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This is the edited version of the Environmental Baseline Study (EBS) referenced in the draft Terms of Reference (ToR) for Liza Phase 1 of development of production facilities within the Stabroek Block, Offshore Guyana, that has been submitted by Esso Exploration and Production Guyana Limited (EEPGL).

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ENVIRONMENTAL BASELINE STUDY

GUYANA STABROEK BLOCK

Prepared for

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July 2014
Executive Summary Report

ENVIRONMENTAL BASELINE STUDY
GUYANA – STABROEK BLOCK

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ACRONYMS AND ABBREVIATIONS

α	parametric probability
µg	microgram
µg L^{-1}	microgram per liter (parts per billion)
µg g^{-1}	microgram per gram (parts per million)
µm	micron (micrometer)
<	less than
>	greater than
≥	greater than or equal to
≤	less than or equal to
/	divider
%	percent
‰	parts per thousand
°	degrees
±	plus or minus
®	registered trade mark
amu	atomic mass unit
As	arsenic
ASE	accelerated solvent extractor
ASTM	American Society for Testing and Materials
ca.	approximately
C	centigrade
cm	centimeter
CPI	carbon preference index
CTD	conductivity, temperature and depth
CV	coefficient of variation
DRC	dynamic reaction cell
DGPS	Differential Global Positioning System
DO	dissolved oxygen
EBS	Environmental Baseline Study
g	gram
GC-FID	gas chromatography/flame ionization detection
GC-MS	gas chromatography/mass spectrometry
GGMC	Guyana Geology and Mines Commission
Hz	hertz
ICP-MS	inductively-coupled plasma/mass spectrometry (ICP)
ID	identifier
km	kilometer
km^2	square kilometer
L	liter
m	meter
m^2	square meter
MDL	method detection limit
mg	milligram
mg L^{-1}	milligram per liter
mL	milliliter

Offshore Guyana EBS Executive Summary Report – Liza and Sorubim

mm	millimeter
m/z	mass to charge ratio
n	number or count
N	North
na	not applicable
NASA	US National Aeronautics and Space Administration
ng g^{-1}	nanogram per gram (parts per billion)
ng L^{-1}	nanogram per liter (parts per trillion)
p	Pearson's Correlation Coefficient
PAH	polycyclic aromatic hydrocarbons
QA/QC	Quality Assurance/Quality Control
RPD	relative percent difference
RSD	relative standard deviation
RTG	Real Time Gypsy
RV	Research Vessel
s^{-1}	records per second
SHC	saturated and aliphatic hydrocarbons, and selected isoprenoids
SIM	selected ion monitoring
SIO	Scripps Institute of Oceanography
SOP	standard operating procedure
TM	Trade mark
TOC	total organic carbon TSS
	total suspended solids
USA	United States of America
USEPA	United States Environmental Protection Agency
W	west
WGS	World Geodetic System
x	multiplier
z	non-parametric probability

EXECUTIVE SUMMARY

This report presents the background, approach, and results of an environmental baseline study (EBS) conducted in April and May 2014 in the Stabroek Block located approximately 130 to 240 km offshore central Guyana. The report describes the characteristics of physical, chemical, and biological properties of sediment and the water column to document baseline conditions prior to planned petroleum exploration and potential development in Liza and Sorubim, two areas located within Stabroek. Profiling of the water column was conducted to provide general information on water quality and physical structure at the time of the survey and to compare results to available regional information.

Background

The EBS emphasized water and sediment because they are a major repository for introduced environmental substances to the marine environment. Sediments can provide an integrated view of historical and contemporary contaminant inputs and depositional events. Benthic infauna (macrofauna) communities are a useful indicator of environmental health, due to their relative sensitivity to changes in sediment physical and chemical conditions. The study documents current concentrations of hydrocarbons and metals in offshore sediments, as these are the main contaminants potentially introduced from petroleum exploration and development.

EBS Objectives

The primary objective of the study was to define the range of sediment habitat conditions at Liza and Sorubim, and to examine chemical and biological patterns of variability in relation to sediment physical characteristics and water depth. To meet this objective, sediments were collected at 18 sampling stations: ten at Liza and eight at Sorubim.

A second objective was to evaluate water column physical structure (salinity, temperature, density, dissolved oxygen, turbidity), general water quality (suspended solids, total organic carbon), and selected chemical concentrations in near-surface, mixed layer, and near-bottom waters. Water data were collected at seven of the sediment station locations: four at Liza and three at Sorubim, effectively covering the area of interest.

Results

Water Physical Structure and Quality. Water column profiling depicted a steep halocline, reaching a maximum salinity of 37‰ at 100 m depth. Water temperature dropped monotonically from 28^{o} C at the surface to 3^{o} C around 2000 m. The water column was highly stratified, likely limiting nutrient flux into surface waters from below the mixed layer. The permanent (non-seasonal) pycnocline extends down to approximately 200 m, below which density increases slowly with depth. The water column was relatively clear, with light transmittance through the 25 cm path length typically greater than 95%. Dissolved oxygen was consistently high, ranging from roughly 6 mg L-1 near the surface to greater than 8 mg L-1 in near-bottom waters, although concentrations dropped as low as 4 mg L-1 at one station.

Water Chemical Results. Petroleum hydrocarbons (PAH and SHC) and ten pollutant-indicator metals were measured at three depths at each station. Concentrations of all metals, including barium, were well below those considered harmful to aquatic organisms in marine waters. Barium was the only metal detected in all samples, also displaying the highest concentrations in all samples (6.04- L-1). Copper, mercury, and zinc were the only other metals detected, with all mercury concentrations <1 ng L-1 (part-per-trillion). Arsenic, cadmium, chromium, copper, and lead were not detected in any sample at the low part-per-billion level (<4 µg L-1).

Total PAH (for 43 compounds) concentrations were extremely low in all samples (≤50 ng L-1). The majority of detected PAH compounds were naphthalene, and C1- and C2-naphthalenes, suggesting potential ultra-trace level introduction from the analytical laboratory. These compounds are ubiquitous laboratory contaminants, commonly found in floor wax, tubing, and other laboratory equipment. Total SHC concentrations were below detection limits (<12 µg L-1) in all but one sample, with a result of 109 µg L-1.
Sediment Particle Size and Chemistry. EBS samples consisted primarily of fine-grained material (avg. 77.3%) (<0.063 mm diameter), averaging 77.3%, with roughly equal portions of silts and clays. Sand comprised the remaining minor fraction in all samples. Concentrations of total organic carbon (TOC) were very low (<1%) in all samples. In general, the highest organic carbon concentrations were observed in sediments closest to shore, and increased with increasing percentage fine-grained sediments.

All of the ten pollutant-indicator metals had concentrations similar to those reported for clean coastal environments, except for arsenic, which was slightly enriched. Arsenic can become elevated from arsenic oxides, a byproduct of gold-mining, which is an established industry in Guyana. Most metals increased significantly with increasing fine-grained sediment and TOC, but either the opposite or no significant relationship was observed with water depth.

Extremely low concentrations of hydrocarbons were measured in sediments at Liza and Sorubim. Total PAH concentrations ranged from 16.48 to 53.36 ng g-1 dry weight in all samples. Concentrations of total SHC [redacted]-1. Relative distributions of hydrocarbon compounds indicated biogenic sources opposed to petroleum or combustion-related sources, which typically dominate the offshore hydrocarbon signature from atmospheric fallout. Biogenic hydrocarbon sources most likely consist of terrestrial plant and humic material transported downslope from river inputs. Both total PAH and total SHC exhibited strong, positive correlations with TOC, also indicating biogenic origins of these trace level hydrocarbons. The dominance of naphthalenes and phenanthrenes (2- and 3-ring PAH) was observed in the majority of samples, suggesting plant biogenesis. In particular, low concentrations of phenanthrene have been measured in bark and twigs of Vismia trees, of which the species Vismia guyana and Vismia baccifera are native to Guyana.

Benthic Infauna. Total abundance was low, averaging 116 organisms m-2. This organism density is below the range of typical abundances reported from other continental slopes. The most abundant major taxonomic groups were polychaete worms, mollusks, and crustaceans. Polychaetes were the numerically dominant group at Liza (41%, avg. 47 m-2), while mollusks were dominant at Sorubim (37.5%, avg. 37.5 m-2). The overall prevalence of these three groups is typical for marine sediments. Polychaetes typically comprise about half of the numbers and a third of the macrofaunal species from deep-water marine habitats worldwide. No other individual major taxa were abundant, and collectively comprised less than 14% of total abundance. The observed impoverished macrofauna is likely ascribed to limited organic food sources, indicated by the extremely low organic carbon content in Liza and Sorubim sediment.

A total of 50 distinct families were identified, with approximately half represented by either one or two individuals. This is a relatively high level of diversity considering the low abundance of the macrofauna. Dominant families were typical cosmopolitan inhabitants of shelf and slope sediments worldwide. These included oweniid polychaetes, pericarid crustaceans, and tindariid and nuculanid (bivalve) mollusks. The relatively low percent coefficient of variation (mean=36) between sampling stations indicates that this is a conservative parameter and a potentially effective index for monitoring potential change induced from oil and gas exploration and development.

