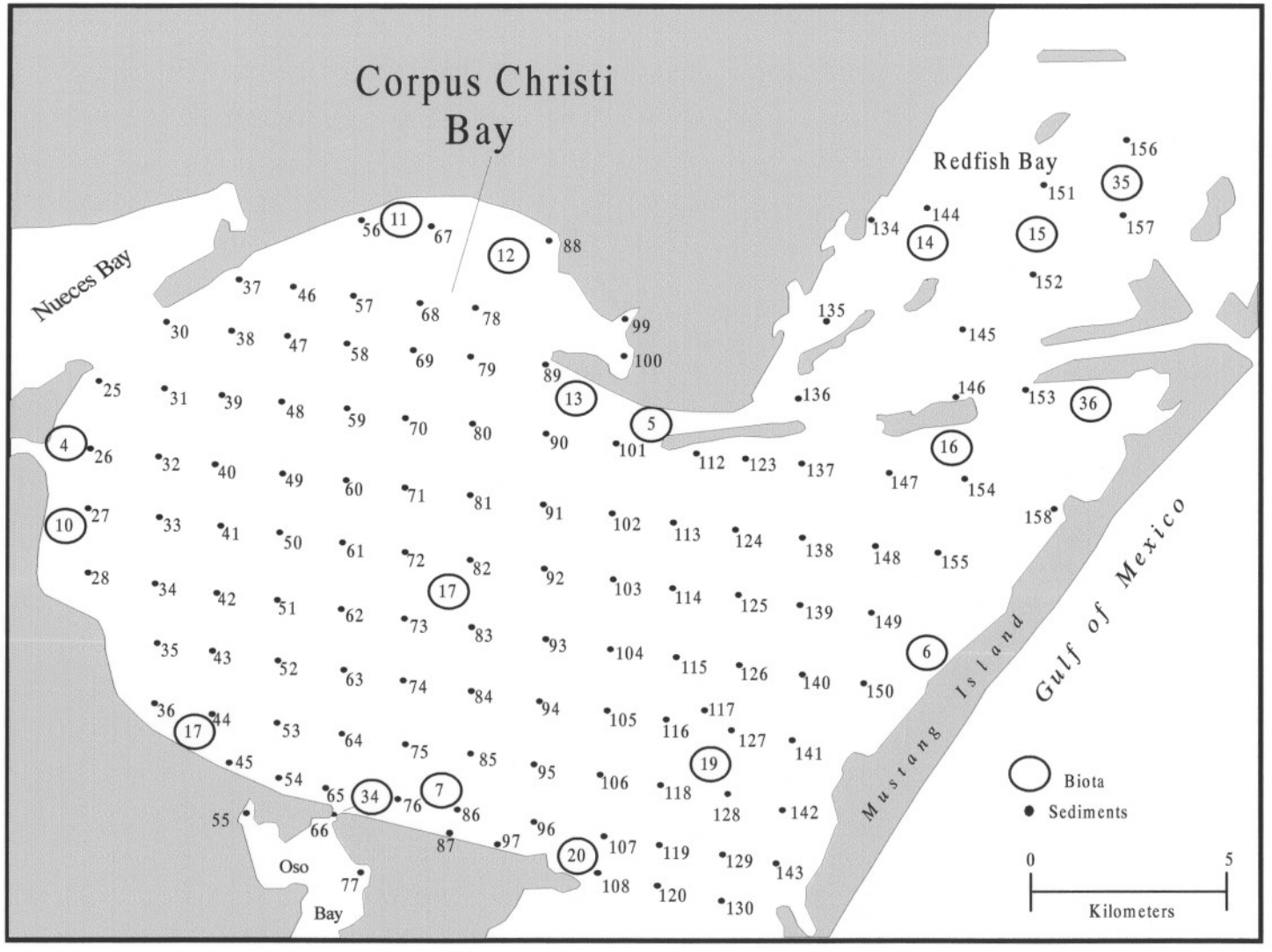


Figure 2. Sediment and biota sampling locations in Redfish, Corpus Christi, and Oso Bays, 1988-1989.

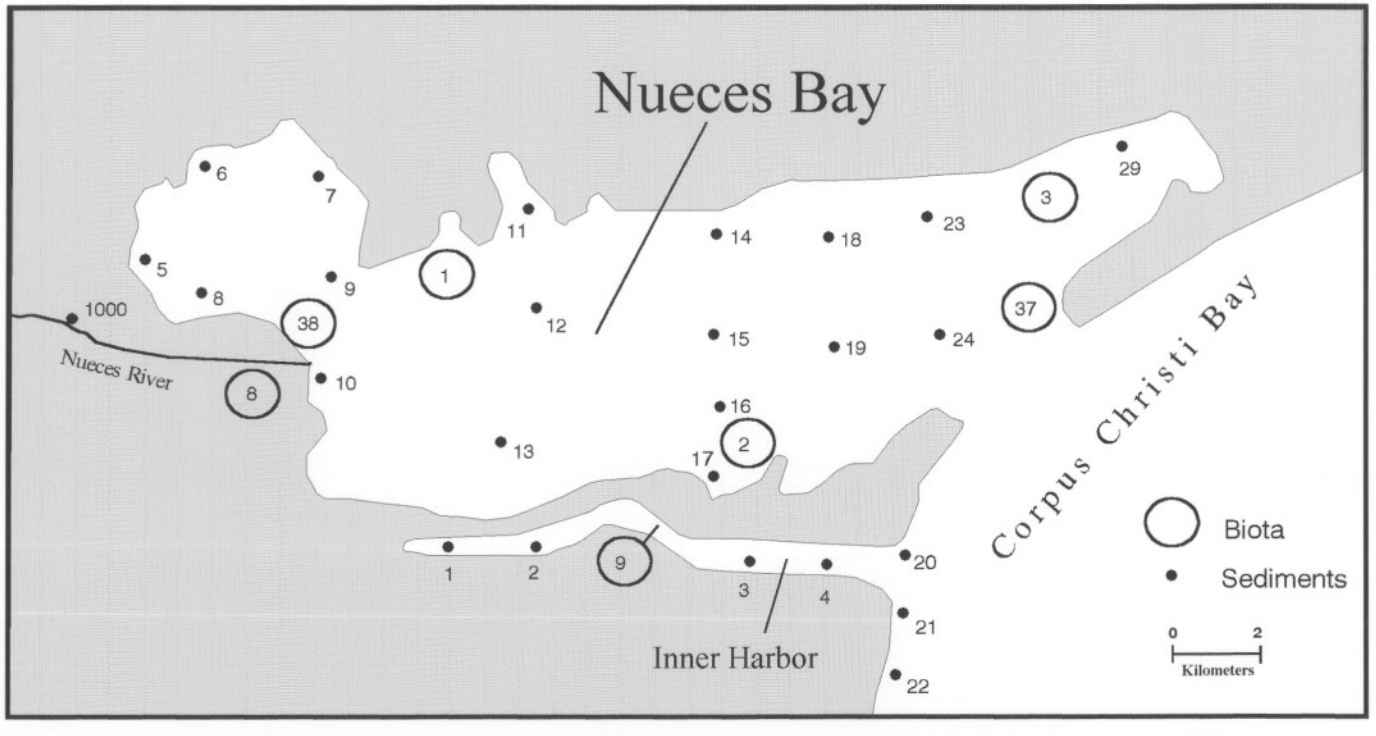


Figure 3. Sediment and biota sampling locations in Nueces Bay, the Inner Harbor, and the Nueces River, 1988-1989.

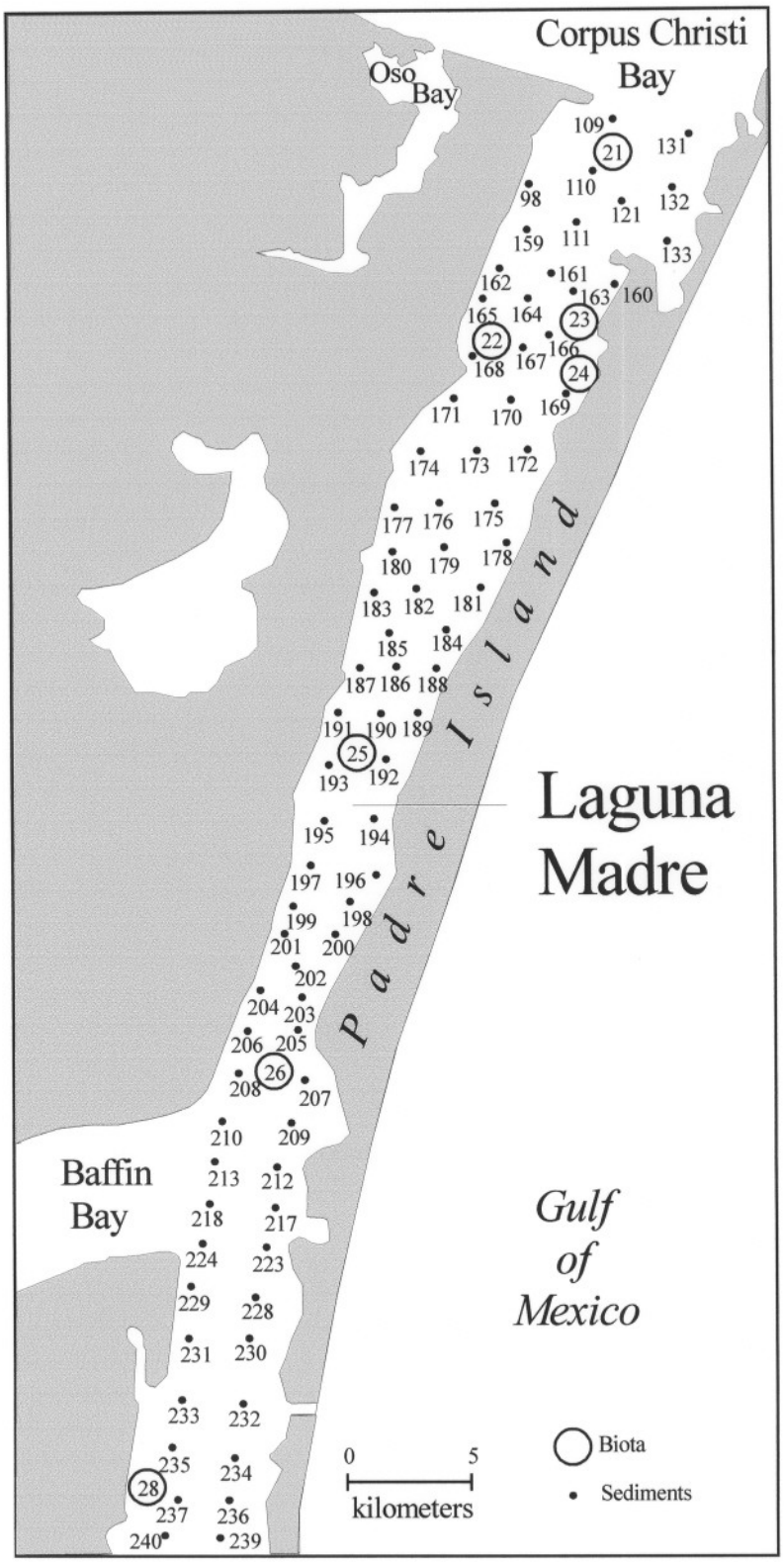


Figure 4. Sediment and biota sampling locations in the Upper Laguna Madre, 1988-1989

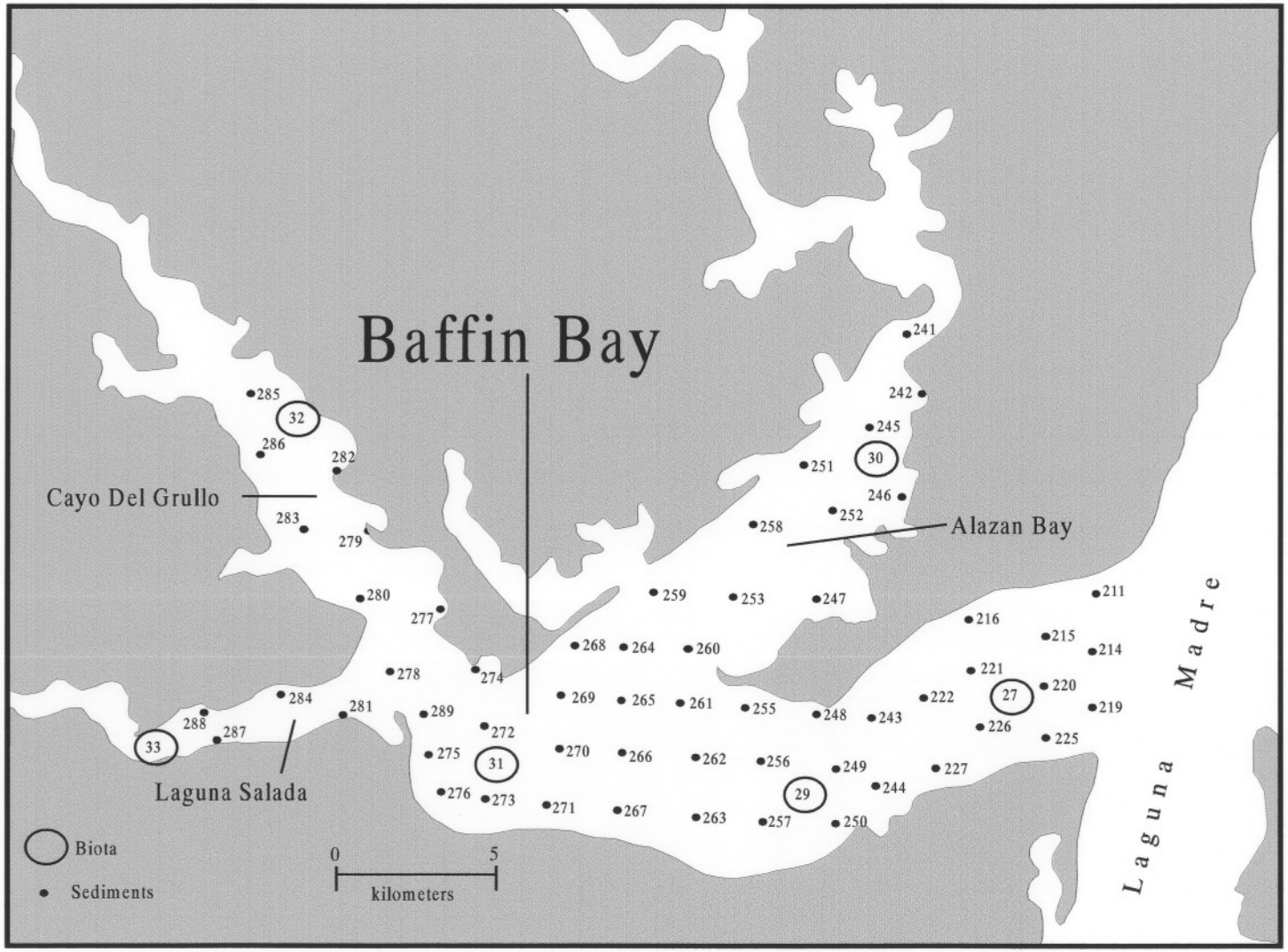


Figure 5. Sediment and biota sampling locations in Baffin Bay, 1988-1989.

Table 2. Elements and compounds analyzed in sediment and biota from the Corpus Christi Bay Complex, Texas, 1988-1989.

Elements	Organochlorines	Aromatic Hydrocarbons[1]
Aluminum (Al)	α-BHC	Naphthalene
Antimony (Sb)	ß-BHC	Fluorene
Arsenic (As)	δ-BHC	Phenanthrene
Barium (Ba)	Γ-BHC	Anthracene
Beryllium (Be)	Heptachlor epoxide	Fluoranthrene
Boron (B)	HCB	Pyrene
Cadmium (Cd)	Total PCBs	Chrysene
Chromium (Cr)	alpha chlordane	Benz(a)anthracene
Copper (Cu)	gamma chlordane	Benzo(b)fluoranthrene
Iron (Fe)	oxychlordane	Benzo(k)fluoranthrene
Lead (Pb)	trans nonachlor	Benzo(a)pyrene
Magnesium (Mg)	cis nonachlor	Benzo(e)pyrene
Manganese (Mn)	Dieldrin	Benzo(g,h,i)perylene
Mercury (Hg)	Endrin	1 Methylnaphthalene
Molybdenum (Mo)	Mirex	2 Methylnaphthalene
Nickel (Ni)	o,p' - DDE	Biphenyl
Selenium (Se)	o,p' - DDD	2,6 Dimethylnaphthalene
Silver (Ag)	o,p' - DDT	Acenaphthylene
Strontium (Sr)	p,p' - DDE	Acenaphthene
Thallium (Tl)	p,p' - DDD	2,3,4-trimethylnaphthalene
Tin (Sn)	p,p' - DDT	1-methylphenanthrene
Vanadium (V)	Toxaphene	Perylene
Zinc (Zn)	Lindane	Indenopyrene
	Aldrin	Dibenzanthracene
		1,2,5,6-dibenzanthracene
Oil and Grease[1]	**Dioxins[2]**	
	2,3,7,8 TCDD	

[1] Analyzed in sediment only
[2] Selected biota samples

contamination were of primary importance, as were habitats important for endangered and threatened species. Site descriptions, locations and numbers of samples per species are provided in Appendix B.

Hardhead catfish (and one composite sample of toadfish) were collected using three inch mesh monofilament gill nets, set lines, and by angling. A sample consisted of a composite of five fish (whole body) with the dorsal and pectoral spines removed. The sample was wrapped in aluminum foil, labeled and kept chilled on ice. Blue crabs were collected using crab traps and were occassionally caught in gill nets. A composite of five individuals (including exoskeleton) made up a single sample. Claws were discarded and the crabs were wrapped in aluminum foil, labeled, and kept chilled on ice. Eastern oysters were collected by tongs on twelve foot poles or by hand on exposed reefs and structures. Oysters were shucked in the field and the soft parts placed in chemically-clean glass jars. Approximately 500 ml of oyster tissue was collected from each site. Shoalgrass samples were collected by hand, rakes, or dredges and rinsed in the overlying water column to remove attached particulate materials, debris, and sediment. Samples included shoots, roots, and rhizomes which were stored in large plastic bags. As with all biota samples, the shoalgrass was kept on ice until placed in freezers where it was stored. Prior to shipping, shoalgrass samples were thawed and only rhizomes, an important food source for wintering waterfowl, were submitted for analyses in 250 ml Whirl Paks®.

The biota samples were sent to one of three laboratories (Environmental Trace Substance Center, Hazelton Laboratory, Inc., and Research Triangle Institute), for analyses of a total of twenty-three elements. Inductively coupled plasma emission spectroscopy was used to determine trace element residues except arsenic, selenium, and mercury. Arsenic and selenium residues were determined by hydride generation and atomic absorption. Cold vapor reduction was used for the mercury analysis. Results are reported in tables and text in ppm dw.

