



Ecological Condition of Coastal Ocean Waters of the Northwestern Gulf of Mexico: 2011

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Table of Contents

1.0	Introduction.....	1
2.0	Methods.....	3
2.1	Sampling Design and Field Collections.....	3
2.2	Water Quality Analysis.....	5
2.3	Sediment TOC and Grain Size Analysis.....	5
2.4	Chemical Contaminant Analysis.....	5
2.4.1	Laboratory Sample Preparation	5
2.4.2	Inorganic Sample Digestion and Analysis	5
2.4.3	Organic Extraction and Analysis	6
2.5	Benthic Community Analysis	9
2.6	Sediment Toxicity Testing.....	9
2.7	Data Analysis	9
3.0	Results and Discussion	13
3.1	Depth and Water Quality	13
3.1.1	Depth.....	13
3.1.2	General Water Characteristics: Temperature, Salinity, Water-Column Stratification, DO, pH, TSS	15
3.1.3	Nutrients and Chlorophyll.....	19
3.2	Sediment Quality	21
3.2.1	Grain Size and TOC.....	21
3.2.2	Chemical Contaminants in Sediments	23
3.2.3	Sediment Toxicity	30
3.3	Chemical Contaminants in Fish Tissues	31
3.4	Status of Benthic Communities.....	36
3.4.1	Taxonomic Composition.....	36
3.4.2	Abundance and Dominant Taxa.....	40
3.4.3	Diversity.....	40
3.4.4	Patterns of benthic infaunal distributions.....	43
3.4.5	Non-indigenous Species.....	48
3.5	Potential Linkage of Biological Condition to Stressor Impacts.....	48
4.0	Literature Cited	50
5.0	Appendices.....	57

List of Figures

Figure 1. Map of targeted study area in the Gulf of Mexico. Due to ship problems, stations in the shaded area (in grey) were not sampled.....	4
Figure 2. Surface (a) and bottom (b) salinities measured at 34 sites in the northwest GOM.	15
Figure 3. Extent of density stratification ($\Delta\sigma_t$) among 34 stations in the northwest GOM. Interpolated surface was obtained using an inverse distance weighted (IDW) technique.....	16
Figure 4. Bottom dissolved oxygen (DO) measured at 34 sites in the northwest GOM. Interpolated surface was obtained using an inverse distance weighted (IDW) technique.....	16
Figure 5. Dissolved oxygen (DO) versus $\Delta\sigma_t$ and depth in bottom waters of the western Gulf of Mexico coastal shelf. Low-DO stations (DO < 2 mg/L) are shown in red.	17
Figure 6. Estimated CDF plots representing percent area (and 95% confidence intervals) of northwestern GOM coastal shelf waters vs. selected water-quality characteristics.	18
Figure 7. Percent area (and 95% confidence intervals) of northwestern GOM coastal shelf waters vs. nutrient, chlorophyll, and TSS concentrations.	20
Figure 8. (A) Percent area (and 95% confidence intervals) represented by varying levels of % silt+clay content of sediment, and (B) percent area having % silt+clay content within specified ranges in the northwest GOM.	21
Figure 9. Percent gravel, sand, and silt+clay content of northwest GOM coastal shelf sediments.	21
Figure 10. (A) Percent area (and 95% confidence intervals) represented by varying levels of TOC content of sediment (mg/g), and (B) percent area having TOC content within specified ranges.	22
Figure 11. Oil and gas platforms (black dots) and pipelines (grey lines) in the GOM (source data: BOEM 2012a, 2012b).	23
Figure 12. Trends in detectable concentrations of metals, PAHs, PCBs, DDTs, and TPH in northwest GOM shelf sediments. Vertical bar in legend provides reference scale for bars in figure.	24
Figure 13. Effects range-mean (ERM) quotients calculated for each of 34 stations in the northwest GOM. (A) Mean ERM quotient; (B) Summed ERM quotient; (C) ERM quotient for metals only.	29
Figure 14. Mean ERM Quotient (ERM-Q) calculated for sediments sampled at 34 stations in the northwest GOM. Symbols marked with a red 'x' also had significant Microtox [®] toxicity (see Section 3.2.3 below).	30
Figure 15. Plot of mean ERM quotient (ERM-Q) vs. longitude for sediments collected at 34 sites in the northwest GOM. Stations represented by solid circles also had significant Microtox [®] toxicity (see Section 3.2.3 below).	30
Figure 16. Mean (plus one standard error) of total metals, PAH, PCB, and DDT concentrations measured in each of three finfish species collected in the northwest GOM.	32

Figure 17. Locations of sites where tissue contaminant levels measured in fish were found to exceed the corresponding non-cancer human health guidelines (U. S. EPA 2000). The lower, non-cancer endpoint for methylmercury (measured as mercury and assumed to be all methylmercury) was exceeded at seven sites (red symbols); the upper, non-cancer endpoint for total PCBs also was exceeded at one of these sites (indicated by starred symbol). Locations of oil and gas platforms and pipelines are shown for reference (see Figure 11)..... 35

Figure 18. Taxonomic composition of benthic infauna as (A) percent of total number of taxa and (B) percent of total density. 38

Figure 19. Percent area (and 95% confidence intervals) of GOM study area vs. benthic infaunal taxonomic richness (A), density (B), and H' diversity (C) 42

Figure 20. Plot of Shannon diversity (H') vs. longitude in the northwest GOM. 43

Figure 21. Dendrogram resulting from hierarchical cluster analysis of Bray-Curtis dissimilarities, calculated from square-root transformed infaunal abundance (after removing rare species), from 34 sites in the northwest GOM. Numbers above each group of branches refer to site groups discussed in the text. Map shows locations of stations and corresponding site group assignments. 44

Figure 22. Ordination plot derived from non-metric multidimensional scaling (NMDS) of Bray-Curtis dissimilarities calculated from square-root transformed infaunal abundance (after removing rare species) from 34 sites in the northwest GOM. 45

Figure 23. Plot of the first two canonical variables for a canonical discriminant model relating sediment % silt-clay, sediment % TOC, mean ERM-Q, and bottom-water DIN and DIP to site groupings derived from hierarchical cluster analysis of Bray-Curtis dissimilarities calculated from square-root transformed infaunal abundance (after removing rare species) from 34 sites in the northwest GOM..... 46

Figure 24. Comparison of measures of benthic infaunal abundance and diversity for the northwest GOM coastal shelf and other surveyed regions of the U.S. Atlantic and Gulf coastal shelf: WI Shelf (Cooksey et al. 2012), SAB (Cooksey et al. 2010), MAB (Balthis et al. 2009), SBNMS (Balthis et al. 2011). 49

List of Tables

Table 1. Analytes measured in northwestern Gulf of Mexico sediment and fish tissue.....	7
Table 2. Thresholds used for classifying samples relative to various environmental indicators..	10
Table 3. ERM and ERL guideline values in sediments (Long et al. 1995).	12
Table 4. Risk-based EPA advisory guidelines for recreational fishers (USEPA 2000).	13
Table 5. Summary of depth and water-column characteristics for near-bottom (within 1.5 – 7.5 m of bottom) and near-surface (2 – 3 m) waters from 34 northwestern GOM coastal ocean sites. .	14
Table 6. Summary of sediment characteristics from 34 northwest GOM coastal shelf sites.	22
Table 7. Summary of chemical contaminant concentrations in northwest GOM sediments ('N.D.' = not detected; '-' = no corresponding ERL or ERM available).	26
Table 8. Finfish specimens retained for tissue chemical contaminant analysis.....	31
Table 9. Summary of contaminant concentrations (wet weight) measured in fish tissues. A total of 38 fish from 16 stations were analyzed. All measured contaminants are included. Concentrations are compared to human-health guidelines where available (from U.S. EPA 2000, also see Table 4 herein).....	33
Table 10. Mean, range, and selected distributional properties of key benthic variables. The benthic measures represent 68 0.04-m ² grabs collected at 34 sites (2 replicate grabs at each station) in the northwest GOM.	37
Table 11. Summary of major taxonomic groups of benthic infauna and corresponding numbers of identifiable taxa based on 68 0.04-m ² grab samples.....	39
Table 12. Fifty most abundant benthic taxa. Mean density (#/m ²), and percent frequency of occurrence are based on 68 0.04-m ² grabs. Classification: Native = native species; Crypto = cryptogenic species (of uncertain origin); Indeter = indeterminate taxon (not identified to a level that would allow determination of origin).	41
Table 13. Total structure coefficients on the first two canonical variables of a canonical discriminant model relating sediment % silt-clay, sediment % TOC, mean ERM-Q, and bottom-water DIN and DIP to site groups obtained from hierarchical cluster analysis of Bray-Curtis dissimilarities calculated from square-root transformed abundance (after removing rare species) from 34 sites in the northwest GOM.....	46

List of Appendices

Appendix A. Locations (latitude, longitude), depth, and sediment characteristics of sampling stations.	57
Appendix B. Near-bottom water characteristics by station.	58
Appendix C. Near-surface water characteristics by station.	59
Appendix D. Summary by station of mean ERM quotients and the number of contaminants that exceeded corresponding ERL or ERM values (from Long et al. 1995).	60
Appendix E. Summary by station of benthic macroinfaunal (>0.5mm) characteristics. Two replicate benthic grabs (0.04m ² each) were processed from each station. H' derived using base 2 logarithms. (*Values within lower 25 th percentile of all values of a specific benthic variable; **values within lower 10 th percentile.).....	61

List of Acronyms

ASE	Accelerated Solvent Extraction
CANDISC	Canonical Discriminant Analysis
CDF	Cumulative Distribution Function
Chl a	Chlorophyll a
CTD	Conductivity-Temperature-Depth
CWA	Clean Water Act
DDT	Dichlorodiphenyltrichloroethane
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphate
DO	Dissolved Oxygen
EC50	Effective Concentration that reduces light output by 50% relative to controls
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
ERL	Effects-Range Low
ERM	Effects-Range Median
ERM-Q	Effects-Range Median Quotient
GC-FID	Gas Chromatography with Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
GFAA	Gas Flame Atomic Absorption
GOM	Gulf of Mexico
GRTS	Generalized Random Tessellation Stratified
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
LME	Large Marine Ecosystem
MAB	Mid-Atlantic Bight
MDL	Method Detection Limit
NAS	National Aquatic Species database
NCA	National Coastal Assessment
NCCOS	National Centers for Coastal Ocean Science
NEMESIS	National Exotic Marine and Estuarine Species Information System
NMDS	Non-metric Multidimensional Scaling
NMS	National Marine Sanctuaries
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
PAH	Polycyclic Aromatic Hydrocarbon
PBDE	Polybrominated Diphenyl Ether
PCB	Polychlorinated Biphenyl
SAB	South Atlantic Bight
SBE	Sea-Bird Electronics
SBNMS	Stellwagen Bank National Marine Sanctuary
SIMPROF	Analysis of Similarity Profiles
SQG	Sediment Quality Guideline
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids

UPGMA	Unweighted Pair Group Method using Arithmetic mean
USGS	U.S. Geological Survey
WI	West Indian

Executive Summary

In August 2011, the NOAA National Ocean Service (NOS) conducted an assessment of the status of ecological condition of soft-bottom habitat and overlying waters of the continental shelf in the northwestern Gulf of Mexico (GOM). The original sampling design included 50 randomly selected sites from the Mississippi River delta to the U.S./Mexican border, representing a total area of 111,162 km²; however, vessel failures and inclement weather precluded sampling at 16 sites in the western-most part of the study region. Sampling was completed at the remaining 34 sites in offshore waters between the Mississippi River delta and Freeport, Texas, representing an estimated 75,591 km². Field sampling followed standard methods and indicators applied in prior NOAA coastal studies and EPA's Environmental Monitoring and Assessment Program (EMAP) and National Coastal Assessment (NCA). A key feature adopted from these studies was the incorporation of a random probabilistic sampling design. Such a design provides a basis for making unbiased statistical estimates of the spatial extent of ecological condition relative to various measured indicators and corresponding thresholds of concern. Indicators included multiple measures of water quality, sediment quality, and biological condition (benthic fauna, fish tissue contaminant levels).

Water depths ranged from 13 – 83 m throughout the study area. About 9 % of the area had sediments composed of sands (< 20 % silt+clay), 47 % of the area was composed of intermediate muddy sands (20 – 80 % silt+clay), and 44 % of the sampled area consisted of mud (> 80 % silt+clay). About 50 % of the area (represented by 17 sites) had sediment total organic carbon (TOC) concentrations < 5 mg/g and all of the sites sampled had levels of TOC < 20 mg/g, well below the range associated with potentially harmful effects to benthic fauna (> 50 mg/g).

Surface salinities ranged from 23.4 – 36.5 psu, with salinity generally increasing with distance west of the Mississippi River delta. Bottom salinities varied between 31.1 and 36.5 psu, with lowest values occurring at shallow, inner-shelf stations. Surface-water temperatures varied between 29.8 and 31.5 °C, while near-bottom waters ranged in temperature from 19.4 – 31 °C. An index of density stratification ($\Delta\sigma_t$) indicated that portions of coastal shelf waters in the northwestern GOM at the time of this sampling were strongly stratified. Values of $\Delta\sigma_t$ at 19 of the 34 sites sampled in this study (56 % of the study area) ranged from 2.2 to 12.4, which is within the range considered to be indicative of strong vertical stratification ($\Delta\sigma_t > 2$). Stratification was strongest close to the Mississippi River delta, and decreased with distance west of the delta.

Levels of dissolved oxygen (DO) ranged from 5.4 – 7.7 mg/L in surface waters, but were highly variable in bottom waters (0 – 6.8 mg/L). Low levels of DO (< 2 mg/L), potentially harmful to benthic fauna and fish, were observed at five stations, representing approximately 15 % of the study area. Some of these low bottom-DO stations were located in a region corresponding roughly to the same area documented as having a high incidence of bottom-water hypoxia in mid-summer along the Louisiana coastal shelf.

Total suspended solids (TSS) in surface waters ranged from 3.4 – 29.5 mg/L, with higher values observed in bottom waters (2.4 – 139.2 mg/L). Most sites (90 % of the area sampled) had concentrations of bottom-water TSS \leq 11.4 mg/L.

Dissolved inorganic nitrogen (DIN: nitrogen as nitrate + nitrite + ammonium) in surface waters ranged from 0.018 mg/L to 0.044 mg/L and averaged 0.026 mg/L. Ninety percent of the study area surface waters had DIN concentrations \leq 0.037 mg/L. Bottom-water concentrations of DIN tended to be higher than surface concentrations. For example, about 50% of bottom waters had DIN $>$ 0.029 mg/L and the average concentration was 0.069 mg/L (range of 0.018 – 0.367 mg/L). The highest bottom-DIN concentrations occurred at the same stations having low levels of bottom DO.

Concentrations of dissolved inorganic phosphorus (DIP) in surface waters ranged between 0.002 mg/L and 0.011 mg/L, averaging 0.004 mg/L. Ninety percent of the study area surface waters had DIP concentrations \leq 0.008 mg/L. Bottom-water concentrations of DIP were somewhat higher than those measured in surface waters, with a range of 0.003 – 0.092 mg/L and mean of 0.01 mg/L.

DIN:DIP ratios in surface waters ranged from 2.79 to 10.69 (mean of 7.28), which are strongly indicative of nitrogen limitation (DIN:DIP $<$ 16).

Surface-water concentrations of chlorophyll *a*, an indicator of phytoplankton biomass and abundance, ranged from $<$ 0.68 μ g/L (the minimum method limit of detection) to 9.36 μ g/L and averaged 1.51 μ g/L. Bottom-water concentrations of chlorophyll *a* were similar to concentrations in surface waters, ranging between $<$ 0.68 μ g/L and 15.07 μ g/L and averaging 2.42 μ g/L.

Bottom sediments appeared to be relatively uncontaminated. No contaminants were found in excess of their corresponding Effects-Range Median (ERM) sediment quality guideline values. The entire survey region was rated in good condition (no chemicals above corresponding ERM values and $<$ 5 chemicals above corresponding Effects-Range Low (ERL) values). Arsenic was the only chemical that exceeded the corresponding ERL guidelines. The ERL exceedances for arsenic occurred at seven sites, representing an estimated 20.6 % of the survey area. The concentration of arsenic at all sites was within the range typical of uncontaminated near-shore marine sediments (5 – 15 μ g/g dry weight total arsenic) and reflects its natural presence at low to moderate concentrations in crustal rocks of the region.

Concentrations of a suite of metals and organic compounds (PAHs, PBDEs, PCBs, and pesticides) were measured in edible tissues (fillets) of 38 fish specimens (representing three distinct species) collected at 16 of the 34 stations and compared to risk-based EPA advisory guidelines for recreational fishers. Only one station where fish were collected and retained for analysis had chemical contaminants in tissues above the corresponding upper human-health endpoint. At this site, near the entrance to Galveston Bay, a silver seatrout (*Cynoscion nothus*) was collected having total PCB concentration of 61.2 ng/g, in excess of the upper, non-cancer human-health endpoint of 47 ng/g. The lower, non-cancer endpoint for methylmercury (measured as mercury and assumed to be all methylmercury) also was exceeded in the specimen listed above, and in specimens of Atlantic croaker (*M. undulatus*) and rock sea bass (*C. philadelphica*) collected at six other sites.

Benthic taxonomic richness was highly variable in shelf assemblages, ranging from 0 – 56 per 0.04-m² grab and averaging 16 taxa/grab. Diversity (Shannon H' (log₂)) averaged 3.0 overall, varying between 0 and 5.2 throughout the study area, and tended to increase with distance west away from the Mississippi River delta. A total of 310 taxa were identified in the 68 grabs collected throughout the study area, of which 189 were identified to species level. Polychaetes were the dominant taxa, both by percent of taxa (47.4 %) and percent abundance (60.2 %). Crustaceans and molluscs (bivalves + gastropods) were the second and third dominant groups in terms of numbers of taxa (22.6 % crustaceans, 24.2 % molluscs), whereas bivalve molluscs and 'other' taxa (i.e., not polychaetes, crustaceans, molluscs, or echinoderms) were the second and third most abundant taxa (16.8 % and 12.2 %, respectively). Densities ranged from 0 – 4,563 ind/m² and averaged 1,215 ind/m².

The 10 dominant (most abundant) taxa, in decreasing order of abundance, included the spionid (Family Spionidae) polychaete *Paraprionospio pinnata*; members of Phylum Nemertea ('ribbon worms'); Phylum Sipuncula ('peanut worms'); the capitellid polychaete genus *Mediomastus*; the polychaete Family Maldanidae; the spionid polychaete *Meredithia uebelackerae* (= *Magelona uebelackerae*); unidentified bivalve molluscs (Class Bivalvia); the lumbrinerid polychaete *Scoletoma verrilli*; the capitellid polychaete *Notomastus daueri*; and unidentified cirratulid polychaetes (Family Cirratulidae).

None of the species collected as part of the present survey are considered to be non-indigenous in the region studied (northwest GOM coastal shelf). A number of specimens were only identified to higher taxonomic level (e.g., Order Actiniaria; Family Mysidae). Hence, it was not possible to determine definitively whether additional known invasives from these groups were present.

Low values of benthic infaunal richness and diversity were associated with poor water quality at two sites, both of which had very low DO (≤ 0.1 mg/L) accompanied by high DIN. Both stations were located in an area known for experiencing annual hypoxia from spring to early fall. However, this study found no evidence of biological impacts linked to poor sediment quality. The highest TOC concentration was 12.9 mg/g, well below published bioeffect thresholds. Also, no ERM exceedances were observed. These results suggest that sediments in the surveyed area of the northwest GOM seem to be in good condition with respect to contaminants and TOC. Indications of stress in benthic infaunal assemblages appear to be related primarily to the well-documented hypoxic "Dead Zone" on the inner Louisiana continental shelf.

1.0 Introduction

The National Oceanic and Atmospheric Administration (NOAA) and the U.S. Environmental Protection Agency (EPA) each perform a broad range of research and monitoring activities designed to assess the status of coastal ecosystems and the potential effects of natural and human impacts. Authority to conduct such work is given by several legislative mandates including the Clean Water Act (CWA) of 1977 (33 U.S.C. §§ 1251 et seq.), National Coastal Monitoring Act of 1992 (Title V of the Marine Protection, Research, and Sanctuaries Act, 33 U.S.C. §§ 2801-2805), and the National Marine Sanctuary Act of 2000. To the extent possible, the two agencies have sought to coordinate related activities and share results in efforts to fulfill common research and management goals. Accordingly, in August 2011, NOAA initiated a study in the northwestern Gulf of Mexico (GOM) as part of a series of collaborative efforts to assess the status of ecological condition and stressor impacts throughout coastal-ocean waters of the U.S.

The protocols and design of these studies are similar to those used in EPA's Environmental Monitoring and Assessment Program (EMAP) and subsequent National Coastal Assessment (NCA), both of which have focused mainly on estuarine and inland waters. The offshore series extends these prior efforts onto the continental shelf, from navigable depths along the coastline seaward to the shelf break (~100-m depth contour). Where applicable, sampling has included NOAA's National Marine Sanctuaries (NMS) to provide a basis for comparing conditions in these protected areas to surrounding non-sanctuary waters. To date such surveys have been conducted throughout the western U.S. continental shelf, from the Straits of Juan de Fuca, WA to the U.S./Mexican border (Nelson et al. 2008); shelf waters of the South Atlantic Bight (SAB) from Cape Hatteras, NC to West Palm Beach, FL (Cooksey et al. 2010); shelf waters of the mid-Atlantic Bight (MAB) from Cape Hatteras to Cape Cod, MA (Balthis et al. 2009); Stellwagen Bank National Marine Sanctuary (SBNMS) in the Gulf of Maine (Balthis et al. 2011); the West Indian (WI) continental shelf off southern Florida, from West Palm Beach in the Atlantic Ocean to Anclote Key in the GOM (Cooksey et al. 2012); and the continental shelf along northeastern GOM (see Cooksey et al. 2010 for cruise report, Cooksey et al. In review).

The present study expands these prior efforts to offshore waters of the northwestern GOM (Figure 1). While the original sampling design included 50 randomly selected sites from the Mississippi River delta to the U.S./Mexican border, representing a total area of 111,162 km², vessel failures and inclement weather precluded sampling at 16 sites in the western-most part of the study region. Sampling was completed at the remaining 34 sites in offshore waters between the delta and Freeport, Texas, representing an estimated 75,591 km².

The overall purpose of the study was to assess the current status of ecological condition and stressor impacts throughout these waters and to provide this information as a framework for evaluating future changes due to natural or human-induced disturbances. To address this objective, the study incorporated standard methods and indicators applied in previous coastal EMAP/NCA projects (U.S. EPA 2001, 2004, 2008), including multiple measures of water quality, sediment quality, and biological condition (benthic community health and fish tissue contamination). Synoptic sampling of the various indicators provided an integrative weight-of-evidence approach to assessing condition at each station and a basis for examining potential associations between the presence of stressors and biological responses. Another key feature

was the incorporation of a probabilistic sampling design with stations positioned randomly throughout the study area. The probabilistic sampling design provided a basis for making unbiased statistical estimates of the spatial extent of condition relative to the various measured indicators and corresponding thresholds of concern. Results of this and the previous two GOM studies from this same offshore series (Cooksey et al. 2012, Cooksey et al. In review) provide broad geographic coverage for a majority of the U.S. continental shelf along the GOM.