Conclusions

Offshore sediments collected from Liza and Sorubim areas of Stabroek Block have metal and hydrocarbon concentrations lower than those reported for undeveloped coastal environments, except for arsenic, which may be slightly enriched through mineral deposits. Biological results indicated a low abundance but relatively diverse macrofauna relative to offshore marine habitats of similar water depth and latitude.

Potential impacts to the macrofauna from petroleum development offshore are unlikely to be significant and restricted to the immediate area, and a steep species accumulation curve should be realized as conditions return to normal. However, there is the potential for pollutant transport from drilling and operations into more sensitive areas of nearshore shallow zones from the dominant longshore current.

1 INTRODUCTION AND EBS OBJECTIVES

This executive summary report presents the results of an environmental baseline study (EBS) conducted offshore Guyana by TDI-Brooks International (TDI) and reported by Maxon Consulting on behalf of Esso Exploration and Production Guyana Ltd. Sampling was conducted in April and May 2014 in the Liza and Sorubim areas slated for oil and gas exploration within the Stabroek Block. Analyses of sediment and water samples were conducted by B&B Laboratory and Albion, located in College Station, Texas, USA. Benthic macrofauna samples were analyzed by Lovell Taxonomic Services with oversight from Maxon Consulting (both located in San Diego, California, USA).

This report focuses on general environmental characteristics of marine sediment and oceanic water in the area of planned exploration. The report objective is to provide information that can be used to support environmental decision making through the evaluation of chemical, physical, and biological properties of sediment and the water column within the Liza and Sorubim sites. Emphasis was placed upon sampling and analysis of the sedimentary environment because sediment and their biota are relatively immobile and integrate the effects of depositional processes, including physical disturbances and potential introduction of contaminants (Boesch and Rabalais 1987). The benthic environment can be a depositional area for discharged drilling cuttings and adhered muds, and is recognized as a sensitive and reliable monitoring indicator for measuring potential impacts from exploration drilling. This report presents survey data and summarizes key environmental features in support of EBS objectives.

1.1 Environmental Baseline Study Objectives

Study objectives were formulated for the successful completion and interpretation of EBS data and are listed below. The objectives are directed toward documenting background environmental conditions in the vicinity of potential sites prior to oil and gas exploration drilling.

1. *Provide comprehensive, descriptive, and quantitative documentation of environmental conditions at Liza and Sorubim sites of potential exploration and development.*

The EBS was designed to cover the estimated range of potential impacts to the environment from exploration drilling and potential well development. The location of offshore sites, Liza and Sorubim, and associated sampling stations are shown in **Figures 1-1** and **1-2**, respectively. Sediment station locations were selected to provide the range of existing environmental conditions prior to future planned exploration and development.

2. *Gain information to assess the significance of environmental impacts to offshore Guyana sediment from potential existing sources, such as atmospheric deposition and hydrodynamic transport.*

Trace level hydrocarbon chemical analyses were conducted to distinguish types and potential sources of petroleum related compounds measured in sediments and water. Biological samples were analyzed using a 0.5 millimeter (mm) screen to describe benthic macrofaunal community structure.

3. *Identify potential confounding factors that may interfere with the interpretation of sediment chemical and biological data to aid sampling design and interpretation of future environmental data.*

Correlation analyses were performed to identify statistically significant co-varying environmental parameters (confounding factors) to help interpret key chemical and biological results. Common confounding factors include sediment particle size, water depth, total organic carbon (TOC), and dissolved oxygen, which can influence hydrocarbon, metal, and/or benthic macrofauna results.

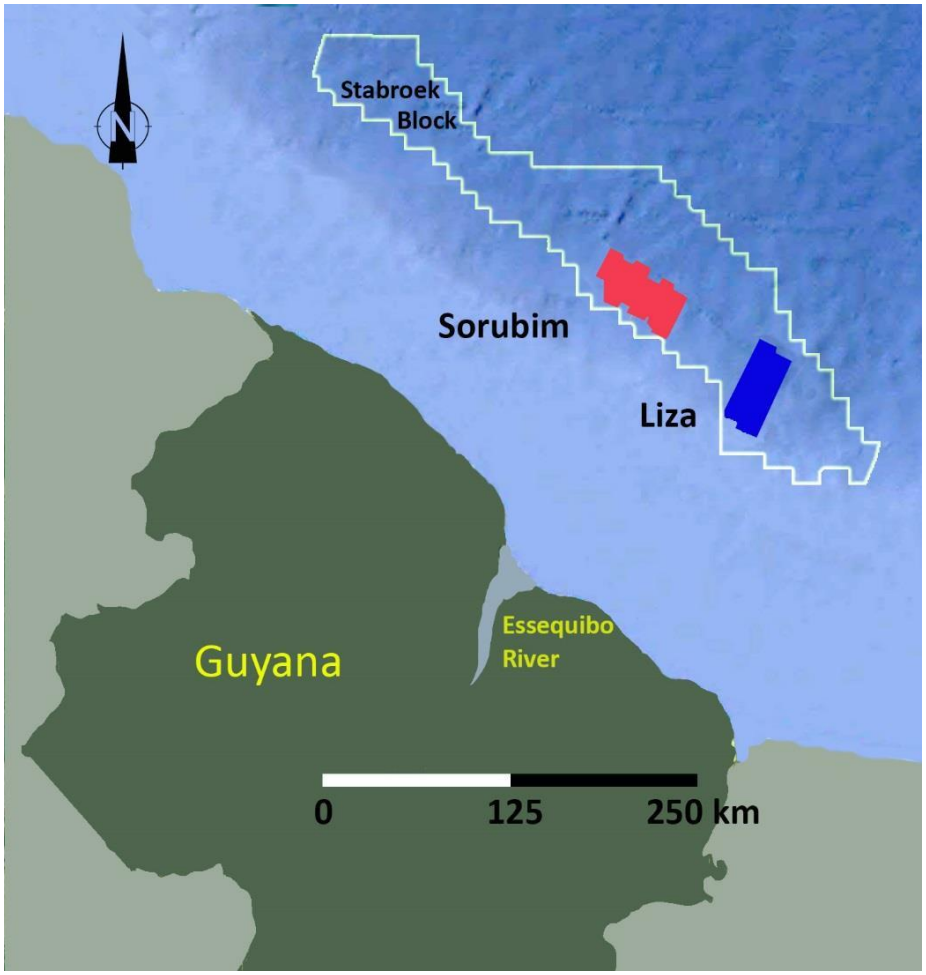

Figure 1-1. Stabroek Block with locations of Liza and Sorubim EBS project areas.

1.2 Sampling Design

Sampling locations (stations), shown in **Figure 1-2**, were selected to encompass the water depth and spatial range of existing conditions over an area of planned exploration drilling. **Table 1-1** presents station names, geographic coordinates, water depths, and types and numbers of samples collected. The sampling areas ranged from approximately 130 to 240 kilometers (km) offshore in water depths of 860 to 2400 meters (m), with Liza slightly shallower than Sorubim (see Table 1-1). Sediment samples were collected at a total of 18 stations (10 at Liza and 8 at Sorubim) using a single 0.25 square meter (m^2) box core.

The physical structure of the water column was electronically profiled at seven stations, four at Sorubim and five at Liza. In addition, three discrete water samples were collected at each station, resulting in a total of 21 discrete water samples. The sampling design supports the following methods of data interpretation to meet the previously stated EBS objectives:

- Describe central tendencies and range of key physical, chemical, and biological data throughout potential areas of oil and gas exploration and development.
- Identify potential confounding factors, such as water depth, sediment grain size, organic carbon content, dissolved solids, and dissolved oxygen that may affect interpretation of important project-related parameters, such as benthic macrofauna abundance/diversity, and concentrations of hydrocarbons and metals in sediment.
- Summarize results for water column key variables to depict existing contaminant concentrations and evaluate potential sources prior to exploration drilling.

Sediment samples were analyzed for benthic macrofauna community structure, grain size, total organic carbon (TOC), petroleum-related hydrocarbons (including polycyclic aromatic hydrocarbons [PAH] and saturated aliphatic hydrocarbons [SHC]), and 12 metals (including barium). Chemical and physical samples were collected from the top 10 cm of sediment. Benthic macrofauna were collected from the top 15 centimeters (cm) of a 0.1 m^2 sample area and retained on a 0.5-mm diameter screen. Discrete water samples were collected near the surface (10 m depth), mid-water, and near-bottom. Samples were analyzed for total organic carbon, total suspended solids, nine metals (including barium), and hydrocarbons (SHC and PAH). Continuous water column profiles were obtained for conductivity/salinity, temperature, density, light transmission (an indicator of water clarity), and dissolved oxygen at each of the seven water stations.