Aliquots of 49 biota samples were also submitted for organochlorine analyses at either of two analytical laboratories (Mississippi State Chemical Laboratory and Geochemical and Environmental Research Group, Tx A&M). CGC with electron capture detector was used for organochlorine pesticides and total PCBs analyses. The results for organochlorine analyses are reported in tables and text in ppm ww. Six biota samples were also submitted for analysis of the dioxin, 2,3,7,8 TCDD to Wright State University, Dayton, Ohio. Dioxin analysis was performed by use of GC-MS analyses, using a DB-DIOXIN capillary and GC column, which is isomer specific for 2,3,7,8 TCDD. Wet weight, whole tissue analysis was performed, and because of the extreme toxicity of TCDD, results are reported in picograms per gram, or parts-per-trillion (ppt). Trace elements and organic compounds are listed in Table 2, and the analytical laboratories, analyses obtained, and the LLD are reported in Appendix A.

DATA ANALYSIS

Minimum and maximum values were determined for all organochlorines in biota and, due to the limited amount of data, results are presented as arithmetic means for each matrices by bay. Minimum and maximum values were also determined for all trace element data, and results are presented as geometric means by bay. Geometric means (GM) were determined for each trace element when more than 50 percent of the samples from a bay contained detectable rresidues. In those cases where geometric means were calculated, one-half the detection limit was used for samples found below the detection limit. Geometric means were calculated by taking a mean of the logs and converting back to the anti-log.

RESULTS AND DISCUSSION

DIOXINS

Polychlorinated dibenzo-para dioxins (PCDD's) originate as by-products of chemical manufacturing. They are also found in trace concentrations as impurities in industrial and hazardous wastes, and in some pesticides. The most toxic PCDD isomer, and possibly the most toxic synthetic chemical, is 2,3,7,8-TCDD (TCDD), a by-product of the manufacture of phenoxy herbicides, including 2,4,5-T, Silvex, and 2,4-D, as well as other manufacturing processes. TCDD is highly stable, persistent, easily incorporated into aquatic biota and ecosystems, and virtually impossible to destroy. A number of laboratory studies have examined TCDD's chemistry and toxicity; however, data on TCDD's fate and persistence within the environment are lacking (Eisler 1986b).

In order to obtain baseline information on the occurrence of dioxins within Corpus Christi Bay Complex biota, six composite biota samples consisting of four blue crab (three from Corpus Christi Bay and one from Laguna Madre), one hardhead catfish (Baffin Bay), and one toadfish sample (Laguna Madre) were analyzed for TCDD. The LLD ranged from 0.252 to 0.644 ppt ww, in blue crabs and hardhead catfish, respectively. Per cent lipids ranged from 0.37% in blue crabs to 3.1% in hardhead catfish. TCDD residues in all six samples were below the LLD, suggesting that dioxin contamination is not a serious threat to Corpus Christi Bay Complex biota, despite the fact that the area is heavily industrialized with facilities primarily involved in petroleum refining and the production of raw organic chemicals, including halogenated hydrocarbons. These results may also be partially due to the discontinued use of phenoxy herbicides, which were phased out of production during the 1970's (Eisler 1986b). According to Eisler (1986b), manufacturing processes which include discharges from the incineration of chlorinated compounds, the burning or heating of commercial and purified chlorophenates, and the pyrolysis of polychlorinated biphenyls contaminated with trichlorbenzenes are currently the most

important contributors of TCDD into the environment. Analytical results for TCDD analysis are reported in Appendix C.

ORGANOCHLORINES

Organochlorine compounds (OCs), such as DDT and polychlorinated biphenyls (PCBs), are persistent and wide-spread environmental contaminants. Despite the fact that the use of DDT in the United States has been banned since 1972, residues of its breakdown metabolites DDD and DDE persist in biota. DDT and its metabolites have long half-lives and are readily soluble in lipids, allowing for incorporation into the food chain (Haseltine et al. 1981). DDE-caused eggshell thinning has been documented for some species of fish-eating birds, such as brown pelicans and bald eagles, and contributed to drastic population declines of these species (Blus et al. 1980 and Weimeyer 1984). Population declines of the white-faced ibis may also be partially attributed to DDE-caused eggshell thinning (King et al. 1980).

Concerns regarding the environmental impacts of PCBs contamination led to a ban on the manufacture and use of the compounds in 1979 (Eisler 1986c). However, because of usage prior to the ban and the extreme environmental stability of these compounds, they remain widespread and continue to be found in detectable amounts in biota. PCBs, as with other OCs, are known to bioaccumulate and biomagnify causing reproductive failure, and other damaging biological effects (Eisler 1986c). Since the ban of PCBs, the Lake Huron population of double-crested cormorants (*Phalacrocorax auritus*) has been rapidly recovering after a decline attributed to egg-failure, as well as other reproductive problems, presumably related to the high levels of PCBs, DDE and mercury contamination found in the eggs (Eisler 1986c).

Forty-nine biota samples, consisting of 4 oyster, 22 blue crab, and 23 hardhead catfish samples were submitted for organochlorine analyses, and 42 (85.7%) had detectable residues of at least one OC (Tables 3 and 4). The following OCs were above detection in at least one sample: alpha-chlordane, oxychlordane, t-nonachlor, cis-nonachlor, p,p'-DDD, p,p'-DDE, and total PCBs. Although they were detected in one hardhead catfish sample (biota site 4, Figure 2), oxychlordane and alpha-chlordane were not included in Table 4 because the residue of each compound equaled the LLD (0.01 ppm ww). Seven sediment samples were also analyzed for organochlorine compounds, but none were found in excess of the LLD (0.01 ppm ww) for any OC.

DDT and Metabolites

DDT was below detection in all biota and sediment samples; however the breakdown metabolites p,p'-DDE and p,p'-DDD were detected in oyster, blue crab, and hardhead catfish. One oyster sample from Nueces Bay (biota site 3, Figure 3), had a p,p'-DDE residue of 0.02 ppm ww. The three other oyster samples, two from Nueces Bay and one from the Inner Harbor, were free of all detectable OCs.

Table 3. Organochlorines in blue crabs from the Corpus Christi Bay Complex, Texas, 1989. Means, ranges (minimum-maximum), and number above detection limit. Reported in ppm wet weight (ww).

Organo-chlorine compound	Redfish Bay N=2	Corpus Christi Bay N=8	Nueces Bay N=3	Inner Harbor N=1	Oso Bay N=1	Laguna Madre N=3	Baffin Bay N=4
p,p'-DDD	BD[1]	--[2] 0.01[3] 1[4]	BD	BD	BD	BD	BD
p,p'-DDE	-- (BD-.01) 1	0.019 (0.01-0.04) 8	0.023 (0.01-0.04) 3	-- 0.01 1	-- 0.01 1	0.02 (0.01-0.03) 3	-- (BD-0.08) 1
Total PCBs	BD	-- (BD-0.23) 2	-- (BD-0.08) 1	BD	BD	BD	BD

[1]Below detection
[2]Arithmetic mean (-- indicates no mean was determined because 50 per cent or more of the values were below the detection limit).
[3]The minimum and maximum detected values (min-max).
[4]The number of samples exceeding the detection limit.

Eighteen out of twenty-two blue crab samples had detectable residues of p,p'-DDD and/or p,p'-DDE. p,p'-DDD was detected in one sample and p,p'-DDE in 18 (Table 3). Although 82% of the blue crab samples did contain detectable amounts of p,p'-DDE, the highest residue was 0.08 ppm ww (biota site 29, Figure 5), an amount substantially lower than the 1 ppm concentration in biota established as a level of protection for aquatic life by the National Academy of Sciences and National Academy of Engineers (1972).

All hardhead catfish samples had detectable amounts of p,p'-DDE, with residues ranging from 0.01-0.37 ppm ww. The sample with the maximum residue was obtained from Corpus Christi Bay (biota site 4, Figure 1). Gamble et al. (1989) reported similar residues of p,p'-DDE in Aransas Bay Complex hardhead catfish, with a GM of 0.095 ppm ww. However, both Corpus Christi and Aransas Bay Complex fish residues were much lower than those reported by Gamble et al. (1988) for 14 species of fish collected from the Lower Rio Grande Valley-Lower Laguna Madre, which had a GM of 0.55 ppm ww p,p,'-DDE (Gamble et al. 1988), and ranged to a maximum of 9.90 ppm ww. Christi Bay Complex hardhead catfish had residues which were within the range of the national geometric mean of 0.19 ppm p,p'-DDE, reported for freshwater fish collected from the nations rivers during late 1984 to 1985 as part of the National Contaminants Biomonitoring Program (NCBP) (Schmitt et al. 1990).

Table 4. Organochlorines in hardhead catfish from the Corpus Christi Bay Complex, Texas, 1989. Means, ranges (minimum-maximum), and number above the detection limit. Reported in ppm wet weight (ww).

Organo-chlorine Compound	Redfish Bay N=2	Corpus Christi Bay N=9	Nueces Bay N=2	Inner Harbor N=1	Nueces River N=1	Oso Bay N=1	Laguna Madre N=3	Baffin Bay N=4
t-nonachlor	BD[1]	0.023[2] (BD-0.09)[3] 6[4]	BD	BD	BD	BD	BD	BD
cis nonachlor	BD	-- (BD-0.04) 3	BD	BD	BD	BD	BD	BD
p,p'-DDD	BD	-- (BD-0.01) 3	BD	BD	BD	BD	BD	BD
p,p'-DDE	0.025 (0.02-0.03) 2	0.13 (0.01-0.37) 9	0.045 (0.04-0.05) 2	-- 0.04 1	-- 0.04 1	-- 0.09 1	0.05 (0.03-0.07) 3	0.048 (0.02-0.07) 4
Total PCBs	-- (BD-0.31) 1	0.87 (BD-3.8) 8	0.635 (0.48-0.79) 2	-- 0.65 1	-- 0.26 1	-- 0.08 1	0.165 (BD-0.31) 2	BD

[1]Below detection
[2]Arithmetic mean (-- indicates no mean was determined because 50 per cent or more of the values were below the detection limit).
[3]The minimum and maximum detected values (min-max).
[4]The number of samples exceeding the detection limit.

Total PCBs

Total PCBs were detected in 3 blue crab samples (Table 3). The maximum blue crab residue was 0.23 ppm ww, detected in a sample from Corpus Christi Bay (biota site 10, Figure 1). This amount is well below the 2 ppm total PCBs level of protection in human food items recommended by the Food and Drug Administration (Food and Drug Administration 1992). Although only three samples of Corpus Christi Bay Complex blue crabs had detectable levels of PCBs, blue crabs collected for baseline contaminants studies of the Aransas Bay Complex (Gamble et al. 1988) and the Lower Rio Grande Valley-Lower Laguna Madre (Gamble et al. 1989) were all below detection for total PCBs.

Sixteen of 23 hardhead catfish samples had detectable residues of total PCBs (Table 4). The greatest mean, 0.87 ppm ww, and the maximum sample residue, 3.8 ppm ww (biota site 4, Figure 1) were both from Corpus Christi Bay. This amount, 3.8 ppm ww, is almost two times greater than the 2 ppm PCBs level of protection recommended by the

FDA (Food and Drug Administration 1992). By comparison, PCBs were below detection in all hardhead catfish collected from the Aransas Bay Complex (Gamble et al. 1989), and only 24% of fish collected by Gamble et al. (1988) in the Lower Rio Grande Valley-Lower Laguna Madre were above detection for PCBs, with residues ranging from 0.1 to 0.11 ppm ww.

The results of the PCBs analyses of blue crabs and hardhead catfish collected for the current study indicate the occurrence of low-level PCBs contamination of Corpus Christi Bay Complex biota, especially when compared to the results reported in the other area baseline contaminants studies. Although most OCs in Corpus Christi Bay Complex biota had residues lower than those reported by Gamble et al. (1988 and 1989), PCBs were more pervasive and exhibited residues many times greater. PCBs residues in most Corpus Christi Bay Complex hardhead catfish were below the FDA level of protection for human food items, but were nonetheless two to ten times greater than PCBs in blue crabs. Additionally, a higher percentage of hardhead catfish samples (70%) were above detection for PCBs than blue crab (17%) or oyster samples (none), indicating the occurrence of biomagnification of the contaminant.

The bioaccumulation of PCBs in fish can have detrimental effects on higher trophic level piscivorous fish and wildlife, such as the Federally listed endangered Brown Pelican. In the Corpus Christi Bay Complex, the Brown Pelican utilizes the surrounding bays for feeding, resting, and nesting purposes. This species has been recovering in the Corpus Christi Bay area since a dramatic population decline during the 1960's and 70's, also related to reproductive failure caused by environmental contamination of OCs (Blus et al. 1974 and King et al. 1977). Royal Terns from Corpus Christi Bay and the middle Texas coast were investigated for DDE-caused eggshell thinning and other reproductive failures (King et al. 1983), with negative results. However, data from the present study demonstrate the overall occurrence of PCB- and to a lesser extent DDE-biomagnification in marine biota from the Corpus Christi Bay Complex (Figure 6 and 7). Sources for PCBs in the Corpus Christi Bay Complex have not been determined, but may be related to the large number of industrial discharges from petroleum refineries and chemical manufacturing plants which occur within the study area.

POLYCYCLIC AROMATIC HYDROCARBONS

There are thousands of PAH compounds, all consisting of hydrogen and carbon arranged in the form of two or more fused benzene rings, and many are either toxic, carcinogenic or both (Eisler 1987b). PAHs are formed by pyrolysis of organic material, the process of fossil fuel formation, and direct biosynthesis by bacteria, fungi, and plants (Neff 1985). PAHs contaminate the environment generally by way of petroleum products, either from oil and gas production, transportation, spillage, industrial production and discharges, and other anthropogenic sources (Eisler 1987b).

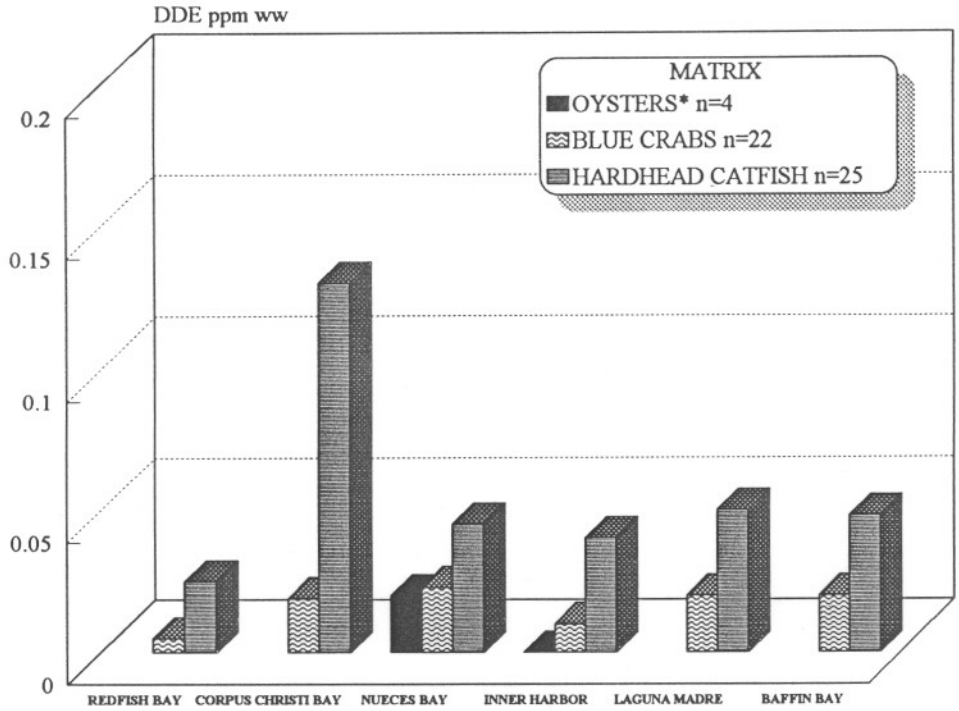


Figure 6. Arithmetic means of DDE in biota from the Corpus Christi Bay Complex, 1989. *Oysters obtained from the Inner Harbor (n=1) and Nueces Bay (n=3) only.

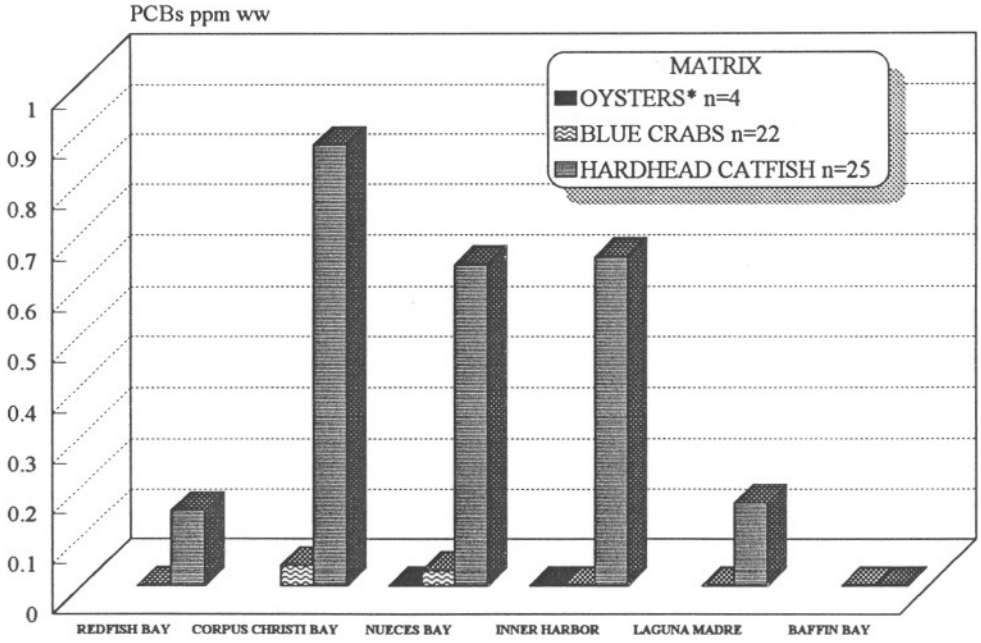


Figure 7. Arithmetic means of PCBs in biota from the Corpus Christi Bay Complex , 1989. *Oysters obtained from the Inner Harbor (n=1) and Nueces Bay (n=3) only.