The GOM constitutes a “Large Marine Ecosystem” (LME) that includes freshwater continental drainage from five countries (Yáñez-Arancibia and Day 2004). As one of 64 LMEs (Sherman and Duda 1999, Sherman and Hempel 2008) generating the overwhelming bulk of the world’s fisheries catch, the GOM is one of the most economically important water bodies within the Mexican and US Exclusive Economic Zones (Vidal and Pauly 2004). The northwest GOM is characterized physiographically by a broad continental shelf extending out from between 50 and 200 km from the coastline. A dominant feature of the northern GOM is the Balize, or Birdfoot, Delta, the youngest and only deepwater delta lobe of the Mississippi River (Trahan, 2000). The Mississippi River system is the largest in North America, draining more than 40% of the contiguous United States and parts of Canada (Wiseman et al. 1997). Freshwater discharge from the plumes of the Mississippi and Atchafalaya Rivers rapidly forms the Louisiana Coastal Current, a highly stratified current that flows, on average, westward along the Louisiana coast and southward along the Texas coast (Rabalais et al. 1996, 2001a). Generally, longshore sediment transport (shore-parallel sand movement driven by longshore currents) is westward west of the Mississippi River, and eastward east of the Mississippi River. The longshore currents driving sediment transport are driven by energy from waves and tides, and to a lesser extent wind (Ellis and Dean 2012).

The Louisiana coastal zone has experienced multiple ecological impacts due to human activities including leveeing of the Mississippi River, large-scale wetland reclamation, water quality deterioration, pollution, and widespread disruption of hydrology. Oil and gas development has contributed significantly to these impacts (Ko and Day 2004). A number of major oil spills have occurred, including the April 20, 2010 *Deepwater Horizon* (DWH) incident, which claimed the lives of eleven drilling-rig personnel and released an estimated 4.9 million barrels of oil into the GOM (NOAA and USGS 2010, Camilli 2010, McNutt et al. 2011).

The inner- to mid-continental shelf, from the Mississippi River delta westward to the upper Texas coast, is also the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean coastal zone (Rabalais et al. 2001a). Spatial and temporal variability in the distribution of hypoxia is at least partially related to the amplitude and phasing of the Mississippi River freshwater discharge and nutrient fluxes (Wiseman et al. 1997, Rabalais et al. 2001a). There is scientific consensus that the effects of climate change on the Gulf region will be pervasive and variable, but one of the most significant impacts of the upward trend in global temperature is sea-level rise (Ellis and Dean 2012). Within the context of the natural and human-induced or -mediated processes described above, the following report attempts to describe the status of ecological condition in the northwestern GOM with respect to the parameters measured in this study. The results of this assessment will contribute to our understanding of the status of the region’s ecological resources and their controlling factors, including impacts of potential

ecosystem stressors, and provide a basis for determining how environmental conditions may be changing in the future.

2.0 Methods

2.1 Sampling Design and Field Collections

The sampling frame for this study was based on a generalized random-tessellation stratified (GRTS) design. The GRTS design represents a unified strategy for selecting spatially balanced probability samples of natural resources, in which sampling sites are more or less evenly dispersed over the extent of the resource (Stevens & Olsen 2004). One feature of the GRTS approach is that it orders the sample points such that any set of consecutively numbered points is in itself a spatially well-balanced sample. This property is useful in adjusting the sample for the frame imperfections common in environmental sampling. However, in an oceanographic setting on a major research vessel (such as the NOAA Ship Nancy Foster), where ship time is limited, the logistics of running multiple transits over hundreds of miles between consecutively-numbered sites positioned randomly throughout the study area is not feasible. Hence, sampling in the present study began at the eastern-most station and proceeded to the nearest stations ordered geographically. This allowed for the most efficient use of allotted ship time. However, because sampling time was cut short due to ship failures and inclement weather, the subset of sites actually sampled (34 of the original 50), though dispersed more or less evenly and randomly over the successfully sampled area, was no longer representative of the entire original study region. For this reason, the boundary of the study region was adjusted by excluding the western-most portion where sampling could not be completed. Hence, results and interpretations presented in this report are limited to the new adjusted area ($\sim 75,591 \text{ km}^2$) represented by the 34 successfully sampled sites (Figure 1, Appendix A).

Vertical water-column profiles of conductivity/salinity, temperature, depth, dissolved oxygen, pH, and turbidity (in Formazin Turbidity Units, FTU) were conducted at each station using a Sea-Bird Electronics (SBE) Conductivity-Temperature-Depth (CTD) profiler, equipped with supplemental dissolved oxygen, pH, and turbidity sensors. The CTD was an SBE 9Plus with an 11Plus deck unit that provided real-time data recording of the vertical profile. The CTD was incorporated into a frame that included a rosette of 12 Niskin bottles used to collect water samples at discrete depths (near-surface, near-bottom). Water samples were analyzed for nutrients, total suspended solids (TSS), turbidity (in Nephelometric Turbidity Units, NTU), and chlorophyll *a*.

The CTD was lowered into the water until completely submerged and held just beneath the surface for three minutes while the water pump was allowed to purge any air from the system. The unit was then lowered to within one meter of the bottom at a rate of approximately 1 m/s. Four Niskin bottles were fired at approximately 1 m below the surface and another four at near-bottom (approximately 1 m off the bottom).

Sediment samples were collected using a 0.04-m² Young-modified Van Veen grab sampler. Two replicate grab samples were retained for analysis of benthic infaunal composition, sieved onboard through a 0.5-mm screen, and preserved in 10% buffered formalin with rose bengal

stain. The upper 2 – 3 cm of sediment from additional grabs (typically 1 or 2) was combined to yield a sediment composite, which was then homogenized and sub-sampled for analysis of metals, organic contaminants (pesticides, PCBs, PAHs, PBDEs), grain size (% silt-clay), and total organic carbon (TOC). Sediment samples (other than infauna) were kept frozen onboard the ship and later transferred to the respective analytical laboratories for analysis.

Hook-and-line fishing was attempted at all 34 stations. Targeted species included members of the orders Pleuronectiformes (flatfishes), families Scianidae (croakers, drums) and Sparidae (porgies, scup), and genus *Centropristis* (sea basses). Specimens from three species representing two (Scianidae, *Centropristis*) of the four groups listed above were collected from 16 of the 34 stations. Edible tissue (skin-on fillets) of 38 specimens was analyzed for metals, pesticides, PAHs, PCBs, and PBDEs.

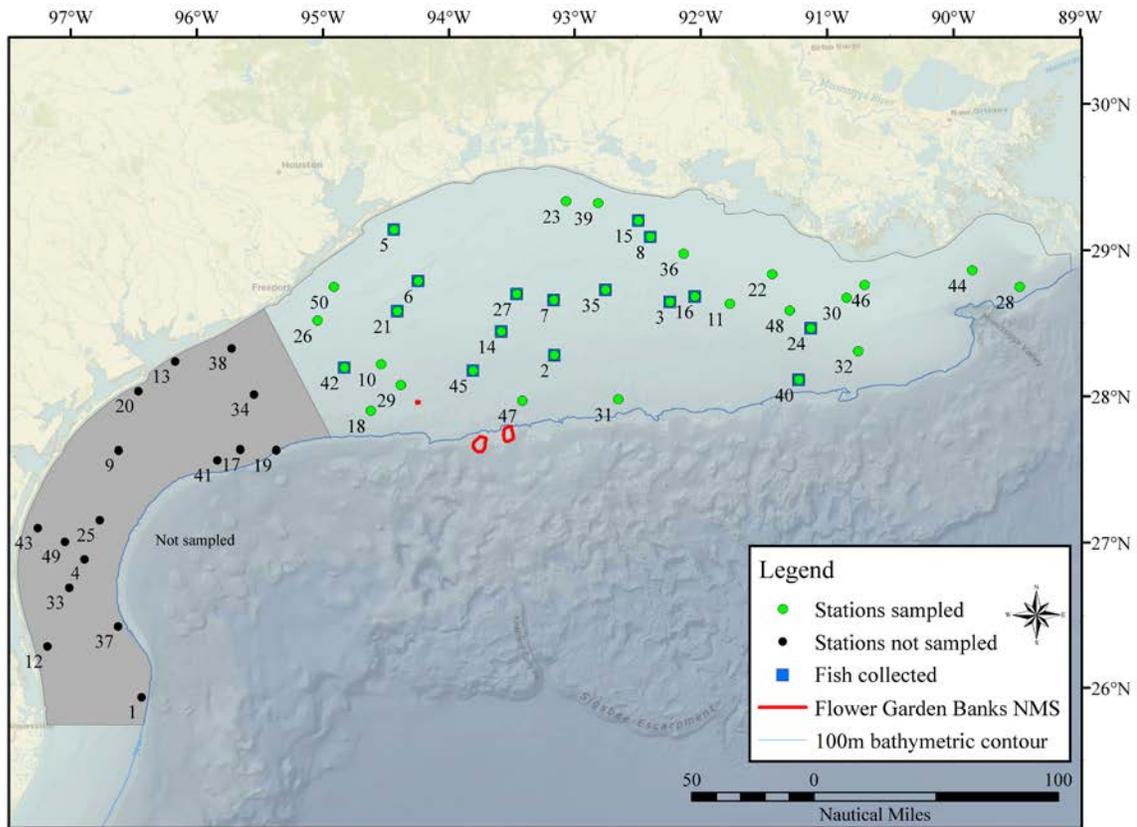


Figure 1. Map of targeted study area in the Gulf of Mexico. Due to ship problems, stations in the shaded area (in grey) were not sampled.

2.2 Water Quality Analysis

Profiles of temperature, conductivity/salinity, dissolved oxygen (DO), depth, pH, and turbidity were recorded directly from the CTD unit during its descent and ascent through the water column. Only surface and bottom values for these various indicators are presented in this report. Data for all depths are included in the study database and are available on request to the authors. An index of density stratification ($\Delta\sigma_t$) was calculated as the difference between the computed bottom and surface density (σ_t) values, where σ_t is the density of a parcel of water with a given salinity and temperature relative to atmospheric pressure (Fofonoff and Millard 1983). Samples for analysis of dissolved inorganic nutrients, including nitrate (NO_3^-), nitrite (NO_2^-), orthophosphate (HPO_4^{2-}), silicate (HSiO_3^-), and ammonium (NH_4^+); chlorophyll *a*; turbidity (NTU); and total suspended solids (TSS) were collected at discrete water depths (near surface and near-bottom) and analyzed following standard methods (U.S. EPA 1997; U.S. EPA 1995).

2.3 Sediment TOC and Grain Size Analysis

Sediment characterization included analyses of total organic carbon (TOC) and grain size distribution. Samples for grain size analysis were prepared by sieve separation followed by timed pipette extractions as described in Plumb (1981). TOC analysis followed USEPA Method 9060. A minimum of 5g (wet weight) of sediment was initially dried for 48 h. Weighed subsamples were ground to fine consistency and acidified to remove sources of inorganic carbon (e.g., shell fragments). The acidified samples were ignited at 950°C and the carbon dioxide evolved was measured with an infrared gas analyzer.

2.4 Chemical Contaminant Analysis

2.4.1 Laboratory Sample Preparation

Sediment samples were kept frozen at approximately - 40 °C prior to analysis. Samples were thawed in closed containers in a 4 °C cooler for approximately 24 hours. Prior to extraction, samples were homogenized thoroughly by hand. Fish tissue samples were frozen upon receipt in the laboratory and stored at - 40 °C until analysis. Fish were removed from the freezer and stored overnight at 4 °C and allowed to thaw partially. The fish were filleted (skin-on) and homogenized using a ProScientific homogenizer in 500 mL Teflon containers. The homogenized tissue sample was split into organic (pre-cleaned glass container) and inorganic (pre-cleaned polypropylene container) aliquots and stored at - 40 °C until extraction or digestion.

A percent dry-weight determination was made gravimetrically on an aliquot of the wet sediment and tissues. A list of analytes is provided in Table 1.

2.4.2 Inorganic Sample Digestion and Analysis

Dried sediment was ground with a mortar and pestle and transferred to a 20 mL plastic screw-top container. A 0.25-g sub-sample of the ground material was transferred to a Teflon-lined digestion vessel and digested in 5 mL of concentrated nitric acid using microwave digestion. The sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water

and stored in a 50-mL polypropylene centrifuge tube until instrumental analysis of Li, Be, Al, Fe, Mg, Ni, Cu, Zn, Cd, and Ag. A second 0.25-g sub-sample was transferred to a Teflon-lined digestion vessel and digested in 5 mL of concentrated nitric acid and 1 mL of concentrated hydrofluoric acid in a microwave digestion unit. The sample was then evaporated on a hot plate at 225 °C to near dryness and 1 mL of nitric acid was added. The sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water and stored in a 50-mL polypropylene centrifuge tube until instrumental analysis for V, Cr, Co, As, Sn, Sb, Ba, Tl, Pb, and U. Selenium was analyzed by hot plate digestion using a third 0.25-g sub-sample and 5 mL of concentrated nitric acid. Each sample was brought to a fixed volume of 50 mL in a volumetric flask with deionized water and stored in a 50 mL polypropylene centrifuge tube until instrumental analysis. Additionally, 2-3 g wet tissue were microwave-digested in Teflon-lined digestion vessels using 10 mL of concentrated nitric acid along with 2 mL of hydrogen peroxide. Digested samples were brought to a fixed volume with deionized water in graduated polypropylene centrifuge tubes and stored until analysis. Lastly, a separate inorganic aliquot was used for mercury analysis for both sediments and tissues. Approximately 0.5 g of wet sediment or tissue was analyzed on a Milestone DMA-80 Direct Mercury Analyzer.

All remaining elemental analyses were performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) except for silver, which was determined using Graphite Furnace Atomic Absorption (GFAA) spectroscopy. Data quality was controlled by using a series of blanks, control solutions (Trace Metals in Drinking Water), and standard reference materials including NRC MESS-3 (Marine Sediments) and NIST 1566b (freeze-dried mussel tissue).

2.4.3 Organic Extraction and Analysis

An aliquot (10 g sediment or 5 g tissue wet weight) was extracted with anhydrous sodium sulfate using Accelerated Solvent Extraction (ASE) in either 1:1 methylene chloride:acetone (sediments) or 100% dichloromethane (tissues) (Schantz et al. 1997). Following extraction, samples were dried and cleaned using Gel Permeation Chromatography and Solid Phase Extraction to remove lipids and then solvent-exchanged into hexane for analysis. Samples were analyzed for PAHs, PBDEs, PCBs (by congener), and a suite of chlorinated pesticides using appropriate GC/MS technology. Data quality was assured by using a series of spiked blanks, reagent blanks, and appropriate standard reference materials including NIST 1944 (sediments) and NIST 1974b (mussel tissue). Total Petroleum Hydrocarbons (TPH or “Total Extractable Matter”) were measured in sediments by Gas Chromatography with a Flame Ionization Detector (GC-FID) using EPA 3550 as the extraction method and 8015B as the analysis method.

Table 1. Analytes measured in northwestern Gulf of Mexico sediment and fish tissue.

PCBs	PAHs
PCB 1 (2-Chlorobiphenyl)	1-Methylnaphthalene
PCB 2 (3-Chlorobiphenyl)	1-Methylphenanthrene
PCB 3 (4-Chlorobiphenyl)	1,6,7-Trimethylnaphthalene
PCB 8/5 Mixture	2-Methylnaphthalene
PCB 9 (2,5-Dichlorobiphenyl)	2,6-Dimethylnaphthalene
PCB 12 (3,4-Dichlorobiphenyl)	Acenaphthene
PCB 15 (4,4'-Dichlorobiphenyl)	Acenaphthylene
PCB 18 (2,2',5'-Trichlorobiphenyl)	Anthracene
PCB 20 (2,3,3'-Trichlorobiphenyl)	Benz[a]anthracene
PCB 26 (2,3',5'-Trichlorobiphenyl)	Benzo[a]pyrene
PCB 28/31 Mixture	Benzo[b]fluoranthene
PCB 29 (2,4,5-Trichlorobiphenyl)	Benzo[e]pyrene
PCB 37 (3,4,4'-Trichlorobiphenyl)	Benzo[g,h,i]perylene
PCB 44 (2,2',3,5'-Tetrachlorobiphenyl)	Benzo[j+k]fluoranthene
PCB 45 (2,2',3,6-Tetrachlorobiphenyl)	Biphenyl
PCB 47/48 Mixture	Chrysene+Triphenylene
PCB 49 (2,2',4,5'-Tetrachlorobiphenyl)	Dibenz[a,h]anthracene
PCB 50 (2,2',4,6-Tetrachlorobiphenyl)	Dibenzothiophene
PCB 52 (2,2',5,5'-Tetrachlorobiphenyl)	Fluoranthene
PCB 56/60 Mixture	Fluorene
PCB 61 (2,3,4,5-Tetrachlorobiphenyl)	Indeno[1,2,3-c,d]pyrene
PCB 63 (2,3,4',5-Tetrachlorobiphenyl)	Naphthalene
PCB 66 (2,3',4,4'-Tetrachlorobiphenyl)	Perylene
PCB 69 (2,3',4,6-Tetrachlorobiphenyl)	Phenanthrene
PCB 70 (2,3',4',5-Tetrachlorobiphenyl)	Pyrene
PCB 74 (2,4,4',5-Tetrachlorobiphenyl)	Pesticides
PCB 76 (2,3',4',5'-Tetrachlorobiphenyl)	2,4'-DDD (o,p'-DDD)
PCB 77 (3,3',4,4'-Tetrachlorobiphenyl)	2,4'-DDE (o,p'-DDE)
PCB 81 (3,4,4',5-Tetrachlorobiphenyl)	2,4'-DDT (o,p'-DDT)
PCB 82 (2,2',3,3',4-Pentachlorobiphenyl)	4,4'-DDD (p,p'-DDD)
PCB 84 (2,2',3,3',6-Pentachlorobiphenyl)	4,4'-DDE (p,p'-DDE)
PCB 87/115 Mixture	4,4'-DDT (p,p'-DDT)
PCB 88 (2,2',3,4,6-Pentachlorobiphenyl)	Aldrin
PCB 89/90 Mixture	alpha-Chlordane
PCB 92 (2,2',3,5,5'-Pentachlorobiphenyl)	alpha-Hexachlorocyclohexane (alpha-BHC)
PCB 95 (2,2',3,5',6-Pentachlorobiphenyl)	beta-Hexachlorocyclohexane (beta-BHC)
PCB 99 (2,2',4,4',5-Pentachlorobiphenyl)	Chlorpyrifos
PCB 101 (2,2',4,5,5'-Pentachlorobiphenyl)	cis-Nonachlor
PCB 103 (2,2',4,5',6-Pentachlorobiphenyl)	Dieldrin
PCB 104 (2,2',4,6,6'-Pentachlorobiphenyl)	Endosulfan I
PCB 105 (2,3,3',4,4'-Pentachlorobiphenyl)	Endosulfan II (Beta-Endosulfan)
PCB 106/118 Mixture	Endosulfan sulfate
PCB 108/107/123 Mixture	Endrin
PCB 110 (2,3,3',4',6-Pentachlorobiphenyl)	gamma-Chlordane
PCB 114 (2,3,4,4',5-Pentachlorobiphenyl)	Heptachlor
PCB 119 (2,3',4,4',6-Pentachlorobiphenyl)	Heptachlor epoxide
PCB 126 (3,3',4,4',5-Pentachlorobiphenyl)	Hexachlorobenzene (HCB)
PCB 128 (2,2',3,3',4,4'-Hexachlorobiphenyl)	Lindane
PCB 130 (2,2',3,3',4,5'-Hexachlorobiphenyl)	Mirex
PCB 132/153/168 Mixture	Oxychlordane
PCB 138/158 Mixture	trans-Nonachlor

Table 1. (continued)

PCBs (continued)	PBDEs
PCB 141 (2,2',3,4,5,5'-Hexachlorobiphenyl)	PBDE 17 (2,2',4-tribromodiphenyl ether)
PCB 146 (2,2',3,4',5,5'-Hexachlorobiphenyl)	PBDE 28 (2,4,4'-tribromodiphenyl ether)
PCB 149 (2,2',3,4',5',6-Hexachlorobiphenyl)	PBDE 47 (2,2',4,4'-tetrabromodiphenyl ether)
PCB 151 (2,2',3,5,5',6-Hexachlorobiphenyl)	PBDE 66 (2,3',4,4'-tetrabromodiphenyl ether)
PCB 154 (2,2',4,4',5,6'-Hexachlorobiphenyl)	PBDE 71 (2,3',4',6-tetrabromodiphenyl ether)
PCB 156 (2,3,3',4,4',5-Hexachlorobiphenyl)	PBDE 85 (2,2',3,4,4'-pentabromodiphenyl ether)
PCB 157 (2,3,3',4,4',5'-Hexachlorobiphenyl)	PBDE 99 (2,2',4,4',5-pentabromodiphenyl ether)
PCB 159 (2,3,3',4,5,5'-Hexachlorobiphenyl)	PBDE 100 (2,2',4,4',6-pentabromodiphenyl ether)
PCB 164/163 Mixture	PBDE 138 (2,2',3,4,4',5'-hexabromodiphenyl ether)
PCB 165 (2,3,3',5,5',6-Hexachlorobiphenyl)	PBDE 153 (2,2',4,4',5,5'-hexabromodiphenyl ether)
PCB 167 (2,3',4,4',5,5'-Hexachlorobiphenyl)	PBDE 154 (2,2',4,4',5,6'-hexabromodiphenyl ether)
PCB 169 (3,3',4,4',5,5'-Hexachlorobiphenyl)	PBDE 183 (2,2',3,4,4',5',6-heptabromodiphenyl ether)
PCB 170/190 Mixture	PBDE 190 (2,3,3',4,4',5,6-heptabromodiphenyl ether)
PCB 172 (2,2',3,3',4,5,5'-Heptachlorobiphenyl)	Metals
PCB 174 (2,2',3,3',4,5,6'-Heptachlorobiphenyl)	Aluminum
PCB 177 (2,2',3,3',4,5',6'-Heptachlorobiphenyl)	Antimony
PCB 180/193 Mixture	Arsenic
PCB 183 (2,2',3,4,4',5',6-Heptachlorobiphenyl)	Barium
PCB 184 (2,2',3,4,4',6,6'-Heptachlorobiphenyl)	Beryllium
PCB 187 (2,2',3,4',5,5',6-Heptachlorobiphenyl)	Cadmium
PCB 188 (2,2',3,4',5,6,6'-Heptachlorobiphenyl)	Chromium
PCB 189 (2,3,3',4,4',5,5'-Heptachlorobiphenyl)	Cobalt
PCB 194 (2,2',3,3',4,4',5,5'-Octachlorobiphenyl)	Copper
PCB 195 (2,2',3,3',4,4',5,6-Octachlorobiphenyl)	Iron
PCB 198 (2,2',3,3',4,5,5',6-Octachlorobiphenyl)	Lead
PCB 200 (2,2',3,3',4,5',6,6'-Octachlorobiphenyl)	Lithium
PCB 201 (2,2',3,3',4',5,5',6-Octachlorobiphenyl)	Manganese
PCB 202 (2,2',3,3',5,5',6,6'-Octachlorobiphenyl)	Mercury
PCB 203/196 Mixture	Nickel
PCB 206 (2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl)	Selenium
PCB 207 (2,2',3,3',4,4',5,6,6'-Nonachlorobiphenyl)	Silver
PCB 208 (2,2',3,3',4,5,5',6,6'-Nonachlorobiphenyl)	Thallium
PCB 209 (2,2',3,3',4,4',5,5',6,6'-Decachlorobiphenyl)	Tin
	Uranium
	Vanadium
	Zinc

2.5 Benthic Community Analysis

Identification and enumeration of benthic fauna were performed by Barry A. Vittor & Associates, Inc., Mobile, Alabama. A minimum of 10% of samples were rechecked by other qualified individuals for accuracy of both sorting and species identification steps. Species lists from different labs were cross-checked and outside experts were consulted for difficult identifications. Judged accuracy rates were well above standard levels for sorting and taxonomy (quality control reworks all > 95 %).