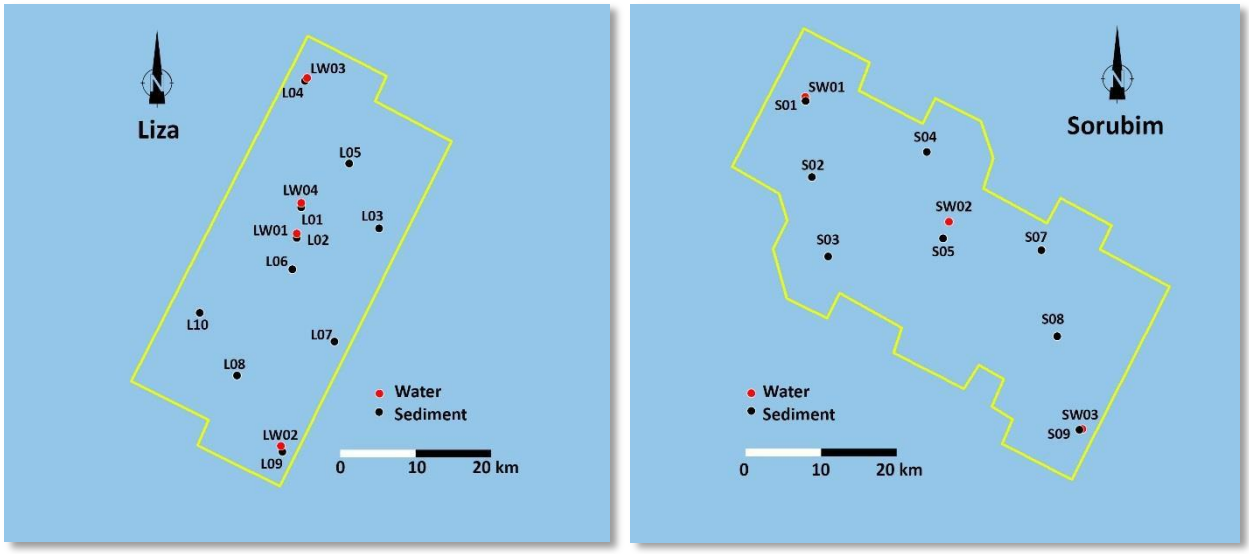

Figure 1-2. Locations of water and sediment sampling stations at Liza and Sorubim.

Table 1-1. Sediment and water station names, locations, and sampling inventory.

Sample ID	Station	Bottom Depth (m)	Latitude[1] (North)	Longitude[1] (West)	Sediment Samples	Water Samples[2]	Water Profiles[3]
Liza							
L-EBC01	L01	1831	8.1109	56.94940	1		
L-EBC02	L02	1741	8.0758	56.95319	1		
L-EBC03	L03	1853	8.0859	56.85493	1		
L-EBC04	L04	2074	8.2560	56.94463	1		
L-EBC05	L05	1931	8.1594	56.89383	1		
L-EBC06	L06	1649	8.0366	56.95963	1		
L-EBC07	L07	1478	7.9527	56.91102	1		
L-EBC08	L08	1106	7.9104	57.02392	1		
L-EBC09	L09	877	7.8214	56.97025	1		
L-EBC10	L10	1328	7.9855	57.06931	1		
L-WAT01	LW01	1216	8.0781	56.95367		1	1
L-WAT02	LW02	1741	7.8273	56.97295		1	1
L-WAT03	LW03	2004	8.2565	56.94205		1	1
L-WAT04	LW04	1772	8.1172	56.94806		1	1
Sorubim							
S-EBC01	S01	2327	8.7627	57.84372	1		
S-EBC02	S02	2171	8.6761	57.82443	1		
S-EBC03	S03	1962	8.5832	57.80321	1		
S-EBC04	S04	2238	8.7077	57.69202	1		
S-EBC05	S05	2038	8.6057	57.66938	1		
S-EBC06	S06	1857	8.4945	57.64313	not collected[4]		
S-EBC07	S07	2204	8.5910	57.55337	1		
S-EBC08	S08	2030	8.4919	57.53158	1		
S-EBC09	S09	1737	8.3840	57.50826	1		
S-WAT01	SW01	2014	8.7736	57.83698		1	1
S-WAT02	SW02	1859	8.6250	57.66557		1	1
S-WAT03	SW03	1491	8.3826	57.50786		1	1

[1]Reported in WGS 84 decimal degrees; [2]Discrete chemistry samples collected at surface, mid-water, and near-bottom depths; [3]Water column profiles of conductivity (salinity), temperature, density, and dissolved oxygen; [4]unable to collect acceptable sediment sample after several attempts.

1.3 Report Organization

This report is organized into two parts, the main report body and Appendices A-C. The main report body is organized into eight sections.

Section 1 – Introduction and EBS Objectives presents the purpose of the environmental baseline survey, the study design and sample inventories for sediment and water, and the site location.

Section 2 – Methods presents field, laboratory, and data analysis procedures. Field methods are presented for navigation and station positioning, and sample collection, processing and transfer to laboratories. Laboratory analytical methods are summarized for chemical, biological and physical samples, including sample preparation, instrumentation, quality control, and reporting. This section includes methods of data analysis, including brief descriptions of statistics used to support interpretation of results.

Section 3 – Water Physical Structure and Discrete Sample Results presents results for seven vertical profiles of conductivity/salinity, water density, temperature, turbidity, and dissolved oxygen. Water structure is discussed in relation to published studies of the region. Summary statistics are presented for discrete water column samples collected at each of three depths for total organic carbon (TOC), total suspended solids (TSS), metals and hydrocarbons.

Section 4 – Sediment Physical and Chemical Results presents results for grain size, total organic carbon, metals and hydrocarbons. Effects of sediment physical characteristics on chemical and biological parameters are emphasized. Statistical results are summarized, presenting central tendencies, range and variation in parameters for each of the two exploration sites. Spatial distributions of key physical and chemical parameters are graphically presented and evaluated.

Section 5 – Biological Characteristics of Sediment discusses patterns of diversity and abundance for benthic macrofauna. Statistical results are presented for central tendencies, range and variation in total abundance, number of distinct taxa, and distributions of selected major family-level taxa for each of the two exploration sites. Statistically significant relationships between key biological parameters and selected sediment physical parameters are reported.

Section 6 – Evaluation of Data Quality for chemical and biological analyses is presented in this section. Study objectives, presented in Section 1, are evaluated with respect to the sampling design and data collected. Laboratory quality control results are assessed for precision and accuracy for key chemical and biological data and the corresponding analytical methods used.

Section 7 - Discussion and Conclusions are presented regarding chemical and biological data for the two combined sites, and the use of these data to assess future potential impacts from oil and gas exploration drilling and development.

Section 8 – References provides full citations for referenced works. Complete results for each sample are presented in the appendices.

2 FIELD AND ANALYITICAL METHODS

Field and laboratory methods describing the collection and analysis of sediment and water data are described in this section. Additionally, statistical and graphical methods used to interpret and present EBS results are discussed.

2.1. Field Methods

Field operations were conducted from the Research Vessel (RV) GYRE, a 55.5-m vessel, outfitted with two hydraulic winches, respectively operating stern and port mounted A-frames. The vessel is equipped with wet and dry laboratories, and storage rooms containing sample freezers and dry storage areas.

A C&C Technologies™ C-Nav 2050 full Differential Global Positioning System (DGPS) and a Winfrog navigation package were used to position and navigate the vessel. C-Nav is based on Real Time Gypsy (RTG) technology developed by the US National Aeronautics and Space Administration (NASA) to achieve position accuracies of ≤0.1m to 2m. Geographical locations of sampling stations were recorded in latitude/longitude decimal degrees (WGS 84 datum). Locations were recorded electronically with station identification and date/time of sample collection and stored on an onboard computer until subsequent transfer to the project database.

Standard operating procedures governing all field operations were reviewed by the scientific team members and included establishing shift assignments, maintaining effective communications, preparing for sampling activities while in transit, recording field data, storing and tracking of samples, and packing and shipping of samples upon cruise completion.

2.1.1 Water Sampling and Profiling

Discrete water samples were collected from the near-surface (5–10 m depth), at the mixed layer (ca. 25-m below surface), and from approximately 5-10 m above the seafloor at each of seven stations. All samples were analyzed for total suspended solids, total organic carbon (TOC), metals, saturated hydrocarbons (SHC), and polycyclic aromatic hydrocarbons (PAH).

Samples were collected using 3- to 5-liter (L) polyvinyl chloride Niskin bottles deployed from a rosette at the targeted depth. Sample bottles were deployed open at both ends, and closed at the targeted depth. Bottles were washed before sampling and between each station with a non-phosphate detergent, then rinsed with de-ionized water and filtered seawater. For hydrocarbon analysis, a 1-L subsample was transferred from the Niskin bottle into a pre-cleaned borosilicate glass jar, containing 1 milliliter (mL) of 50% hydrochloric acid preservative to prevent bacterial degradation of hydrocarbons. For metals, a 500-mL aliquot was collected from the Niskin bottle directly into a pre-cleaned polyethylene jar containing 0.5 mL of 50% hydrochloric acid preservative. All chemistry water samples were refrigerated at 4^{o}celcius (C) while on board ship.

The water column was electronically profiled with the CTD, augmented with additional sensors for dissolved oxygen and percent light transmission (turbidity). Water column data were collected at a rate of 2 records per second (s^{-1}) throughout the water column.

2.1.2 Sediment Sampling

Sediments were sampled with a 50 x 50 centimeter (cm) steel box corer, providing a sediment surface area of 0.25 m^2.