Fifty sediment samples were submitted for analyses of twenty-five PAH compounds (Table 2). All samples had detectable residues of at least one PAH, although the detectable residues were present at very low levels (0.01-0.49 ppm ww). Three samples had residues of flouranthrene, pyrene, and/or chrysene above 0.3 ppm. One sample from the Inner Harbor (sediment site 4, Figure 3) had 0.38 ppm flouranthrene and 0.38 ppm pyrene. A Nueces Bay sample collected from White Point (sediment site 7, Figure 3), an area of current and historic petroleum production and produced brine-water discharges, had 0.3 flouranthrene, 0.3 pyrene, and 0.49 ppm chrysene. A sample collected from Corpus Christi Bay near Shamrock Island (sediment site 150, Figure 2), another area of historic petroleum production and waste hydrocarbon disposal, had 0.45 ppm flouranthrene and 0.33 ppm pyrene. Gamble et al. (1989) did not report PAHs in sediments and found biota from the Aransas Bay Complex to be free of PAHs, except for low levels in one hardhead catfish and one oyster sample (0.23 and 0.051 ppm ww, respectively). Gamble et al. (1988) reported the presence of PAHs in five of fifteen sediment samples from the Lower Rio Grande Valley-Lower Laguna Madre, with residues ranging from 0.01 ppm ww phenanthrene to 6.50 ppm ww benzo(b)fluoranthrene. Multiple benzene ring compounds, such as flouranthrene (3 benzene rings), pyrene (4 benzene rings), and chrysene (4 benzene rings) are known to be carcinogenic. The larger the number of benzene rings the more likely the compound will induce tumor formation in animals and resist environmental degradation (Cain 1993).

OIL and GREASE

Two hundred and eighty out of 282 sediment samples were above detection for oil and grease. The arithmetic mean of oil and grease residues in Corpus Christi Bay Complex sediments was 234 ppm ww, an amount lower than that reported by Gamble et al. (1989) for Aransas Bay Complex sediments, 423 ppm ww (n=376). Only five 5 samples in the current study had oil and grease residues above 500 ppm, three were above 1,000 ppm, and the maximum residue was 2200 ppm ww, detected in a sample collected from Nueces Bay (sediment site 14, Figure 3).

The oil and grease constituent is composed of several types of organic compounds, including hydrocarbons, fatty acids, soaps, fats, waxes, and oils. Few standards have been developed for judging the significance of oil and grease levels, however, Prater and Hoke (1980) used three ranges of oil and grease to describe the relative extent of sediment contaminations: (1) levels less than 1,000 ppm are unpolluted, (2) levels from 1,000 to 2,000 ppm are moderately polluted, (3) levels above 2,000 ppm are heavily polluted. Based on this ranking system, all sediment samples collected for the current study from the Corpus Christi Bay Complex, except for three, are in the unpolluted range. Appendix D contains the results of all organic analyses for sediments and biota.

TRACE ELEMENTS

All twenty-three trace elements were found above detection limits in at least one sediment and/or biota sample. The trace element analyses were performed by four different laboratories, and both detection limits and the chemicals analyzed for were different for each laboratory, complicating data comparisons (see Appendix A). Data for selected trace elements in sediments, shoal grass, eastern oysters, blue crabs, and hardhead catfish are presented in Tables 5-9 in ppm dry weight (dw). Each table contains the following information categorized by bay (or other water body such as the Nueces River, and the Inner Harbor): geometric means, ranges (minimum and maximum residues), and number of samples above the detection limit. Due to the limited number of samples with detectable residues of antimony, silver, thallium, and tin, these data are included in the appendices only. All trace element raw data for both sediments and biota, are reported in ppm dw and included in Appendix E.

Twenty-two out of twenty-three trace elements were found above detection limits in sediments. Silver was detected in only two samples, molybdenum in eighteen (all from the Laguna Madre), and tin was not detected in sediments. Inner Harbor sediments had the highest GMs of eleven trace elements, including aluminum, beryllium, cadmium, chromium, copper, iron, lead, manganese, mercury, vanadium, and zinc. Corpus Christi Bay sediments had the highest GMs of arsenic, barium, and nickel, while boron, magnesium, and strontium residues were highest in Baffin Bay sediments. GMs of cadmium (1.21 ppm), lead (36.41 ppm), mercury (0.205 ppm), and zinc (179.5 ppm), all from the Inner Harbor, were elevated above background levels (Table 5). Additionally, GMs of arsenic (4.39 ppm from Corpus Christi Bay), copper (16.82 ppm from the Inner Harbor), and nickel (7.7 ppm from Corpus Christi Bay) were above background levels and/or those reported by other investigators (Table 10) (Gamble et al. 1989, Robertson et al. 1991, Gamble et al. 1988, and Shacklett and Boernaen 1984 et al. 1988) .

Twenty-one out of 23 trace elements were found above detection in one or more biota samples. Silver and thallium were below detection in all samples, while antimony was detected in only two (both shoal grass), and beryllium was detected in three. Trace element raw data are presented in Appendix E for the following: 16 shoalgrass (from all areas except the Nueces River and Inner Harbor), 4 oyster (Nueces Bay and the Inner Harbor), 33 blue crab (all areas), one calico crab (Corpus Christi Bay), 25 hardhead catfish (all areas), and one toadfish sample (Laguna Madre).

Table 5. Selected trace elements in Corpus Christi Bay Complex sediments (ppm dry weight). Geometric mean, range, and number of samples above the detection limit are presented for each bay, the Inner Harbor and the Nueces River.

Trace Metal	Redfish Bay N=10	Corpus Christi Bay N=111	Nueces Bay N=18	Inner Harbor N=7	Nueces River N=1	Oso Bay N=3	Laguna Madre N=73	Baffin Bay N=59
Al	2571[1] (870-14800)[2] 10[3]	10484 (615-24800) 111	5194 (1150-16300) 18	12924 (6190-25400) 7	-- 5040 1	7517 (4800-15500) 3	4349 (321-31500) 73	12669 (1210-46900) 59
As	3.18 (0.85-12) 10	4.39 (0.52-8.3) 111	2.73 (0.95-5.6) 18	3.89 (2.2-6.8) 7	-- 2.4 1	1.94 (1.4-3.5) 3	2.55 (0.4-27.8) 73	3.31 (0.59-7.95) 59
Ba	196 (70.3-774) 10	362 (35.7-872) 111	347 (70.6-2320) 18	279 (104-1530) 7	-- 544 1	319 (139-670) 3	141 (15.8-865) 73	249 (19.3-2380) 59
Be	0.147 (<0.1-0.91) 7	0.66 (<0.01-1.4) 105	0.31 (<0.1-1.1) 16	0.76 (0.39-1.3) 7	-- 0.36 1	0.375 (0.2-0.88) 3	-- (<0.1-1.3) 36	0.62 (<0.1-5.5) 37
B	6.14 (3-25) 10	11 (<2-25) 104	-- (<2-14) 8	8.17 (<2-18) 6	-- 5 1	11.58 (7.9-24) 3	26.9 (<2-343) 70	30.85 (5-103) 59
Cd	BD[4]	-- (<0.2-0.7) 45	.34 (<0.2-3.3) 11	1.21 (0.4-4.6) 7	-- 1.6 1	-- (<0.2-0.7) 1	-- (<0.2-1.2) 11	-- (<0.2-1.69) 15
Cr	3.33 (1-17) 10	10.9 (<0.1-24) 111	5.49 (2-14) 18	17.13 (8.4-31) 7	-- 5 1	7.2 (4.6-15) 3	5.63 (<1.2-31) 72	13.14 (1-38.5) 59
Cu	2.9 (0.5-14) 10	7.3 (0.3-17) 111	4.6 (2-9.9) 18	16.82 (6.9-52.3) 7	-- 6.1 1	4.58 (3.1-10) 3	6.48 (0.73-52.2) 73	9.99 (0.65-53.1) 59
Fe	2767 (1240-15100) 10	9119 (637-18200) 111	4711 (1010-12900) 18	9671 (5050-17900) 7	-- 4150 1	5015 (3310-9720) 3	3672 (493-26800) 73	8475 (821-29200) 59
Pb	4.09 (<4-18) 5	15 (<4-28) 105	9.8 (<4-25) 16	36.01 (13-110) 7	-- 16 1	11.7 (8-20) 3	-- (<4-79.8) 35	17.84 (<4-87.3) 48
Mg	2668 (1320-12200) 10	6688 (565-13300) 111	2684 (679-7910) 18	5808 (3240-9640) 7	-- 2330 1	5865 (3610-7850) 3	4945 (569-43900) 73	8104 (1170-17300) 59
Mn	97.5 (29.8-290) 10	220.7 (10-522) 111	84.5 (15-223) 18	243 (106-494) 7	-- 160 1	93.6 (60.4-166) 3	79.7 (9.53-630) 73	214 (28.7-554) 59
Hg	0.024 (0.01-0.069) 10	0.063 (<0.01-1.1) 110	0.089 (0.03-0.93) 18	0.205 (0.072-0.92) 7	-- 0.43 1	0.046 (0.03-0.074) 3	0.033 (<0.01-0.52) 57	0.051 (<0.01-0.32) 49
Ni	2.77 (<2-15) 8	7.7 (<1-15) 108	3.22 (<2-8.8) 16	7.2 (4-13) 7	-- 3 1	4.2 (3-8) 3	3.95 (<1-18.5) 40	6.03 (<1-18.3) 41
Se	BD	-- (<0.1-0.5) 43	-- (<0.1-0.4) 4	0.27 (<0.1-0.87) 5	BD	BD	-- (<0.1-1.9) 26	-- (<0.14-0.51) 15
Sr	173.5 (13.8-736) 10	122 (14.1-1380) 111	173.1 (13.4-5570) 18	80.55 (50.7-103) 7	-- 87.8 1	81.43 (67.2-107) 3	203 (22.2-1780) 73	219 (72.9-2170) 59
V	4.3 (2-17) 10	9.7 (1.7-19) 111	5.77 (2.5-11) 18	12.06 (7.3-20) 7	-- 5.9 1	6.15 (4.3-8.6) 3	7.33 (<6-50) 52	12 (<6-45.5) 52
Zn	16 (5.5-59.3) 10	56.8 (2.6-127) 111	55.59 (18-239) 18	179.5 (67.6-645) 7	-- 133 1	23 (16-42.3) 3	18.57 (3.8-248) 73	29.6 (3.1-86.3) 59

[1]Geometric Mean (-- indicates no GM was determined because 50 per cent or more of the values were below the detection limit).
[2]The minimum and maximum detected values (min-max).
[3]The number of samples exceeding the detection limit.
[4]Below detection.

Table 6. Selected trace elements in shoalgrass from the Corpus Christi Bay Complex (ppm dry weight). Geometric mean, range, and number of samples above the detection limit are presented for each bay.

Trace Metal	Redfish Bay N=2	Corpus Christi Bay N=3	Nueces Bay N=2	Oso Bay N=1	Laguna Madre N=4	Baffin Bay N=4
Al	164[1] (142-189)[2] 2[3]	144 (72.2-426) 3	114.8 (98.5-133.9) 2	-- 245 1	121 (84-220) 4	257 (189-396) 4
As	BD[4]	0.64 (<0.3-1.21) 2	-- (<0.44-0.75) 1	-- 1.04 1	0.43 (<0.37-0.91) 2	1.94 (1.07-3.47) 4
Ba	6.9 (5.99-7.94) 2	4.89 (3.19-7.72) 3	5.3 (4.79-5.9) 2	-- 5.65 1	5.06 (3.73-9.74) 4	5.46 (3.65-11.2) 4
B	255 (243-267) 2	263 (176-324) 3	236 (167.4-332) 2	-- 208 1	239 (209-275) 4	225 (180-306) 4
Cd	0.18 (0.166-0.193) 2	0.52 (0.224-1.03) 3	0.521 (0.198-1.37) 2	-- 2.38 1	0.39 (0.22-0.604) 4	1.85 (0.146-5.05) 4
Cr	1.51 (1.45-1.58) 2	1.74 (1.19-2.48) 3	-- (<0.44-1.66) 1	-- 1.48 1	1.01 (<0.39-1.91) 3	1.4 (0.804-1.93) 4
Cu	2 (1.9-2.06) 2	2.76 (1.25-6.7) 3	3.14 (2.04-5.81) 2	-- 6.91 1	2.53 (1.16-5.26) 4	8.4 (3.24-14.7) 4
Fe	171 (130-225) 2	164 (98.5-348) 3	134.6 (121-149.8) 2	-- 171 1	106 (85.4-134) 4	474 (193-1079) 4
Pb	2.75 (2.67-2.83) 2	5.62 (2.25-16.1) 3	-- (BD-4.14) 1	-- 3.1 1	2.39 (<1.51-8.54) 3	1.39 (<1.5-3.4) 2
Mg	5521 (5210-5850) 2	6038 (5060-6950) 3	6208 (4934-7810) 2	-- 7760 1	7107 (5810-9920) 4	10520 (8948-12500) 4
Mn	18.8 (13.8-25.6) 2	22.5 (12.3-34) 3	26.33 (25.4-27.3) 2	-- 95.7 1	42.8 (29.1-77) 4	42.9 (10.3-80.5) 4
Mo	1.46 (0.759-2.79) 2	0.93 (0.25-3.25) 3	-- (BD-1.05) 1	BD	0.69 (<0.5-1.98) 2	0.28 (<0.5-0.62) 2
Ni	BD	1.06 (0.688-1.68) 3	-- (BD-0.624) 1	-- 0.71 1	-- (<0.5-0.75) 1	0.93 (0.734-1.12) 4
Sr	117 (114-121) 2	120 (96.5-134) 3	107 (82-140) 2	-- 101 1	107 (98.7-119) 4	112 (38.1-175) 4
V	2.1 (1.6-2.76) 2	2.58 (0.62-8.36) 3	-- (BD-2.63) 1	BD	0.94 (<1-1.81) 3	1.1 (0.55-1.65) 4
Zn	21 (18.9-23.5) 2	19.75 (13.2-28.2) 3	17.3 (8.5-35.07) 2	-- 23.7 1	16.5 (14.44-18.9) 4	15 (1.2-111) 4

[1]Geometric mean (-- indicates no GM was determined because 50 per cent or more of the values were below the detection limit).
[2]The minimum and maximum detected values (min-max).
[3]The number of samples exceeding the detection limit.
[4]Below detection

Table 7. Selected trace elements in eastern oysters from the Corpus Christi Bay Complex (ppm dry weight), compared to data reported in other Texas coastal baseline contaminants studies (ppm wet weight). Data include geometric means, ranges, and number of samples above the detection limit.

Trace Metal	Nueces Bay N=3	Inner Harbor N=1	Lower Laguna Madre[1] N=2	Aransas Bay Complex[2] N=9
Al	299[3] (149-592)[4] 3[5]	-- 232 1	-- (67.5-103.4) 2	NA[7]
As	5 (4.23-6.48) 3	-- 8.69 1	-- (2.18-4.4) 2	0.8 (0.5-1.2) 9
Ba	45 (23.27-83) 3	-- 5.53 1	-- (0.51-1.61) 2	NA
B	30 (24.9-33.52) 3	-- 30 1	-- (3.8-4) 2	NA
Cd	12.3 (6.79-17.62) 3	-- 8.76 1	-- (0.273-0.46) 2	0.7 (0.48-1.21) 9
Cr	2.95 (0.95-13.4) 3	-- 1.92 1	-- (0.29-0.2) 2	0.1 (0.07-0.16) 9
Cu	280 (156-400) 3	-- 1330 1	-- (9.99-23) 2	21.1 (9.9-37.7) 9
Fe	344 (284-402) 3	-- 273 1	-- (66.2-85.2) 2	NA
Pb	BD[6]	-- 3.5 1	-- (0.12-0.17) 2	0.07 (0.04-0.13) 9
Mg	4553 (3420-5327) 3	-- 5640 1	-- (835-902) 2	NA
Mn	23 (18.83-28.33) 3	-- 19 1	-- (4.6-5) 2	NA
Hg	0.37 (0.167-0.732) 3	BD	-- (0.022-0.036) 2	0.008 (0.004-0.012) 9
Mo	-- (<0.5-0.834) 1	-- 1.32 1	-- (0.02-0.04) 2	NA
Ni	2.94 (1.04-9.14) 3	-- 1.06 1	-- (0.15-0.17) 2	0.27 (0.23-0.31) 9
Se	4.46 (4.01-4.88) 3	-- 4.72 1	-- (0.28-0.33) 2	0.38 (0.33-0.46) 9
Sr	84 (66-123) 3	-- 73.2 1	-- (15.1-20.6) 2	NA
V	-- (<0.1-0.99) 1	-- 1.17 1	-- (0.24-0.26) 2	NA
Zn	6006 (5196-7180) 3	-- 11600 1	-- (225.7-284) 2	125 (68.9-221.5) 9

[1]Gamble et al. 1988. Data presented in ppm wet weight.
[2]Gamble et al. 1989. Data presented in ppm wet weight.
[3]Geometric mean (-- indicates no GM was determined because 50 per cent or more of the values were below the detection limit).
[4]The minimum and maximum detected values (min-max).
[5]The number of samples exceeding the detection limit.
[6]Below detection.
[7]Not available (information not available).

Table 8. Selected trace elements in blue crabs from the Corpus Christi Bay Complex (ppm dry weight). Geometric means, ranges, and number of samples above the detection limit were determined for blue crabs obtained from all the study area water bodies.