Characteristics of benthic communities were assessed using standard measures of total faunal density (#/m²), individual species abundance, species richness (number of taxa), and diversity (Shannon H'; Shannon 1948, Hayek and Buzas 1997). H' was calculated using base-2 logarithms. Total faunal abundance was used to rank dominant taxa. Taxa were grouped according to higher taxonomic classifications to determine relative percentages (by abundance and number of taxa) of major groups of organisms (i.e., polychaetes, crustaceans, molluscs, echinoderms, other taxa). The full list of identified taxa also was examined to evaluate the incidence of non-indigenous species vs. native species, or those with indeterminate status relative to invasiveness. Spatial patterns in benthic faunal distributions were also examined using a combination of hierarchical cluster analysis and non-metric multidimensional scaling (Clarke & Warwick 2001).

2.6 Sediment Toxicity Testing

Microtox[®] assays were conducted using standardized solid-phase test protocols (Microbics Corporation 1992) and a Microtox Model 500 analyzer (Strategic Diagnostics Inc., Newark, DE). In this assay, sediment was homogenized and a 7.0 – 7.1 g sediment sample was used to make a series of sediment dilutions with 3.5 % NaCl diluent, which were incubated for 10 minutes at 15 °C. Luminescent bacteria (*Vibrio fischeri*) were then added to the test concentrations. The liquid phase was filtered from the sediment phase and bacterial post-exposure light output was measured using Microtox[®] Omni Software. An EC₅₀ value (the sediment concentration that reduces light output by 50 % relative to the controls) was calculated for each sample. Triplicate samples were analyzed simultaneously. Sediment samples were classified as either toxic or nontoxic using criteria developed by Ringwood et al. (1997; Table 2 herein).

2.7 Data Analysis

The probabilistic sampling design used in this study allows calculation of estimates of the percent area of the resource that corresponds to specified values of a given parameter under consideration. Estimated cumulative distribution functions (CDFs), point estimates, and 95% confidence intervals were developed for water quality, sediment, and biological parameters measured in this study using formulas described in the EMAP statistical methods manual (Diaz-Ramos 1996). Calculation of CDFs was facilitated using algorithms (*spsurvey* package; Kincaid 2008) developed for R, a language and environment for statistical computing and graphics (R Development Core Team 2008).

Measured parameters were compared to established thresholds of concern, where available (Table 2 - Table 4), and the corresponding percentiles of the estimated CDFs were reported. Where no such recommended levels of concern exist (e.g., benthic metrics), common distributional properties are reported (e.g., lower or upper percentiles).

Table 2. Thresholds used for classifying samples relative to various environmental indicators.

Indicator	Threshold	Reference
<u>Water Quality</u>		
Salinity (psu)	< 5 = Oligohaline 5 – 18 = Mesohaline >18 – 30 = Polyhaline > 30 = Euhaline	Carriker 1967
$\Delta \sigma_t$	> 2 = strong vertical stratification	Nelson et al. 2008
DO (mg/L)	< 2 = Low (Poor) 2 – 5 = Moderate (Fair) > 5 = High (Good)	USEPA 2008; Diaz and Rosenberg 1995
DIN/DIP	> 16 = phosphorus limited < 16 = nitrogen limited	Geider and La Roche 2002
<u>Sediment Quality</u>		
Silt-Clay Content (%)	> 80 = Mud 20 – 80 = Muddy Sand < 20 = Sand	USEPA 2008
TOC Content (mg/g)	> 50 = High (Poor) 20 – 50 = Moderate (Fair) < 20 = Low (Good)	USEPA 2008
	> 36 = High (Poor)	Hyland et al. 2005
Overall chemical contamination of sediments	≥ 1 ERM value exceeded = High (Poor); ≥ 5 ERL values exceeded = Moderate (Fair); No ERMs exceeded and < 5 ERLs exceeded = Low (Good)	USEPA 2008
Individual chemical contaminant concentrations in sediments	> ERM = High probability of bioeffects < ERL = Low probability of bioeffects	Long et al. 1995; Table 2 herein
Sediment toxicity using Microtox [®] assay	Silt-clay < 20 %: Toxic if EC50 < 0.5 % Silt-clay ≥ 20 %: Toxic if EC50 < 0.2 %	Ringwood et al. 1997

Table 2. (continued).

Indicator	Threshold	Reference
<u>Biological Condition</u>		
Reduced benthic taxonomic richness, diversity, or abundance	≤ lower 10 th percentile of all values for corresponding variable	Nelson et al. 2008
Chemical Contaminants in Fish Tissues	≥ 1 chemical exceeded Human Health upper limit = High (Poor) ≥ 1 chemical within Human Health risk range ^a = Moderate (Fair) All chemicals below Human Health lower risk limit = Low (Good)	USEPA 2008
Individual chemical contaminants in fish tissues	Non-cancer (chronic systemic effects) endpoints based on consumption of four 8-ounce meals per month (general adult population). Cancer risk endpoints (1 in 100,000 risk level) based on consumption of four 8-ounce meals per month (general adult population).	USEPA 2000; Table 3 herein

^a Range of concentrations of a given chemical contaminant considered safe at a consumption rate of four 8-oz fish meals/month.

Table 3. ERM and ERL guideline values in sediments (Long et al. 1995).

Chemical	ERL	ERM
Metals ($\mu\text{g/g}$)		
Arsenic	8.2	70
Cadmium	1.2	9.6
Chromium	81	370
Copper	34	270
Lead	46.7	218
Mercury	0.15	0.71
Nickel	20.9	51.6
Silver	1	3.7
Zinc	150	410
Organics (ng/g)		
Acenaphthene	16	500
Acenaphthylene	44	640
Anthracene	85.3	1,100
Fluorene	19	540
2-Methylnaphthalene	70	670
Naphthalene	160	2,100
Phenanthrene	240	1,500
Benzo[a]anthracene	261	1,600
Benzo[a]pyrene	430	1,600
Chrysene	384	2,800
Dibenz[a,h]Anthracene	63.4	260
Fluoranthene	600	5,100
Pyrene	665	2,600
Low molecular weight PAHs	552	3,160
High molecular weight PAHs	1,700	9,600
Total PAHs	4,020	44,800
4,4-DDE	2.2	27
Total DDT	1.58	46.1
Total PCBs	22.7	180

Table 4. Risk-based EPA advisory guidelines for recreational fishers (USEPA 2000).

	Non-cancer Health Endpoint ^a			Cancer Health Endpoint ^b		
Metals (µg/g)						
Arsenic (inorganic) ^c	>0.35	–	0.70	>0.0078	–	0.016
Cadmium	>0.35	–	0.70			
Mercury (methylmercury) ^d	>0.12	–	0.23			
Selenium	>5.90	–	12.00			
Organics (ng/g)						
Chlordane	>590	–	1,200	>34	–	67
Chlorpyrifos	>350	–	700			
DDT (total)	>59	–	120	>35	–	69
Dieldrin	>59	–	120	>0.73	–	1.5
Endosulfan	>7,000	–	14,000			
Heptachlor epoxide	>15	–	31	>1.3	–	2.6
Hexachlorobenzene	>940	–	1,900	>7.3	–	15.0
Lindane	>350	–	700	>9.0	–	18
Mirex	>230	–	470			
Toxaphene	>290	–	590	>11.0	–	21
PAHs (benzo[a]pyrene)				>1.6	–	3.2 ^e
PCB (total)	>23	–	47	>5.9	–	12.0

^a Range of concentrations for non-cancer health endpoints are based on the assumption that consumption over a lifetime of four 8-oz meals per month would not generate a chronic, systemic health risk.

^b Range of concentrations for cancer health endpoints are based on the assumption that consumption over a lifetime of four 8-oz meals per month would yield a lifetime cancer risk no greater than an acceptable risk of 1 in 100,000.

^c Inorganic arsenic, the form considered toxic, estimated as 2% of total arsenic.

^d Because most mercury in fish and shellfish tissue is present primarily as methylmercury and because of the relatively high cost of analyzing for methylmercury, the conservative assumption was made that all mercury is present as methylmercury (U.S. EPA, 2000).

^e A non-cancer concentration range for PAHs does not exist.

3.0 Results and Discussion

3.1 Depth and Water Quality

3.1.1 Depth

Bottom depths for the 34 stations sampled ranged from 13.0 m to 83.0 m (Table 5). As expected, the shallowest sites were located in near-coastal waters off of Texas and Louisiana, with depths generally increasing offshore towards the 100 m depth contour. The mean depth of all sites sampled was 33.1 m.

Table 5. Summary of depth and water-column characteristics for near-bottom (within 1.5 – 7.5 m of bottom) and near-surface (2 – 3 m) waters from 34 northwestern GOM coastal ocean sites.

	Near-bottom water					Near-surface water				
	Mean	Range	CDF 10 th pctl	CDF 50 th pctl	CDF 90 th pctl	Mean	Range	CDF 10 th pctl	CDF 50 th pctl	CDF 90 th pctl
Depth (m)	33	13 - 83	13	26	61	—	—	—	—	—
$\Delta\sigma_t$	3.4	0.001 - 12.4	0.1	2.4	8.1	—	—	—	—	—
Temperature (°C)	26.4	19.4 - 31	20.6	26.3	30.6	30.7	29.8 - 31.5	30	30.7	31.1
Salinity (psu)	35.6	31.1 - 36.5	33.8	36.1	36.4	32.9	23.4 - 36.5	26	33.3	36.4
DO (mg/L)	5.1	0 - 6.8	0.2	5.9	6.7	6.4	5.4 - 7.7	6.2	6.4	6.7
pH	8.0	7.7 - 8.1	7.7	8.0	8.1	8.1	8 - 8.3	8.1	8.1	8.2
DIN (mg/L)	0.069	0.018 - 0.367	0.02	0.029	0.145	0.026	0.018 - 0.044	0.018	0.024	0.037
DIP (mg/L)	0.01	0.003 - 0.092	0.003	0.004	0.015	0.004	0.002 - 0.011	0.002	0.003	0.008
DIN/DIP	8.22	3.46 - 25.5	3.75	7.26	12.72	7.28	2.79 - 10.69	4.23	7.73	9.42
Chl <i>a</i> (µg/L)	2.42	0.68* - 15.07	0.68*	0.73	4.53	1.53	0.68* - 9.36	0.68*	0.68*	3.72
Turbidity (NTU)	2.5	0.4 - 14.1	0.5	1.7	6.5	1.1	0.2 - 6.1	0.3	0.6	2.7
TSS (mg/L)	12.6	2.4 - 139.2	5.6	7.6	11.4	7.6	3.4 - 29.5	4.2	7.4	9.4

* Represents the minimum method detection limit for chlorophyll *a*.

3.1.2 General Water Characteristics: Temperature, Salinity, Water-Column Stratification, DO, pH, TSS

Temperatures of surface water (upper 2 – 3 m) ranged from 29.8 °C to 31.5 °C and averaged 30.7 °C (Table 5). Bottom-water temperatures (lower 1.5 – 7.5 m of the water column, depending on station depth) were more variable and somewhat colder, ranging from 19.4 °C to 31 °C and averaging 26.4 °C. Fifty percent of the study area had bottom-water temperatures ≤ 26.3 °C and only 10 % had values exceeding 30.6 °C. In general, there was a decreasing trend of bottom-water temperatures with increasing depth.

Surface salinities varied between 23.4 psu and 36.5 psu. The mean and 50th percentile (latter based on area) were 32.9 psu and 33.3 psu, respectively, with 10 % of the area having surface salinities between 23.4 psu and 26 psu. Surface salinities generally increased with distance west of the Mississippi River delta (Figure 2). Bottom salinities varied between 31.1 and 36.5 psu and averaged 35.3 psu. Bottom salinities were lowest at shallow, inner-shelf stations (Figure 2).

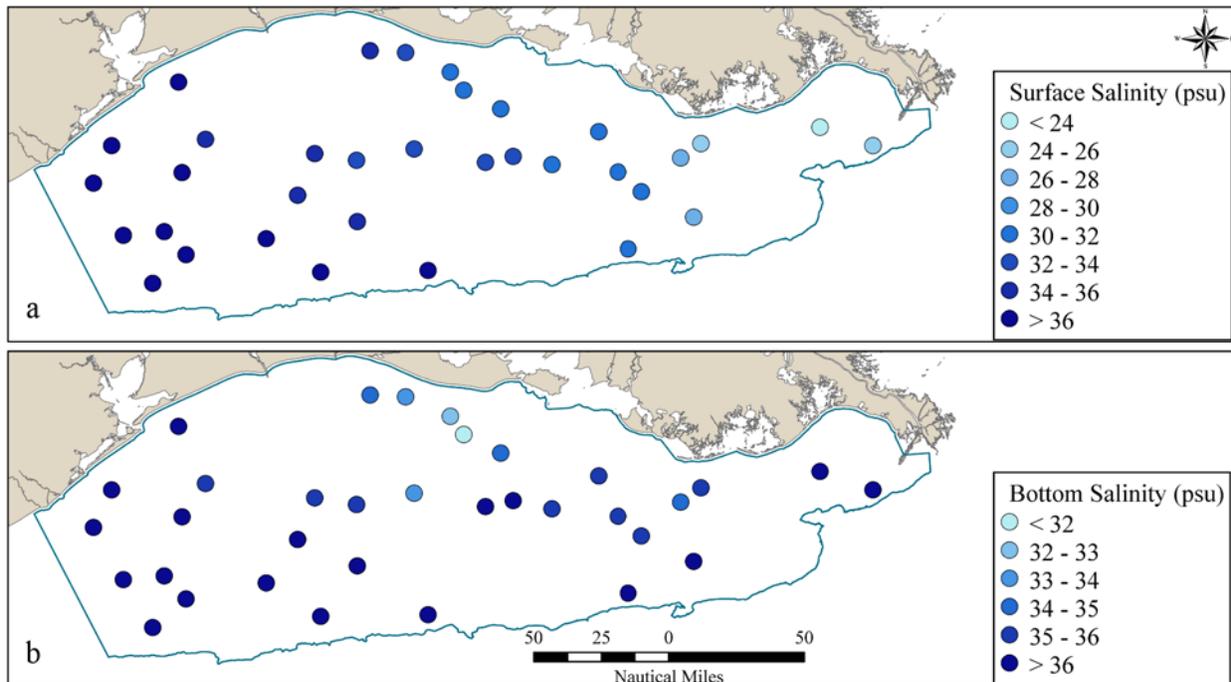


Figure 2. Surface (a) and bottom (b) salinities measured at 34 sites in the northwest GOM.

Strong density stratification was observed at some of the stations sampled in this study. Computed values of $\Delta\sigma_t$ indicated that portions of coastal shelf waters in the western GOM at the time of this sampling were strongly stratified, with 50 % of the survey area having values of $\Delta\sigma_t > 2.4$. Values of $\Delta\sigma_t$ at 19 of the 34 sites sampled in this study (56 % of the study area) ranged from 2.2 to 12.4, which is within the range considered to be indicative of strong vertical stratification ($\Delta\sigma_t > 2$; Nelson et al. 2008). Stratification was strongest close to the Mississippi River delta, steadily decreasing with distance west of the delta (Figure 3).

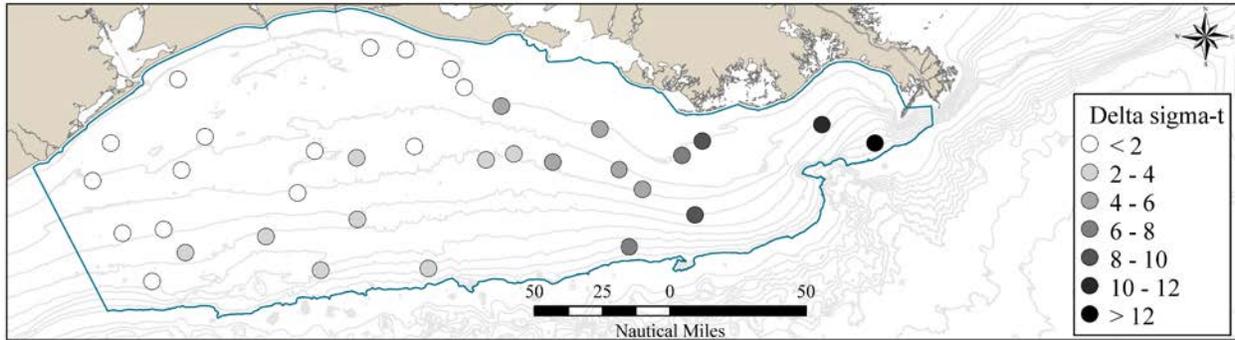


Figure 3. Extent of density stratification ($\Delta\sigma_t$) among 34 stations in the northwest GOM. Interpolated surface was obtained using an inverse distance weighted (IDW) technique.

Concentrations of DO in surface waters ranged from 5.4 – 7.7 mg/L (mean of 6.4 mg/L). Bottom-water concentrations were more variable, with values ranging from 0 – 6.8 mg/L and averaging 5.1 mg/L. Low levels of DO (< 2 mg/L), potentially harmful to benthic fauna and fish, were observed at 5 stations (Figure 4) which represent approximately 15 % of the study area. This footprint corresponds fairly closely to the region of strongest density stratification (Figure 3). The lowest bottom DO levels also were observed in a region corresponding roughly to the same area having the highest incidence of bottom-water hypoxia in mid-summer along the Louisiana-Texas shelf for 1985 – 2002 (see Figure 1 in Turner et al. 2006).

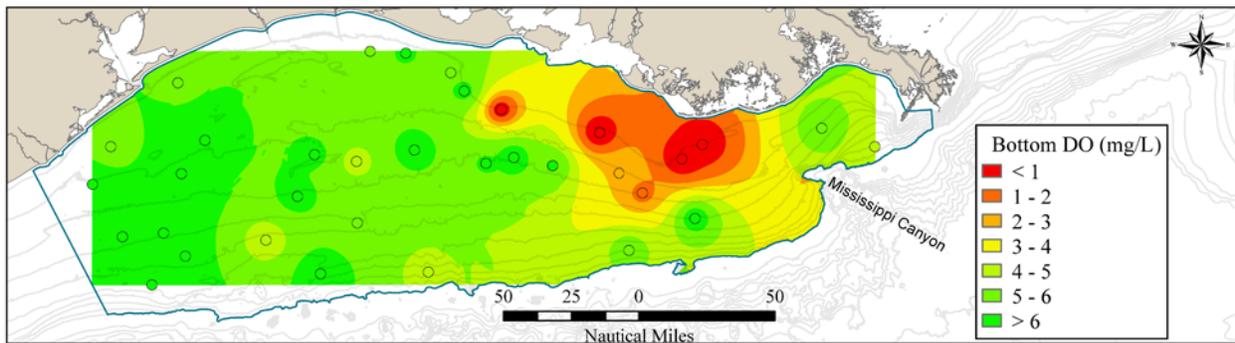


Figure 4. Bottom dissolved oxygen (DO) measured at 34 sites in the northwest GOM. Interpolated surface was obtained using an inverse distance weighted (IDW) technique.

While low-DO sites corresponded to areas of moderate-to-high levels of density stratification ($4 < \Delta\sigma_t < 10$, see Figure 3), bottom DO appeared also to be influenced by station depth. The highest degree of density stratification (as measured by $\Delta\sigma_t$) was observed at stations 44 and 28 ($\Delta\sigma_t$ of 12 and 12.4, respectively), yet these sites had relatively high bottom-DO levels (5.7 and 4.5 mg/L, respectively). A possible explanation is the combination of depth (34 and 83 m, respectively), bottom topography, and proximity of these two sites to Mississippi Canyon (see Figure 4), a potential source of deep, oxygen-rich oceanic bottom-water. As illustrated in Figure 5, sites with the lowest DO concentrations tended to be relatively shallow, with strong density stratification ($\Delta\sigma_t > 2$). These five sites had a well-defined pycnocline at approximately mid-depth. Of the five sites indicated in Figure 5 (red symbols), stations with depths of 13 – 15 m had a pycnocline at 6 – 8 m depth; the pycnocline at the deepest of the five sites (30 m) was located at about 15 m depth.

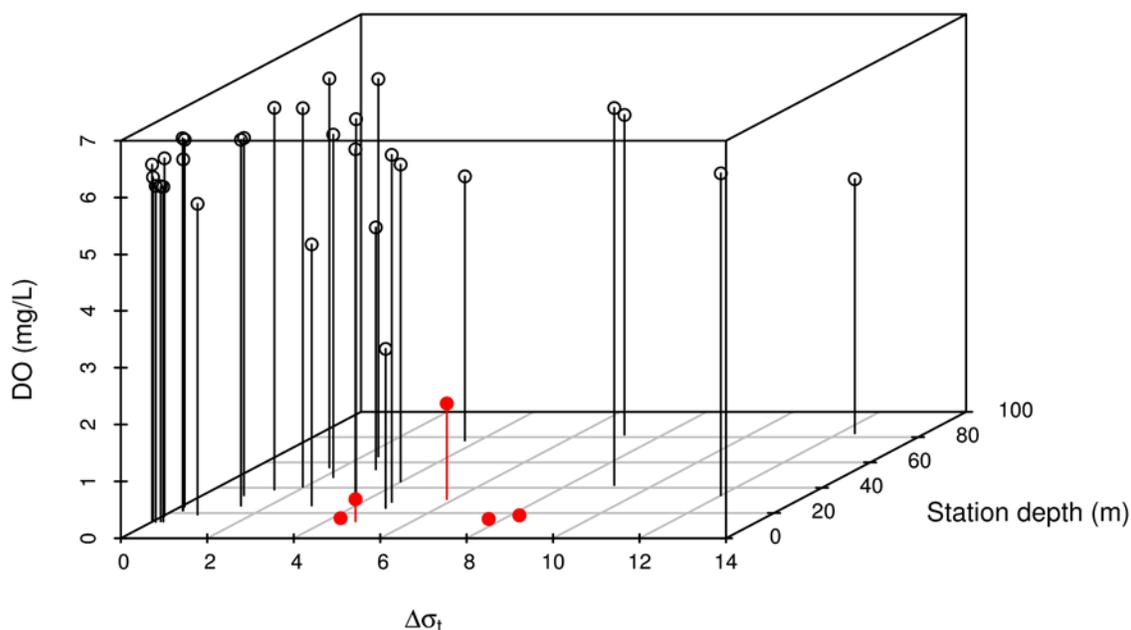


Figure 5. Dissolved oxygen (DO) versus $\Delta\sigma_t$ and depth in bottom waters of the western Gulf of Mexico coastal shelf. Low-DO stations (DO < 2 mg/L) are shown in red.