Benthic Macrofauna. A 0.1 m^2 square, stainless steel sleeve was used to subsample the box core. The sleeve was inserted into one corner of the box core to a depth of 15 cm. The entire volume of sediment was collected (including overlying water) from the sleeve and placed into a plastic bucket. The sediment and collected water were transferred within 30 minutes of collection to a flow-through sieve with a 0.5-mm mesh. After sieving, macrofauna samples and retained sediments were transferred to plastic containers and preserved with approximately 50% volume of 10% buffered formalin and rose bengal dye. The preservative was sufficient to cover the entire sample, and exceeded the retained material volume by at least 10%. Rose bengal, which is a vital stain, stained living biological material red, facilitating the efficient removal of biological material during subsequent laboratory sample sorting. If necessary, high-volume samples were stored in more than one sample container, and labeled accordingly. Each sample was inverted several times to ensure thorough mixing of the preservative. Preserved samples were stored in plastic coolers at ambient temperature.

2.2 Analytical Methods

The environmental baseline analytical program was designed to provide high quality, detailed chemical and biological data to meet program objectives. **Table 2-1** lists the physical, chemical and biological tests, corresponding matrices, analytical methods, and processing laboratories.

Table 2-1. Analytical methods, laboratory, and number and type of EBS samples.

Parameter	Sediment Samples	Water Samples	Analytical Method
B&B Laboratories, College Station, Texas, USA			
Total Suspended Solids	-	21	Filtration and gravimetric determination
Total Organic Carbon	18	21	Combustion with infra-red detection
Polycyclic Aromatic Hydrocarbons (PAH)	18	21	GC-MS SIM, USEPA 8270-modified
Saturated Hydrocarbons (SHC)	18	21	GC-FID, USEPA 8015-modified
Albion Laboratory, College Station, Texas, USA			
Metals (except mercury)	18	21	ICP-MS, USEPA Methods 1638 & 200.8
Mercury	18	21	Cold vapor with atomic fluorescence
Lovell Benthic Laboratory, San Pedro, California, USA			
Benthic macrofauna	18	-	0.5mm sieve; identification and enumeration at

ICP=inductively coupled plasma spectroscopy detector
ICP-MS= ICP with mass detector
GC-FID = gas chromatography with flame ionization
GC-MS = gas chromatography with mass detector

2.2.1 TSS, TOC, and Sediment Particle Size

Total suspended solids (TSS) in water samples were analyzed using a standard filtration and gravimetric method following USEPA Method 160.3. In summary, a 1-L sample obtained from the Niskin sampler at each depth was volumetrically determined using a graduated cylinder and then passed through a 0.45 micron (µm) filter in the vessel laboratory. The filter was then wrapped in foil, labeled, and stored refrigerated until shipment back to B&B Laboratory for analysis. In the laboratory, the sample was dried in a desiccator and weighed to the nearest 0.01 milligram (mg). Results were reported in mg L^{-1} for each sample.

Total organic carbon (TOC) was analyzed using a persulfate digestion of carbon at 100° C followed with detection of organic carbon using an O.I. Analytical Model 700 TOC Analyzer based on USEPA methods 9060 and 415.1. Water samples were acidified to a pH of <2 and analyzed unfiltered. The reported TOC results are the total of dissolved and particulate organic carbon.

Sediment TOC samples were digested with a 50% by volume phosphoric acid solution. The acid-sediment slurry was oven dried at 105° C, weighed. The resulting moisture-free sample was combusted at 1350° C and TOC was quantified using a Leco CR-412 Total Carbon Analyzer to remove chlorine interferences in marine samples by filtering gases through a magnesium perchlorate, halogen trap column.

Sediment particle size was determined for the four major size classes: gravel, sand, silt, clay using a sieve and hydrometer technique. Sediment samples analyzed for grain size were thoroughly mixed. Approximately 100 to 150 g of each sample was weighed into receiving containers. Ten (10) mL of deflocculent solution (1% solution of sodium hexametaphosphate in deionized water) was added to the jar and shaken until the sample was totally disaggregated. The disaggregated sample was poured through a number 230 sieve into a 1000-mL graduated cylinder. The sieved sample is washed with deionized water. Sediment retained on the number 230 sieve was transferred into a pre-weighed beaker and oven dried (70-90° C) for at least 24 hours. Dried sediment was transferred to a series of stacked sieves, shaken and the contents of each weighed. Sediment passing through the smallest sieve was added to the 1000-mL graduated cylinder and further processed using the hydrometer settling method ASTM D-422. Percent gravel, sand, silt, clay and several graphic sediment parameters were calculated from initial weights and retained fractions.

2.2.2 Metals

Water samples were analyzed for nine metals and sediment samples were analyzed for 12 metals (see Appendices A and B for respective metals).

Water samples (except those analyzed for mercury) were preserved under clean room conditions to a pH of <2 using ultrapure nitric acid. Preserved samples were allowed to equilibrate for at least 24 hours to insure all metals adsorbed to the container walls were re-solubilized. A near-total (≥90%) recoverable digest was then performed on the preserved total recoverable samples. Additional acid was added and the samples were heated for at least two hours at 85° C, and allowed to cool prior to analysis. In addition, all samples were subjected to an additional 48 hour ultraviolet digestion procedure. The ultraviolet procedure insured that all dissolved organic chelates that could interfere with extraction efficiency were decomposed, prior to pre-concentration.

Mercury water samples were preserved under clean room conditions with bromine monochloride (BrCl) and digested (equilibrated) for at least 24 hours prior to analysis. The composite was analyzed under clean room conditions by dual gold amalgam trap cold vapor atomic fluorescence, following USEPA method 1631 revision E.

Sediment samples were analyzed for the same nine metals analyzed in water samples plus aluminum, cadmium, and iron. Except for mercury, sediment metals were analyzed using either standard inductively coupled plasma spectrometry (ICP) with mass detector (ICP-MS) (USEPA method 200.8), or in the case of chromium and iron, ICP-MS modified to use an ammonia gas dynamic reaction cell (DRC)-ICP-MS. Prior to ICP analysis, sediment samples were homogenized, sub-sampled and freeze-dried to a constant weight. The dried sediment was then ground to a fine powder. For USEPA method 200.8, approximately 0.2 g of the dried and powdered sediment samples were subjected to a strong acid leaching digestion at 95° C for 4 hours. Ultra-pure deionized water was then added to the acid leachate to achieve a final volume of approximately 20 mL. The leachate (digestate) was then diluted further to keep the solution concentration within the calibration range of the ICP-MS instrument, and to adjust the acid strength for analysis. Sediment mercury samples also were analyzed using USEPA method 1631 revision E.

2.2.3 Hydrocarbons

Extraction of Hydrocarbons. A sediment aliquot was dried in a convection oven at 40° C, and then thoroughly homogenized using a ceramic mortar and pestle. An additional aliquot of approximately 1 g of wet sediment was removed and dried in an oven at 105° C to a constant weight for percent moisture determination. Samples were extracted using a Dionex ASE200 Accelerated Solvent Extractor (ASE). The dried sample was loaded into 22- or 33-mL stainless steel ASE extraction tubes. The extractions were performed using 100% dicholormethane at 100° C and 2000 psi. The extracted organics dissolved in the solvent were collected in 60-mL glass vials. The extract was concentrated to approximately 10 mL in the collection vials and then transferred to 25-mL Kurdena-Danish concentrator tubes. The sample extract was concentrated to 3 mL in a water bath at 55 to 60° C. Additional cleanup procedures were used for sediments including high-pressure liquid chromatography fractionation followed by silica gel and alumina-column cleanup. Cleanup procedures were performed to remove potentially interfering non-target compounds.

The sample extract was loaded on top of 300 mm x 19 mm glass liquid chromatography columns packed with 10 g of deactivated alumina and 20 g of deactivated silica gel. The columns were loaded in 100% dichloromethane. The dichloromethane was replaced by adding 40 mL of pentane. The extract was carefully added to the top of the chromatography column. The column was flushed at a rate of 1 to 2 mL per minute using 200 mL of 50:50 pentane/dichloromethane and collected into 250-mL flasks. The eluent collected in the 250-mL flask was evaporated to 2 mL using a water bath at 55 to 60° C. The samples were transferred into 2 mL amber vials. The concentrated extract was then analyzed by GC-MS for polycyclic aromatic hydrocarbons (PAHs) or by GC-FID for saturated hydrocarbons and selected isoprenoids.

If the extract was colored it was processed through silica gel/alumina chromatography columns. The sample extract was then loaded on top of 300 mm x 19 mm glass liquid chromatography columns packed with 10 g of deactivated alumina and 20 g of deactivated silica gel. The columns were loaded in 100% dichloromethane. The dichloromethane was replaced by adding 40 mL of pentane. The extract was carefully added to the top of the chromatography column. The column was flushed at a rate of 1 to 2 mL per minute using 200 mL of 50:50 pentane/dichloromethane and collected into 250-mL flasks. The eluent collected in the 250-mL flask was evaporated to 2 mL using a water bath at 55 to 60° C. The samples were transferred into 2-mL amber vials. The concentrated extract was then analyzed by GC-MS with selected ion monitoring (SIM) for polycyclic aromatic hydrocarbons or GC-FID for saturated hydrocarbons.