Trace Metal	Redfish Bay N=2	Corpus Christi Bay N=13	Nueces Bay N=3	Inner Harbor N=1	Nueces River N=1	Oso Bay N=1	Laguna Madre N=6	Baffin Bay N=6
Al	67.82[1] (45.1-102)[2] 2[3]	129 (<2-692.6) 12	-- (<2-208) 1	BD[4]	-- 463 1	-- 136 1	47 (<2-378) 4	33.2 (<2-1428) 4
As	11.23 (8.52-14.8) 2	12.4 (5.54-22.4) 13	5.56 (4.51-7.12) 3	-- 8.45 1	-- 2.06 1	-- 6.43 1	27.85 (11.1-101.74) 6	22.53 (19.1-27.8) 6
Ba	37.36 (26.9-51.9) 2	51.7 (32.8-170) 13	106 (73.6-147) 3	-- 50.1 1	-- 222.5 1	-- 44.3 1	36.4 (25.1-55.22) 6	38.9 (18.6-79.2) 6
B	10.12 (8.3-12.3) 2	12.4 (8.9-19.9) 13	13.62 (12.5-15.1) 3	-- 9.46 1	-- 10.1 1	-- 6.08 1	15.32 (10.1-23.91) 6	24.4 (8.89-41.7) 6
Cd	0.96 (0.68-1.36) 2	0.79 (<0.2-1.73) 12	1.36 (1.24-1.51) 3	-- 1.86 1	-- 0.53 1	-- 0.277 1	1.13 (0.497-5.43) 6	0.96 (<1-1.8) 5
Cr	1.092 (0.99-1.21) 2	1.42 (0.87-3.4) 13	1.17 (0.796-1.64) 3	-- 1.24 1	-- 2.82 1	-- 1.13 1	1.64 (0.741-4.94) 6	1.41 (1.09-1.9) 6
Cu	72.5 (59.6-88.2) 2	62.44 (32.2-88) 13	44.16 (34.7-62.5) 3	-- 52.4 1	-- 46.22 1	-- 29 1	44.34 (35-68.26) 6	30 (3.21-69) 6
Fe	118 (102-137) 2	191 (34.9-517) 13	159 (117-261) 3	-- 83.8 1	-- 201 1	-- 108 1	123 (36.2-248) 6	187 (74.6-287) 6
Pb	1.11 (<1.5-1.65) 1	-- (<1.5-2.52) 1	BD	-- 2.39 1	BD	BD	-- (<1.5-1.51) 1	-- (<0.5-1.56) 1
Mg	4240 (3610-4980) 2	5444 (3870-7351) 13	4363 (3120-6524) 3	-- 3570 1	-- 5789 1	-- 2810 1	5149 (3360-7391) 6	4489 (2725-6010) 6
Mn	41 (31.2-53.6) 2	97.4 (64.1-207) 13	132 (112-146) 3	-- 301 1	-- 191 1	-- 46.8 1	75.1 (61-103) 6	83 (20.4-140) 6
Hg	0.036 (<0.05-0.052) 1	0.145 (<0.05-0.37) 11	0.135 (.055-0.274) 3	-- 0.08 1	-- 0.411 1	BD	0.089 (<0.01-0.19) 5	0.07 (<0.05-0.152) 4
Mo	BD	-- (<0.5-0.51) 1	BD	BD	BD	BD	-- (<0.5-0.61) 1	-- (<0.5-0.558) 1
Ni	0.6 (0.57-0.63) 2	-- (<0.5-8.5) 5	BD	BD	-- 2.39 1	-- 0.542 1	0.636 (<0.5-7.48) 3	0.89 (<0.5-4.24) 5
Se	2.53 (1.87-3.41) 2	3.52 (2.26-5.11) 13	2.69 (2.3-3.26) 3	-- 3.96 1	-- 2.11 1	-- 1.68 1	3.02 (2.29-3.49) 6	3.38 (2.92-4.12) 6
Sr	812 (706-935) 2	1281 (874-2052) 13	1228 (812-1690) 3	-- 919 1	-- 1689 1	-- 624 1	1252 (884-1950) 6	1041 (568-1390) 6
V	0.77 (0.702-0.854) 2	-- (<0.5-1) 3	0.87 (0.69-1.1) 3	BD	BD	BD	0.36 (0.05-0.93) 5	1.02 (<0.5-1.43) 5
Zn	87.5 (75.8-101) 2	101 (61-139) 13	86 (78.2-104) 3	-- 109 1	-- 116.3 1	-- 35.1 1	90 (73.9-118) 6	107 (68.9-517) 6

[1]Geometric mean (-- indicates no GM was determined because 50 per cent or more of the values were below the detection limit).
[2]The minimum and maximum detected values (min-max).
[3]The number of samples exceeding the detection limit.
[4]Below detection

Table 9. Selected trace metals in hardhead catfish from the Corpus Christi Bay Complex (ppm dry weight). Geometric means, ranges, and number of samples above the detection limit were determined for hardhead catfish obtained from all the study area water bodies.

Trace Metal	Redfish Bay N=2	Corpus Christi Bay N=9	Nueces Bay N=2	Inner Harbor N=1	Nueces River N=1	Oso Bay N=1	Laguna Madre N=4	Baffin Bay N=5
Al	52.65[1] (23.7-117)[2] 2[3]	50.8 (19.3-203) 9	124 (100-153) 2	-- 20.5 1	-- 307 1	-- 306 1	18.62 (2.5-450.3) 4	182 (95.9-426) 5
As	12.08 (8.79-16.6) 2	6.05 (0.38-17.26) 9	5.57 (4.56-6.81) 2	-- 4.1 1	BD	-- 20.5 1	9.91 (1.29-20.60) 4	17.68 (14-22.3) 5
Ba	10.12 (6.92-14.8) 2	10.4 (7.04-17.17) 9	27.8 (16.9-45.7) 2	-- 6.48 1	-- 26.4 1	-- 18.5 1	9.87 (8.06-10.8) 4	21.4 (17.6-31) 5
B	4.36 (3.61-5.27) 2	4.92 (4.01-7.05) 9	6.01 (5.69-6.35) 2	-- 4.1 1	-- 4.96 1	-- 6.08 1	5.95 (4.97-8.16) 4	10.9 (7.71-20.6) 5
Cd	BD[4]	0.24 (<0.1-1.95) 7	0.09 (<0.1-0.18) 1	-- 0.4 1	BD	BD	-- (<0.1-0.9) 1	-- (<0.1-0.737) 1
Cr	1.52 (1.38-1.67) 2	2.59 (1.66-5.04) 9	2.04 (1.92-2.17) 2	-- 1.68 1	-- 3.05 1	-- 1.9 1	1.68 (0.86-2.79) 4	1.74 (0.87-2.24) 5
Cu	2.27 (2.07-2.5) 2	2.4 (1.45-3.45) 9	2.37 (2.09-2.69) 2	-- 4.35 1	-- 2.2 1	-- 2.35 1	2.28 (1.43-2.84) 4	4.57 (2.43-36.5) 5
Fe	158 (123-204) 2	163 (79.5-260) 9	192 (155-238) 2	-- 92 1	-- 312.1	-- 243 1	88.4 (45.9-124) 4	213 (163-247) 5
Pb	BD	-- (<1.5-1.76) 1	0.63 (<0.5-1.60) 1	BD	BD	BD	BD	-- (<1.5-1.62) 2
Mg	1718 (1530-1930) 2	1857 (1400-2792) 9	2018 (1940-2100) 2	-- 1380 1	-- 1550 1	-- 1970 1	1938 (1590-2557) 4	2908 (2170-5712) 5
Mn	18.73 (15.8-22.2) 2	20.6 (9.57-47.79) 9	20.9 (17.4-25) 2	-- 13.3 1	-- 30.53 1	-- 26.1 1	25 (21.6-30.3) 4	33 (22.7-97.3) 5
Hg	0.547 (0.49-0.61) 2	0.91 (0.37-1.39) 9	0.667 (0.53-0.84) 2	-- 0.434 1	-- 0.472 1	-- 0.128 1	0.45 (0.3-0.86) 4	0.365 (0.18-0.49) 5
Mo	BD	-- (<0.5-4.42) 4	0.39 (<0.5-0.6) 1	BD	-- 2.06 1	BD	BD	-- (<0.5-0.54) 1
Ni	BD	-- (<0.5-4.2) 3	BD	BD	-- 2.59 1	BD	-- (<0.5-0.89) 1	-- (<0.5-0.53) 2
Se	2.53 (2.03-3.15) 2	2.12 (1.07-3.06) 9	2.53 (2.17-2.95) 2	-- 3.02 1	-- 2.16 1	-- 1.54 1	1.54 (1.24-1.82) 4	2.07 (1.36-2.49) 5
Sr	391 (378-404) 2	416 (249-885) 9	540 (441-662) 2	-- 276 1	-- 387 1	-- 449 1	482 (413-701) 4	739 (527-1028) 5
V	0.77 (0.7-0.85) 2	-- (<0.1-1.57) 4	0.87 (0.69-1.1) 2	-- 0.61 1	BD	-- 1.27 1	0.36 (<0.1-0.93) 2	1.03 (0.63-1.43) 5
Zn	469.5 (449-491) 2	538 (330-1108) 9	956 (855-1070) 2	-- 1960 1	-- 1191.5 1	-- 587 1	367 (67.7-746) 4	440 (169-596) 5

[1]Geometric mean (-- indicates no GM was determined because 50 per cent or more of the values were below the detection limit).
[2]The minimum and maximum detected values (min-max).
[3]The number of samples exceeding the detection limit.
[4]Below detectionTable 9

Table 10. Geometric means and ranges of selected elements (ppm dry weight) in sediments collected for U.S. Fish And Wildlife Service baseline and contaminants studies from the cental and lower coast of Texas, and western United States soil baseline information.

TRACE ELE-MENT	CORPUS CHRISTI BAY COMPLEX n=282	ARANSAS BAY COMPLEX[1] n=201	ARANSAS BAY DREDGE SPOIL[2] n=25	LOWER RIO GRANDE VALLEY[3] n=95	SOIL BASELINES FOR THE WESTERN U.S.[4]
As	3.39[5] 0.4-27.8[6] 282[7]	1.8 (0.5-5.0) ---	3.98 (0.59-7.46) 25	2.6 (0.1-15) 95	5.5 (1.2-22) ---
B	15.27 0-343 261	NA[8]	25.46 (2.26-186) 23	1.5 (1-110) 51	23 (5.8-91) ---
Cd	-- 0-4.6 91	-- (0.3-0.5) ---	BD[9]	-- (0.2-2) 44	NA
Cr	8.85 0-38.5 280	5.9 (2-20) ---	14.57 (2.06-33.8) 25	8.7 (3-32) 94	41 (8.5-200) ---
Cu	7.3 0.3-53.1 282	3.2 (0.4-22) ---	15.9 (5.63-26.2) 25	8.3 (2.2-72.8) 95	21 (4.9-90) ---
Pb	12.43 0-110 185	5.1 (4-19) ---	23.96 (5.1-66.2) 19	10.7 (3-240) 92	17 (5.2-55) ---
Hg	0.05 0.01-1.1 255	-- (0.05-0.5) ---	-- (0.03-0.05) 4	0.04 (0.05-0.5) 48	0.046 (0.009-0.25) ---
Ni	5.61 0-18.3 224	4.8 (1-15) ---	9.7 (2.05-20.5) 20	7.9 (2.2-16) 94	15 (3.4-66) ---
Se	-- 0-1.9 97	-- (0.2-5.1) ---	BD	0.28 (0.2-0.66) 59	0.23 (0.04-1.4) ---
Zn	36.69 26-645 282	16.7 (0.2-79.2) ---	35.86 (3.7-83.2) 25	34.7 (1.6-439) 95	55 (17-180) ---

[1] Data from Gamble et al. 1989
[2] Data from Robertson et al. 1991
[3] Data from Gamble et al. 1988
[4] Data from Shacklett and Boernaen 1984
[5] Geometric mean (-- indicates no GM determined because 50% or more of the samples were below the detection limit).
[6] The minimum and maximum detected values (min-max).
[7] Number of samples above the detection limit (--- indicates information not available)
[8] Information not available
[9] Below detection limit

Arsenic

Arsenic was detected in all sediment samples, and GMs ranged from 1.94 ppm dw in Oso Bay to 4.39 ppm dw in Corpus Christi Bay sediments. The maximum sample residue was 27.8 ppm dw from the Laguna Madre (sediment site 171, Figure 4), a residue more than twice as high as that of any other sample. However, most arsenic residues were not elevated in Corpus Christi Bay Complex sediments when compared to levels reported in other baseline contaminants studies (Gamble et al. 1988 and Gamble et al. 1989), or in contaminants assessment reports of Texas estuarine sediments (Robertson et al. 1991 and Cain 1989) (Tables 5 and 10). Gamble et al. (1988) reported an arsenic GM of 2.6 ppm dw and a maximum residue of 15 ppm dw in sediments from the Lower Rio Grande Valley-Lower Laguna Madre. Aransas Bay Complex (Gamble et al. 1989) sediments had an arsenic GM of 1.8 ppm dw, and the maximum sample residue was 5 ppm dw (Gamble et al. 1989). A contaminants assessment of dredge material taken from five spoil disposal areas adjacent to the Aransas Wildlife Refuge revealed an arsenic GM of 3.98 ppm dw, and samples ranged to a maximum of 7.46 ppm dw (Robertson et al. 1991). Inner Harbor sediments sampled in 1982 and 1984 by the Texas Department of Water Resources (Bowman and Jensen 1985, and Davis 1984) had arsenic levels up to 7.98 ppm dw. Cain (1989) reported a mean of 6 ppm dw arsenic in bottom sediments collected from the Houston Ship Channel by the U.S. Army Corps of Engineers in 1976, 1983, and 1986.

The EPA has no sediment criteria for arsenic (EPA 1986), however, the EPA threshold concentration is 33 ppm in sediments (Bolton et al. 1985) and acute toxicity occurs to salt water aquatic life at 508 ppb for recoverable trivalent arsenic (EPA 1980). Trivalent arsenic is the most abundant arsenic species in reduced sediments, the type which would be expected in the Inner Harbor and other sediments within the study area, and is also the most readily soluble kind (EPA 1980). Environmental conditions, such as pH, Eh, and suspended solids and sediments affect the availability of arsenic (EPA 1986). The sample obtained from the Laguna Madre, which contained 27.8 ppm arsenic, is approaching the EPA threshold level. Samples from Corpus Christi Bay, Baffin Bay and Laguna Madre exceeded the Threshold Effects Level (TEL) of 7.24 ppm, but were below the Probable Effects Level (PEL) (41.6 ppm) of the sediment quality assessment guidelines (SQAGS) established by the Florida Department of Environmental Protection (MacDonald Environmental Sciences Ltd. 1994). Long et al. (1995) also developed a set of guidelines for sediment quality assessment. Three Laguna Madre samples exceeded the Effects Range-Low concentration of 8.2 ppm for these guidelines indicating that adverse biological effects may occasionally occur. According to Eisler (1988a), anthropogenic sources such as smelting and mining, combustion of fossil fuels, agricultural use, and sewage waste are the most common causes of elevated levels of arsenic in sediments. The source for elevated arsenic in Laguna Madre sediments is unknown, but should be investigated, especially considering there are no point source discharges into the area.

Arsenic was detected in 10 out of 16 shoalgrass samples (62.5%). The greatest GM, 1.94 ppm dw, and maximum sample residue, 3.47 ppm dw (biota site 30 Figure 5) were

detected in Baffin Bay shoalgrass. Additionally, all Baffin Bay shoal grass samples (4 out of 4) were above detection for arsenic, unlike shoal grass samples from Corpus Christi Bay (2 out of 3), Laguna Madre (2 out of 4) or Redfish Bay (2 out of 3). Furthermore, the arsenic residues in Baffin Bay shoal grass were up to five times greater than residuesin shoal grass from other Corpus Christi Bay Complex sites (Table 6). Although little comparative data are available regarding arsenic in Texas shoal grass, the concentrations reported in the current study are much lower than those found by Custer and Mitchell (1993), who reported a GM of 12.2 ppm dw, and residues ranging from 2-25 ppm dw in shoal grass collected from the Lower Laguna Madre in 1987. Heavy use of agricultural chemicals in the Lower Rio Grande Valley was believed to have contributed to the high levels of arsenic in shoal grass (Custer and Mitchell 1993). Background residues of arsenic in shoal grass from other areas are not available, but marine algae can contain from 0.05 to 5 ppm dw arsenic in green algae, and brown and other species of algae may have up to 100 ppm dw (Eisler 1988a). According to Eisler (1988a), marine plants readily absorb arsenic from the water (in the form of several different organoarsenicals) or sorb it to their cell surfaces. Because the arsenic is generally in the form of arsenobetaines, it is relatively harmless to other organisms or human consumers (Kaise et al. 1985).

All oyster samples (n=4) were above detection for arsenic, with residues ranging from 4.23 ppm dw in Nueces Bay to 8.69 ppm dw in Inner Harbor oysters (Table 7). These levels are two times greater than arsenic in Aransas Bay Complex oysters, which had a GM of 0.8 ppm ww (≈5.2 ppm dw)[1] and a maximum residue of 1.2 ppm ww arsenic (≈6 ppm dw) (Gamble et al. 1989). However, oysters from the Lower Laguna Madre (n=2) had greater amounts of arsenic, 2.18 and 4.4 ppm ww (≈14.1 and 28.4 ppm dw), than Corpus Christi Bay Complex oysters (Gamble et al. 1988). The same agricultural sources believed responsible for elevated arsenic in Lower Laguna Madre shoal grasses were also the likely source of elevated arsenic in oysters from that area. Arsenic concentrations in oysters above 7.5 ppm fresh weight are known to cause sublethal effects (Eisler 1988a).

Twenty-six blue crab samples, or 79%, were above detection for arsenic. Laguna Madre blue crabs had the highest GM, 27.85 ppm dw (Table 8), as well as the highest sample residue, 101.74 ppm dw (biota site 25 Figure 4). Baffin Bay blue crabs also had a relatively elevated arsenic GM, 22.53 ppm dw. These GMs are 4 to 5 times higher than arsenic GMs in blue crabs from other Texas Bays. Gamble et al. (1988) reported a GM of 1.57 ppm ww (≈5.6 ppm dw)[2] from the Lower Laguna Madre, and Aransas Bay Complex blue crabs had a GM of 1.4 ppm ww (≈5.0 ppm dw) (Gamble et al 1989). According to Eisler (1988a), arsenic is frequently higher in marine organisms than fresh water ones, and levels in marine crustaceans can range up to 100 ppm dw (Eisler 1988a). In seafood, arsenic residues are limited to 6 to 10 ppm (fresh weight) for the protection of human health (Eisler 1988a).

[1] Dry weight conversion for eastern oysters made using typical moisture content of 84.5% for oysters from Texas waters.

[2] Dry weight conversion for blue crabs made using typical moisture content of 71.9% for blue crabs from Texas waters.

All twenty-five hardhead catfish samples had detectable arsenic residues. The greatest GM and maximum residue were 17.68 ppm dw and 22.3 ppm dw, respectively, both from Baffin Bay (Table 9). Just as was true with sediments and blue crabs, arsenic was greater in most hardhead catfish samples from the Corpus Christi Bay Complex than those from other Texas bays. Gamble et al. (1989) reported an arsenic GM of 2.1 ppm ww (≈7.5 ppm dw) in hardhead catfish from the Aransas Bay Complex, and a maximum residue of 7 ppm ww (≈24.8 ppm dw)[3]. Lower Rio Grande Valley-Lower Laguna Madre fish (thirty-three samples, composed of fourteen species, including hardhead catfish) had much less arsenic, with a GM of 0.21 ppm ww (0.8 ppm dw) (Gamble et al. 1988). Sheepshead minnows (*Cyprinidon variegatus*) collected for the Aransas Bay dredge disposal study had 1.45 ppm dw arsenic (Robertson et al. 1991), and six species of fish from Burgentine Lake on the Aransas National Wildlife Refuge had a GM of 0.5 ppm ww (≈1.8 ppm dw) arsenic (Maurer et al. 1989).