The range of pH values was 8.0 – 8.3 for surface waters and 7.7 – 8.1 for bottom waters (Table 5, Figure 6), which falls within the normal range for seawater of 7.5 – 8.5 (Pinet 2006).

Turbidity of surface waters averaged 1.1 NTU and ranged from 0.2 – 6.1 NTU. Bottom-water turbidity was higher, with values ranging from 0.4 – 14.1 NTU and averaging 2.5 NTU. Highest bottom-water turbidity (14.1 NTU) occurred at station 30, which also had the lowest DO concentrations observed (0 mg/L).

Total suspended solids (TSS) ranged from 3.4 – 29.5 mg/L in surface waters. Fifty percent of the area had TSS values \leq 7.4 mg/L, and 90 % of the area had surface TSS values \leq 9.4 mg/L. Four stations with surface TSS above 9.4 mg/L were distributed across the mid- to outer-shelf mainly in the western portion of the study area. TSS concentrations in bottom waters were higher than those of surface waters. The area-weighted 50th and 90th percentiles were 7.6 mg/L and 11.4 mg/L, respectively, with concentrations at one site near the Mississippi River delta (station 44) equal to 139.2 mg/L. The high TSS concentrations at this one site are more typical of estuaries, while the remaining bottom TSS values are similar to those observed in other shelf waters of the U.S. Atlantic coast (Balthis et al. 2009, 2011; Cooksey et al. 2010) and GOM (Cooksey et al., In review).

The full range of values across all northwest GOM stations, for the various water-quality variables discussed above, is displayed as CDF plots in Figure 6. The mean values by station (average of multiple CTD measurements for near-surface and near-bottom waters for each station) appear in Appendix B and Appendix C.

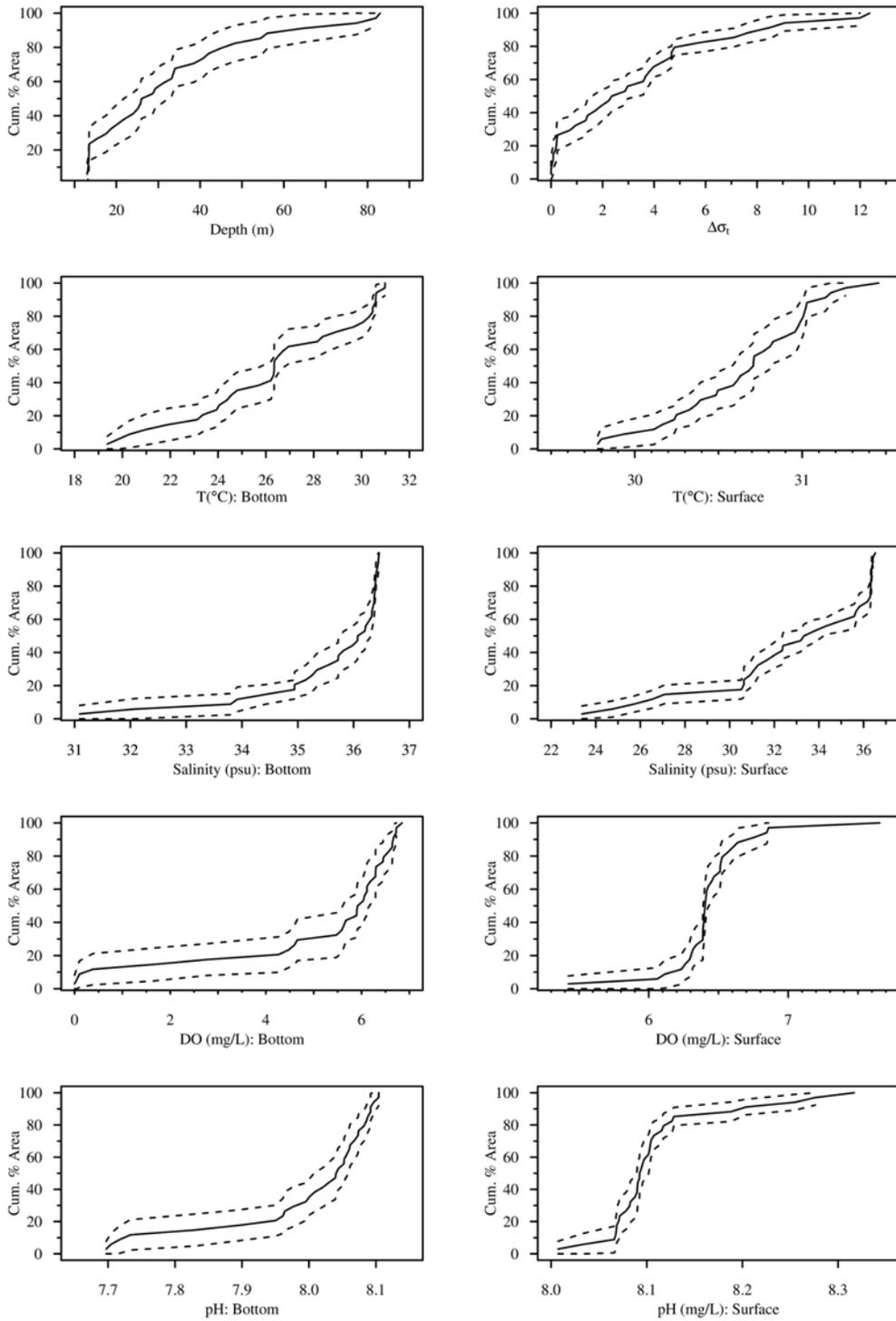


Figure 6. Estimated CDF plots representing percent area (and 95% confidence intervals) of northwestern GOM coastal shelf waters vs. selected water-quality characteristics.

3.1.3 Nutrients and Chlorophyll

An extensive zone of hypoxia forms annually along the inner shelf of the northern GOM adjacent to the outflows of the Mississippi and Atchafalaya Rivers (Rabalais et al. 2001b, 2002; Dagg et al. 2007). This area of the inner- to mid-continental shelf, from the Mississippi River delta west to the upper Texas coast, is the second largest human-caused hypoxic area in the global ocean (Rabalais et al. 2010, Turner et al. 2012). This so-called “dead zone” typically peaks in mid-summer when consumption of oxygen in bottom water layers exceeds re-supply from the surface, as vertical stratification of the water-column (due to differences in temperature and/or salinity) prevents exchange of oxygen between surface and bottom layers. Nitrogen supplied from the Mississippi and Atchafalaya Rivers, combined with high freshwater discharge in the spring, fuels increased production of organic matter in surface waters, which falls through the water column to the bottom where respiration of available oxygen results in hypoxic conditions in a zone that persists from spring through early fall (Turner et al. 2012).

In the present study, the concentration of dissolved inorganic nitrogen (DIN: nitrogen as nitrate + nitrite + ammonium) in surface waters ranged from 0.018 mg/L to 0.044 mg/L and averaged 0.026 mg/L (Table 5, Figure 7). Ninety percent of the study area surface waters had DIN concentrations \leq 0.037 mg/L. Bottom-water concentrations of DIN tended to be higher than surface concentrations. For example, about 50% of bottom waters had DIN $>$ 0.029 mg/L and the average concentration was 0.069 mg/L (range of 0.018 – 0.367 mg/L). The highest bottom-DIN concentrations occurred at the same stations having low levels of bottom DO.

Concentrations of dissolved inorganic phosphorus (DIP) in surface waters ranged between 0.002 mg/L and 0.011 mg/L, averaging 0.004 mg/L (Table 5). Ninety percent of the study area surface waters had DIP concentrations \leq 0.008 mg/L. Bottom-water concentrations of DIP were somewhat higher than those measured in surface waters, with a range of 0.003 – 0.092 mg/L and mean of 0.01 mg/L.

The ratio of DIN to DIP was calculated as an index of nutrient limitation. A DIN:DIP ratio $>$ 16 is considered to be indicative of phosphorus limitation, while values of DIN:DIP $<$ 16 suggest that nitrogen is the limiting factor for primary production (Geider and La Roche 2002). DIN:DIP ratios (Table 5) ranged from 2.79 to 10.69 (mean of 7.28) in surface waters, which is strongly indicative of nitrogen limitation. Bottom DIN:DIP ratios were $<$ 16 at all but one site (station 31), which had DIN:DIP = 25.5 as a result of very low levels of DIP.

Surface-water concentrations of chlorophyll *a* (Chl *a*), an indicator of phytoplankton biomass and abundance, ranged from $<$ 0.68 μ g/L (the minimum method limit of detection) to 9.36 μ g/L and averaged 1.51 μ g/L (Table 5). Bottom-water concentrations of chlorophyll *a* were similar to concentrations in surface waters, ranging from $<$ 0.68 μ g/L and 15.07 μ g/L and averaging 2.42 μ g/L.

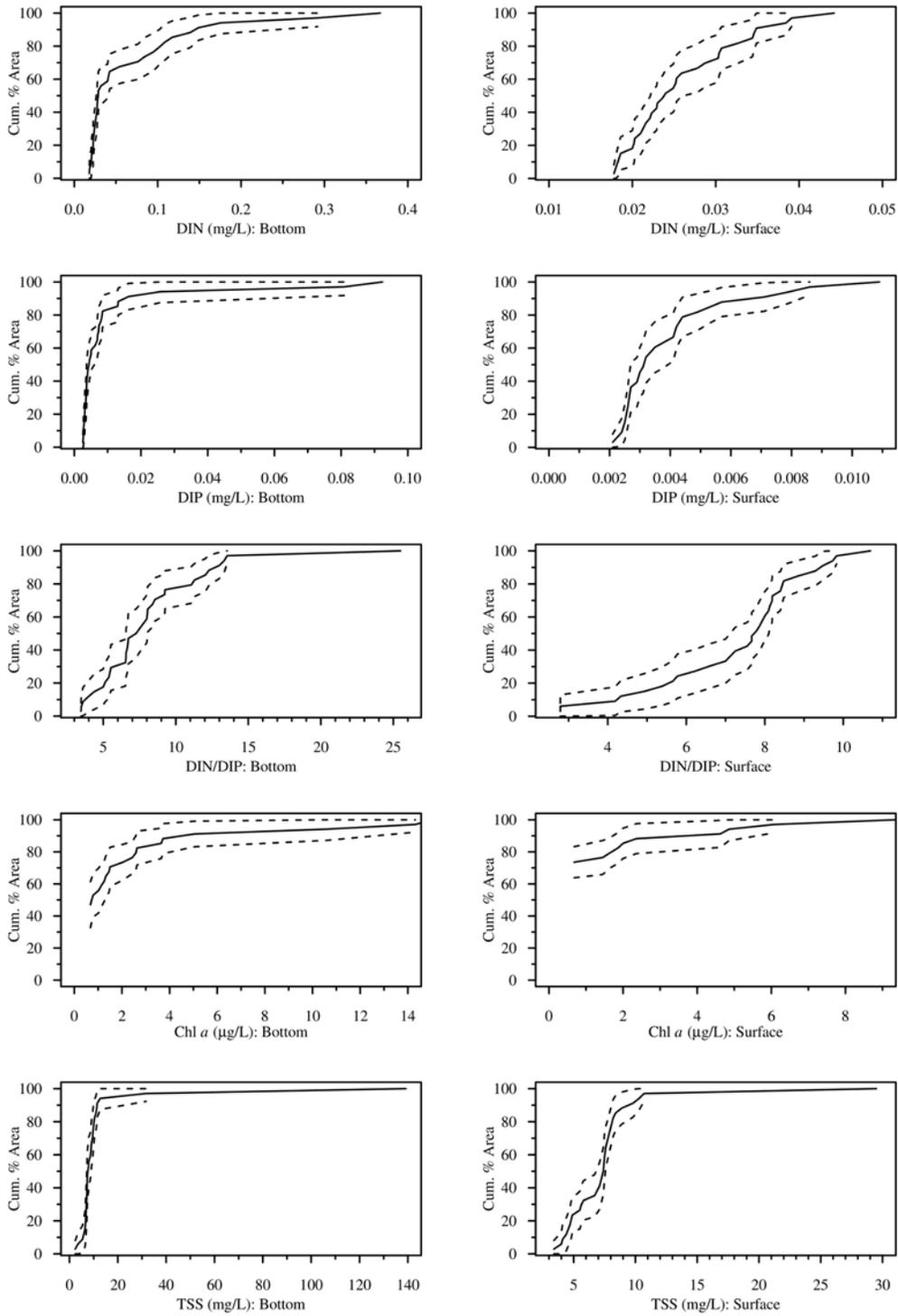


Figure 7. Percent area (and 95% confidence intervals) of northwestern GOM coastal shelf waters vs. nutrient, chlorophyll, and TSS concentrations.

3.2 Sediment Quality

3.2.1 Grain Size and TOC

A small proportion (9 % area) of the study region consisted of sediments composed mainly of sands (< 20 % silt+clay content, Figure 8). Slightly less than half (47 % area) had sediments consisting of muddy sand (20 – 80 % silt+clay), with the remaining 44 % of the area characterized by muddy sediments (> 80 % silt+clay). Sediments at some sites also included a gravel component, but this was typically < 1 % (Appendix A). Higher proportions of % sand were more prevalent in the western portion of the study area, while fine-grained muds were found in closer proximity to the Mississippi and Atchafalaya River deltas (Figure 9).

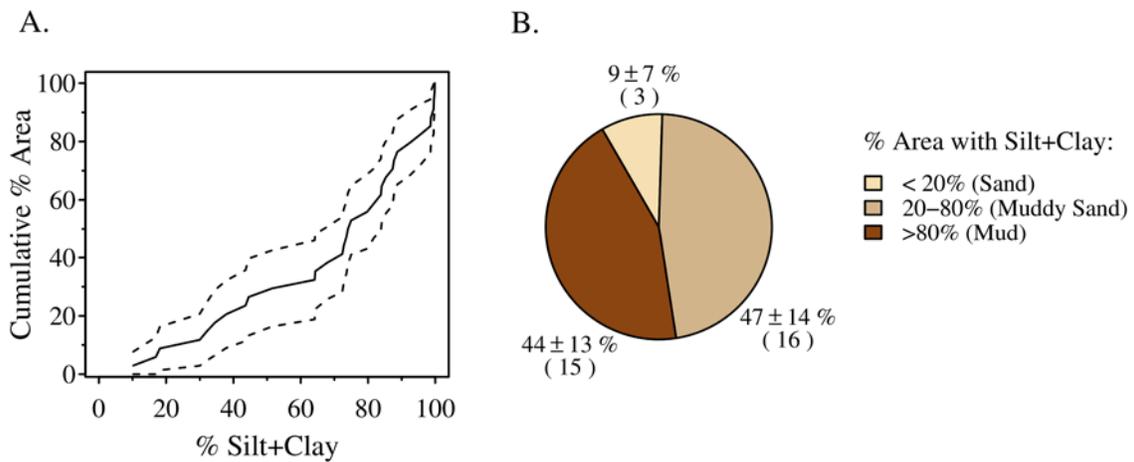


Figure 8. (A) Percent area (and 95% confidence intervals) represented by varying levels of % silt+clay content of sediment, and (B) percent area having % silt+clay content within specified ranges in the northwest GOM.

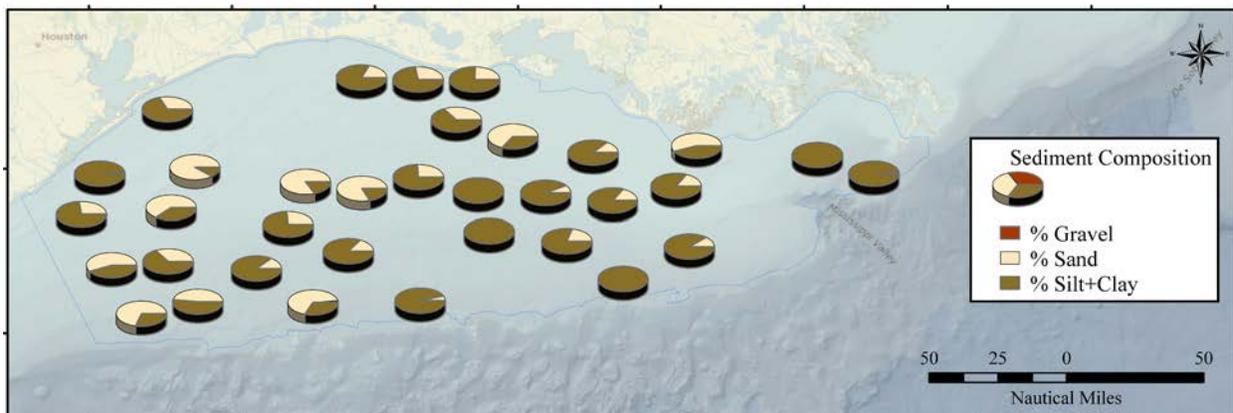


Figure 9. Percent gravel, sand, and silt+clay content of northwest GOM coastal shelf sediments.

TOC content of sediments in general was low, ranging from 1.2 – 12.9 mg/g and averaging 5.2 mg/g throughout the study area (Table 6). All of the region surveyed (34 sites, 100 % area) had sediment TOC concentrations in the low range, < 20 mg/g based on EMAP/NCA cutpoints (EPA 2008) (Figure 10). Of the 34 stations sampled, 17 (representing 50 % of the area) had sediment TOC < 5 mg/g and all but four (representing 90 % of the area) had TOC ≤ 9.2 mg/g. The highest TOC concentrations were observed mainly in the eastern portion of the study region or close to shore near the entrance to Galveston Bay.

Table 6. Summary of sediment characteristics from 34 northwest GOM coastal shelf sites.

Parameter	Mean	Range	CDF 10th pctl	CDF 50th pctl	CDF 90th pctl
% Silt+Clay	69	10.2–99.8	22.9	74	99.2
TOC (mg/g)	5.2	1.2–12.9	1.5	4.9	9.2

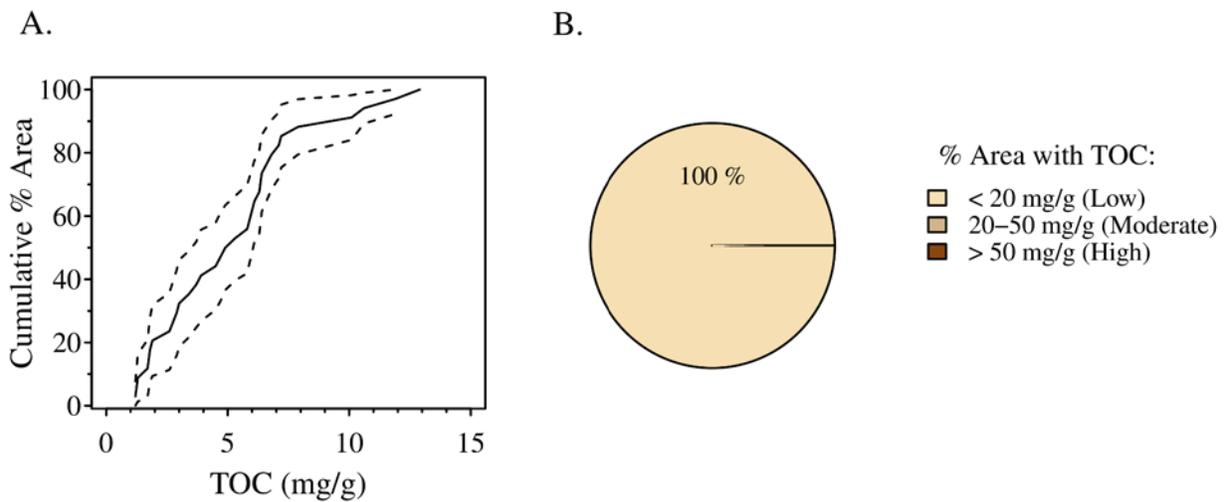


Figure 10. (A) Percent area (and 95% confidence intervals) represented by varying levels of TOC content of sediment (mg/g), and (B) percent area having TOC content within specified ranges.

3.2.2 Chemical Contaminants in Sediments

The U.S. outer continental shelf (OCS) along the GOM has one of the greatest developments of oil and gas production in the world, with over 3,000 oil and gas platforms and over 25,000 miles of oil and gas pipeline on the GOM sea floor (BOEM 2013a, 2013b). The majority of oil and gas platforms are on the OCS off the Louisiana coast (Figure 11). Potential ecological impacts may result from toxicity of spilled oil and secondary or indirect effects due to construction of pipelines and navigation channels (Ko and Day 2004).

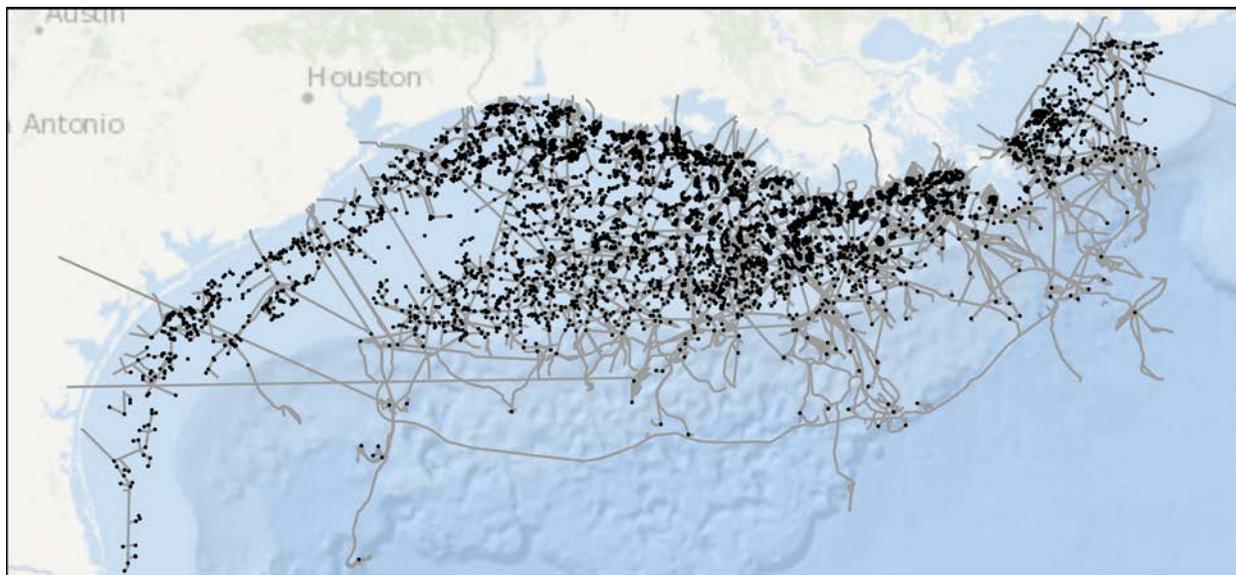


Figure 11. Oil and gas platforms (black dots) and pipelines (grey lines) in the GOM (source data: BOEM 2012a, 2012b).