***Polycyclic aromatic hydrocarbon (PAH) analysis*.** Parent PAHs and their alkylated homologues were analyzed in sample extracts by a HewlettPackard model 5890 GS and model 5972 MS, operated in SIM mode, using a capillary column. A list of analyzed compounds is provided in Appendices A1 and B1 for water and sediment samples. The GC was operated in splitless mode and the capillary column was an Agilent Technologies HP-5MS (60 m x 0.25 mm ID and 0.25 mm film thickness). The carrier gas was helium at a flow rate of 1 mL min^{-1}. The temperature of the injection port was 300° C and transfer line was 290° C. The initial oven temperature was 60° C and the ramp rate was 7° C per minute to a final oven temperature of 310° C, held for 20 minutes. For analyte identification, the extracted ion current profiles of the primary m/z and the confirmatory ion for each analyte must be at a maximum in the same scan or within one scan of each other and the retention time must fall with 5 seconds of the retention time of the authentic standard or alkyl homologue grouping. The pattern of alkylated PAH homologue groupings was established by analysis of reference oil standards. The relative peak heights of the primary mass ion compared to the confirmation or secondary mass ion must fall within 30% of the relative intensities of these masses in a reference mass spectrum.

Saturated hydrocarbons (SHC) analysis. Saturated hydrocarbons are defined as a group of straight- and branched-chained (saturated) as well as cyclic hydrocarbons that are typically found in petroleum related products and crude oil. In sediments, a complete range of these "saturated" hydrocarbons were analyzed that encompass light and heavy fractions of petroleum (e.g., Nc_9-nC_{40}) and selected isoprenoids, including pristine and phytane. A list of analyzed compounds is provided in Appendices A1 and B1 for water and sediment samples. Target analytes were extracted with PAH compounds and analyzed using gas chromatography with flame ionization detection (GC-FID). Measured concentrations were calculated against the surrogate compounds (e.g., tetracosane-d50) added prior to the extraction.

2.2.4 Benthic Macrofauna

Benthic macrofaunal samples were sorted in order to remove the fauna from the sediment and separate them into major taxonomic groups for taxonomic analysis by specialty taxonomists. Sorting was performed under dissecting microscopes with fiber optic lighting. Small volumes of sediment were spread out in sorting trays and systematically inspected. Animals were removed from each sample and separated into vials representing five major sorting groups: polychaetes, crustaceans, mollusks, echinoderms, and miscellaneous phyla. Borosilicate glass vials with poly-seal lids were used for sorted fractions. Each vial was labeled with sample ID and taxonomic group. Labels were written on rag paper using India ink pen. Each tray of sediment was inspected until the sorter was confident that all animals were removed. The sorted sediments were placed into a separate labeled jar and the process continued until the entire sample was sorted.

Prior to sorting, samples collected for identification and enumeration of benthic infauna were sieved again and separated into three size fractions that were examined separately under a dissecting scope: 1) easily suspended material (e.g., light bodied/typically non-shell bearing specimens and detritus; 2) large heavy material (e.g., shell hash, large shell bearing mollusks and large worm tubes); and 3) coarse sediments (i.e., aggregated clay). Easily suspended material was washed under a fume hood into a 2-L beaker. Sample material was thoroughly suspended/agitated with freshwater dispensed from a ½ inch Tygon hose attached to a municipal water line. Suspended material was allowed to settle for a few seconds before decanting supernatant onto an ASTM Standard 35 (500 µm) sieve.

The process was repeated 5 to 10 times, until the wash water was visibly clear. Material retained on the sieve was washed into a labeled 50-mL beaker. Large heavy material retained in the 2-L beaker was washed on an ASTM Standard 10 (2 mm) sieve fitted above an ASTM Standard 35 (500 µm) sieve. Material retained on the 2-mm screen was washed with fresh water dispensed from a spray wand attached to a municipal water line to remove any residual fine materials. Retained coarse material was washed into a labeled 100-mL beaker. Coarse sediment was pre-sieved on the 2-mm sieve and retained on the underlying 500-µm sieve, and washed with freshwater dispensed from a 1-cm diameter Tygon hose and fine spray wand attached to a municipal water line to remove any residual sand and silt. Material retained on the 500-µm sieve was washed into a labeled 500-mL beaker. All material retained on sieves was examined under a fluorescent magnifier to ensure that all organisms had been removed.

The three sieved fractions were consolidated during the picking (sorting) process. Picked specimens were transferred to labeled glass vials containing 70% ethanol. Dissecting and compound microscopes with standard magnifications of 6x-50x and 40x-1000x were used to examine the specimens. Fiber optic lighting was used to illuminate specimens under the dissecting microscope.

Infauna were separated into four major taxonomic groups: polychaeta, mollusca, crustacea, and combined other taxa. Abundances were recorded to the family level, with names reported for the taxonomic categories of annelids, crustaceans, echinoderms, mollusks, and miscellaneous grouped phyla. The number of organisms reported accounted for all organisms in a sample that were alive at the time of collection. Empty mollusk shells or crustacean molts were not counted. Limitations that effect the level of identification are lack of published literature for the area; condition of the specimens (fragmented, poorly preserved); and juvenile, reproductive, or other poorly documented life stage.

Specialty taxonomists used taxonomic literature pertinent to the region from which the samples were collected. Additional literature from other regions or literature of a general nature was used as necessary. When possible, specimens not attributable to a described family were given a unique provisional name and notes on its unique taxonomic characteristics were made to facilitate subsequent identifications. Damaged or juvenile specimens were identified to the family level whenever possible.

Quality control included two forms of oversight. First, all material processed by each of two pickers was reexamined by the taxonomist for each benthic category. Second, instruction and guidance from the lead taxonomist was available and frequently provided to pickers throughout the analysis. To maintain consistent standards resulting taxonomic lists from provided to an alternative taxonomist for verification. Any discrepancies in identification were corrected by the lead taxonomist and standardized in the taxonomic database.

2.2.5 Sample Archival

Sediment not consumed by analyses is stored frozen for up to one year under strict chain-of-custody procedures at B&B Laboratory, College Station, Texas.

Representative organisms from processed macrofauna samples were preserved in 70% ethanol and submitted for archival at Scripps Institute of Oceanography (SIO), Benthic Invertebrate Collection, La Jolla, California (http://collections.ucsd.edu/bi/index.cfm). The SIO Benthic Invertebrate Collection contains over 750,000 specimens, with approximately 20,000 identified to genus level and 14,500 to species level. The collection supports scientific research by providing specimens for study on the taxonomy, evolution, and ecology of benthic invertebrates. Archived specimens are available for examination at SIO and for loan to researchers at academic institutions.

2.3 Quality Control (QC)

Details on the type, quantity, and performance results specific to each method are presented in Section 6 (Evaluation of Data Quality). A complete suite of laboratory QC samples was run with sediment and water chemistry samples to confirm method performance and control. Method-specific required laboratory QA/QC samples included a control blank, duplicate samples, performance validation samples, standard reference materials, and various recovery and check standards, depending on the analysis.

Results that were collected using electronic or remotely deployed instruments were checked for accuracy and precision by the equipment manufacturer (e.g., Seabird Electronics, Winfrog Navigation) or by the scientific team, following guidance from the manufacturer.

2.4 Data Management and Analysis

All data management and analysis tasks were performed using the SAS™ Software System (version 9.4) in batch programming mode. SAS™ is a data management, statistical, and graphical system that is widely used and is the recognized standard by many academic, government and medical/health industries worldwide. Graphical presentations of data were performed using Surfer® (version 10, Golden Software, Inc.) and Grapher (version 9, Golden Software, Inc.) software. Data were translated from Microsoft Excel files to SAS™ data sets, and all analyses were performed within the SAS™ system. Statistical results were output as text, rich text format and Microsoft Excel files. Key parameters used in statistical analyses are shown in **Table 2-2**.

Table 2-2. EBS key parameters used in statistical analyses.

Chemical Parameters	***Benthic Macrofauna***	***Water Quality Parameters***
Barium	Total Abundance	Total Suspended Solids
Cadmium	Polychaeta Abundance	Total Organic Carbon
Chromium	Crustacea Abundance	pH
Copper	Echinodermata Abundance	Dissolved Oxygen
Iron	Family Diversity	Turbidity
Lead	Mollusca Abundance	Salinity
Mercury	Other Grouped Phyla Abundance	Density
Nickel	***Sediment Physical Parameters***	Temperature
Vanadium	Sediment particle size (various)	Depth
Zinc	Total Organic Carbon	
Total PAH	Depth	
Total Resolved SHC		
Total Unresolved SHC		
Total SHC		

2.4.1 Descriptive Statistics

Descriptive statistics were performed for key variables of the physical, chemical, and biological data sets. Summary statistics included computations for sample mean, mean standard deviation, range of values, and where appropriate, frequencies of detectable concentrations. Average results were used in cases where duplicate samples were analyzed by the laboratory. These results were then used to generate statistical results (e.g., central tendencies) for the entire data set. Values equal to one-half of the method detection limit were used for non-detect chemistry results in statistical calculations. Computations were performed on final results that passed data quality objectives.

2.4.2 Correlation Analysis

Correlation analysis provides insight into the relationship between two analysis variables. Pearson Product-Moment correlation coefficients were calculated for pair-wise variables of interest within the data set. The significance of correlations between meaningful pairs of environmental variables (e.g., depth and total abundance) is discussed in Sections 3 through 5, providing results for the correlation coefficient and probability level of statistical significance.

2.4.3 Graphical Presentations of Data

Bar plots showing concentrations of hydrocarbon compounds at selected individual stations were produced in Excel (Microsoft Office, Version 2013). Contour maps were produced by the rectangular grid-based contouring program, Surfer® (Golden Software, Version 10). This program interpolates irregularly spaced data into a regularly spaced grid, and places interpolated data in a grid file. Original data included station coordinates and selected chemical and biological parameters for each station.