Boron

Boron was detected in 261, or 93% of the sediment samples. GMs ranged from a low of 6.14 ppm dw in Redfish Bay, to highs of 26.9 ppm and 30.85 ppm in Laguna Madre and Baffin Bay, respectively, the two hypersaline areas. The highest residue in an individual sample was 343 ppm dw detected in a sample from the Laguna Madre (sediment site 171, Figure 4), the same site which had the elevated arsenic. Most boron residues in the Corpus Christi Bay Complex sediments were below levels of concern reported by Eisler (1990a); however, they were well above residues detected in other area bays. Lower Rio Grande Valley-Lower Laguna Madre sediments ranged to 110 ppm dw boron, and the GM was 1.5 ppm dw (Gamble et al. 1988). White et al. (1983) found boron concentrations ranging from less than 10 ppm dw to 120 ppm dw in Corpus Christi Bay sediments, with higher boron residues found to be associated with sediments containing a higher percentage of mud. The hypersaline environment of the Laguna Madre was an exception to this; boron ranged from 62-110 ppm dw in sediments which contained minor amounts of mud (White et al. 1983).

Boron, an essential plant nutrient, was above detection in all biota samples. The highest GM in shoalgrass was 278 ppm dw, from Redfish Bay. Marine vegetation bioconcentrates boron, and sediments in Redfish Bay had a GM of 6.14 ppm dw boron. Baseline data on boron in sea grasses are limited; however, widgeon grass collected in 1987 from Burgentine Lake, an oligohaline body of water on the Aransas National Wildlife Refuge, had a mean tissue concentration of 16.1 ppm ww (≈63.9 ppm dw)[4] boron

[3] Dry weight conversion for hardhead catfish made using typical moisture content of 71.8% for hardhead catfish from Texas waters.

[4] Dry weight conversion for widgeon grass made using typical moisture content of 74.8%.

(Maurer et al 1989). Little other information on the amounts of boron which are hazardous to plants is available. It is known that concentrations of 100 mg/L in marine waters inhibit growth in 12 out of 19 species of marine algae (Eisler 1990).

Nueces Bay oysters had a GM of 30 ppm dw boron and a maximum sample residue of 33.5 ppm dw. Oysters obtained from the Lower Laguna Madre by Gamble et al. (1988) had 3.8 and 4 ppm ww (≈24.6 and 25.9 ppm dw) boron. Eisler (1990) reported two species of oysters having fresh weight concentrations of 3.1 to 4.0 ppm boron. The relatively elevated levels of boron in Nueces Bay oysters may be due to the complicated chemistry of various metal species occurring in the bay as a result of wastewater discharges from industrial sources, the disposal of contaminated Inner Harbor dredge material adjacent to the bay, and oil and gas production in and around Nueces Bay.

The highest GMs in blue crabs and hardhead catfish were from Baffin Bay, 24.4 ppm dw in blue crabs and 10.9 ppm dw in hardhead catfish (20.6 ppm dw maximum residue). Little comparative data from other studies are available, however Maurer et al. (1989) found much lower concentrations of boron in blue crabs obtained from Burgentine Lake, 0.5 ppm ww (≈1.9 ppm dw), and Gamble et al. (1988) reported 4.6 ppm ww (≈16.4 ppm dw) in Lower Laguna Madre blue crabs. Eisler (1990) reported 1.8 ppm (fresh weight) boron in dungeness crabs. The hypersalinity of Baffin Bay probably contributed to the higher concentrations of boron in blue crabs and hardhead catfish obtained from that bay.

Boron is an essential element for the growth of plants and becomes more concentrated in irrigation waters and wastewater outfalls. It accumulates in aquatic ecosystems, and excessive amounts, which vary depending on a variety of chemical and physical parameters, can be toxic to plants, fish, amphibians, birds, and mammals (Eisler 1990). The proposed boron criteria includes a level of 1 mg/L B in discharges for the protection of fish and oysters, and less than 13 ppm fresh weight in the diet of waterfowl, for no observed adverse effects (Eisler 1990).

Cadmium

Cadmium was found above the detection limit in 91 out of 282 samples (32%). GMs were determined for Nueces Bay (0.34 ppm dw) and Inner Harbor (1.21 ppm dw) sediments only, and the maximum residue was 4.6 ppm dw from the Inner Harbor (sediment site 3 Figure 3). These levels are higher than those reported by Holmes et al. (1974), who found cadmium concentrations of 0.1 to 1.9 ppm dw in the northeastern part of Corpus Christi Bay and at the mouth of the Inner Harbor. Holmes et al. (1974) determined a strong correlation between the occurrence of cadmium and zinc contamination, indicating a common source for both metals. Cadmium and zinc remain high in Inner Harbor sediments more than fifteen years after the Holmes et al. (1974) study. Six samples from the Inner Harbor exceeded the TEL of 0.68 ppm and one exceeded the PEL of 4.21 ppm, a level considered to pose an immediate hazard to aquatic organisms (MacDonald Environmental Sciences Ltd. 1994).

Inner Harbor sediments (0.4 to 4.6 ppm dw), and some from Nueces Bay (up to 3.3 ppm dw), had cadmium residues several times higher than those reported in other studies of Texas coastal sediments (Table 10). By comparison, the maximum concentration of cadmium in Aransas Bay Complex sediments was 0.5 ppm dw, and no GM was determined because less than 50% of the samples were above the detection limit (Gamble et al. 1989). Lower Rio Grande Valley-Lower Laguna Madre sediments had cadmium residues ranging from 0.2 to 2 ppm dw, and again, no GM was determined (Gamble et al. 1988). Cain (1993) found cadmium below levels of concern, less than 0.25 ppm dw, in sediments taken from the San Bernard National Wildlife Refuge.

Cadmium is a rare and biologically nonessential trace element which may produce teratogenic and mutagenic effects in fish and wildlife at ambient water concentrations of 37 to 57 ppb and greater (Eisler 1985a). Background levels in uncontaminated marine sediments have up to 1 ppm dw cadmium; higher levels are associated with industrialization and urbanization (Eisler 1985a). The industrial source of cadmium in Inner Harbor and Nueces Bay sediments is well established; however, the source(s) of cadmium in Nueces River, Laguna Madre and Baffin Bay sediments (one sample from each area was above 1 ppm dw), are unknown and should be investigated.

Cadmium was detected in all shoal grass and oyster samples. The greatest GM and maximum sample residue were 1.85 and 5.05 ppm dw, respectively, detected in shoal grass from Baffin Bay. Other studies have reported much lower concentrations of cadmium in sea grasses. Cadmium was below detection in Lower Laguna Madre shoal grass sampled in 1987 by Custer and Mitchell (1993), and Pulich (1980) characterized cadmium residues of 0.25 to 2.25 ppm dw in Corpus Christi Bay shoal grass as elevated. Pulich (1980) collected shoal grass samples seasonally (winter, spring, summer and fall), and recorded the highest concentrations of trace metals during the early and late growing seasons. Cadmium uptake appears to be regulated by the cadmium to zinc ratio in the environment. A high zinc to cadmium ratio suppresses cadmium uptake due to the chemical similarity of the two elements, which compete for binding sites. Pulich (1980) theorized that high zinc concentrations in sediments suppressed the cadmium levels in shoal grass, which could have been even higher under more suitable conditions, such as, oxidized, slightly acidic sediments, which increase the bioavailability of cadmium (Gambrell et al. 1976).

Nueces Bay oysters had a GM of 12.3 ppm dw and a maximum sample residue of 17.62 ppm dw. These elevated residues are almost ten times greater than those detected in oysters from the Lower Laguna Madre, which had 0.273 to 0.46 ppm ww ($\approx$1.8 to 3.0 ppm dw) cadmium (Gamble et al. 1988), and four times greater than Aransas Bay Complex oysters, which had a GM of 0.7 ppm ww ($\approx$4.5 ppm dw) cadmium (Gamble et al. 1989).

Thirty-one blue crab samples were above detection for cadmium. The greatest GM was 1.36 ppm dw from Corpus Christi Bay, and the maximum sample residue was 5.43 ppm dw from the Laguna Madre (biota site 25, Figure 4). These data support Eisler's (1985) contention that lower trophic level organisms tend to biomagnify cadmium more readily than higher trophic level organisms. Hardhead catfish, the highest trophic level organisms collected for the current study, had residues of cadmium in 44% of the samples. However the invertebrates, oysters and blue crabs, had detectable residues of cadmium in 100% and 91% of the samples, respectively.

Cadmium was detected in eleven out of twenty-five hardhead catfish samples; 7 from Corpus Christi Bay, one from Nueces Bay, one from the Inner Harbor, one from Laguna Madre, and one from Baffin Bay. Corpus Christi Bay was the only bay in the study area which had greater than 50% of the samples above the detection limit; the GM was 0.24 ppm dw and the maximum residue was 1.95 ppm dw. By comparison, cadmium was detected in 9 out of 33 fish samples collected from the Lower Rio Grande Valley-Lower Laguna Madre by Gamble et al. (1988), and cadmium was detected at levels of 0.003 to 0.031 ppm ww (≈0.01 to 0.1 ppm dw). Gamble et al. (1989) reported a cadmium GM (n=11, all above detection) of 0.04 ppm ww (≈0.14 ppm dw) in hardhead catfish from Aransas Bay.

Cadmium, a nonessential trace element, is teratogenic, mutagenic, and toxic to most fish and wildlife at concentrations of 2.0 ppm fresh weight and greater (Eisler 1985a). Freshwater organisms are more sensitive to cadmium than marine organisms, which can accumulate greater concentrations due to the occurrence of cadmium complexes in the water column. However, current cadmium criterion may not adequately protect some commercially important species (EPA 1986).

Chromium

Chromium was detected in 280 sediment samples, more than 99%. The greatest GM, 17.13 ppm dw, was detected in Inner Harbor sediments, and the maximum residue was 38.5 ppm dw detected in a sample obtained from Baffin Bay. Thirty-three sediment samples from Baffin Bay (56%) had chromium residues of 20 ppm dw or higher. By comparison, the chromium GM in Aransas Bay complex sediments was 5.9 ppm dw and the maximum residue was 20 ppm dw, detected in one sample only (Gamble et al. 1989).

Chromium is highest in sediments of small grain size and high organic and iron content, and estuarine sediments may have residues ranging from 3.9 to 162 ppm (Eisler 1986a). The most common sources of chromium contamination of the environment are industrial and municipal discharges (Eisler 1986a). The source of elevated levels of chromium in Baffin Bay sediments is unknown, but possibly related to the production of oil and gas in the bay and surrounding area.

Chromium was detected in 14 shoal grass samples, or 87%. The highest GM was 1.74 ppm dw from Corpus Christi Bay and the maximum residue was 2.48 ppm dw, also from Corpus Christi Bay. Custer and Mitchell (1993) reported a much higher GM of chromium in Lower Laguna Madre shoal grass, 13.2 ppm dw. Why chromium residues were so much higher in shoal grass from the Lower Laguna Madre is not known, but may be related to sediment grain size. Excessive chromium in the environment is an indication of pollution, usually from industrial or municipal discharges (Eisler 1986a).

All oyster, blue crab and hardhead catfish samples were above detection for chromium. The oyster GM from Nueces Bay was 2.95 ppm dw and the maximum residue was 13.4 ppm dw, also from Nueces Bay. As with the other trace metals, these residues are many times higher than chromium detected in oysters from other area bays (Table 7). The highest GM in blue crabs was 1.64 ppm dw from the Laguna Madre, and the maximum sample residue was 4.94 ppm dw, also from Laguna Madre blue crabs. The highest GM in sea catfish was 2.59 ppm dw and the maximum residue was 5.04 ppm dw, both from Corpus Christi Bay. Excess chromium can cause lethal and sublethal effects to fish and wildlife; tissue levels in excess of 4 ppm dry weight may be indicative of chromium contamination (Eisler 1986a). While chromium is an essential element, high environmental concentrations can have mutagenic, teratogenic and carcinogenic effects (Eisler 1986a).

Copper

All sediment samples had detectable residues of copper. The highest GM was 16.82 ppm dw from Inner Harbor sediments. Four samples had residues of 50 ppm dw or higher: 53.1 ppm dw, Baffin Bay; 52.3 ppm dw, Inner Harbor; 52.2 ppm dw, Laguna Madre; and 50 ppm dw, Laguna Madre. These residues are elevated when compared to background sediment GMs of 3.2 ppm dw from Aransas Bay (Gamble et al. 1989) and 8.3 ppm dw from the Lower Rio Grande Valley-Lower Laguna Madre (Gamble et al. 1988). Adverse biological effects are possible when concentrations are above the TEL of 18.7 ppm dw (MacDonald Environmental Sciences Ltd. 1994). A total of sixteen samples from Baffin Bay exceeded this limit, as well as five from the Laguna Madre and two from the Inner Harbor.

Copper is an essential nutrient which can be toxic to organisms at even slightly elevated levels. Concentrations of 1.0 to 10 ppb are usually reported for unpolluted surface waters of the United States (EPA 1986), and acute sensitivities of saltwater animals range from 5.8 ppb for blue mussels to 600 ppb for the green crab. Potential sources for copper contamination can include municipal and industrial discharges, especially those resulting from refining, smelting and metal plating industries (EPA 1980). Copper contamination of Inner Harbor sediments has been well documented (Holmes et al. 1974, Davis 1984, Bowman and Jensen 1985, and White et al. 1983). However, the sources for elevated residues of copper in Laguna Madre and Baffin Bay sediments are unknown.

Copper was detected in all biota samples. The greatest GM in shoal grass, 8.4 ppm dw, and the maximum sample residue, 14.7 ppm dw (biota site 30, Figure 5), were both from Baffin Bay. These levels are approximately equal to the highest residues reported by Pulich (1980) from Corpus Christi Bay at Indian Point, 7.5 ppm dw, and Corpus Christi Bay at Ingleside Point, 15 ppm dw. Pulich (1980) reported greater amounts of copper in samples of shoal grass leaves only, with residues of 20 ppm dw and greater in samples obtained from the aforementioned sites. Roots had much lower residues of all trace metals, including copper (Pulich 1980). It is unknown why Baffin Bay sea grasses collected for the current study contained levels of copper equal to or greater than the amounts found in sea grasses growing in waters which receive industrial discharges. The complex water chemistry associated with hypersaline bay waters may be responsible.

Nueces Bay oysters had a GM of 280 ppm dw (ranging from 156 to 400 ppm dw), copper, and the Inner Harbor oyster sample had a residue of 1330 ppm dw copper. These concentrations are more than 100 times greater than copper in oysters obtained from other Texas bays (Table 6). It is well established that oysters are poorly able to regulate tissue levels of trace metals, and instead concentrate metals, including copper (Phillips and Ruso 1978, Abbe and Sanders 1986). Oysters can bioaccumulate copper up to 28,200 times without mortality, but bay scallops are killed at 5 μg/L, long-term exposure (EPA 1986). The Texas Department of Health compiled contaminants data on fish, oysters, and blue crabs collected from Texas bays during the years of 1980-1993 (Texas Department Health 1994a). Oysters sampled from 1980 to 1990 were found to have copper residues generally ranging from 10 to 20 ppm ww. The highest residues, 48 and 51 ppm ww, were detected in oysters collected from Nueces Bay in 1984. In 1994, the Texas Department of Health sampled Nueces Bay oysters again and even greater amounts of copper, 63.22 and 71.83 ppm ww (Texas Department of Health 1994b). Based on these data, Nueces Bay and Inner Harbor oysters may have the highest residues of copper of any oysters in Texas.

Redfish Bay blue crabs had the highest GM and maximum sample, 72.5 and 88.2 ppm dw, respectively. These residues are greater than copper in Aransas Bay Complex oysters, which had a GM of 11.8 ppm ww (≈76.3 ppm dw) (Gamble et al. 1989), and almost three times greater than copper in Lower Rio Grande Valley-Lower Laguna Madre blue crabs, with a GM of 6.15 ppm ww (≈21.9 ppm dw) (Gamble et al. 1988). Crabs, like other invertebrates, have been shown experimentally to regulate internal copper concentrations and avoid toxic levels (Rainbow 1985).

For hardhead catfish, the highest GM and maximum sample residue were 4.57 and 36.5 ppm dw copper, respectively, both from Baffin Bay. Robertson et al. (1991), by comparison, reported a copper GM of 5.27 ppm dw for sheepshead minnows obtained from Aransas Bay dredge spoil islands. Gamble et al. (1988) reported copper GMs of 0.45 ppm ww (≈1.6 ppm dw) in fourteen species of fish (both fresh and saltwater

species) from the Lower Laguna Madre and 0.06 ppm ww (≈0.2 ppm dw) in hardhead catfish from the Aransas Bay Complex (Gamble et al. 1989). Corpus Christi Bay Complex hardhead catfish, particularly those from Baffin Bay (as well as sediments and shoal grass from that area), appear to be at elevated levels for copper, a trace element which may be a major threat to ecosystem health (Breteler 1984).

Lead

Sixty-five percent of the sediment samples (n=185) were above the detection limit for lead. Inner Harbor sediments had the highest lead GM, 36.01 ppm dw, as well as the maximum sample residue, 110 ppm dw. Baffin Bay sediments also contained elevated levels of lead; the GM was 17.84 ppm dw and samples ranged to a maximum of 87.3 ppm dw (sediment site 251). Seventeen samples from Baffin Bay surpassed the lower limit of the Florida SQAGS (30.2 ppm dw) (MacDonald Environmental Sciences Ltd. 1994) and thirteen exceeded the lower limit of the SQAGS (46.7 ppm dw) developed by Long et al. (1995) indicating possible biological affects. By comparison, sediments collected from the Aransas Bay Complex (Gamble et al. 1989) and Aransas dredge spoil islands (Robertson et al. 1991) had lead GMs of 5.1 ppm and 23.96 ppm dw, respectively. Sediments from the Lower Rio Grande Valley-Lower Laguna Madre had an overall lead GM of 10.7 ppm dw and a maximum residue of 240 ppm dw (Gamble et al. 1988).

Inner Harbor sediments are known to have been contaminated with lead by industrial discharges and processes (Holmes et al. 1974), but the source for elevated lead in Baffin Bay sediments is unknown. The oil and gas production which occurs in the bay and in the surrounding uplands may be the source. According to Eisler (1988b), sediments now constitute the largest global reservoir of lead, with most lead ultimately being incorporated into marine sediments.

Lead, a biologically non-essential trace metal, was detected in 12 out of 16 shoal grass samples (75%). The highest GM and the maximum residue were 5.62 ppm dw and 16.1 ppm dw, respectively, both from Corpus Christi Bay shoal grass. These residues are comparable to those reported by Custer and Mitchell (1993) in Lower Laguna Madre shoal grass, which had a GM of 1.99 ppm dw and a maximum residue of 4.6 ppm dw. Lead is actively transported to plant tissues via roots, and is also absorbed through foliage (Eisler 1988b). The oldest parts of plants, rather than shoots or flowers, concentrate lead (Eisler 1988b). Roots and rhizomes (the parts submitted for this study) are the oldest parts of shoal grass, and as such, are the best part of the sea grass to indicate environmental lead contamination.