Concentrations of chemical contaminants in sediments were generally at low background levels, below expected bioeffect ranges (Table 7, see further discussion below), though a number of metals, PAHs, PCBs, pesticides, and total petroleum hydrocarbons (TPH) were measured at concentrations above the minimum method detection limit (MDL). Spatial trends in concentrations of these contaminants are shown in Figure 12. For all categories of chemicals, concentrations tended to be highest in the easternmost portion of the study area, which includes the Louisiana Bight and Southwest Pass region where the Mississippi River empties into the GOM. Total metals (sum of Ag, As, Cd, Cr, Cu, Hg, Pb, Zn) were detectable throughout the study region, but tended to decrease with distance west (which was true in general for all contaminants). Total PAHs (sum of 24 PAHs) were found at concentrations above the MDL at only one site (station 28), which was the easternmost station sampled. Concentrations of total PCBs were elevated at station 28, but also at two stations farther west and offshore of the Atchafalaya River delta. Total DDTs also were elevated in the same general area as total PCBs. Total petroleum hydrocarbons (TPH) concentrations were highest in the Louisiana Bight, but similar levels also were observed at other offshore sites in the central and western portion of the study region.

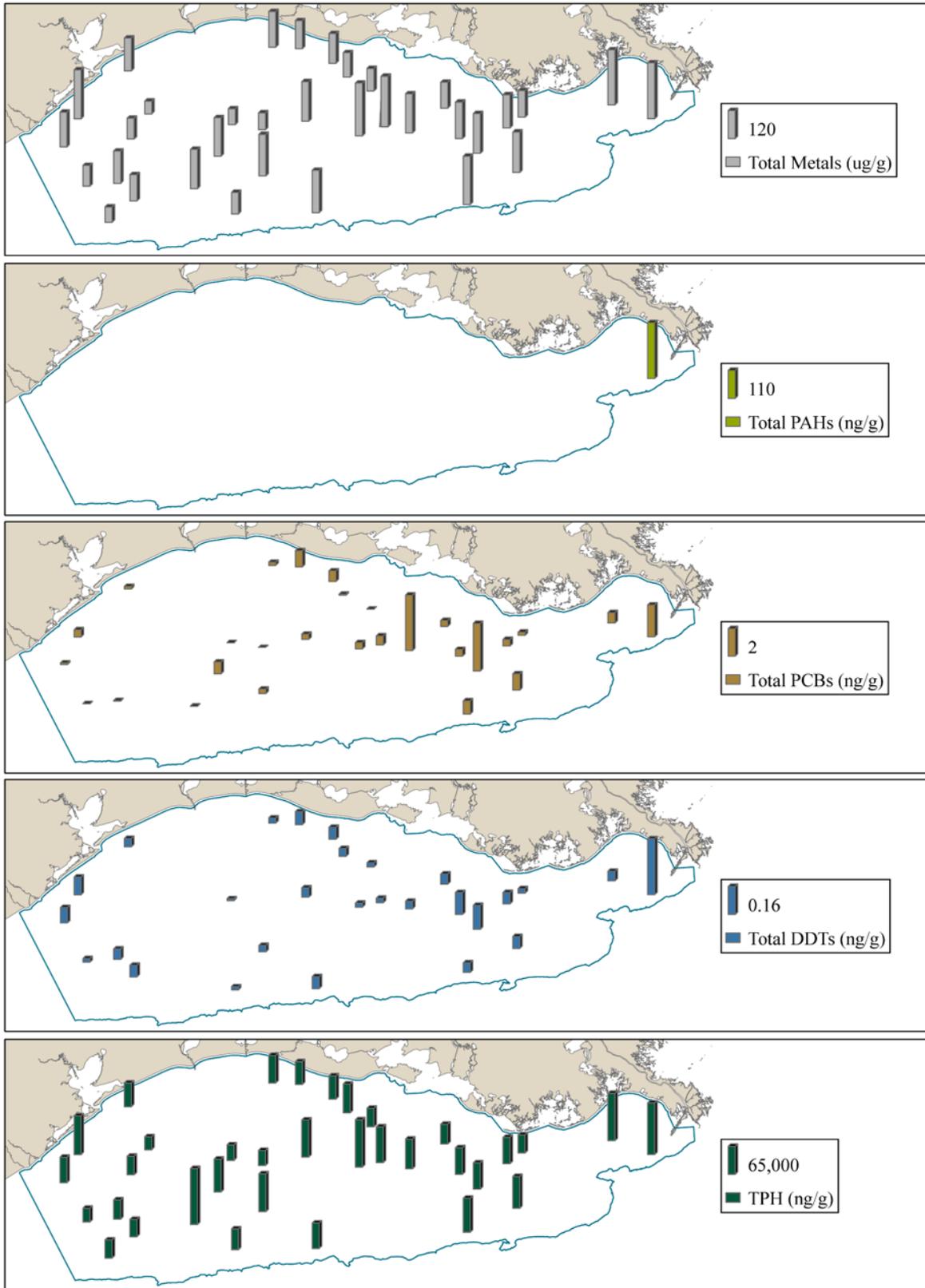


Figure 12. Trends in detectable concentrations of metals, PAHs, PCBs, DDTs, and TPH in northwest GOM shelf sediments. Vertical bar in legend provides reference scale for bars in figure.

The biological significance of chemical contamination of sediments was evaluated by comparing measured contaminant concentrations to sediment quality guidelines (SQGs) developed by Long et al. (1995). Effects-Range Low (ERL) values represent lower bioeffect limits, below which adverse effects of contaminants on sediment-dwelling organisms are not likely to occur (the ERL corresponds to an expected incidence of toxicity of about 10%). Effects-Range Median (ERM) values are mid-range concentrations above which adverse biological effects are more likely to occur (the ERM is the concentration corresponding to an expected incidence of toxicity of about 50%). Any site having one or more chemicals in excess of their corresponding ERM values (see Table 3) was rated as having poor sediment quality; any site with five or more chemicals between the corresponding ERL and ERM values was rated as fair; any site with no ERMs exceeded and < 5 ERLs exceeded was rated as having good sediment quality (sensu U.S. EPA 2008).

No ERM exceedances were observed for any contaminant at any of the sites sampled in this study. Arsenic was the only chemical that exceeded the corresponding ERL guideline. The ERL exceedances for arsenic occurred at seven sites, representing an estimated 20.6 % of the survey area (Table 7). The concentration of arsenic at these sites was within the range typical of uncontaminated near-shore marine sediments (5 – 15 µg/g dry weight total arsenic) and reflects its natural presence at low to moderate concentrations in crustal rocks of the region (Neff 1997). Hence, using the criteria above, all 34 sites sampled in this study would be classified as having good sediment quality with respect to chemical contamination (i.e., no ERMs exceeded and < 5 ERLs exceeded).

Concentrations of TPH in sediments averaged 64.5 µg/g and ranged from 30 – 130 µg/g across the survey area. There are no ERL/ERM values for TPH. However, for comparison, typically in oil-impacted areas following historical spill events or near other point sources, total oil concentrations in sediments have been well in excess of 1,000 ug/g dry weight. For example, TPH concentrations within 3 km of the DWH wellhead, coinciding with an area of benthic impacts (Montagna et al. 2013), ranged from 103 - 5,023 µg/g, based on data from DWH Response efforts as presented in the “Environmental Response Management Application (ERMA)” Gulf Response website (<<http://gomex.erma.noaa.gov>>). In spite of the many potential sources of oil within the offshore GOM region, sediment TPH concentrations in the present study were found at low background levels – just above method detection limits in all cases – and well below reported bioeffect ranges.

Table 7. Summary of chemical contaminant concentrations in northwest GOM sediments ('N.D.' = not detected; '-' = no corresponding ERL or ERM available).

Analyte	Mean	(Std. Dev.)	Range	Concentration > ERL, < ERM		Concentration > ERM	
				# Stations	% Area	# Stations	% Area
Metals (% dry)							
Aluminum	3.44	(1.587)	0.853 – 6.251	–	–	–	–
Iron	2.065	(0.798)	0.636 – 3.609	–	–	–	–
Trace Metals (µg/g dry mass)							
Silver	N.D.	N.D.	N.D.	0	0	0	0
Antimony	N.D.	N.D.	N.D.	–	–	–	–
Arsenic	6.451	(1.982)	3.550 – 10.896	7	20.6	0	0
Cadmium	0.034	(0.074)	0 – 0.219	0	0	0	0
Chromium	41.576	(12.323)	16.446 – 62.270	0	0	0	0
Copper	8.923	(5.154)	0 – 21.941	0	0	0	0
Lead	16.622	(4.502)	9.612 – 26.033	0	0	0	0
Manganese	389.143	(158.675)	204.286 – 931.363	–	–	–	–
Mercury	0.027	(0.013)	0.007 – 0.057	0	0	0	0
Nickel	18.734	(7.477)	5.531 – 35.034	0	0	0	0
Selenium	0.382	(0.126)	0.174 – 0.630	–	–	–	–
Tin	1.562	(0.583)	0.627 – 2.859	–	–	–	–
Zinc	66.649	(26.647)	23.381 – 118.030	0	0	0	0
PAHs (ng/g dry)							
Acenaphthene	N.D.	N.D.	N.D.	0	0	0	0
Acenaphthylene	0.598	(3.486)	0 – 20.329	0	0	0	0
Anthracene	0.429	(2.502)	0 – 14.586	0	0	0	0
Benz[a]anthracene	0.451	(2.629)	0 – 15.332	0	0	0	0
Benzo[a]pyrene	0.556	(3.244)	0 – 18.916	0	0	0	0
Benzo[b]fluoranthene	0.569	(3.316)	0 – 19.337	–	–	–	–
Benzo[g,h,i]perylene	N.D.	N.D.	N.D.	–	–	–	–
Benzo[j+k]fluoranthene	0.565	(3.297)	0 – 19.226	–	–	–	–
Biphenyl	N.D.	N.D.	N.D.	–	–	–	–
Chrysene	0.489	(2.851)	0 – 16.624	0	0	0	0
Dibenz[a,h]anthracene	N.D.	N.D.	N.D.	0	0	0	0
Dibenzothiophene	N.D.	N.D.	N.D.	–	–	–	–
Fluoranthene	0.866	(5.049)	0 – 29.442	0	0	0	0
Fluorene	N.D.	N.D.	N.D.	0	0	0	0
Indeno[1,2,3-c,d]pyrene	N.D.	N.D.	N.D.	–	–	–	–
Naphthalene	0.398	(2.323)	0 – 13.542	0	0	0	0
1-Methylnaphthalene	N.D.	N.D.	N.D.	–	–	–	–

Table 7. (continued).

Analyte	Mean	(Std. Dev.)	Range	Concentration > ERL, < ERM		Concentration > ERM	
				# Stations	% Area	# Stations	% Area
2-Methylnaphthalene	N.D.	N.D.	N.D.	0	0	0	0
2,6-Dimethylnaphthalene	N.D.	N.D.	N.D.	-	-	-	-
Phenanthrene	0.512	(2.988)	0 - 17.422	0	0	0	0
1-Methylphenanthrene	0.139	(0.812)	0 - 4.736	-	-	-	-
Pyrene	0.821	(4.788)	0 - 27.919	0	0	0	0
Low Molecular Weight PAHs	2.077	(12.111)	0 - 70.616	0	0	0	0
High Molecular Weight PAHs	3.752	(21.878)	0 - 127.570	0	0	0	0
Total PAHs ^a	6.345	(36.996)	0 - 215.720	0	0	0	0
TPH (ng/g)	64,471	(25,739)	30,000 - 130,000	-	-	-	-
PCBs (ng/g dry)							
Total PCBs ^b	0.602	(0.954)	0 - 4.095	0	0	0	0
Pesticides (ng/g dry)							
2,4'-DDD (o,p'-DDD)	N.D.	N.D.	N.D.	-	-	-	-
2,4'-DDE (o,p'-DDE)	N.D.	N.D.	N.D.	-	-	-	-
2,4'-DDT (o,p'-DDT)	N.D.	N.D.	N.D.	-	-	-	-
4,4'-DDD (p,p'-DDD)	N.D.	N.D.	N.D.	-	-	-	-
4,4'-DDE (p,p'-DDE)	0.053	(0.059)	0 - 0.320	0	0	0	0
4,4'-DDT (p,p'-DDT)	N.D.	N.D.	N.D.	-	-	-	-
Aldrin	N.D.	N.D.	N.D.	-	-	-	-
alpha-Chlordane	0.007	(0.012)	0 - 0.036	-	-	-	-
Dieldrin	N.D.	N.D.	N.D.	-	-	-	-
Endosulfan I	N.D.	N.D.	N.D.	-	-	-	-
Endosulfan sulfate	0.030	(0.057)	0 - 0.172	-	-	-	-
Endrin	N.D.	N.D.	N.D.	-	-	-	-
gamma-HCH (g-BHC, Lindane)	N.D.	N.D.	N.D.	-	-	-	-
Hexachlorobenzene	0.001	(0.004)	0 - 0.021	-	-	-	-
Heptachlor	N.D.	N.D.	N.D.	-	-	-	-
Heptachlor epoxide	N.D.	N.D.	N.D.	-	-	-	-
Mirex	N.D.	N.D.	N.D.	-	-	-	-
total DDTs	0.053	(0.059)	0 - 0.320	0	0	0	0
trans-Nonachlor	N.D.	N.D.	N.D.	-	-	-	-

^a Sum of 24 measured PAHs.

^b Sum of 84 measured PCB congeners.

^c Sum of 2,4'-DDD, 4,4'-DDD, 2,4'-DDE, 4,4'-DDE, 2,4'-DDT, and 4,4'-DDT.

Overall sediment contamination from multiple chemicals also was expressed through the use of mean ERM quotients (sensu Long et al. 1998; Hyland et al. 1999, 2003). The mean ERM quotient (mean ERM-Q) is the mean of the ratios of individual chemical concentrations in a sample relative to corresponding published ERM values (using all chemicals in Table 3 except nickel, low- and high-molecular-weight PAHs, and total PAHs). A useful feature of this method is that overall contamination in a sample from mixtures of multiple chemicals present at varying concentrations can be expressed as a single number that can be compared to values calculated the same way for other samples (either from other locations or sampling occasions).

Mean ERM-Qs ranged from 0.009 – 0.045, with an overall mean of 0.023. The relative contribution of individual contaminants (or contaminant classes) is illustrated in Figure 13. Few stations had mean ERM-Qs high enough to suggest significant risks of adverse effects on benthic fauna. Hyland et al. (2003) reported a very high incidence of impaired benthic assemblages (92% of samples) in Louisianian Province estuaries at mean ERM-Qs above a critical point of 0.062, a high incidence (86% of samples) at mean ERM-Qs >0.036 - 0.062, a medium incidence (52% of samples) at mean ERM-Qs >0.013 - 0.036, and a low incidence of effects (30% of samples) at mean ERM-Qs \leq 0.013. Although in the present study we are dealing with offshore benthic fauna rather than estuarine fauna, these are the most applicable guidelines known to us for interpretation purposes. Only two stations, representing 5.9% of the survey area, had mean ERM-Qs in the high (0.036-0.062) range. These two stations were the eastern-most sites sampled and were the stations closest to the Mississippi River delta (Figure 14). These two sites also had sediments with \geq 99 % silt-clay content. No sites had mean ERM-Qs in the highest (> 0.062) range. Mean ERM-Qs generally decreased with longitude west (i.e., with increasing distance west of the Mississippi River delta; Figure 15). Individual mean ERM-Qs and ERL/ERM exceedances are listed for all sites in Appendix D.

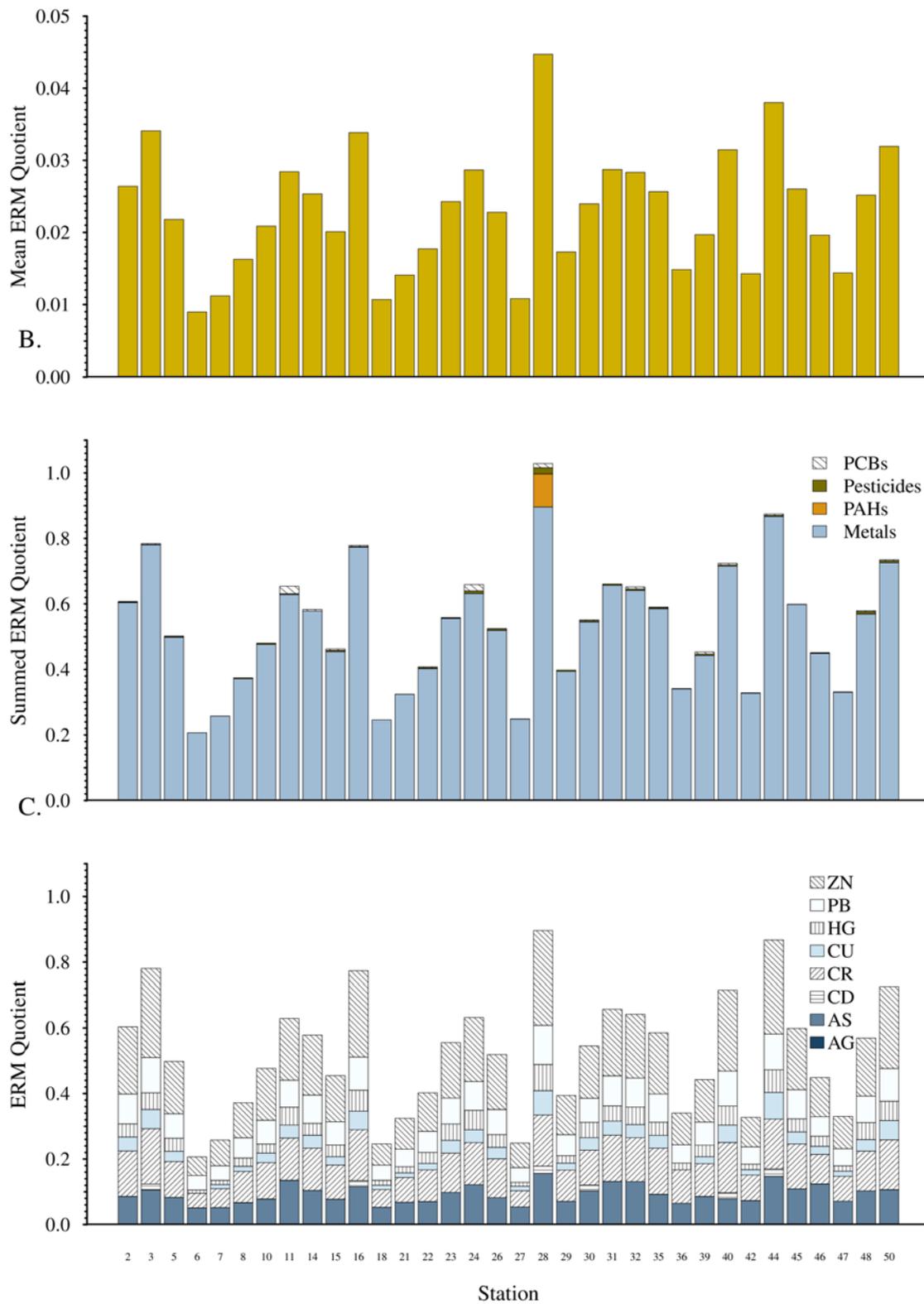


Figure 13. Effects range-mean (ERM) quotients calculated for each of 34 stations in the northwest GOM. (A) Mean ERM quotient; (B) Summed ERM quotient; (C) ERM quotient for metals only.

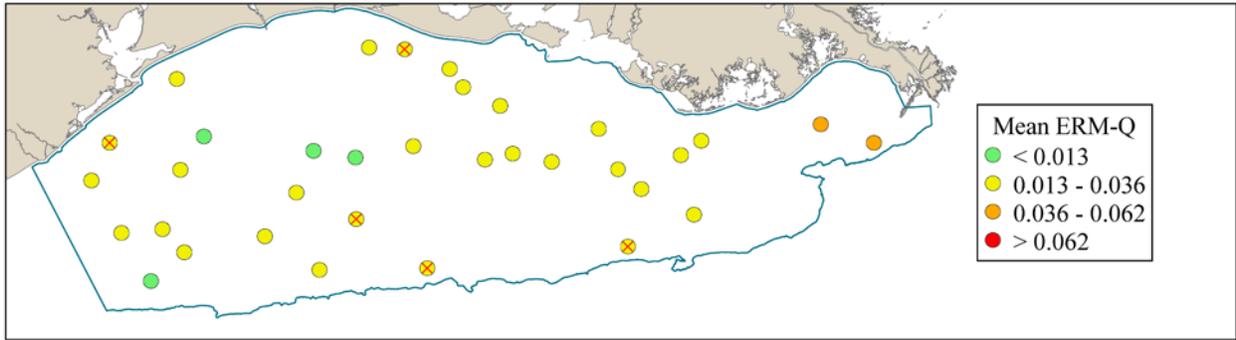


Figure 14. Mean ERM Quotient (ERM-Q) calculated for sediments sampled at 34 stations in the northwest GOM. Symbols marked with a red 'x' also had significant Microtox[®] toxicity (see Section 3.2.3 below).

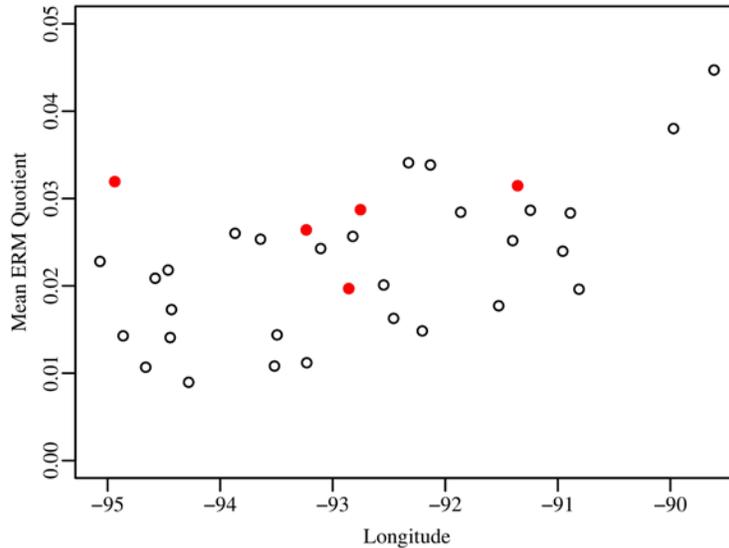


Figure 15. Plot of mean ERM quotient (ERM-Q) vs. longitude for sediments collected at 34 sites in the northwest GOM. Stations represented by solid circles also had significant Microtox[®] toxicity (see Section 3.2.3 below).