2.4.4 Analysis of Hydrocarbon Source

General sources of hydrocarbons were identified by evaluation of selected diagnostic ratios and parameters (Douglas et al. 1996; Steinhauer and Boehm 1992). Indices and parameters used to identify hydrocarbon source are shown in **Table 2-3**. Characteristics based on PAH compounds provide information on the source of hydrocarbon contaminants, whereas SHC-based parameters are used primarily to distinguish between biogenic and petroleum-derived sources. Parameters based on both PAH and SHC compounds were used to discern hydrocarbon sources in offshore Guyana sediment (see Section 4).

Table 2-3. Diagnostic ratios and parameters of SHC and PAH used to identify hydrocarbon source.

Parameter or Ratio	Relevance in Environmental Samples
Saturated Hydrocarbons (SHC)	
Pristane/Phytane	Source of phytane is mainly petroleum, whereas pristane is derived from both biological matter and oil. In "clean" environmental samples, this ratio is > 1.0 and decreases as oil is added.
nC16/(nC15 + nC17)	The ratio of hexadecane (nC16) over pentadecane (nC15) plus heptadecane (nC17). At "background" levels, hydrocarbon nC15 and nC17 can be used as indicators of plankton (algae) hydrocarbon inputs. As plankton productivity increases the ratio decreases.
Carbon Preference Index (CPI)	The total odd-chain hydrocarbons divided by the total even-chain HC. A value of 2-4 indicates input from plants, as oil is added the value decreases, approaching 1.0
Polycyclic Aromatic Hydrocarbons (PAH)	
N/P	The ratio of summed naphthalene alkylated homologues (C1-C4) over summed phenanthrene-anthracene alkylated homologues (C1-C4); this ratio decreases with increased weathering of oil.
Perylene	A biogenic compound formed during early diagenesis in marine and lacustrine sediments; usually associated with terrestrial plants.
Total PAH	The sum of all PAH target analytes including 2- through 6-ring parent PAH and C1 - C4 alkyl substituted PAH. General indicator of petroleum hydrocarbon sources.
Pyrogenic	The sum of combustion PAH compounds (4-, 5-, and 6-ring PAHs): fluoranthene, pyrene, chrysene, B(a)A, B(b)F, B(k)F, B(a)P, D(a,h)A, B(g,h,i)P
Petrogenic	The sum of petrogenic PAH compounds (2-, 3-, and 4 -ring PAHs): naphthalenes, acenaphthene, acenaphthylene, fluorene, phenanthrenes, dibenzothiophenes, chrysenes, and fluoranthenes/pyrenes
Petrogenic/Pyrogenic	Useful to determine relative contributions of pyrogenic and petrogenic hydrocarbons in differentiating sources. The ratio increases as inputs from petroleum increase.

adapted from Steinhauer and Boehm (1992).

3 WATER COLUMN RESULTS

This section presents results for water column profiles and chemical/physical analyses of collected (discrete) water samples. Four profiles and 12 samples (4 stations x 3 depths) were collected at Liza; and three profiles and nine samples (3 stations x 3 depths) were collected at Sorubim.

3.1 Background

Guyana's Atlantic Ocean coastline is approximately 430 kilometers (km) in length, bounded by Suriname on the east and Venezuela on the west. Guyana has a land area of approximately 214,970 km^2, and also shares a border with Brazil on the west and south. The country is situated between 1 and 9 north latitude and between 56 and 62 west longitude. The offshore region, including Liza and Sorubim, located 130 to 240 km offshore and along a combined total of 120 km of coastline, is primarily under the influence of large scale oceanic processes overlying the upper continental slope, and are generally beyond the immediate influence of coastal shore processes of localized runoff, sedimentation, and thermal structuring. Guyana generally has an equatorial climate with year-round rainfall; however, variations in rainfall affect surface water features accordingly, both locally and through runoff from its four major rivers, including the Essequibo River delta (see Figure 1-1, Section 1).

3.2 Water Column Profiles

Depth profiles of salinity, temperature, density, dissolved oxygen, and percent light transmittance (as an indicator of turbidity) are shown in **Figures 3-1** through **3-4** for each of seven water stations. Summary statistics for profiled data collected at the same station depth as discrete samples are presented in **Table 3-1.** Results indicate a consistent water column structure over the survey period and sampling area. A lens of relatively low salinity (~ 33‰) water gives way to a steep halocline, reaching a maximum salinity of 37‰ at 100 m at both sites. Water temperature drops monotonically from 28° C at the surface to 3° C around 2000m. The resulting density profiles indicate a highly stratified water column, which likely limits nutrient flux into surface waters from below the mixed layer. There is a sharp increase (step) in density at the 100m salinity maximum in most profiles. The permanent (non-seasonal) pycnocline extends down to approximately 200m, below which density increases slowly with depth. The water column is relatively clear, with light transmittance through the 25 cm path length typically greater than 95%. A minor accumulation of material appears to rest on the 100 m step in the density profile, where transmittance drops to 92% in several profiles. Dissolved oxygen profiles show high levels (ca. 6 mg L^{-1}) near the surface and even higher levels (>8 mg L^{-1}) below 1000 m. The water column properties are quite reasonable, given the local oceanography. The profiles were collected approximately 175 km offshore of the delta of the Essequibo River, Guyana's largest river. Guyana annual precipitation is very high, averaging between 250–350 cm. The lower salinity surface layer is most likely maintained by river and rainfall input. The wind-driven coastal North Brazil Current and Guyana Current (Lumpkin and Garzoli 2005), resulting from the North Equatorial Current from the east (Tomczak and Godfrey 2003), determine water conditions above the permanent pycnocline. Salinities range from 36 to 37‰ and temperatures range from 22° to 28.5° C

(http://oceancurrents.rsmas.miami.edu/atlantic/guiana.html).

The conditions below the permanent pycnocline are maintained by Antarctic Intermediate Water down to approximately 1000m, and below that by North Atlantic Deep Water (Tomczak and Godfrey 2003). The Antarctic water is characterized as relatively fresh (34.3‰) and cold (2° C). The underlying North Atlantic Deep Water, formed when the salty Gulf Stream is cooled off Labrador, sinks and moves southward. It is more salty (35‰), has high oxygen concentrations (6–8 mg L^{-1}) and is identifiable down to 4000 m. The coincident increase in salinity and dissolved oxygen below 1200m can be seen in nearly every one of the corresponding profiles.

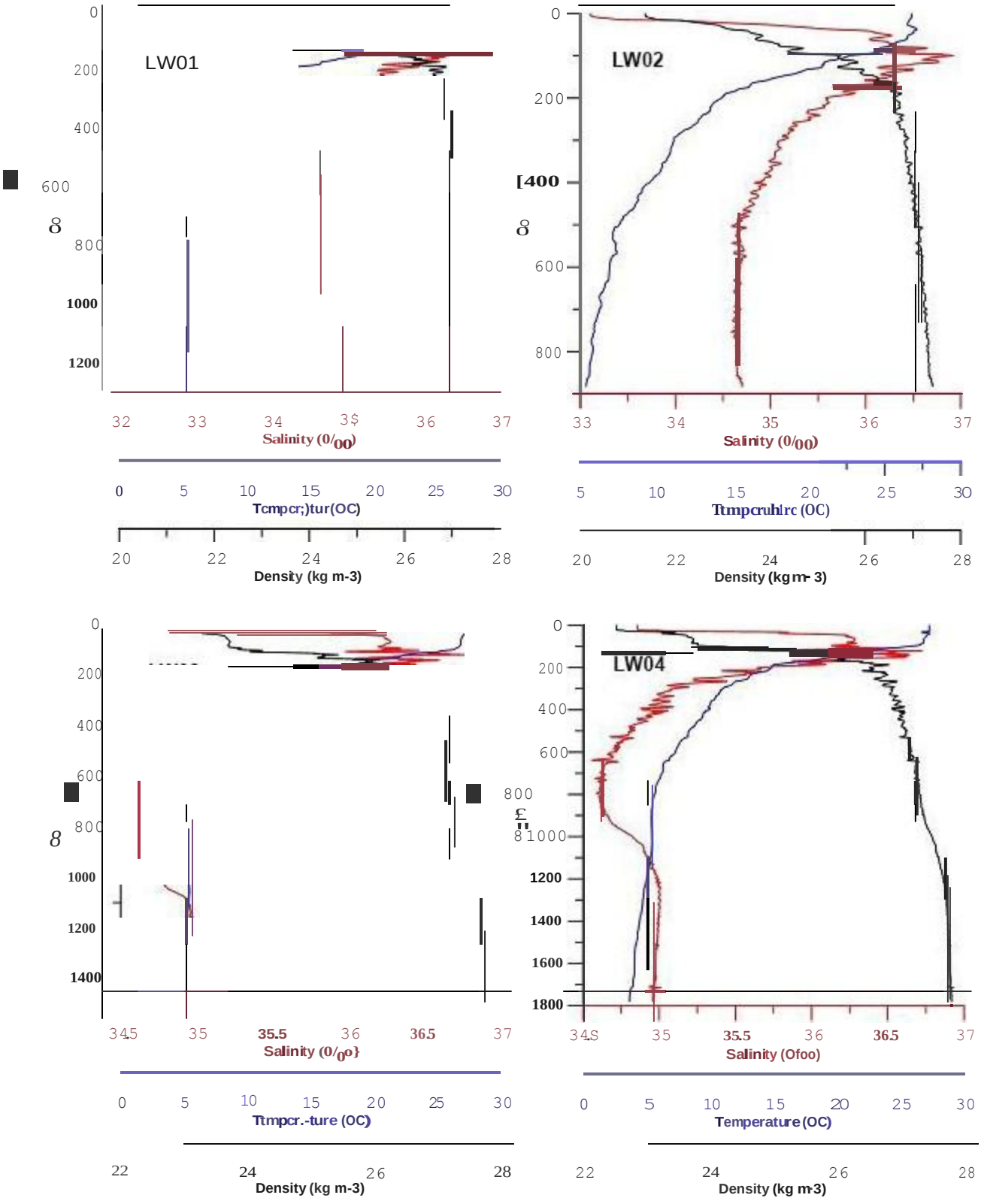

Figure3-1. Profiles of salinity, temperature, and water density at each of four stations at Liza.