Only seven animal tissues were above detection for lead: one oyster sample, 3.5 ppm dw (Inner Harbor); five blue crab samples, 1.65 ppm dw (Redfish Bay), 2.39 ppm dw (Inner Harbor), 2.52 ppm dw (Corpus Christi Bay), 1.51 ppm dw (Laguna Madre), and 1.56 ppm dw (Baffin Bay); and one hardhead catfish sample, 1.60 ppm dw (Nueces Bay). Lead was at elevated concentrations in sediments from the Inner Harbor and Baffin Bay, but

biota from these areas (other than Inner Harbor oysters), did not exhibit excessive residues of lead. Our data support the conclusions of Eisler (1988b) that lead does not generally biomagnify through food chains. Although some lead salts are soluble in water, the presence of calcium, cadmium, iron, manganese, and zinc salts (the case in Inner Harbor sediments) decreases lead solubility (Eisler 1988b). Lead is known to cause severe adverse effects to fish and wildlife, therefore species such as waterfowl and halophytic plants (other than shoal grass), should be sampled for lead in and around Baffin Bay and the Inner Harbor (areas of elevated sediment lead) in the near future to determine the extent to which lead contamination of the resource may be occurring.

Mercury

Mercury was detected in 90% of the sediment samples (n=255), with Inner Harbor sediments having the highest GM, 0.205 ppm dw. The maximum sample residue was 1.1 ppm dw from Corpus Christi Bay (sediment site 150, Figure 2), in the Shamrock Cove area. Shamrock Island is the site of historic and ongoing oil and gas production. The island is also the site of waste hydrocarbon disposal, much of which remains in leaking below-ground storage tanks on the island. Erosion of the island shoreline has allowed the waste hydrocarbons to escape into the sediments and water column, and may be a contributing factor in the mercury contamination of the area sediments. Mercury exceeded the upper limit (0.7 ppm) of both SQAGS (MacDonald Environmental Sciences Ltd. 1994, Long et al. 1995) at several sites in Corpus Christi Bay, Nueces Bay and the Inner Harbor, indicating probable adverse effects to aquatic organisms. The large number of oil and gas production facilities, both currently and historically operating within the Corpus Christi Bay Complex, may also have contributed to the widespread occurrence of mercury in sediments throughout the bay system.

Other Texas coastal contaminants studies have reported lower sediment residues and a lower percentage of samples with detectable mercury. Gamble et al. (1988) reported a GM of 0.04 ppm and a maximum sample residue of 0.5 ppm dw mercury in sediments from the Lower Rio Grande Valley-Lower Laguna Madre, and only 52% of the samples were above detection. Gamble et al. (1989) reported mercury in less than 50% of Aransas Bay Complex sediments, and the maximum residue was 0.5 ppm dw. Robertson et al. (1991) reported mercury in only 16% of Aransas dredge spoil island samples, and the maximum residue was 0.05 ppm dw. Contaminants studies of sediments from Lavaca Bay, a site of documented mercury contamination and an EPA designated Superfund Site, have reported greater amounts of mercury. Holmes (1977) reported a large area of sediments contaminated with mercury at 1 ppm and greater extending south from Point Comfort and the Alcoa plant. Reigel (1990) reported mercury residues up to 1.8 ppm dw, and Shultz et al. (1994) up to 1.18 ppm dw.

The occurrence of mercury in over 90% of the samples and in all bays within the study area indicates wide-spread, albeit low-level, mercury contamination of Corpus Christi Bay Complex sediments. Additionally, Corpus Christi Bay is the most industrialized bay south

of Lavaca Bay. According to Eisler (1987a), mercury in sediments has increased 5 to 10 times since prehistoric times. The residence time of mercury in estuarine sediments is unknown, but estimated to be greater than 250 million years in oceanic sediments, and the difference between biologically tolerable and natural background levels is extremely small (Eisler 1987a).

Mercury is a non-essential trace element which bioaccumulates and biomagnifies, resulting in deleterious reproductive and physiological consequences for fish and wildlife (Eisler 1987a). No mercury was detected in any shoal grass; however, mercury was detected in 75% of the oyster samples, including all the oysters from Nueces Bay. Inner Harbor oysters were below detection for mercury. The GM of mercury in Nueces Bay oysters was 0.37 ppm dw, with a maximum residues of 0.72 ppm dw, an amount equal to or greater than that found in many oyster samples from Lavaca Bay (Palmer 1992, Reigel 1990, Schultz et al. 1994, and Texas Department Health 1994). Although mercury in Nueces Bay oysters was less than the FDA Action Level of 1 ppm methyl mercury (ww) (Food and Drug Administration 1992), it was still more than ten times greater than mercury in oysters from other Texas Bays. Gamble et al. (1988) reported mercury in Lower Laguna Madre oysters at levels of 0.022 and 0.036 ppm ww (0.11 and 0.18 ppm dw), and Gamble et al. (1989) reported mercury in Aransas Bay oysters 0.008 ppm ww (0.04 ppm dw). When compared to mercury in oysters from other Texas bays, Nueces bay oysters appear to be moderately contaminated with mercury.

Twenty-six out of 33 blue crab samples (76%) were above detection for mercury. The highest GM was 0.145 ppm dw from Corpus Christi Bay and the maximum sample residue was 0.411 dw from Nueces River blue crabs. These levels were not above the FDA level of concern, 1 ppm methyl mercury (FDA 1992), but they were greater than residues in blue crabs from other Texas bays, except Lavaca Bay. Gamble et al. (1989) reported a GM of 0.038 ppm ww mercury from Aransas Bay Complex, and Gamble et al. (1988) reported 0.05 ppm ww from Lower Laguna Madre crabs. Commercially harvested blue crabs from Lavaca Bay were frequently reported to exceed the FDA guidelines of 1.0 ppm methylmercury (Evans and Engel 1994).

All hardhead catfish were above detection for mercury, with residues two to three times greater than those found in oysters and crabs. The highest GM and maximum sample residue were 0.91 ppm dw and 1.39 ppm dw, respectively, both from Corpus Christi Bay fish. Five samples from Corpus Christi Bay contained residues greater than 1 ppm mercury. By comparison, all hardhead catfish from Aransas Bay Complex had detectable residues of mercury, but the GM and maximum sample residue were 0.173 ppm ww and 0.315 ppm ww, respectively (Gamble et al. 1989). Twenty-two out of 32 fish samples from the Lower Rio Grande Valley-Lower Laguna Madre had mercury, and the GM and maximum sample residue were 0.062 ppm and 0.431 ppm ww, respectively (Gamble et al. 1988).

These data demonstrate that mercury is bioaccumulating and biomagnifying in Corpus

Christi Bay biota. Furthermore, the consequences to higher trophic level, longer-lived organisms utilizing the bays, such as brown pelicans and sea turtles, are unknown. Mercury has a high potential for bioaccumulation which tends to be rapid in aquatic organisms, and a strong tendency to biomagnify in food chains, and is slow to depurate (Eisler 1987a). Little is known regarding the level of mercury in prey items which may cause or contribute to reproductive failure in birds. However, experimental studies revealed that residues of 0.5 to 1.5 ppm in ring-necked pheasant (*Phasianus colchicus*) eggs were linked to reproductive failure (Fimreite 1971). Heinz (1979) reported reproductive success lower in second and third generation Mallards (*Anas platyrhynchos*) with mean liver mercury concentrations up to 0.49 ppm ww mercury.

Nickel

Two hundred and twenty-four sediment samples (79%) had detectable residues of nickel. The two highest GMs were 7.7 ppm dw from Corpus Christi Bay and 7.2 ppm dw in Inner Harbor sediments. The highest nickel residues in individual sediment samples were 18.3 ppm dw from Baffin Bay and 18.5 ppm dw from Laguna Madre. These residues are comparable to those reported by Gamble et al. (1989), who found a GM of 4.8 ppm dw and a maximum residue of 15 ppm dw in Aransas Bay Complex sediments. Lower Rio Grande Valley-Lower Laguna Madre sediments contained a GM of 7.9 ppm and a maximum residue of 16 ppm. Robertson et al. (1991) found a GM of 9.7 ppm dw nickel in Aransas dredge spoil sediments and a maximum residue of 20.5 ppm dw. Overall, the nickel residues in Corpus Christi Bay Complex sediments were comparable to those in sediments from other Texas bays, with slightly higher values being found in individual samples from the Laguna Madre and Baffin Bay. Nickel in Corpus Christi Bay Complex sediments is not above background levels, which range from 3.4 to 66 ppm dw (Shacklett and Boernaen 1984 et al. 1988).

Nickel was detected in 9 shoal grass samples, or 56%. The highest GM was 0.93 ppm dw from Corpus Christi Bay, and the maximum residue was 1.68 ppm dw, also from Corpus Christi Bay shoal grass. These residues are lower than those found by Pulich (1980) and Custer and Mitchell (1993). Pulich (1980) reported nickel residues in shoal grass roots ranging from 2.0 ppm dw in Corpus Christi Bay to almost 5.0 ppm dw in the Laguna Madre, and Custer and Mitchell (1993) found 2.45 ppm dw nickel in Lower Laguna Madre shoal grass.

All oyster samples were above detection for nickel. The Nueces Bay GM was 2.94 ppm dw and the maximum residue was 9.14 ppm dw; Inner Harbor oysters had 1.06 ppm dw nickel. Corpus Christi Bay Complex oysters had up to ten times the nickel of oysters from Aransas Bay, which had a GM of 0.27 ppm ww (Gamble et al. 1989), and the Lower Laguna Madre, with residues of 0.17 and 0.15 ppm ww (Gamble et al. 1988).

Nickel was detected in twelve blue crab samples, 36%. The greatest GM was 0.89 ppm dw in Baffin Bay blue crabs, and the maximum residue was 7.48 ppm dw in Laguna

Madre crabs. Lower Rio Grande Valley-Lower Laguna Madre blue crabs had nickel residues ranging from 0.08 to 0.21 ppm ww, with a GM of 0.09 ppm ww nickel. Aransas Bay Complex blue crabs had a GM of 0.10 ppm ww nickel and a maximum residue of 0.39 ppm ww nickel.

Only six hardhead catfish samples had detectable residues of nickel, and none were above levels of concern. Small amounts of nickel are essential to animals, however large amounts are toxic. Laboratory studies have shown that exposure to high levels of nickel can cause miscarriage, and nickel compounds can affect the kidneys, blood, and growth of some animals (U.S. Public Health Service 1987). There is little literature on the toxicity of nickel to marine organisms, however, according to Phillips and Russo (1978), nickel does not accumulate in aquatic organisms. The Panel on Nickel (1975) determined that levels of nickel equal to or less than 0.75 ppm ww in aquatic organisms were normal. Although nickel was far above this level in some invertebrate samples, most noticeable oysters from Nueces Bay and blue crabs from the Laguna Madre, these data demonstrate that biomagnification of the metal is not occurring within the Corpus Christi Bay Complex.

Selenium

Selenium was detected in 97 sediment samples (33%). The Inner Harbor was the only area with greater than 50% of the samples above detection (GM = 0.27 ppm dw). The maximum sample residue, 1.9 ppm dw, was from Laguna Madre sediment site 171 (Figure 5), the same site which had elevated arsenic. The levels of selenium found in sediments from the current study area were not elevated when compared to those reported in other Texas coastal studies. Gamble et al. (1988) reported a GM of 0.28 ppm dw selenium in Lower Rio Grande Valley sediments, and a maximum sample residue of 0.66 ppm dw. Aransas Bay Complex sediments had selenium residues ranging up to 5.1 ppm dw, but no GM was determined (Gamble et al. 1989). The baseline range for the soils in the western United States is 0.039 to 1.4 ppm dw and selenium was detected at 0.3-0.7 ppm dw in the Lower Rio Grande Valley in 1986 (Shacklett and Boernaen 1984 et al. 1988).

Selenium was below detection in shoal grass, but all oyster, blue crab, and hardhead catfish samples were above detection. Nueces Bay oysters had a GM of 4.46 ppm dw, and Inner Harbor oysters had a residue of 4.72 ppm dw selenium. These levels are four to five times greater than selenium in Lower Laguna Madre oysters, which had residues of (n=2) 0.33 and 0.28 ppm ww (≈2.1 and 1.8 ppm dw) (Gamble et al. 1988). Aransas Bay Complex oysters, which had a GM of 0.38 ppm ww (≈2.5 ppm dw), also had much less selenium than Nueces Bay and Inner Harbor oysters. The origin of selenium is believed to be the same petroleum and industrial sources responsible for high levels of other trace metals in Corpus Christi Bay Complex oysters.

Blue crabs had slightly less selenium than oysters; the highest GM was 3.52 ppm dw from Corpus Christi Bay. Blue crabs from the Lower Laguna Madre, with a GM of 0.42 ppm ww (≈1.5 ppm dw) had less than half the selenium (Gamble et al. 1988). Aransas Bay Complex oysters, with a GM of 0.62 ppm ww, also had less than half the selenium of Corpus Christi Bay Complex oysters.

A GM of 2.53 ppm dw was detected in both Redfish Bay and Nueces Bay hardhead catfish, and the maximum sample residue was 3.15 ppm dw from Redfish Bay. Selenium is an essential trace element for humans, some plants, and animals, and may protect mammals and birds against toxic effects of mercury, cadmium, arsenic, thallium, and paraquat. It may also be toxic at levels as low as 4.00 ppm in human food items. The main source of environmental selenium is the weathering of rocks, but it is also being introduced into the environment by anthropogenic sources, notably the burning of coal (Eisler 1985b).

Zinc

All Corpus Christi Bay Complex sediments were above detection for zinc. Three samples from Nueces Bay, five samples from the Inner Harbor and one sample from the Laguna Madre surpassed the concentration limit of the Florida SQAGS (124 ppm), indicating possible adverse biological effects (MacDonald Environmental Sciences Ltd. 1994). Inner Harbor sediments had the highest GM, 179.5 ppm, and the maximum sample residue, 645 ppm dw. These concentrations are up to ten times greater than zinc in Aransas Bay Complex sediments, which had a GM of 16.7 ppm dw and a maximum sample residue of 79.2 ppm dw (Gamble et al. 1989). Lower Rio Grande Valley-Lower Laguna Madre sediments had a GM of 34.7 ppm dw (Gamble et al. 1988) and a maximum sample residue of 439 ppm dw zinc. The lone elevated sample was obtained from the Brownsville Ship Channel, an area contaminated by a ship dismantling operation and an ore loading facility (Gamble et al. 1988). Finally, Aransas dredge spoil island sediments, had a GM of 35.86 ppm dw and maximum residue of 83.2 ppm dw (Robertson et al. 1991).

The elevated Inner Harbor GM (179 ppm dw), as well as that of Corpus Christi Bay (56.8 ppm dw), and Nueces Bay (55.59 ppm dw) reflect the lingering effects of historic zinc contamination, which has been documented to extend far beyond the Inner Harbor, well into Corpus Christi Bay (Holmes et al. 1974) and Nueces Bay. Zinc contamination of Laguna Madre sediments, however, has not been documented until this study. The GM of zinc in Laguna Madre sediments was within the normal range, 18.57 ppm dw, but one individual sample had a residue of 248 ppm dw (biota site 171). This sample was the same one which had elevated residues of arsenic, copper, mercury, and selenium. The source of Laguna Madre zinc is unknown, but could possibly be related to the oil and gas activity within the bay, and/or barge traffic utilizing the GIWW.

Zinc was detected in all biota samples. The highest zinc GM in shoalgrass was 19.75 ppm dw from Corpus Christi Bay. The maximum residue was 111 ppm dw from Baffin Bay (biota site 32) shoalgrass, an amount three times greater than that of any other shoalgrass sample collected as part of this study. Little comparison data exists on zinc in Texas sea grasses. In 1988 (Mauer et al. 1989) collected widgeon grass from St. Charles Bay and Burgentine Lake at the Aransas National Wildlife Refuge and found zinc residues ranging from 2-3 ppm ww (≈7.9-11.9 ppm dw). Shoal grass roots examined by Pulich (1980) had zinc residues ranging from less than 10 ppm dw in Redfish Bay to 70 ppm dw in Corpus Christi Bay at Ingleside Point. These residues are comparable to Corpus Christi Bay Complex residues, except for the elevated Baffin Bay sample, which was 1.5 times greater than any reported by Pulich.

Oysters from both Nueces Bay and the Inner Harbor had extremely elevated levels of zinc. Nueces Bay oysters had a GM of 6006 ppm dw and a maximum sample residue of 7180 ppm dw. Inner Harbor oysters had 11600 ppm dw zinc. Because of concerns regarding the safety of seafood obtained from Nueces Bay, the Texas Department of Health (TDH) collected fish, crab and oyster samples in August 1994 and also found extremely elevated levels of zinc in oysters. Oyster residues in the two TDH samples were 2294 and 2483 ppm ww zinc (≈14800 and 16019 ppm dw) (Texas Department of Health 1994).

As stated previously, zinc contamination, as well as that of cadmium and copper, is well documented for the Inner Harbor (Holmes et al. 1974, Davis 1984, and Bowman and Jensen 1985). Much of the contamination apparently originated from the operation of a zinc smelting facility which ceased operation in the early 1980's. However, the geographic extent of the zinc contamination has not been fully identified, and a more thorough assessment of the area should be undertaken. The occurrence of significantly contaminated biota from Nueces Bay indicates that this bay is in need of additional contaminants assessment of the biota and sediments.

Baffin Bay blue crabs had the greatest zinc GM, 107 ppm dw, as well as the maximum sample residue, 517 ppm dw (biota site 31). These results were unexpected since Nueces Bay, which had a blue crab zinc GM of 86 ppm dw, and the Inner Harbor, which had a zinc residue of 109 ppm dw in blue crabs, are the areas of known zinc contamination. By comparison, blue crabs from the Lower Laguna Madre, which had a GM of 12.7 ppm ww zinc (≈45.2 ppm dw) had less than half as much zinc as the Baffin Bay blue crabs (Gamble et al. 1988). Aransas Bay Complex blue crabs, on the other hand, had a comparable zinc GM of 22.1 ppm ww (≈78.7 ppm dw) (Gamble et al. 1989). Data collected for this study indicate that, except for the elevated Baffin Bay sample (517 ppm dw zinc), blue crabs from the Corpus Christi Bay Complex had zinc residues which were comparable, or only slightly elevated, above those of other Texas Bays. New data collected by the Texas Department of Health in 1994, however, revealed much higher residues of zinc in Nueces Bay blue crabs, which had a composite zinc residue of 50.66

ppm ww zinc (≈180.3 ppm dw) (Texas Department of Health 1994). The explanation for an increase in zinc residues in Nueces Bay biota (including oysters, blue crabs, and fish) over a five year period is unknown but may be related to runoff from areas of dredge material disposal or aerial deposition.