3.2.3 Sediment Toxicity

Sediments from five of the 34 stations, representing 14.7 % area, were found to be toxic, based on the criteria for the Microtox[®] assay listed in Table 2 (Ringwood et al. 1997). Although contaminant concentrations at these sites were somewhat elevated (mean ERM-Qs from 0.02 – 0.032, see Figure 15), no clear associations could be found between Microtox[®] toxicity and any of the other water or sediment parameters measured.

3.3 Chemical Contaminants in Fish Tissues

Collection of fish specimens by hook-and-line fishing was successful at 16 of the 34 stations sampled in this study. At most three specimens of any given species from each station were retained, resulting in 38 individual specimens (representing three distinct species) that were analyzed for chemical contamination of tissues. Species retained for analysis and the corresponding stations where they were collected are displayed in Table 8.

Table 8. Finfish specimens retained for tissue chemical contaminant analysis.

Station	Common Name	Scientific Name	No. of specimens
02	Atlantic croaker	<i>Micropogonias undulatus</i> ¹	3
03	Atlantic croaker	<i>M. undulatus</i> ²	3
05	Silver seatrout	<i>Cynoscion nothus</i> ³	3
06	Atlantic croaker	<i>M.undulatus</i>	3
07	Atlantic croaker	<i>M.undulatus</i>	3
08	Atlantic croaker	<i>M.undulatus</i>	2
14	Atlantic croaker	<i>M.undulatus</i>	2
15	Atlantic croaker	<i>M.undulatus</i>	1
16	Atlantic croaker	<i>M.undulatus</i>	1
21	Atlantic croaker	<i>M.undulatus</i>	1
24	Atlantic croaker	<i>M.undulatus</i> ⁴	3
27	Atlantic croaker	<i>M.undulatus</i>	2
35	Atlantic croaker	<i>M.undulatus</i>	3
40	Rock sea bass	<i>Centropristis philadelphica</i>	2
42	Rock sea bass	<i>C. philadelphica</i>	3
45	Rock sea bass	<i>C. philadelphica</i>	1
45	Atlantic croaker	<i>M.undulatus</i>	2
Total			38

¹ Three specimens selected randomly from 4 available.

² Three specimens selected randomly from 6 available.

³ Three specimens selected randomly from 4 available.

⁴ Three specimens selected randomly from 4 available.

Concentrations of a suite of metals and organic compounds (PAHs, PBDEs, PCBs, and pesticides) were measured in edible tissues (homogenized, skin-on fillets) of fish specimens listed in Table 8. Contaminants in fish tissues were present at detectable levels for 17 of 22 trace metals, 7 of 25 PAHs, 5 of 13 PBDEs, 72 of 84 PCB congeners, and 14 of 24 pesticides measured. Mean concentrations (and one standard error) of metals, PAHs, PCBs, and DDTs, averaged across the 16 stations where fish were caught are illustrated in Figure 16 for each of the three fish species.

Tissue contaminant levels were compared to risk-based EPA advisory guidelines for recreational fishers (Table 4). These guidelines set recommended consumption limits based on concentration ranges of a number of contaminants with respect to risk of cancer and non-cancer (chronic systemic) human-health effects. Only one station where fish were collected and retained for analysis had chemical contaminants in tissues above the corresponding upper non-cancer human-health endpoints (Table 9). At station 05, near the entrance to Galveston Bay, a silver seatrout (*C. nothus*) was collected having total PCB concentration of 61.2 ng/g, in excess of the upper

non-cancer human-health endpoint of 47 ng/g. The lower, non-cancer endpoint for methylmercury (measured as mercury and assumed to be all methylmercury) also was exceeded in the specimen listed above, and in specimens of Atlantic croaker (*M. undulatus*) and rock sea bass (*C. philadelphica*) collected at six additional stations (Figure 17).

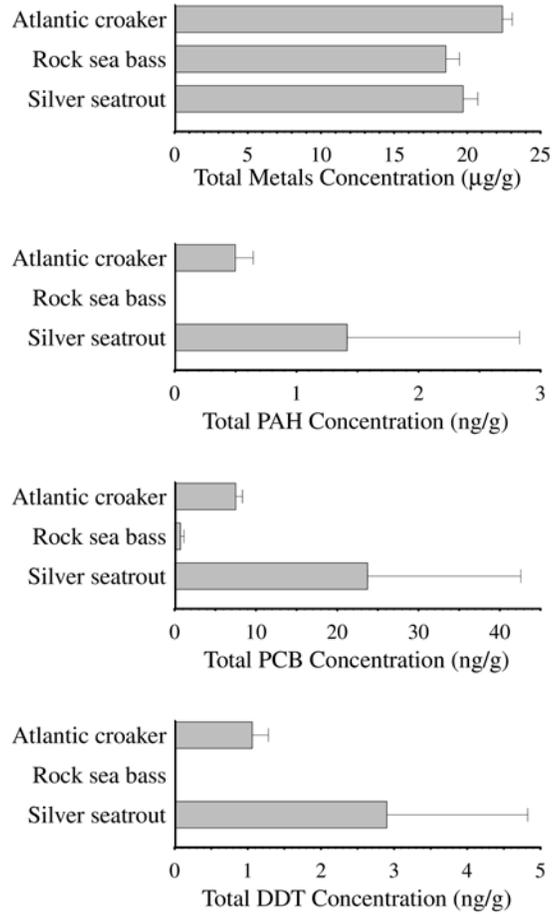


Figure 16. Mean (plus one standard error) of total metals, PAH, PCB, and DDT concentrations measured in each of three finfish species collected in the northwest GOM.

Table 9. Summary of contaminant concentrations (wet weight) measured in fish tissues. A total of 38 fish from 16 stations were analyzed. All measured contaminants are included. Concentrations are compared to human-health guidelines where available (from U.S. EPA 2000, also see Table 4 herein).

Analyte	Mean	Range	No. of Fish Exceeding Non-Cancer Endpoints	
			> Lower, ≤ Upper	> Upper
Metals (ug/g wet weight)				
Aluminum	2.649	1.323 – 8.195	–	–
Antimony	0.000	0.000 – 0.000	–	–
Arsenic	1.755	0.397 – 3.026	–	–
Inorganic Arsenic ^a	0.035	0.008 – 0.061	0	0
Barium	0.098	0.008 – 0.274	–	–
Beryllium	0.000	0.000 – 0.000	–	–
Cadmium	0.000	0.000 – 0.000	0	0
Cobalt	0.002	0.000 – 0.038	–	–
Chromium	0.287	0.140 – 0.377	–	–
Copper	0.432	0.162 – 1.294	–	–
Iron	9.896	6.553 – 16.669	–	–
Lithium	0.011	0.000 – 0.063	–	–
Manganese	0.338	0.080 – 0.823	–	–
Mercury ^b	0.078	0.008 – 0.212	7	0
Nickel	0.040	0.000 – 0.159	–	–
Lead	0.012	0.000 – 0.048	–	–
Selenium	0.870	0.453 – 1.209	0	0
Silver	0.001	0.000 – 0.031	–	–
Thallium	0.000	0.000 – 0.000	–	–
Tin	0.005	0.000 – 0.027	–	–
Uranium	0.000	0.000 – 0.000	–	–
Vanadium	0.186	0.037 – 0.565	–	–
Zinc	4.901	3.285 – 7.955	–	–
PAHs (ng/g wet weight)				
Acenaphthene	0.154	0.000 – 1.239	–	–
Acenaphthylene	0.082	0.000 – 1.819	–	–
Anthracene	0.116	0.000 – 2.423	–	–
Benz[a]anthracene	0.000	0.000 – 0.000	–	–
Benzo[a]pyrene	0.000	0.000 – 0.000	0	0
Benzo[e]pyrene	0.000	0.000 – 0.000	–	–
Benzo[b]fluoranthene	0.042	0.000 – 1.016	–	–
Benzo[j+k]fluoranthene	0.000	0.000 – 0.000	–	–
Benzo[g,h,i]perylene	0.000	0.000 – 0.000	–	–
Biphenyl	0.000	0.000 – 0.000	–	–
Chrysene+Triphenylene	0.000	0.000 – 0.000	–	–
Dibenz[a,h]anthracene	0.000	0.000 – 0.000	–	–
Dibenzothiophene	0.000	0.000 – 0.000	–	–
Fluoranthene	0.000	0.000 – 0.000	–	–
Fluorene	0.023	0.000 – 0.893	–	–
Indeno[1,2,3-c,d]pyrene	0.000	0.000 – 0.000	–	–
Naphthalene	0.000	0.000 – 0.000	–	–
1-Methylnaphthalene	0.013	0.000 – 0.507	–	–
2-Methylnaphthalene	0.000	0.000 – 0.000	–	–
2,6-Dimethylnaphthalene	0.059	0.000 – 1.497	–	–

Table 9. (continued).

Analyte	Mean	Range	No. of Fish Exceeding Non-Cancer Endpoints	
			> Lower, ≤ Upper	> Upper
1,6,7-Trimethylnaphthalene	0.000	0.000 – 0.000	–	–
Perylene	0.000	0.000 – 0.000	–	–
Phenanthrene	0.000	0.000 – 0.000	–	–
1-Methylphenanthrene	0.000	0.000 – 0.000	–	–
Pyrene	0.000	0.000 – 0.000	–	–
Total PAHs	0.491	0.000 – 4.242	–	–
PBDEs (ng/g wet weight)				
Total PBDEs ^c	0.111	0.000 – 2.100	–	–
PCBs (ng/g wet weight)				
Total PCBs ^d	7.715	0.185 – 61.193	0	1
Pesticides (ng/g wet weight)				
2,4'-DDD (o,p'-DDD)	0.000	0.000 – 0.000	–	–
2,4'-DDE (o,p'-DDE)	0.007	0.000 – 0.195	–	–
2,4'-DDT (o,p'-DDT)	0.013	0.000 – 0.481	–	–
4,4'-DDD (p,p'-DDD)	0.046	0.000 – 0.782	–	–
4,4'-DDE (p,p'-DDE)	0.967	0.000 – 5.457	–	–
4,4'-DDT (p,p'-DDT)	0.005	0.000 – 0.112	–	–
Total DDTs	1.038	0.000 – 6.547	–	–
Aldrin	0.000	0.000 – 0.000	–	–
cis- Chlordane	0.022	0.000 – 0.574	–	–
Chlorpyrifos	0.000	0.000 – 0.000	–	–
cis- Nonachlor	0.059	0.000 – 1.006	–	–
Dieldrin	0.060	0.000 – 0.524	0	0
Endosulfan I	0.000	0.000 – 0.000	0	0
Endosulfan II	0.000	0.000 – 0.000	–	–
Endosulfan sulfate	0.000	0.000 – 0.000	–	–
trans- Chlordane	0.005	0.000 – 0.200	–	–
Heptachlor	0.000	0.000 – 0.000	–	–
Heptachlor epoxide	0.002	0.000 – 0.063	0	0
Hexachlorobenzene	0.013	0.000 – 0.211	0	0
Lindane	0.000	0.000 – 0.000	0	0
Mirex	0.005	0.000 – 0.061	0	0
Oxychlordane	0.004	0.000 – 0.101	–	–
Total Chlordane ^c	0.166	0.000 – 3.079	0	0
trans- Nonachlor	0.076	0.000 – 1.199	–	–

^a Estimated as 2% of the measured total arsenic.

^b Measured as total mercury and assumed to be all methylmercury.

^c Sum of 13 measured PBDE congeners.

^d Sum of 84 measured PCB congeners.

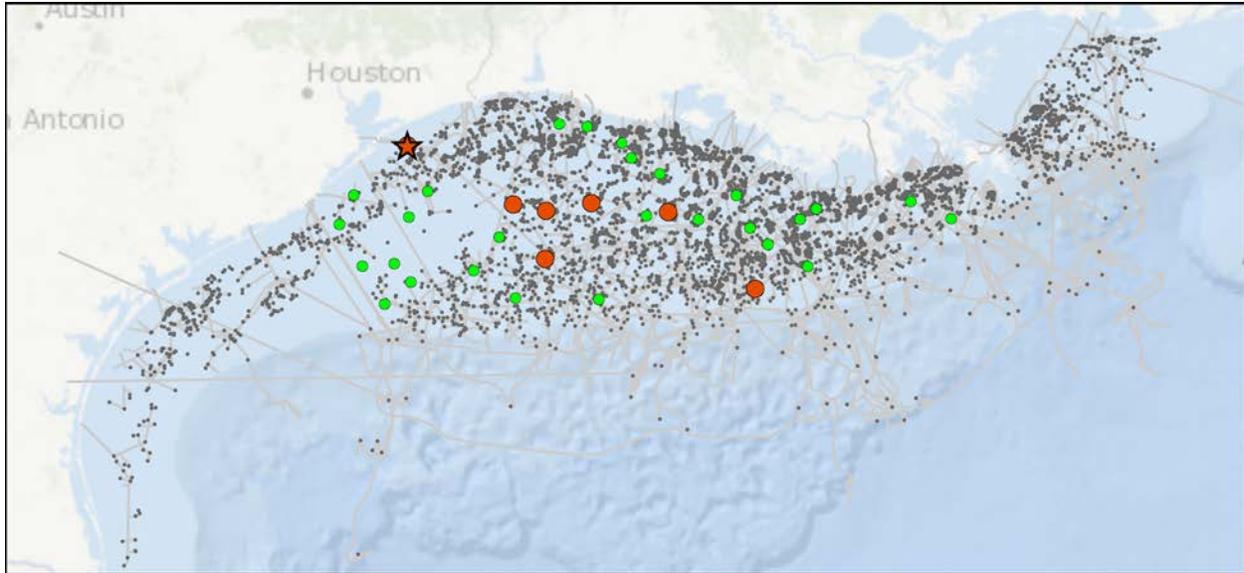


Figure 17. Locations of sites where tissue contaminant levels measured in fish were found to exceed the corresponding non-cancer human health guidelines (U. S. EPA 2000). The lower, non-cancer endpoint for methylmercury (measured as mercury and assumed to be all methylmercury) was exceeded at seven sites (red symbols); the upper, non-cancer endpoint for total PCBs also was exceeded at one of these sites (indicated by starred symbol). Locations of oil and gas platforms and pipelines are shown for reference (see Figure 11).

3.4 Status of Benthic Communities

Macrobenthic infauna (those retained on a 0.5-mm sieve) were collected at all 34 stations. Two grabs (0.04 m² each) were collected at each station, resulting in a total of 68 grabs. Measures of taxonomic diversity and abundance were calculated separately for each of the 68 grabs and averaged by station where indicated in Table 10 (e.g., mean # taxa/0.04 m², mean H'/0.04 m²). The resulting data were used to assess the status of benthic community characteristics (taxonomic composition, diversity, abundance, and dominant taxa), the incidence of non-indigenous species, and potential linkages to ecosystem stressors throughout northwest GOM shelf waters.

3.4.1 Taxonomic Composition

A total of 310 taxa were identified throughout the study area, of which 189 were identified to the species level. Polychaetes were the dominant taxa (Figure 17, Table 11), both by percent of taxa (47.4 %) and percent abundance (60.2 %). In terms of numbers of taxa, crustaceans and molluscs (bivalves + gastropods) were the second and third dominant taxa (22.6 % crustaceans, 24.2 % molluscs), whereas bivalve molluscs and 'other' taxa (see Table 11 for list of members of this group) were the second and third most abundant taxa (16.8 % and 12.2 %, respectively). Collectively, polychaetes, crustaceans, and molluscs made up 94.2 % of total taxa (by percent number of taxa), while polychaetes, bivalve molluscs, and 'other' taxa comprised 89.2 % of total faunal abundance. Crustaceans were represented primarily by amphipods (23 identifiable taxa, 7.4 % of the total number of taxa), followed by decapods (22 taxa, 7.1 % of total taxa), isopods (9 taxa, 2.9 % of total taxa), and tanaidaceans and cumaceans (7 taxa each, 4.6 % of total taxa both groups combined; Table 11). Molluscs were represented mainly by bivalves (53 taxa, 17.1 % of total taxa), followed by gastropods (22 taxa, 7.1 % of total taxa).

Table 10. Mean, range, and selected distributional properties of key benthic variables. The benthic measures represent 68 0.04-m² grabs collected at 34 sites (2 replicate grabs at each station) in the northwest GOM.

	Overall Mean	Overall Range	Area-based Percentiles ^a			Frequency-based percentiles ^b				
			CDF 10 th pctl	CDF 50 th pctl	CDF 90 th pctl	10 th	25 th	50 th	75 th	90 th
Total # Taxa/0.08 m ²	27	0–90	3	18	62	4	13	18	31	62
Mean # Taxa/0.04 m ²	16	0–56	3	11	38	4	9	12	17	38
Mean Density (#/m ²)	1,215	0–4,563	108	600	3,028	138	375	675	2,238	3,113
Mean H'/0.04 m ²	3.0	0–5.2	1.3	2.8	4.8	1.7	2.2	2.9	3.7	4.9

^a Value of benthic variable corresponding to the designated cumulative % area of the estimated CDF.

^b Corresponding lower 10th percentile, lower quartile, median, upper quartile, and upper 10th percentile of all values for each benthic variable.

Mean # taxa, mean density, and mean H' represent the average of each of those measures calculated separately for the two grabs.

Total # taxa is the total number of taxa in both replicate grabs combined (0.08 m²).

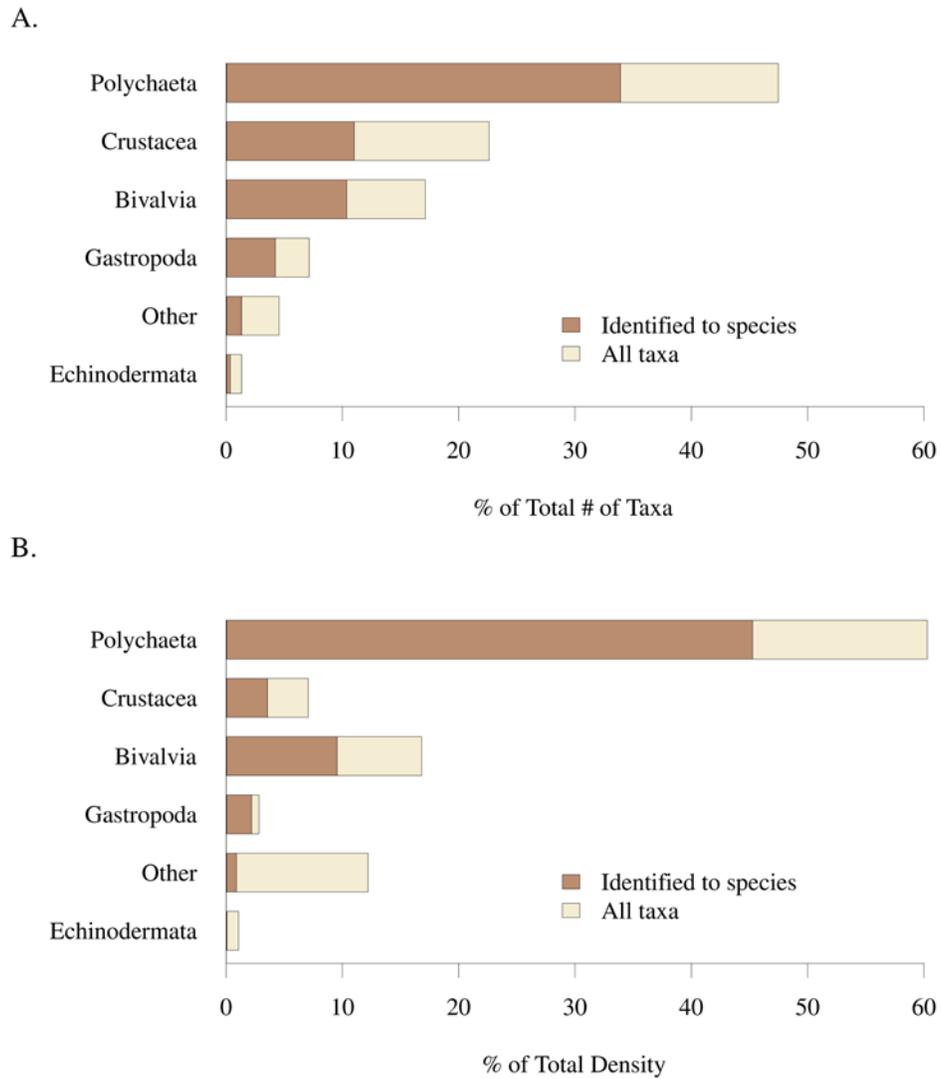


Figure 18. Taxonomic composition of benthic infauna as (A) percent of total number of taxa and (B) percent of total density.

Table 11. Summary of major taxonomic groups of benthic infauna and corresponding numbers of identifiable taxa based on 68 0.04-m² grab samples.

Taxonomic Group	Number identifiable taxa	% Total identifiable taxa
Phylum Annelida		
Class Clitellata		
Subclass Oligochaeta*	1	0.3
Class Polychaeta	147	47.4
Phylum Arthropoda		
Subphylum Crustacea		
Class Malacostraca		
Order Amphipoda	23	7.4
Order Cumacea	7	2.3
Order Decapoda	22	7.1
Order Isopoda	9	2.9
Order Mysida	1	0.3
Order Stomatopoda	1	0.3
Order Tanaidacea	7	2.3
Phylum Brachiopoda*	1	0.3
Phylum Cnidaria*	1	0.3
Phylum Echinodermata		
Class Asteroidea	2	0.6
Class Ophiuroidea	2	0.6
Phylum Hemichordata*	1	0.3
Phylum Mollusca		
Class Aplacophora*	1	0.3
Class Bivalvia	53	17.1
Class Gastropoda	22	7.1
Class Scaphopoda	4	1.3
Phylum Nemertea*	1	0.3
Phylum Sipuncula*	4	1.3
<i>Total</i>	<i>310</i>	<i>100</i>

* Taxonomic groups followed by an asterisk were assigned to the group 'Other' in Figure 17.

3.4.2 Abundance and Dominant Taxa

A total of 3,304 individuals were collected across the 34 stations (68, 0.04 m² grabs) sampled for benthos. Mean densities at each site ranged from 0 – 4,563 ind/m² and averaged 1,215 ind/m² (Table 10, Appendix E). On an area-weighted basis, 10 % of the survey area (lower 10th percentile) had mean densities ≤ 108 ind/m² and 50 % of the area had mean densities ≤ 600 ind/m² (Table 10, Figure 18).

The 50 most abundant taxa collected in the northwest GOM coastal shelf study area are listed in Table 12. The top 10 dominants, in decreasing order of abundance, included the spionid (Family Spionidae) polychaete *Paraprionospio pinnata*; members of Phylum Nemertea ('ribbon worms'); Phylum Sipuncula ('peanut worms'); the capitellid polychaete genus *Mediomastus*; the polychaete Family Maldanidae; the spionid polychaete *Meredithia uebelackerae* (= *Magelona uebelackerae*); unidentified bivalve molluscs (Class Bivalvia); the lumbrinerid polychaete *Scoletoma verrilli*; the capitellid polychaete *Notomastus daueri*; and unidentified cirratulid polychaetes (Family Cirratulidae).