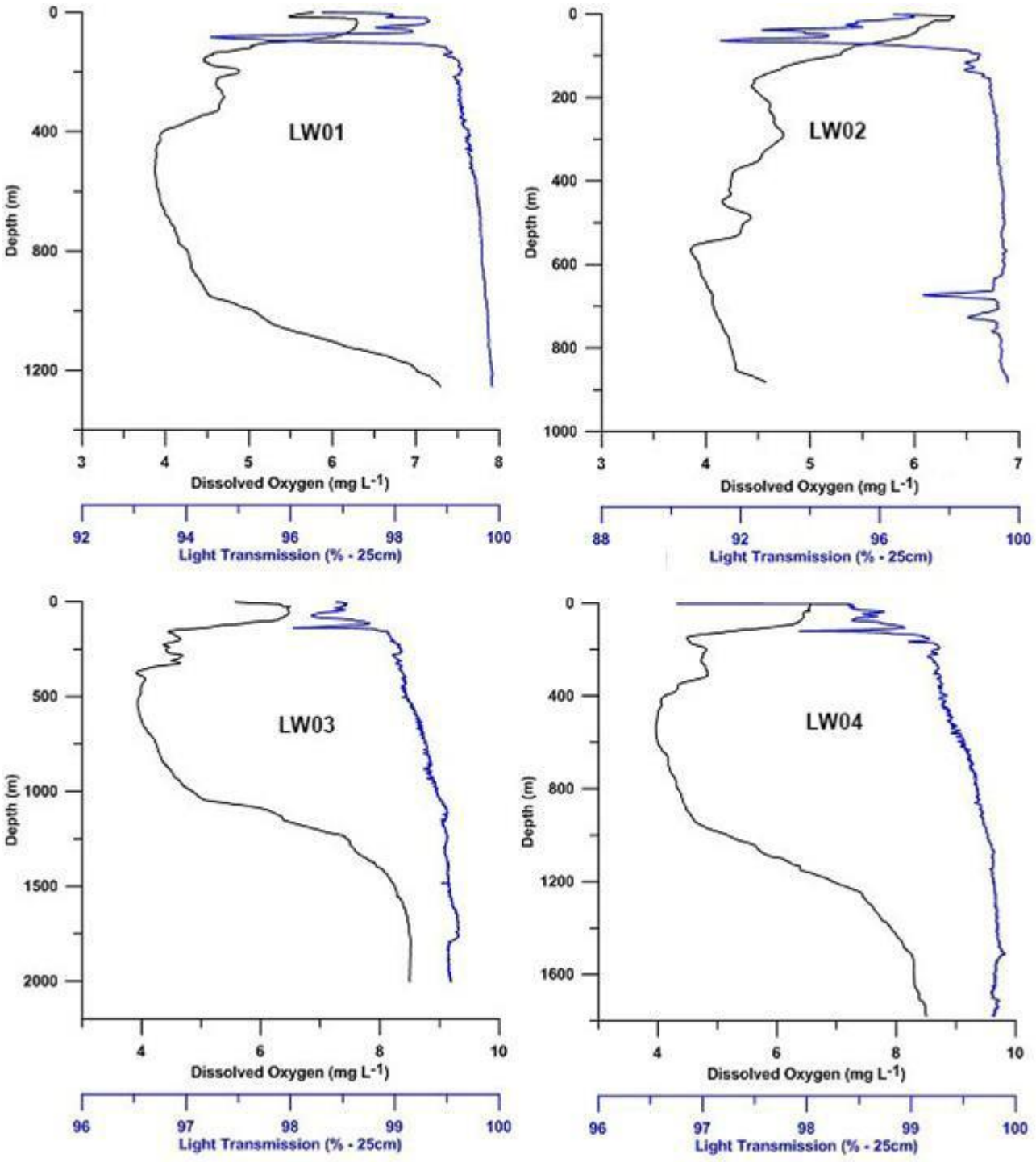

Figure 3-2. Profiles of dissolved oxygen and percent light transmission at each of four stations at Liza.

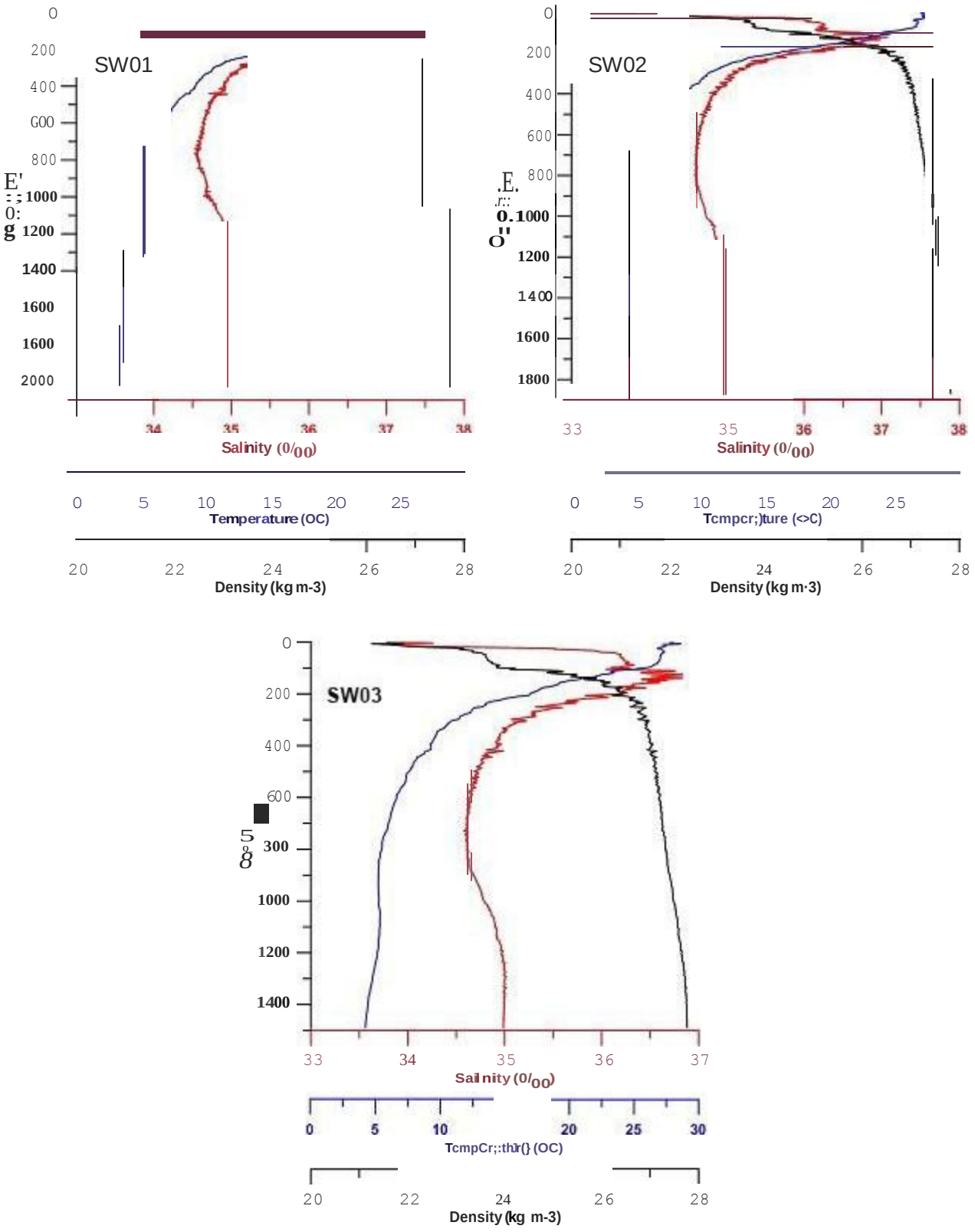

Figure3-3. Profiles of salinity, temperature, and water density at each of three stations at Sorubim.