The highest zinc GM in hardhead catfish was 956 ppm dw detected in fish from Corpus Christi Bay, and the maximum sample residue was 1960 ppm dw, found in Inner Harbor fish. Other hardhead catfish samples with elevated residues of zinc were obtained from the Nueces River (1191.5 ppm dw), Nueces Bay (1070 ppm dw from biota site 1; Figure 1), and Corpus Christi Bay (1008.9 and 1108 ppm from biota sites 16 and 18; Figure 2). By comparison, Aransas Bay Complex hardhead catfish had a GM of 146.9 ppm ww (ranging from 79 to 229 ppm ww) (Gamble et al. 1989), and Lower Laguna Madre fish had a GM of 16.9 ppm ww zinc (ranging from 0.5 to 146.7 ppm ww) (Gamble et al. 1988).

These data demonstrate that zinc contamination of Corpus Christi Bay Complex biota is a problem at all trophic levels and in many geographical areas (Inner Harbor, Nueces Bay, Corpus Christi Bay, and Baffin Bay). The 1994 TDH data demonstrate that the problem of zinc bioaccumulation has not abated in Nueces Bay invertebrates (oysters and blue crabs), but is instead, exacerbated as compared to five years earlier.

According to Eisler (1993), background concentrations of zinc seldom exceed 40 μg/L in water, or 200 ppm in soils and sediments (Inner Harbor, Nueces Bay, and Laguna Madre sediments exceeded background). Proposed criteria for protection of aquatic life include mean zinc concentrations of <58 to <86 μg/L in seawater. Results of recent studies, however show significant adverse effects to a number of saltwater biota between 9-50 μg/L, suggesting that downward modification in the proposed criteria is necessary (Eisler 1993).

The interactions of zinc and other trace metals can have significant environmental effects. Zinc-cadmium interactions diminish negative cadmium effects (Eisler 1993). Copper-zinc and mercury-zinc mixtures and interactions are more than additive in toxicity to many aquatic organisms, including oyster larvae (Eisler 1993). Zinc can depress copper accumulation in catfish; however, simultaneous exposure to copper and zinc can result in enhanced uptake of both metals. Zinc-lead interactions are more than additive in toxicity to marine copepods; they delayed mud crab development, and lead accumulated at ten times greater concentrations in fish in the presence of zinc. Nickel-zinc interactions also had an additive toxicity effect to biota. In addition, zinc reacts with a wide variety of inorganic, organic, and biological agents, but little information is available on the consequences of these interactions (Eisler 1993).

SUMMARY AND RECOMMENDATIONS

Corpus Christi Bay Complex sediments remained at low levels of organic compound contamination despite the large volume of shipping traffic, industrial discharges, aerial emissions, and non-point source runoff from the surrounding petrochemical industry. OCs were below detection in all fifty sediment samples submitted for analyses. At least one PAH was detected in each of the fifty sediment samples analyzed, but at residues ranging from 0.01-0.49 ppm ww. Three samples, which were collected from areas of known hydrocarbon contamination, had PAH residues of chrysene, flouranthrene, and/or pyrene above 0.3 ppm ww. Although oil and grease residues were detected in all 282 samples submitted for analysis, the residues were below those found in sediments from nearby Aransas Bay in 1985-1986. However, because of recent oil spills, areas important to colonial nesting birds should continue to be monitored for PAHs and alkane contamination. Important rookery areas include Pelican Island (north of the Corpus Christi ship channel), Shamrock Island in Corpus Christi Bay, and rookery islands in Nueces Bay (which were heavily impacted by a 1994 oil spill), Redfish Bay and the Laguna Madre.

Organic analyses of Corpus Christi Bay Complex biota revealed limited, but widespread contamination of the resource. Although the dioxin 2,3,7,8-TCDD was below detection in all six biota samples submitted for analysis, DDT metabolites, p,p'-DDD and/or p,p'-DDE, were detected in one of four oyster samples (0.01 ppm ww p,p'-DDE; Nueces Bay), 18 of 22 blue crab samples (0.01 ppm ww p,p'-DDD and 0.01-0.08 ppm ww p,p'-DDE; all bays), and all 23 hardhead catfish samples (0.01 ppm ww p,p'-DDD and 0.01-0.37 ppm ww p,p'-DDE; all bays). PCBs were detected in three blue crab samples and 16 of 23 hardhead catfish samples, one of which contained 3.8 ppm ww PCBs, an amount almost two times greater than the FDA level of concern of 2 ppm ww PCBs. OCs, particularly DDE and PCBs, appear to be biomagnifying and bioaccumulating in the higher trophic level organisms of the Corpus Christi Bay Complex. However, one important revelation of the current study was the lower number of OCs, especially those formerly used as pesticides (such as DDT and Heptachlor, and their break-down metabolites) that were detected in biota. Half the number of OCs as were detected in Aransas Bay Complex hardhead catfish four years earlier (14 compounds) (Gamble et al. 1989), and less than half detected in Lower Rio Grande Valley-Lower Laguna Madre fish in 1985 (16 compounds) (Gamble et al. 1988), were detected in Corpus Christi Bay Complex biota collected in 1989 (7 compounds).

Most sediments throughout the study area remained at low levels of trace element contamination, except for certain hotspot areas, such as the Inner Harbor (aluminum, cadmium, chromium, copper, lead, mercury, and zinc), Nueces Bay (cadmium, mercury, and zinc), parts of Corpus Christi Bay (arsenic, mercury, and zinc), and isolated areas of both Baffin Bay (arsenic, boron, chromium, copper, and lead) and the Laguna Madre (arsenic, boron, chromium, copper, and zinc). Instead of diminishing, trace elements in

Inner Harbor sediments, especially zinc, remained at levels of contamination which met or exceeded those found in previous studies (Holmes 1974, Davis 1984, Bowman and Jensen 1985). Maps showing the distribution of mercury and zinc in Corpus Christi Bay sediments reveal patterns of contamination which may be related to the circulation of metals originating from the Inner Harbor area (Figures 8 and 9).

Baffin Bay shoalgrass had the greatest GMs of arsenic, cadmium, and copper, as well having elevated zinc (111 ppm dw) in one sample. Corpus Christi Bay shoalgrass had the greatest GMs of chromium, lead, nickel, and zinc; Redfish Bay shoal grass had the greatest GM of boron. Compared to the results of other studies, these data demonstrate that bioaccumulation of zinc (Corpus Christi, Nueces, and Baffin Bays), cadmium (Baffin Bay), copper (Baffin Bay), and lead (Corpus Christi Bay) are occurring in Corpus Christi Bay Complex shoalgrass. The consequences to the resource posed by this environmental contamination, especially when combined with the damaging effects produced by the on-going brown tide, are unknown.

Trace metal contamination of Corpus Christi Bay Complex biota was most evident in oysters, which were heavily contaminated with cadmium and zinc. Nueces Bay oysters may be accumulating zinc and other trace element contamination due to the discharge Nueces Bay receives from Central Power and Light Company's Nueces Bay Power Plant. The plant is located adjacent to the Inner Harbor, which serves as the source for the power company's water intake, and the discharge then empties into Nueces Bay. Zinc may also continue to contaminate Nueces Bay via wind-blown materials from the adjacent dredge disposal sites which contain materials dredged from the Inner Harbor. Oysters from Nueces Bay and the Inner Harbor also had elevated residues of every trace metal, with residues ranging from four to 100 times greater than trace elements found in oysters from Aransas Bay and the Lower Laguna Madre (Table 7). Cadmium, copper, lead, mercury, nickel, and zinc, all of which have additive toxicity effects (Eisler 1993), were at levels many times greater than in oysters from the other locations. Elevated residues of arsenic, cadmium, and chromium were also detected in blue crabs from the Laguna Madre, and zinc residues were elevated in blue crabs from Baffin Bay. Hardhead catfish from Baffin Bay had elevated arsenic and copper residues, Laguna Madre hardhead catfish had elevated arsenic, Corpus Christi Bay hardhead catfish had elevated mercury and zinc, and hardhead catfish from the Inner Harbor, Nueces River, Corpus Christi Bay, and Nueces Bay also had elevated zinc (Figures 10-15).

Biota from the hypersaline bays, Baffin Bay and Laguna Madre, had the greatest residues of arsenic, most likely related to ionic concentrations in the waters. The source(s) of elevated zinc and other trace elements in Baffin Bay and Laguna Madre biota are unknown and have been previously unreported. An investigation utilizing sediments and sediment ingesting benthic organisms (such as polychaetes, and/or filter-feeding fauna, such as oyster, clams or mussels), and focusing on hot spot areas of Baffin Bay, Nueces Bay, Laguna Madre and Corpus Christi Bay is recommended. There are potentially

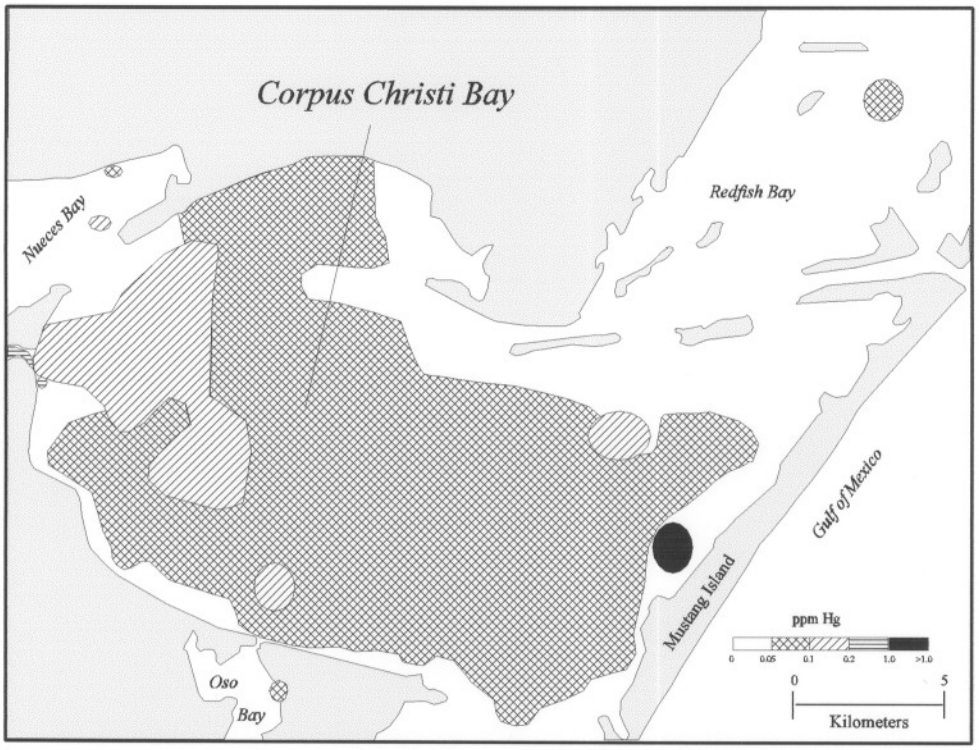


Figure 8. Distribution of mercury in sediments in Corpus Christi Bay, 1988-89.

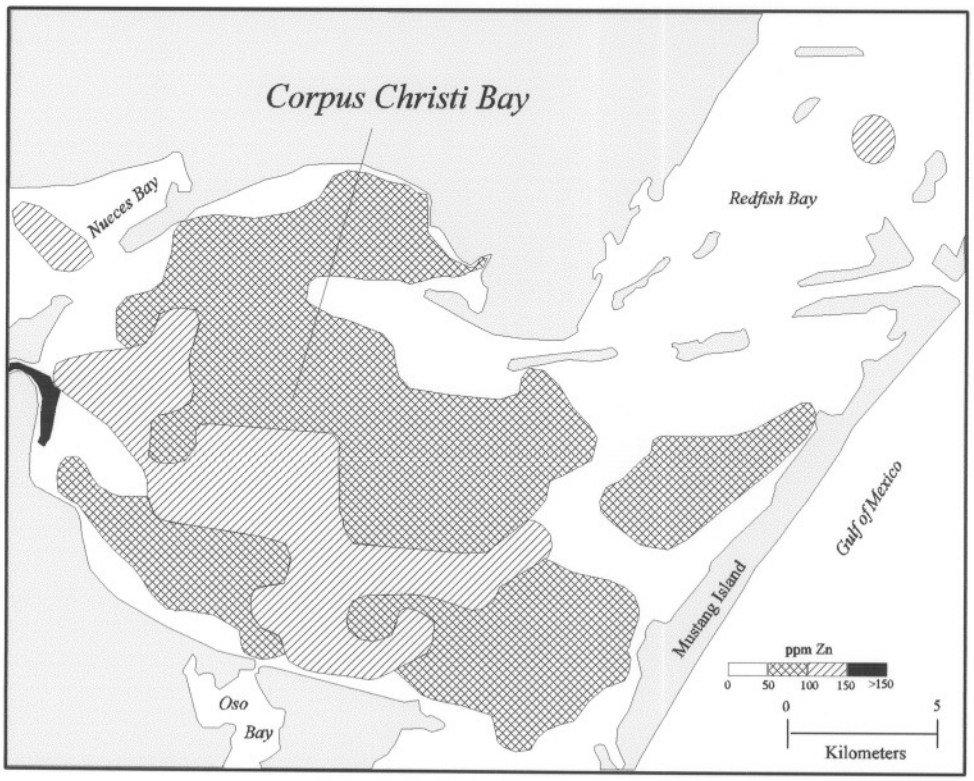


Figure 9. Distribution of zinc in sediments in Corpus Christi Bay, 1988-89.

serious cumulative problems involving zinc-trace metal interactions (especially with cadmium, chromium, copper, lead, and mercury), which may lead to unknown additive effects. Because of lead found in Baffin Bay shoal grass, the proposed sampling regime should also attempt to obtain lead-sensitive species, such as waterfowl, in order to determine whether an actual lead problem exists in sediments and biota within the Corpus Christi Bay Complex.

In summary, we recommend a more intensive sampling regime in areas where elevated trace elements were detected in order to accurately determine the geographic extent and toxicological magnitude of the contamination problem, and make recommendations regarding dredging and dredge material disposal practices. Furthermore, we submit the following recommendations:

- The most heavily contaminated area examined in this study was the Corpus Christi Inner Harbor, an area utilized by endangered Brown Pelicans for feeding and loafing. The potential danger to pelicans and other species should be further investigated by expanding the number of fish samples collected and including prey species preferred by pelicans.

- Baffin Bay and the Laguna Madre, environmentally sensitive areas important to waterfowl and fishery species, both had contaminant hotspots that may be related to maintenance dredging of the Gulf Intracoastal Waterway (GIWW), the disposal of the dredge material, GIWW barge traffic, and/or oil and gas operations. Sediment and pore water sampling and toxicological testing should be performed, especially at sediment sites 171 and 251 where residues of boron, cadmium, copper, lead, mercury and zinc were at relatively elevated levels.

- Non-point sources, such as agricultural operations which use cotton defoliants, may have contributed to elevated levels of arsenic. An investigation of the creeks leading to Baffin Bay, including toxicity testing of sediments and pore water, is suggested.

- Sediments near rookery islands in the Corpus Christi Bay Complex should be monitored for PAHs and alkanes.

- Total organic carbon (TOC) content and acid volite sulfides (AVS) should be determined for any sediments taken as part of Phase II.

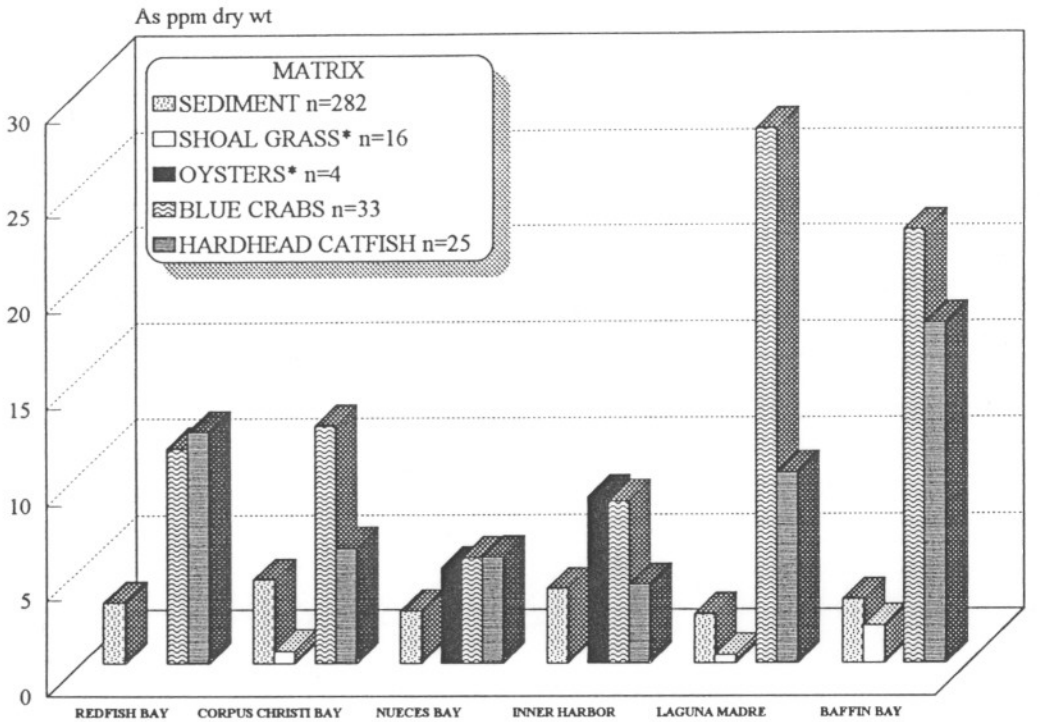


Figure 10. Arsenic in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.