3.4.3 Diversity

A total of 310 taxa were identified (189 to species) in 68 grabs collected throughout the study area. Means, ranges, and other distributional properties are displayed in Table 10, with the full distribution of area-weighted estimates illustrated in Figure 18. Taxonomic richness, expressed as the mean number of taxa present in replicate 0.04 m² grabs at a station, ranged from 0 to 56 taxa/grab, with an overall mean of 16 taxa/grab. Shannon H' diversity (base-2 logarithms) varied between 0 and 5.2 (mean of 3.0), and was inversely correlated with longitude (i.e., diversity increased with distance west away from the Mississippi River delta; Figure 19).

Table 12. Fifty most abundant benthic taxa. Mean density (#/m²), and percent frequency of occurrence are based on 68 0.04-m² grabs. Classification: Native = native species; Crypto = cryptogenic species (of uncertain origin); Indeter = indeterminate taxon (not identified to a level that would allow determination of origin).

Taxon	Group	Classification	Density	Frequency (% of samples)
<i>Paraprionospio pinnata</i>	Polychaeta	Native	7,513	73.5
Nemertea	Other	Indeter	2,188	69.1
Sipuncula	Other	Indeter	2,038	44.1
<i>Mediomastus</i> sp.	Polychaeta	Native	1,400	45.6
Maldanidae	Polychaeta	Indeter	1,200	30.9
<i>Meredithia uebelackerae</i>	Polychaeta	Native	1,075	32.4
Bivalvia	Bivalvia	Indeter	1,013	33.8
<i>Scoletoma verrilli</i>	Polychaeta	Native	925	35.3
<i>Notomastus daueri</i>	Polychaeta	Native	800	27.9
Cirratulidae	Polychaeta	Indeter	600	29.4
<i>Cossura soyeri</i>	Polychaeta	Native	550	22.1
<i>Ampelisca</i> sp.	Crustacea	Native	488	25.0
<i>Crassinella lunulata</i>	Bivalvia	Native	475	11.8
<i>Diplodonta semiaspera</i>	Bivalvia	Native	463	13.2
<i>Sigambra tentaculata</i>	Polychaeta	Native	438	32.4
<i>Cirrophorus lyra</i>	Polychaeta	Native	388	14.7
<i>Tellina</i> sp.	Bivalvia	Native	388	17.6
<i>Gouldia cerina</i>	Bivalvia	Native	375	8.8
Spionidae	Polychaeta	Indeter	363	14.7
<i>Volvulella texasiana</i>	Gastropoda	Native	363	25.0
Lucinidae	Bivalvia	Indeter	350	5.9
<i>Thyasira trisinuata</i>	Bivalvia	Native	350	2.9
<i>Paramphinome</i> sp. B	Polychaeta	Native	325	19.1
<i>Nereis micromma</i>	Polychaeta	Native	325	13.2
<i>Levinsenia reducta</i>	Polychaeta	Native	325	11.8
<i>Notomastus</i> sp.	Polychaeta	Native	325	19.1
<i>Tellina versicolor</i>	Bivalvia	Native	325	5.9
<i>Apoprionospio dayi</i>	Polychaeta	Native	313	4.4
<i>Nuculana acuta</i>	Bivalvia	Native	300	17.6
<i>Xenanthura brevitelson</i>	Crustacea	Native	300	13.2
<i>Prionospio</i> sp.	Polychaeta	Native	288	17.6
<i>Clymenella torquata</i>	Polychaeta	Native	288	16.2
Ophiuroidea	Echinodermata	Indeter	275	14.7
<i>Sabaco elongatus</i>	Polychaeta	Native	263	23.5
<i>Corbula</i> sp.	Bivalvia	Native	263	7.4
<i>Terebellides stroemi</i>	Polychaeta	Native	250	11.8
Actiniaria	Other	Indeter	238	14.7
Onuphidae	Polychaeta	Indeter	225	13.2
<i>Levinsenia gracilis</i>	Polychaeta	Native	225	20.6
<i>Cossura delta</i>	Polychaeta	Native	225	17.6
<i>Fabricinuda trilobata</i>	Polychaeta	Native	225	5.9
<i>Nucula proxima</i>	Bivalvia	Native	225	13.2
Corbulidae	Bivalvia	Indeter	225	16.2
<i>Monticellina dorsobranchialis</i>	Polychaeta	Native	213	13.2
<i>Notomastus latericeus</i>	Polychaeta	Native	213	13.2
Nereididae	Polychaeta	Indeter	200	14.7
Aricidea	Polychaeta	Indeter	200	16.2
<i>Apoprionospio pygmaea</i>	Polychaeta	Native	200	2.9
<i>Magelona</i> sp. L	Polychaeta	Native	200	14.7
<i>Sthenelais</i> sp. A	Polychaeta	Native	175	5.9

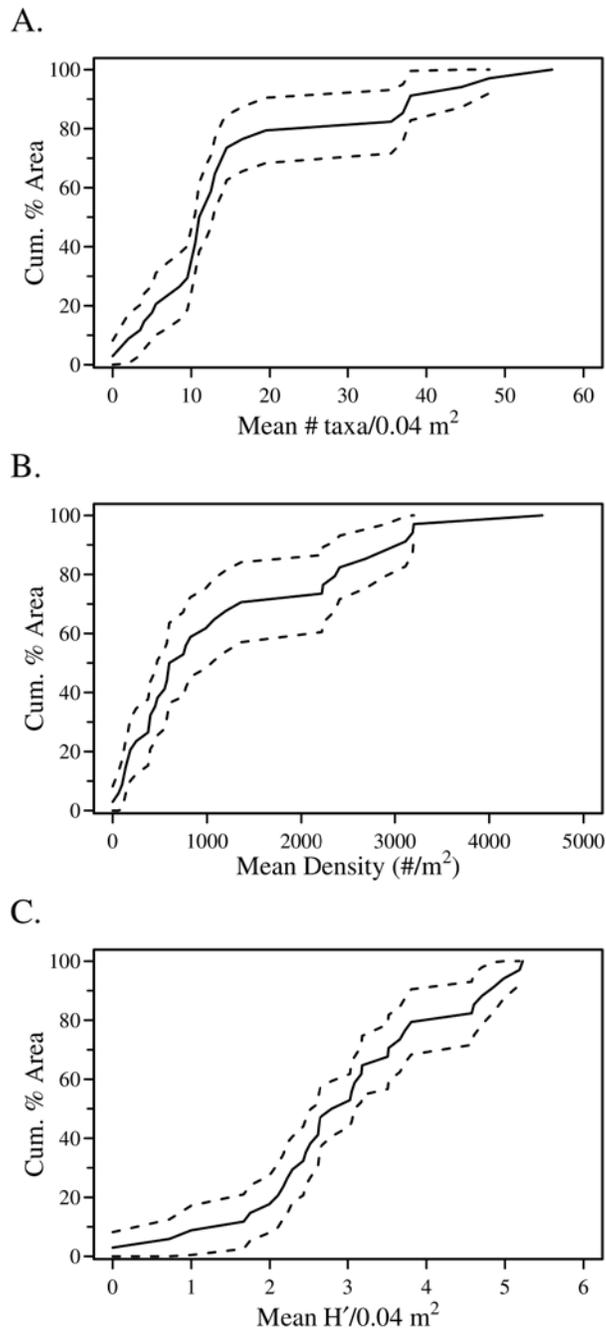


Figure 19. Percent area (and 95% confidence intervals) of GOM study area vs. benthic infaunal taxonomic richness (A), density (B), and H' diversity (C)

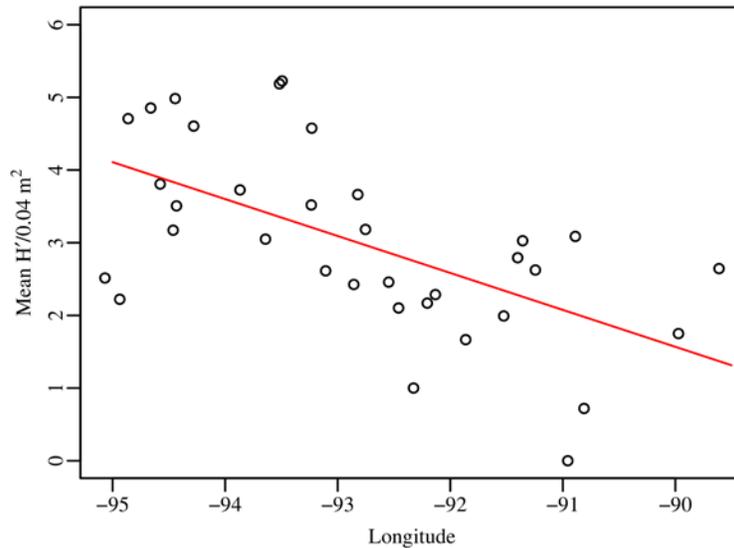


Figure 20. Plot of Shannon diversity (H') vs. longitude in the northwest GOM.

3.4.4 Patterns of benthic infaunal distributions

Benthic ecological community data were analyzed for patterns in faunal distributions using hierarchical cluster analysis of Bray-Curtis dissimilarities (unweighted pair-group method with arithmetic mean, or UPGMA) and analysis of similarity profiles (SIMPROF) to identify significant site groups. Non-metric multidimensional scaling (NMDS) was also used to confirm the site groups obtained from hierarchical cluster analysis. Canonical discriminant analysis (CANDISC) was used to help explain the observed groupings based on measured abiotic factors. Analyses were performed on a species-by-station matrix of square root-transformed abundances after removing rare species (those occurring in less than 5 % of all samples) and a station-by-variable matrix of environmental (abiotic) factors.

Four overall site groupings (Figure 20) emerged from the hierarchical cluster analysis and analysis of similarity profiles (SIMPROF). Significant clusters were identified by comparing the observed similarity profiles to the mean of 1,000 permuted profiles (performed across sites for each species) at a significance level of 0.1 % ($\alpha=0.001$). Results of NMDS ordination confirmed the site groupings identified in the cluster analysis, as illustrated in Figure 21.

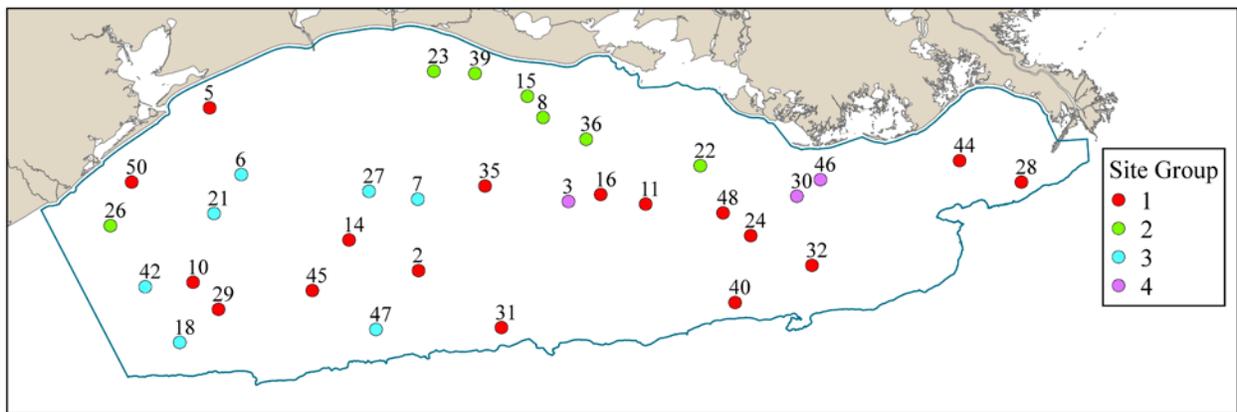
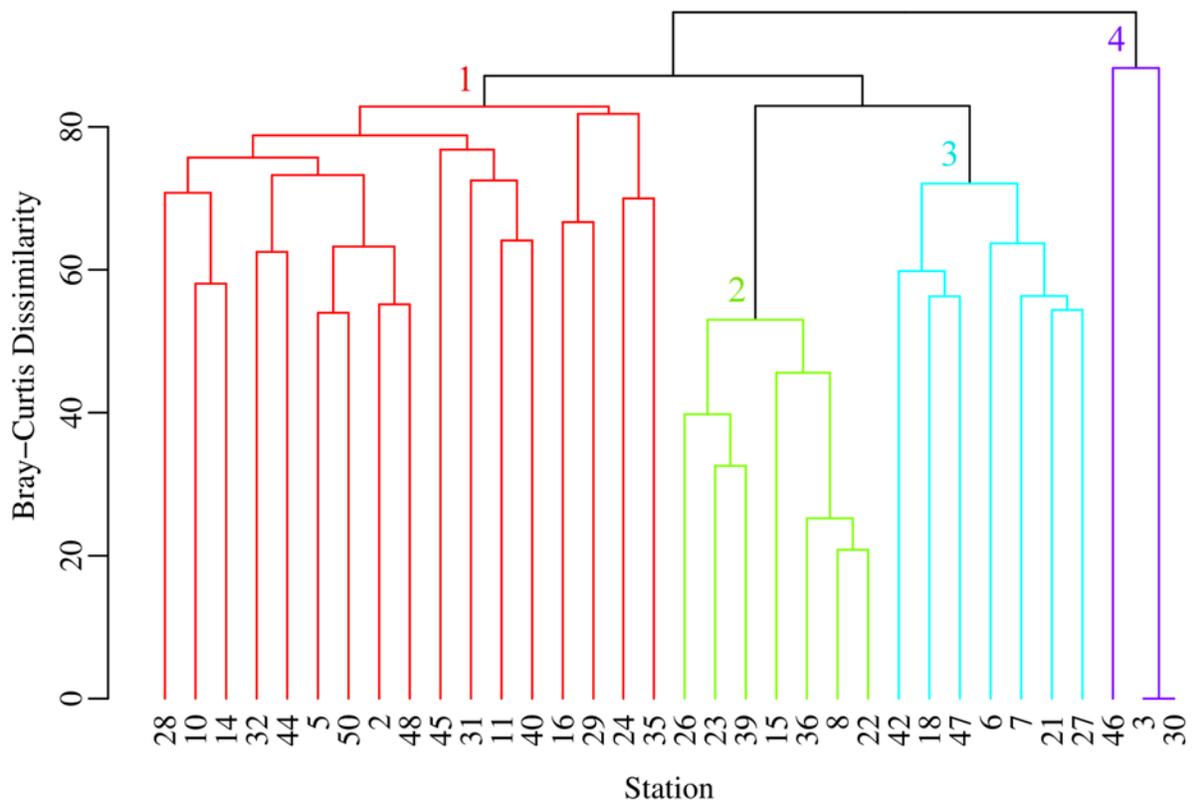


Figure 21. Dendrogram resulting from hierarchical cluster analysis of Bray-Curtis dissimilarities, calculated from square-root transformed infaunal abundance (after removing rare species), from 34 sites in the northwest GOM. Numbers above each group of branches refer to site groups discussed in the text. Map shows locations of stations and corresponding site group assignments.

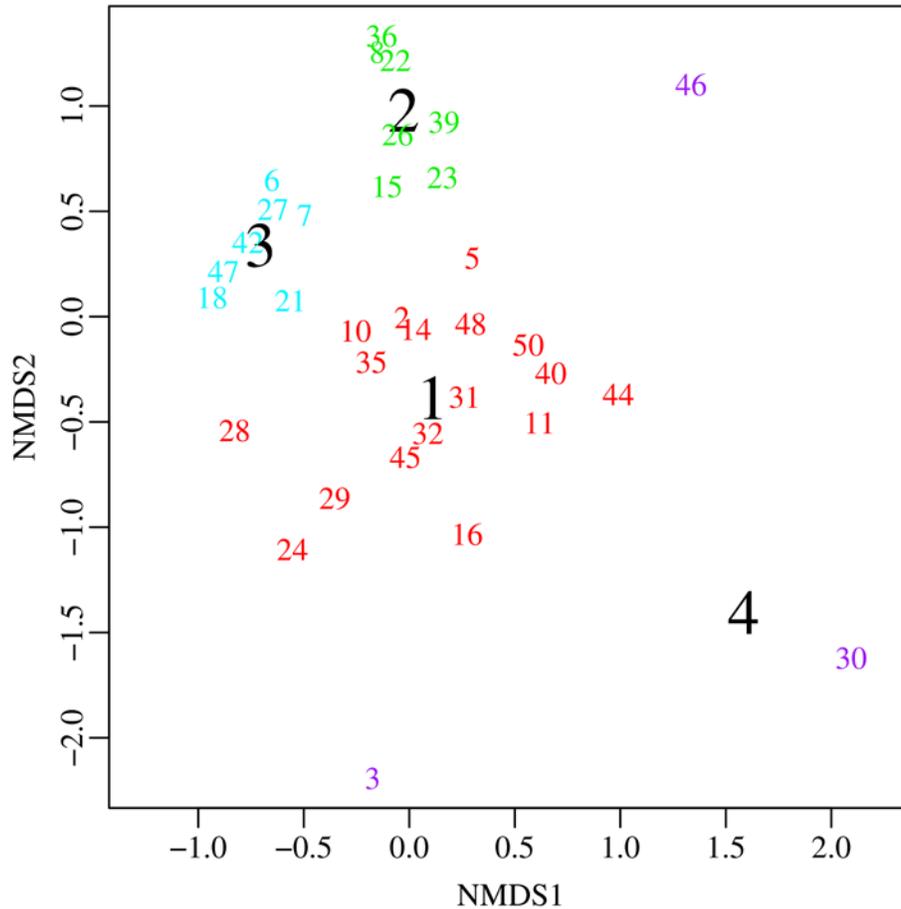


Figure 22. Ordination plot derived from non-metric multidimensional scaling (NMDS) of Bray-Curtis dissimilarities calculated from square-root transformed infaunal abundance (after removing rare species) from 34 sites in the northwest GOM.

CANDISC analysis suggests that the four site clusters can be explained by a relatively small number of environmental factors. A preliminary CANDISC analysis was run on the following abiotic factors: % silt-clay, % TOC, mean ERM-Q, TPH, DIN, DO, $\Delta\sigma_t$, longitude, Chl *a* ($\mu\text{g/L}$), dissolved silicate (SI $\mu\text{g/L}$), TSS (mg/L), and station depth (m). Factors for which univariate analysis of variance (ANOVA) tests were non-significant were removed first, followed by those with small factor loadings in the CANDISC. Environmental variables with the highest factor loadings (total structure coefficients) on the first two canonical variables included % silt-clay, % TOC, mean ERM-Q, DIN, and DIP (Table 13). Together, the first two canonical variables explained 92.4 % of the variance among site groups. Scores for the first two canonical variables are plotted in Figure 22, with 95 % confidence circles and variable vectors for each of the five abiotic factors listed in Table 13.

Table 13. Total structure coefficients on the first two canonical variables of a canonical discriminant model relating sediment % silt-clay, sediment % TOC, mean ERM-Q, and bottom-water DIN and DIP to site groups obtained from hierarchical cluster analysis of Bray-Curtis dissimilarities calculated from square-root transformed abundance (after removing rare species) from 34 sites in the northwest GOM.

Variable	Can1 (59.4%)	Can2 (33.0%)
% Silt-Clay	0.794058	-0.578323
% TOC	0.722009	-0.285885
Mean ERM-Q	0.754175	-0.461349
DIN (mg/L)	0.624628	0.451858
DIP (mg/L)	0.594892	0.696552

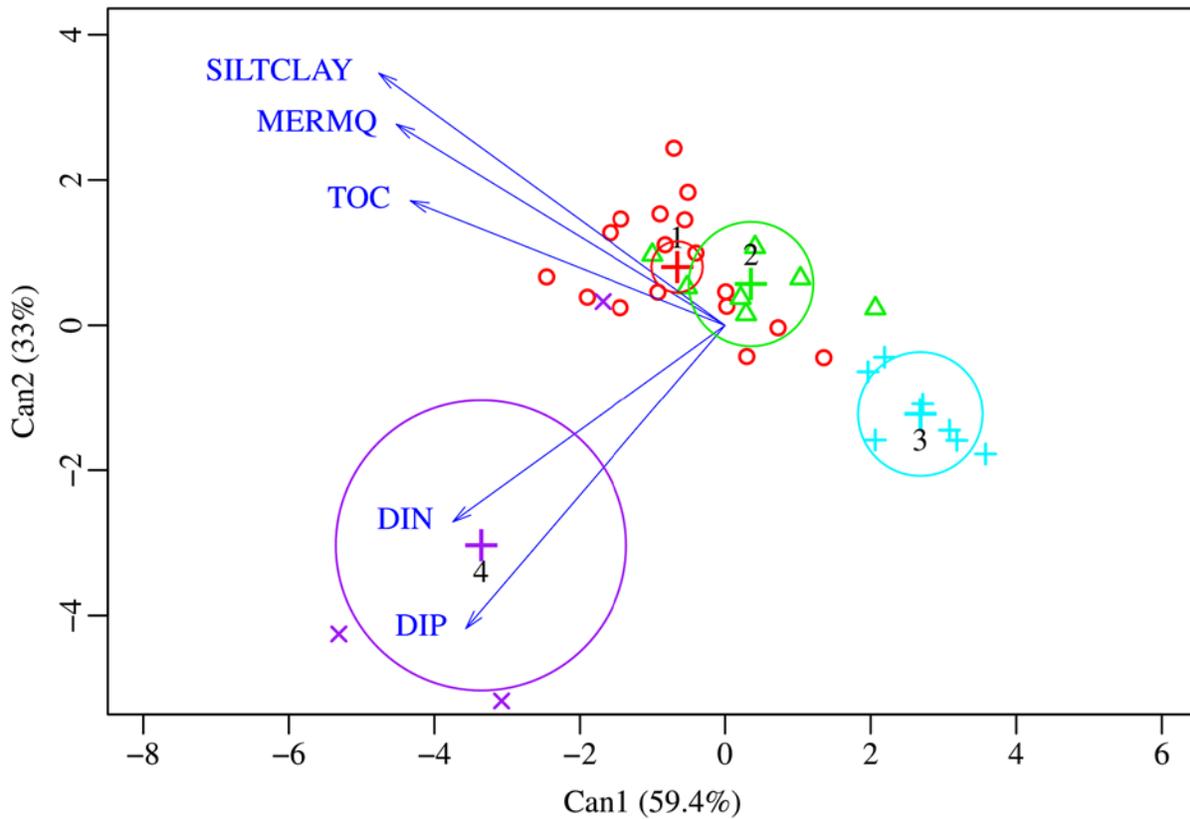


Figure 23. Plot of the first two canonical variables for a canonical discriminant model relating sediment % silt-clay, sediment % TOC, mean ERM-Q, and bottom-water DIN and DIP to site groupings derived from hierarchical cluster analysis of Bray-Curtis dissimilarities calculated from square-root transformed infaunal abundance (after removing rare species) from 34 sites in the northwest GOM.