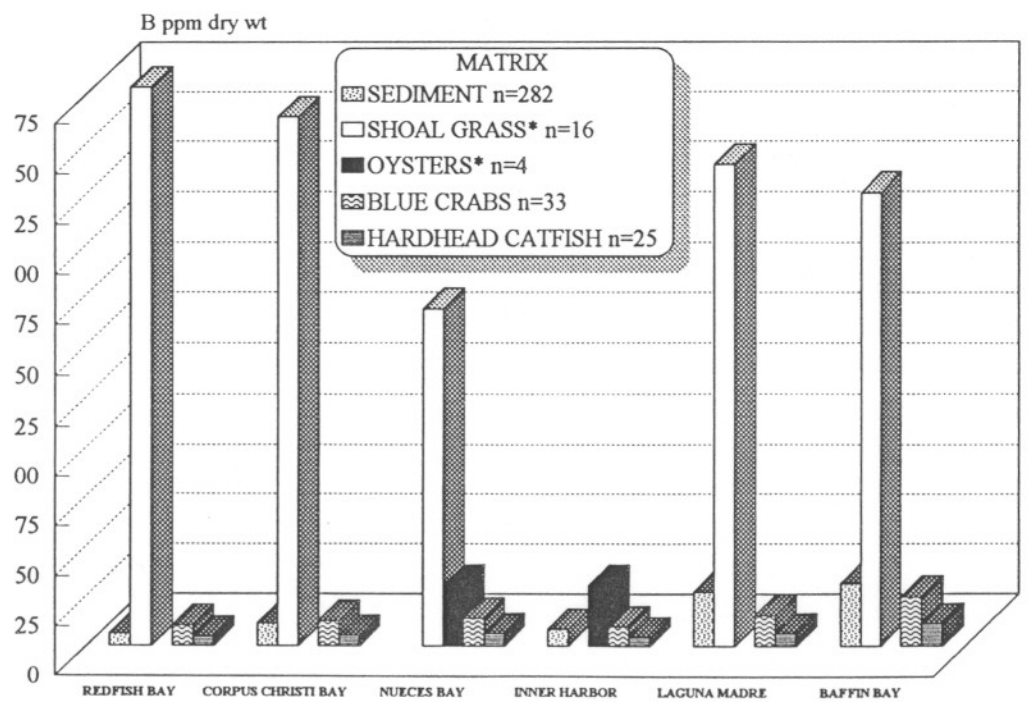


Figure 11. Boron in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.

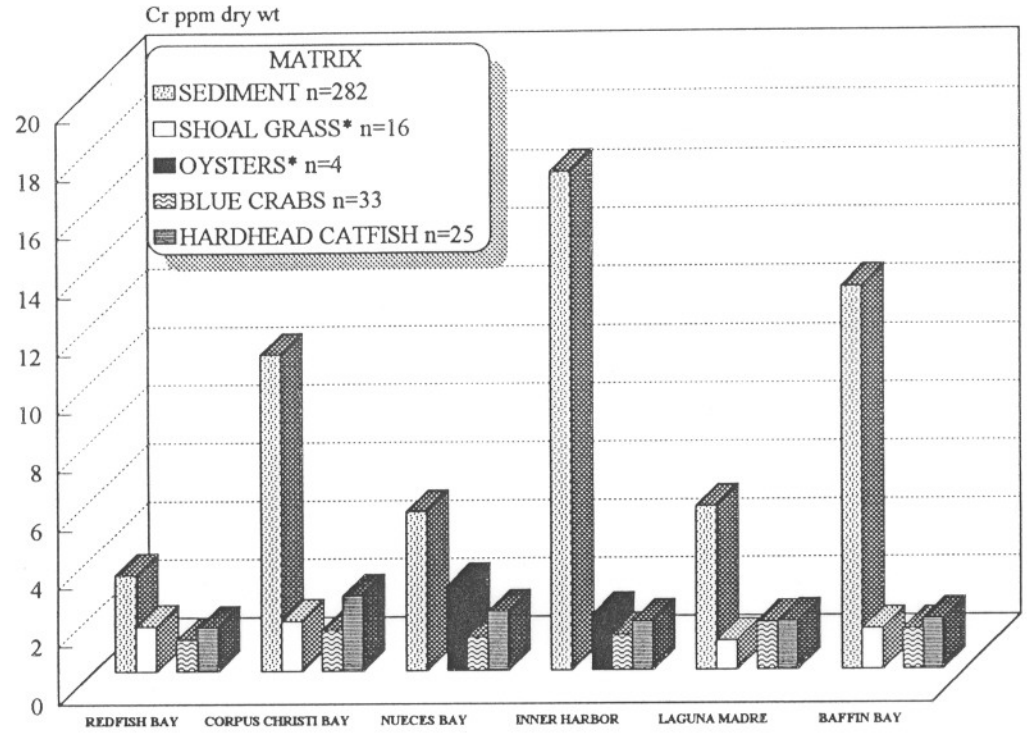


Figure 12. Chromium in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.

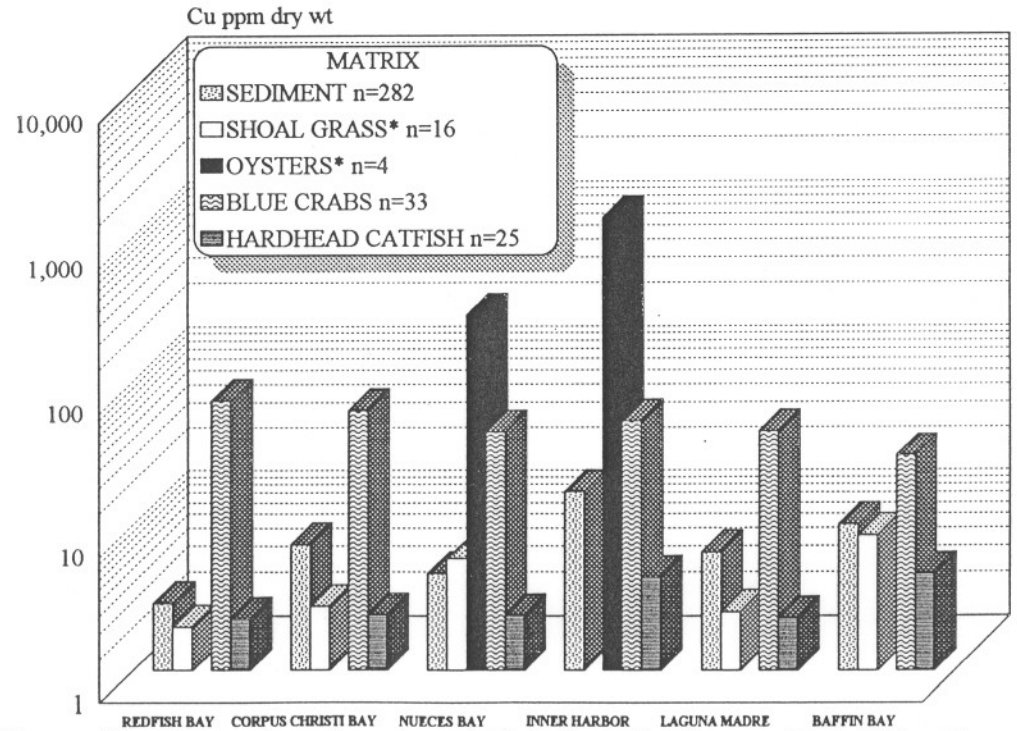
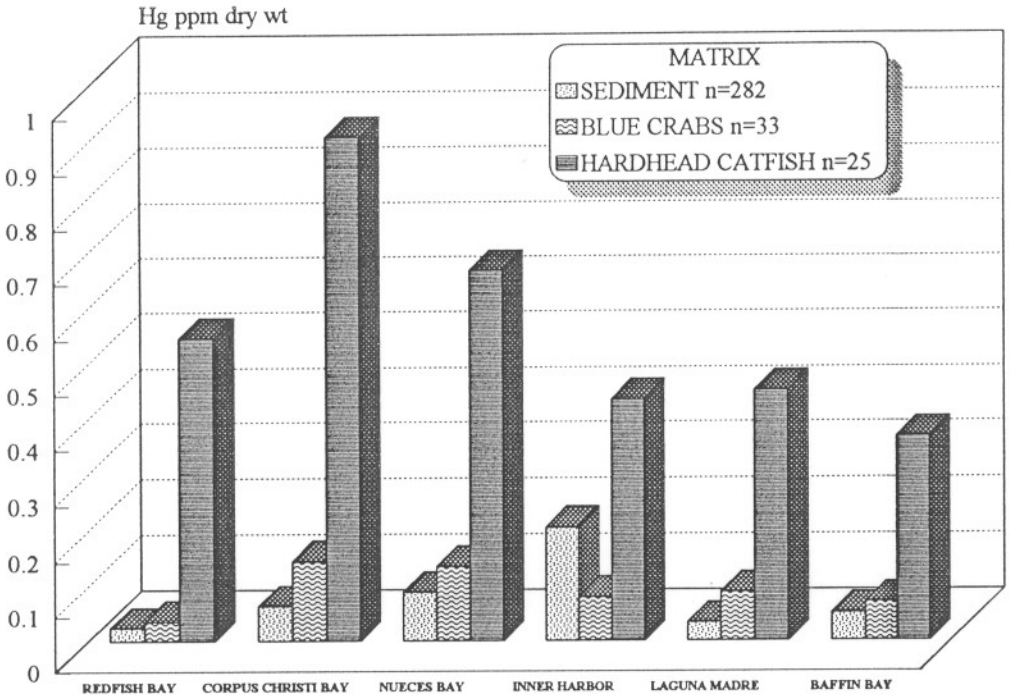


Figure 13. Copper in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.



Figures 14. Mercury in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.

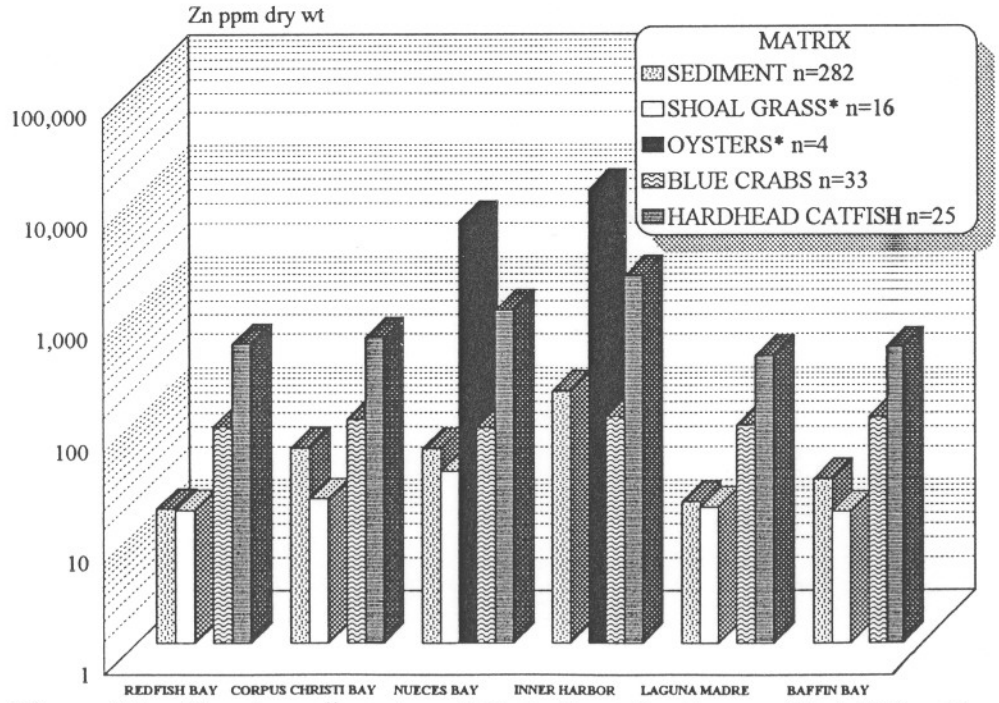


Figure 15. Zinc in sediments and biota from the Corpus Christi Bay Complex, 1988-1989. *Shoal grass and oysters not collected from all locations.

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APPENDIX A: Analyses, detection limits, and laboratories used for sediment and biota samples collected from the Corpus Christi Bay Complex, Texas, 1988-1989.

Appendix A. Analyses, detection limits, and laboratories used for sediment and biota samples collected from the Corpus Christi Bay Complex, Texas, 1988-1989.

Trace Elements	Detection limit (ppm dry weight)			
Al	1[1]	2[2]	3[3]	10[4]
Sb	1	5	-	0.025
As	0.1	0.3	0.05	0.005
Ba	0.5	0.5	0.1	5
Be	0.05	0.1	0.1	0.5
B	0.5	0.5	2	5
Cd	0.05	0.1	0.2	0.5
Cr	0.1	0.5	1	1
Cu	0.25	0.5	0.3	2.5
Fe	1	10	1	10
Pb	0.3	1.5	4	10
Mg	10	10	0.1	100
Mn	0.13	0.5	0.2	1.5
Hg	0.025	0.05	0.01	0.025
Mo	0.5	0.5	1	5
Ni	0.4	0.5	2	4
Se	0.1	0.3	0.2	0.1
Ag	0.5	3	2	5
Sr	0.1	0.5	0.1	1
Tl	2	-	5	0.1
Sn	0.5	3	-	5
V	0.5	0.5	0.4	5
Zn	0.2	1	0.2	2

Organic Compounds	Detection limit (ppm wet weight)	
Alkanes	0.01[5]	-
Organochlorines	0.01	0.01[6]
Toxaphenes	0.01	0.05
PCBs	0.01	0.05
PAHs	0.01	0.01
Oil and Grease	-	50

Compound	Detection limit
TCDD	picograms/gram[7]

[1] Hazelton Laboratory, Inc., Madison, Wisconsin. Catalog bio6427.
[2] Research Triangle Institute, Research Triangle, North Carolina. Catalogs bio6386 and bio2050003.
[3] Environmental Trace Substance Research Center, Columbia, Missouri. Catalog sed5609.
[4] Hazelton Laboratory, Inc., Madison, Wisconsin. Catalog sed5661.
[5] Geochemical and Environmental Research Group, Tx A&M University. Catalogs bio6427 and sed5661
[6] Mississippi State Chemical Laboratory, Miss. State Univ. Catalogs bio6386 and sed5609. Oil and grease analyzed in 50 sediment samples only.
[7] Wright State University, Dayton, Ohio. Catalog bio2050003. Biota, 6 samples only.

APPENDIX B: Biota sample sites and numbers of samples collected from each bay.

Appendix B. Biota sample sites and numbers of samples collected from each bay.

BAY	BIOTA SITE #	SITE DESCRIPTION	GR[1]	OY	BC	CC	HH	TF	TOTAL # SAMPLES PER BAY
Corpus Christi Bay	4	Inside breakwater at Texas State Aquarium			✓		✓		
	5	Inside moorings E side Sun Oil dock Ingleside			✓		✓		
	6	Shamrock Cove	✓		✓		✓		
	7	200 m offshore NAS discharge point			✓		✓		
	10	T-Head			✓		✓		
	11	Offshore Portland golf course			✓				
	12	Marker 17, across from Oxychem	✓		✓		✓		
	13	La Quinta & CC Ship Channel at Marker 3			✓	✓			
	16	S side Pelican Island			✓		✓		
	17	200 m offshore Ocean Dr. at Doddridge			✓				
	18	Mid-bay 2 km S markers 55-56 CC Ship Channel			✓		✓		
	19	Amidst platforms at GIWW marker 78			✓				
	20	NAS east point breakwater			✓		✓		
	36	East Flats, 1 mi E Pelican Island, S side Pt of Mustangs	✓						
CORPUS CHRISTI BAY TOTAL BIOTA SITES = 14			**3**	**-**	**13**	**1**	**9**	**-**	**26**
Redfish Bay	14	In channel between GIWW markers 51-53	✓		✓		✓		
	15	E of Morris and Cummings Cut	✓		✓		✓		
	35	0.5 mi SE Morris and Cummings Cut							
REDFISH BAY TOTAL BIOTA SITES =3			**2**	**-**	**2**	**-**	**2**	**-**	**6**
Nueces Bay	1	SE side White Pt. <50 m from brine discharge		✓	✓		✓		
	2	Centex Channel			✓		✓		
	3	NW side Nueces Bay Causeway, Gunderland channel near marina	✓	✓	✓				
	37	W side Nueces Bay Causeway near Indian Pt.	✓						
	38	0.5 mi N mouth of Nueces River		✓					
NUECES BAY TOTAL BIOTA SITES = 5			**2**	**3**	**3**	**-**	**2**	**-**	**10**
Oso Bay	34	In mouth of bay near bridge	✓		✓		✓		
OSO BAY TOTAL BIOTA SITES = 1			**1**	**-**	**1**	**-**	**1**	**-**	**3**
Nueces River	8	3rd battery tanks upstream of mouth			✓		✓		
NUECES RIVER TOTAL BIOTA SITES = 1			**-**	**-**	**1**	**-**	**1**	**-**	**2**
Inner Harbor	9	W Lift Bridge on S side harbor near ASARCO		✓	✓		✓		
INNER HARBOR TOTAL BIOTA SITES = 1			**-**	**1**	**1**	**-**	**1**	**-**	**3**
Laguna Madre	21	Boat Hole, east of NAS	✓		✓				
	22	Along NE side Pita Island	✓				✓		
	23	Between GIWW markers 53-54	✓		✓		✓		
	24	Padre Isles near entrance channel	✓		✓		✓		
	25	S Bird Island			✓		✓		
	26	E side GIWW markers 191-193			✓			✓	
	28	W side GIWW markers 39-43			✓				
LAGUNA MADRE TOTAL BIOTA SITES = 7			**4**	**-**	**6**	**-**	**4**	**1**	**15**
Baffin Bay	27	0.5 mi N Baffin Bay Channel marker 9			✓				
	29	0.25 mi S Baffin Bay Channel markers 22-24			✓		✓		
	30	Upper end Alazan Bay	✓		✓		✓		
	31	Amidst 3 platforms near Baffin Bay Channel markers 36 and 38	✓		✓		✓		
	32	Cayo del Grullo, across from oil tanks	✓		✓		✓		
	33	Upper end Laguna Salada	✓		✓		✓		
BAFFIN BAY TOTAL BIOTA SITES = 6			**4**	**-**	**6**	**-**	**5**	**-**	**15**
TOTAL BIOTA SITES FROM ALL BAYS = 37			**16**	**4**	**33**	**1**	**25**	**1**	**80**

[1]GR=shoal grass, OY=eastern oyster, BC=blue crab, CC=calico crab, HH=hardhead catfish, TF=toad fish

APPENDIX C: The results of dioxin analysis for 2,3,7,8-TCDD in biota samples collected from the Corpus Christi Bay Complex, 1989.

Appendix C. The results of dioxin analysis for 2,3,7,8-TCDD in biota samples collected from the Corpus Christi Bay Complex, 1989. The lower limit of detection (LLD) is reported in picograms per gram, parts per trillion (ppt), wet weight.

SAMPLE SITE	SPECIES	BAY[2]	LLD (ppt)[3]	2,3,7,8-TCDD (ppt)	% LIPIDS
11[1]	Blue crab	CC	0.252	BD[4]	0 .37
13	Blue crab	CC	0.386	BD	1.33
20	Blue crab	CC	0.403	BD	1.14
21	Blue crab	LM	0.255	BD	0.63
28	Toad fish	LM	0.284	BD	3.08
31	Hardhead catfish	BB	0.644	BD	3.10

[1]Biota sampling locations provided in Figures 2-5.
[2]CC = Corpus Christi Bay, LM = Laguna Madre, BB = Baffin Bay.
[3]Lower limit of detection, parts per trillion wet weight.
[4]Below the detection limit.