Strong correlations were noted among some of the remaining factors not retained from the CANDISC analysis. For example, bottom DIN was highly (positively) correlated with bottom DIP, SI, and Chl *a*. All of these variables (bottom DIN, DIP, SI, and Chl *a*) had significant negative correlations with bottom DO. Chlorophyll *a* also was highly correlated with $\Delta\sigma_t$, but only for relatively shallow sites (those with depths < ~30 m). Also, several variables showed strong correlations with longitude: higher levels of bottom DIN, DIP, sediment silt-clay, TOC, and mean ERM-Q were associated with longitudes in closer proximity to the Mississippi and Atchafalaya River deltas, as were lower levels of bottom DO.

Site group (SG) 4 was characterized mainly by stations having high bottom DIN and DIP, and low bottom DO (2 of 3 stations). Two stations in SG4 (stations 30 and 46) had $DO \leq 0.1$ mg/L and sediments had an odor of hydrogen sulfide (indicative of bacterial decomposition of organic matter under anaerobic conditions). All three stations in SG4 had very low species richness and abundance (one site was azoic). Site groups 2 and 3 separated from the other two site groups mainly on the basis of % TOC, having low concentrations of TOC compared to site groups 1 and 4. While SGs 2 and 3 both had relatively low levels of TOC, they differed from one another in levels of % silt-clay, with SG2 having more fine-grained sediments (mean silt-clay fraction = 70 %) compared to SG3 (mean silt-clay fraction = 27 %). Stations in SG3 also had the highest species richness and diversity compared to the other site groups. In addition to SG4 having low DO and high nutrients, SG1 and SG4 both were mainly characterized by sediments with high % silt-clay and TOC, and moderate (> 0.013 – 0.036) mean ERM-Q values (with the exception of two sites near the Mississippi River delta having mean ERM-Q values of 0.038 and 0.045, as noted previously). With only a few exceptions, most stations in SG1 had relatively high DO concentrations (> 5 mg/L) and low DIN (< 0.1 mg/L).

3.4.5 Non-indigenous Species

The list of taxa was examined for the occurrence of non-native and exotic species by searching NISbase, a distributed database on non-indigenous species that queries a number of different information systems. Databases that are part of NISbase include the U.S. Geological Survey (USGS) National Aquatic Species Database (NAS, U.S. Geological Survey 2004), the Smithsonian National Exotic Marine and Estuarine Species Information System (NEMESIS, Fofonoff et al. 2003), and the NOAA National Benthic Inventory (NBI 2004), among others. None of the species collected as part of the present survey are considered to be non-indigenous in the region studied (northwest GOM coastal shelf). A number of specimens collected in this study were only identified to higher taxonomic level (e.g., Order Actiniaria; Family Mysidae). Hence, it was not possible to determine definitively whether additional known invasives from these groups were present.

3.5 Potential Linkage of Biological Condition to Stressor Impacts

Multi-metric benthic indices are commonly used to summarize and classify benthic habitat conditions along the continuum from non-degraded to degraded (see review by Diaz et al. 2004) and have been developed for a variety of estuarine applications (Engle et al. 1994, Weisberg et al. 1997, Van Dolah et al. 1999, Llansó et al. 2002a, 2002b, Hale and Heltshe 2008). A desired characteristic of these indices is the ability to discriminate between impaired versus unimpaired benthic condition, based on key biological attributes (e.g., numbers of species, diversity, abundance, biomass, relative proportion of pollution-sensitive or pollution-tolerant species), while taking into account natural controlling factors. As examples, such indices have been developed for estuaries of the mid-Atlantic states and Chesapeake Bay (Weisberg et al. 1997, Llansó et al. 2002a, 2002b), southeastern estuaries (Van Dolah et al. 1999), estuaries of the northern Gulf of Mexico (Engle et al. 1994, Engle and Summers 1999), the southern California mainland shelf (Smith et al. 2001), nearshore Gulf of Maine (Hale and Heltshe 2008), and near-coastal waters off NJ (Strobel et al. 2008). More recently, a benthic index has been developed for estuarine and near-coastal waters of the entire GOM (Tetra Tech 2011), but no such index exists that would be directly applicable to offshore waters of the northwest GOM continental shelf.

In the absence of a benthic index, we attempted to assess potential stressor impacts in the present study by evaluating linkages between reduced values of biological attributes (numbers of taxa, diversity, and abundance) and synoptically measured indicators of poor sediment or water quality. Using the lower 10th percentile as a basis for defining 'low' values, we looked for co-occurrences of low values of biological attributes with indications of poor sediment or water quality defined as follows (U.S. EPA 2008): ≥ 1 chemical in excess of ERMs (from Long et al. 1995), TOC > 50 mg/g, and DO in near-bottom water < 2.0 mg/L.

In the present study, average station values for all three measures of benthic infaunal abundance, richness, and diversity were lower in comparison to related studies conducted in other U.S. Atlantic and GOM shelf regions (Figure 23). Low values of taxa richness and diversity were associated with poor water quality (as defined above) at two of these sites (stations 30 and 46), both of which had very low DO (< 0.1 mg/L) accompanied by high DIN. Both stations were

located in an area known for experiencing annual hypoxia from spring to early fall (Rabalais et al. 2002, Turner et al. 2012). Other investigators have documented that below oxygen concentrations of 0.5 mg/L there is a fairly linear decline in species richness, abundance and biomass of benthic macroinfauna on the Louisiana continental shelf (Levin et al. 2009, Rabalais et al. 2001b).

In contrast, we found no association of low values of the above biological attributes with indicators of poor sediment quality, since none of the measures of sediment quality fell within the poor range (as defined here). The highest TOC concentration was 12.9 mg/g (Appendix A), well below the 50 mg/g bioeffect threshold used here (from EPA 2008) as well as the more conservative bioeffect threshold of 35 mg/g TOC published by Hyland et al. (2005). Also, no ERM exceedances were observed (Appendix D). These results suggest that sediments in the surveyed area of the northwest GOM seem to be in good condition with respect to contaminants and TOC. Indications of stress in benthic infaunal assemblages appear to be related primarily to the well-documented hypoxic “Dead Zone” along the inner Louisiana continental shelf.

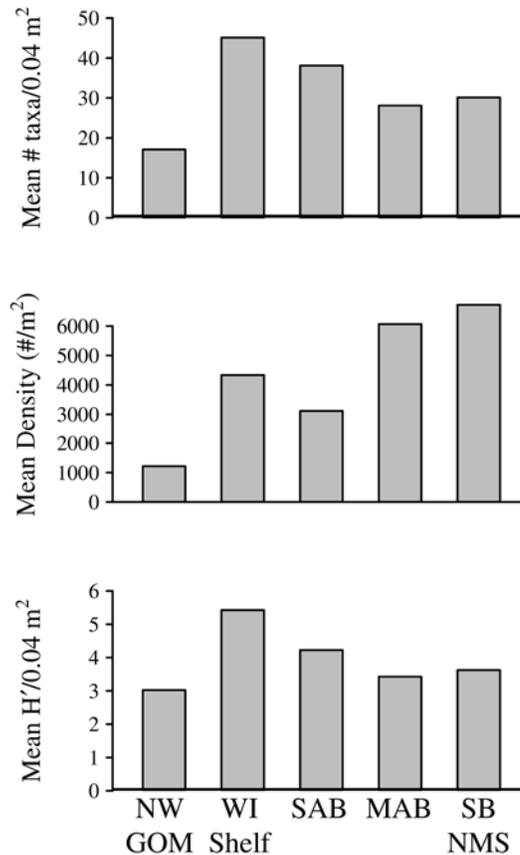


Figure 24. Comparison of measures of benthic infaunal abundance and diversity for the northwest GOM coastal shelf and other surveyed regions of the U.S. Atlantic and Gulf coastal shelf: WI Shelf (Cooksey et al. 2012), SAB (Cooksey et al. 2010), MAB (Balthis et al. 2009), SBNMS (Balthis et al. 2011).

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5.0 Appendices

Appendix A. Locations (latitude, longitude), depth, and sediment characteristics of sampling stations.

Station	Latitude	Longitude	Depth (m)	Gravel (%)	Sand (%)	Silt-Clay (%)	TOC (mg/g)
2	28.46568	-93.23498	44.9	0.0	14.8	85.3	6.6
3	28.80551	-92.32641	33.2	0.0	0.2	99.9	10.1
5	29.35128	-94.46214	13.4	0.0	32.1	67.9	5.9
6	28.99617	-94.27983	17.5	0.6	89.1	10.2	1.2
7	28.84163	-93.23053	26.0	0.1	81.7	18.1	1.3
8	29.25348	-92.45907	13.0	0.0	35.9	64.1	1.8
10	28.43109	-94.57719	40.7	0.0	35.7	64.3	4.9
11	28.77335	-91.86272	28.7	0.2	7.5	92.3	4.7
14	28.63782	-93.64192	34.0	0.0	26.4	73.6	5.3
15	29.36910	-92.54710	13.0	0.8	24.2	75.0	3.0
16	28.83473	-92.13220	29.3	0.0	0.5	99.5	7.1
18	28.11170	-94.66162	56.0	0.3	69.7	30.0	1.9
21	28.79222	-94.44418	25.1	0.9	61.2	37.9	1.3
22	28.96346	-91.52482	13.5	0.0	12.7	87.3	2.6
23	29.51665	-93.10694	13.2	0.0	18.2	81.8	4.5
24	28.58138	-91.24372	31.0	0.0	20.3	79.7	6.3
26	28.73637	-95.06802	22.0	0.0	27.2	72.8	6.1
27	28.89327	-93.51757	22.0	0.2	82.9	16.9	1.8
28	28.78113	-89.61170	83.0	0.0	1.3	98.7	11.9
29	28.28362	-94.43266	48.3	0.4	48.1	51.5	3.4
30	28.77697	-90.95576	15.3	0.0	16.2	83.8	7.2
31	28.15103	-92.75326	77.3	0.0	4.5	95.5	6.8
32	28.40644	-90.88850	42.1	0.8	10.6	88.7	5.8
35	28.90307	-92.82142	25.8	0.0	26.0	74.0	6.1
36	29.12817	-92.20402	13.5	0.1	65.4	34.5	1.7
39	29.49957	-92.85714	13.4	0.0	27.7	72.4	3.7
40	28.23202	-91.35672	82.0	0.0	0.2	99.8	7.9
42	28.41152	-94.86200	38.5	0.9	55.5	43.6	2.9
44	28.91518	-89.97200	34.0	0.0	0.4	99.6	12.9
45	28.37622	-93.86803	54.5	0.0	12.3	87.7	6.4
46	28.85815	-90.81122	13.5	0.1	55.3	44.5	3.9
47	28.16147	-93.49432	64.8	1.5	66.4	32.1	2.9
48	28.70927	-91.40098	24.0	0.0	15.9	84.1	6.4
50	28.96487	-94.93657	18.7	0.0	1.4	98.6	10.6

Appendix B. Near-bottom water characteristics by station.

Station	Temp. (°C)	Salinity (psu)	DO (mg/L)	pH	DIP (mg/L)	DIN (mg/L)	Nitrate+ Nitrite (µg/L)	Ammonium (µg/L)	N/P	Silicate (µg/L)	Chlorophyll <i>a</i> (µg/L)	Turbidity (NTU)	TSS (mg/L)
2	21.9	36.3	5.6	8.0	0.004	0.055	21.7	33.0	13.34	500.0	2.04	1.7	6.8
3	26.3	36.1	6.1	8.0	0.004	0.023	2.7	20.0	5.54	180.0	1.50	2.5	9.6
5	30.5	36.3	5.9	8.0	0.006	0.028	4.5	23.0	4.37	220.0	2.44	5.5	7.0
6	30.6	35.8	6.3	8.1	0.003	0.027	4.4	23.0	8.06	230.0	0.68	0.8	7.4
7	26.9	35.5	4.6	8.0	0.004	0.025	1.9	23.0	6.73	300.0	0.68	0.4	6.7
8	30.6	31.1	6.3	8.1	0.004	0.020	3.2	17.0	5.46	260.0	0.68	0.8	5.4
10	24.4	36.4	6.7	8.1	0.003	0.021	2.0	19.0	7.50	810.0	0.68	0.7	7.2
11	26.7	36.0	6.1	8.1	0.003	0.023	2.5	20.0	7.26	150.0	1.46	3.8	7.2
14	28.9	36.1	6.3	8.1	0.004	0.032	3.9	28.0	8.39	280.0	0.68	1.8	7.9
15	30.6	32.1	5.9	8.1	0.003	0.027	4.4	23.0	8.56	460.0	2.63	2.0	6.6
16	28.2	36.2	6.7	8.1	0.003	0.018	3.1	15.0	6.70	130.0	0.68	1.4	10.4
18	24.8	36.5	6.8	8.1	0.004	0.024	4.5	19.0	6.53	230.0	0.68	0.5	6.4
21	30.1	36.3	6.5	8.1	0.003	0.018	2.4	16.0	6.57	270.0	0.68	0.6	8.6
22	26.2	35.1	0.1	7.7	0.026	0.139	107.0	32.0	5.39	1140.0	15.07	2.4	6.4
23	31.0	34.4	5.9	8.1	0.008	0.028	3.9	24.0	3.49	340.0	2.59	6.6	11.0
24	24.5	35.7	1.7	7.8	0.013	0.176	157.0	19.0	13.54	870.0	1.32	3.1	11.5
26	29.7	36.4	6.6	8.1	0.003	0.029	5.7	23.0	9.26	210.0	0.68	0.4	7.4
27	30.3	35.7	6.2	8.1	0.004	0.029	2.8	26.0	8.00	270.0	0.68	0.7	7.4
28	19.4	36.4	4.5	8.0	0.007	0.084	61.2	23.0	12.03	540.0	0.68	2.5	9.2
29	23.4	36.4	6.0	8.1	0.004	0.023	2.6	20.0	5.14	280.0	0.73	1.8	8.0
30	26.3	34.9	0.0	7.7	0.092	0.367	3.0	364.0	3.97	1820.0	10.56	14.1	3.5
31	19.8	36.4	4.7	8.0	0.005	0.117	98.3	19.0	25.50	300.0	0.79	2.9	9.9
32	24.1	36.2	6.6	8.0	0.005	0.041	24.0	17.0	8.04	120.0	1.02	1.2	7.4
35	30.5	33.9	6.4	8.1	0.003	0.024	3.0	21.0	9.23	150.0	0.68	0.7	31.7
36	26.3	34.9	0.4	7.7	0.013	0.149	119.0	30.0	11.29	860.0	3.65	3.4	6.9
39	31.0	33.8	6.1	8.0	0.009	0.043	19.5	23.0	5.00	840.0	5.07	6.5	9.0
40	20.3	36.4	5.6	8.0	0.007	0.076	56.4	20.0	11.07	590.0	0.68	1.9	11.3
42	25.7	36.4	6.7	8.1	0.003	0.021	3.0	18.0	6.56	310.0	0.68	0.5	12.7
44	23.9	36.4	5.7	8.0	0.007	0.095	55.9	39.0	13.00	250.0	0.68	0.7	139.2
45	21.0	36.4	4.3	8.0	0.008	0.102	83.0	19.0	12.29	400.0	1.26	2.8	10.1
46	26.3	35.3	0.1	7.7	0.081	0.292	5.8	286.0	3.61	1710.0	14.31	8.4	2.4
47	23.1	36.3	6.6	8.1	0.007	0.026	3.6	22.0	3.46	210.0	0.68	0.6	8.9
48	26.5	35.3	2.8	7.9	0.016	0.109	88.5	20.0	6.66	820.0	3.72	1.3	9.7
50	28.4	36.4	5.5	8.0	0.005	0.040	27.0	13.0	8.00	310.0	1.13	1.1	7.6

Appendix C. Near-surface water characteristics by station.

Station	Temp. (°C)	Salinity (psu)	DO (mg/L)	pH	DIP (mg/L)	DIN (mg/L)	Nitrate+ Nitrite (µg/L)	Ammonium (µg/L)	N/P	Silicate (µg/L)	Chlorophyll <i>a</i> (µg/L)	Turbidity (NTU)	TSS (mg/L)
2	31.1	34.9	6.4	8.1	0.005	0.038	21.4	17.0	7.25	280.0	0.68	0.5	4.1
3	30.6	33.2	6.4	8.1	0.003	0.021	3.3	18.0	8.19	170.0	0.68	0.3	7.4
5	31.0	36.4	6.8	8.1	0.004	0.018	1.2	17.0	4.33	280.0	1.65	2.8	4.8
6	30.7	35.8	6.3	8.1	0.003	0.020	3.3	17.0	7.00	220.0	0.68	0.5	7.7
7	30.9	33.3	6.3	8.1	0.003	0.025	2.3	23.0	9.73	150.0	0.68	0.8	6.7
8	30.6	31.1	6.3	8.1	0.004	0.020	2.2	18.0	5.77	300.0	0.68	0.9	7.6
10	30.2	36.3	6.4	8.1	0.003	0.020	2.0	18.0	8.00	130.0	0.68	0.3	3.4
11	31.0	31.7	6.5	8.1	0.003	0.021	2.0	19.0	8.40	210.0	0.68	0.4	5.5
14	30.7	35.6	6.4	8.1	0.005	0.035	3.9	31.0	7.12	270.0	0.68	0.6	7.9
15	30.6	32.0	6.2	8.1	0.003	0.025	4.2	21.0	8.13	550.0	1.86	0.9	7.2
16	31.0	32.4	6.5	8.1	–	–	–	–	–	–	0.68	0.6	7.5
18	29.8	36.3	6.4	8.1	0.003	0.024	3.6	20.0	7.87	300.0	0.68	0.4	8.2
21	30.4	36.4	6.5	8.1	0.003	0.022	2.6	19.0	8.00	190.0	0.68	0.5	5.6
22	29.8	30.9	5.4	8.0	0.011	0.030	4.4	26.0	2.79	740.0	4.86	1.4	5.8
23	31.5	34.3	6.3	8.1	0.009	0.024	3.0	21.0	2.79	370.0	2.36	4.2	7.1
24	30.5	30.5	6.4	8.1	0.003	0.023	3.0	20.0	7.67	380.0	0.68	0.6	8.2
26	30.2	36.4	6.4	8.1	0.002	0.019	2.6	16.0	8.86	420.0	0.68	0.3	8.0
27	30.8	35.7	6.3	8.1	0.004	0.025	2.9	22.0	5.66	180.0	0.68	0.4	7.5
28	31.3	24.7	6.6	8.3	0.003	0.028	3.8	24.0	10.69	270.0	1.45	1.1	4.7
29	30.2	36.3	6.4	8.1	0.004	0.035	2.6	32.0	8.44	250.0	0.68	0.2	8.4
30	30.5	26.5	6.1	8.2	0.008	0.039	20.1	19.0	4.95	560.0	9.36	4.1	4.7
31	31.2	36.2	6.4	8.1	0.002	0.018	2.4	16.0	7.67	150.0	0.68	0.6	8.9
32	31.0	27.1	6.9	8.2	0.003	0.018	2.8	15.0	6.59	210.0	0.68	1.1	4.0
35	31.0	32.4	6.5	8.1	0.002	0.022	5.3	17.0	9.29	70.0	0.68	0.6	29.5
36	30.8	30.6	6.5	8.1	0.004	0.033	4.7	28.0	7.79	240.0	0.68	1.1	7.1
39	31.0	33.8	6.1	8.0	0.007	0.044	19.2	25.0	6.23	550.0	6.07	6.1	7.6
40	30.8	31.3	6.5	8.1	0.003	0.023	3.9	19.0	8.48	110.0	0.68	0.7	10.3
42	29.9	36.4	6.4	8.1	0.004	0.034	5.4	29.0	9.83	340.0	0.68	0.4	10.7
44	31.0	23.4	6.8	8.3	0.003	0.030	3.3	27.0	9.47	330.0	2.00	1.1	4.9
45	30.1	36.3	6.4	8.1	0.003	0.022	5.1	17.0	8.19	330.0	0.68	0.3	9.8
46	30.3	25.7	7.7	8.3	0.006	0.031	12.7	18.0	5.39	440.0	4.62	2.6	4.4
47	30.7	36.4	6.4	8.1	0.003	0.026	2.9	23.0	8.09	110.0	0.68	0.4	7.5
48	30.4	30.6	6.6	8.1	0.004	0.029	2.7	26.0	7.55	210.0	0.68	0.5	7.3
50	30.7	36.5	6.6	8.1	0.004	0.018	3.0	15.0	4.19	440.0	0.68	1.0	7.9

Appendix D. Summary by station of mean ERM quotients and the number of contaminants that exceeded corresponding ERL or ERM values (from Long et al. 1995).

Station	# of ERLs Exceeded	# of ERMs Exceeded	Mean ERM-Q
2	0	0	0.026
3	0	0	0.034
5	0	0	0.022
6	0	0	0.009
7	0	0	0.011
8	0	0	0.016
10	0	0	0.021
11	1	0	0.028
14	0	0	0.025
15	0	0	0.020
16	0	0	0.034
18	0	0	0.011
21	0	0	0.014
22	0	0	0.018
23	0	0	0.024
24	1	0	0.029
26	0	0	0.023
27	0	0	0.011
28	1	0	0.045
29	0	0	0.017
30	0	0	0.024
31	1	0	0.029
32	1	0	0.028
35	0	0	0.026
36	0	0	0.015
39	0	0	0.020
40	0	0	0.031
42	0	0	0.014
44	1	0	0.038
45	0	0	0.026
46	1	0	0.020
47	0	0	0.014
48	0	0	0.025
50	0	0	0.032

Appendix E. Summary by station of benthic macroinfaunal (>0.5mm) characteristics. Two replicate benthic grabs (0.04m² each) were processed from each station. H' derived using base 2 logarithms. (*Values within lower 25th percentile of all values of a specific benthic variable; **values within lower 10th percentile.)

Station	Mean # Taxa per Grab	Total # Taxa	Mean Density (# / m ²)	Mean H' per Grab
2	17	31	775	3.5
3	2**	4**	63**	1.0**
5	12	20	588	3.2
6	36	62	2900	4.6
7	38	61	3200	4.6
8	11	13*	2363	2.1*
10	20	32	1075	3.8
11	4*	7*	138**	1.7**
14	11	18	600	3.0
15	15	22	1363	2.5
16	5*	8*	138**	2.3
18	45	69	3188	4.9
21	37	60	2238	5.0
22	13	18	2413	2.0*
23	13	18	750	2.6
24	7*	13*	250*	2.6
26	12	17	1200	2.5
27	48	79	3113	5.2
28	10	16	825	2.6
29	13	23	550	3.5
30	0**	0**	0**	0.0**
31	11	19	400	3.2
32	10	17	388	3.1
35	14	23	450	3.7
36	11	16	2225	2.2*
39	10	13*	988	2.4
40	11	19	575	3.0
42	38	58	2688	4.7
44	4*	4**	100**	1.8*
45	14	23	475	3.7
46	2**	4**	163*	0.7**
47	56	90	4563	5.2
48	9*	16	375*	2.8
50	6*	10*	188*	2.2*

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