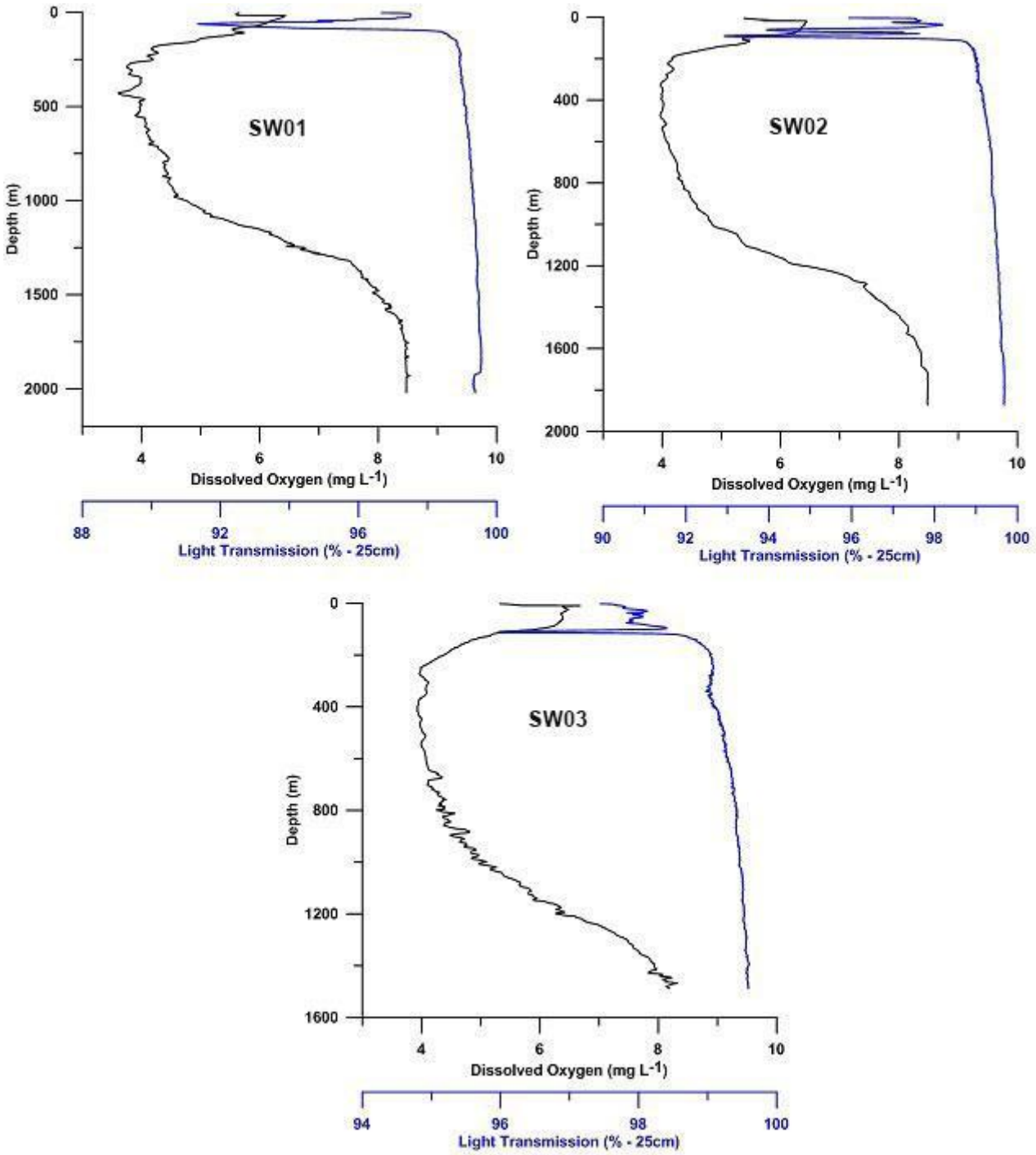

Figure 3-4. Profiles of dissolved oxygen and percent light transmission at each of three stations at Sorubim.

Table 3-1. Summary statistics for water physical structure data.

Parameter	Units	Mean	Standard Deviation	Minimum	Maximum
		Liza (n=12)			
Temperature[1]	°C	19.67	11	3.42	27.36
pH[2]	pH units	8.1	0.13	7.84	8.19
Salinity[1]	‰	34.74	0.79	32.9	35.7
Dissolved Oxygen[1]	mg L^{-1}	5.47	0.76	3.86	8.39
		Sorubim (n=9)			
Temperature[1]	°C	19.37	11.79	3.34	27.47
pH[2]	Unit	8.11	0.1	7.94	8.19
Salinity[1]	‰	34.56	0.63	33.7	35.2
Dissolved Oxygen[1]	mg L^{-1}	5.99	0.67	5.52	8.48

[1]profile results measured at discrete sample water depth; [2]results for discrete samples

3.3 Discrete Water Sample Results

Summary statistics for water physical parameters, metals, and hydrocarbons are shown in **Tables 3-2** through **3-4**.

3.3.1 Total Suspended Solids (TSS) and Total Organic Carbon (TOC)

Total suspended solids can be an important water quality parameter with respect to sediment transport and discharges to the water column from exploration or development drilling. There were no significant trends between depths, with results ranging from very clear (<1 mg L^{-1}) to moderately turbid (8.85 mg L^{-1}) water. Unlike turbidity, there was no clear trend in TSS with water depth. Although the limited number of depth strata sampled may not have been sufficient to detect depth-related trends, it appears to have adequately captured the range of results for the water column. Although collected over a limited time period, these results are assumed to represent seasonal background conditions for the study area. Background concentrations during heavy rain may be significantly higher due to suspended material broadcast from the Essequibo River.

Total organic carbon (particulate + dissolved organic carbon) concentrations provide rough estimations of productivity in ocean water when not confounded by anthropogenic inputs, such as treated sewage, agricultural runoff, or other organic inputs. Results for all samples were low, at ≤1.2 mg L^{-1}, with mean concentrations of 0.42 and 0.46 mg L^{-1}, respectively, for Liza and Sorubim samples. These results are comparable to a concentration of 0.83 mg L^{-1} TOC for an open ocean surface water sample collected from the Gulf of Mexico that was analyzed for quality control purposes. There were no significant differences (α=0.05) in mean TOC concentrations between sample depths at either site.

Table 3-2. Summary results TOC and TSS for Liza and Sorubim discrete water samples.

Parameter (mg L^{-1})	Mean	Standard Deviation	Minimum	Maximum
Liza (n=12)				
Total Organic Carbon (TOC)	0.81	0.26	0.42	1.13
Total Suspended Sediment (TSS)	4.3	1.92	1.4	7.25
Sorubim (n=9)				
Total Organic Carbon (TOC)	0.81	0.24	0.46	1.04
Total Suspended Sediment (TSS)	4.77	2.38	0.35	8.95

3.3.2 Heavy Metals and Other Elements

Except for barium, nearly all results were below laboratory detection limits (**Table 3-3**). Barium was detected in all samples, with concentrations well within the natural range for ocean water (Morel et al. 2006). An ultra-trace method used to analyze mercury produced detectable concentrations of sub-part-per-trillion (<1 ng L^{-1}) in only two samples, both collected at Liza. All reported concentrations were well below those considered harmful to aquatic organisms in marine receiving waters (Buchman 2008).

Table 3-3. Summary results for metals in Liza and Sorubim water samples. Results reported in µg L^{-1}.

Parameter	No. of Detects	Mean	Standard Deviation	Minimum	Maximum
Liza (n=12)					
Arsenic	0	<2	NA	<2	<2
Barium	12	7.5	0.83	6.4	9.21
Cadmium	0	<2	NA	<2	<2
Chromium	0	<5	NA	<5	<5
Copper	1	1.68	0.63	<3	3.68
Lead	0	<0.6	NA	<0.6	<0.6
Mercury	2	0.000124	0.000057	<0.0002	0.000254
Nickel	0	<4	NA	<4	<4
Vanadium	0	<4	NA	<4	<4
Sorubim (n=9)					
Arsenic	0	<2	NA	<2	<2
Barium	9	7.62	0.93	6.04	8.81
Cadmium	0	<2	NA	<2	<2
Chromium	0	<5	NA	<5	<5
Copper	0	<3	NA	<3	<3
Lead	0	<0.6	NA	<0.6	<0.6
Mercury	0	<0.0002	NA	<0.0002	<0.0002
Nickel	0	<4	NA	<4	<4
Vanadium	0	<4	NA	<4	<4
Zinc	1	2.38	1.13	<4	5.38

Note: ½ of the detection limit was used for non-detect results in all statistical calculations; NA=not applicable

3.3.3 Hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) and saturated aliphatic hydrocarbons (SHC) were measured as general indicators of petroleum-related contamination. Although hydrocarbons are fairly hydrophobic, trace concentrations of dissolved and adsorbed (to suspended material) compounds persist in many offshore water bodies throughout the world's oceans, with the highest concentrations typically reported for waters near populated industrial areas with nearby rivers (Kennish 1992).

Most hydrocarbons attain peak concentrations in rivers, and estuarine and coastal environments, as there is a strong tendency to adsorb to suspended particles that settle before being carried offshore. Hydrocarbons enter the ocean environment from various sources including natural oil seeps, spills from vessels and drilling rigs, incorporation of airborne particulate matter and down-slope transport of contaminated sediment. Ultimately, they degrade, are taken up by biota in the water column, or are sequestered in sediment.

Summary results for total PAH and total SHC are shown in **Table 3-4** for Liza and Sorubim water samples. Total PAH concentrations (based on the sum of 43 analytes) were extremely low in all samples (≤50 ng L^{-1}). The only PAH compounds detected were naphthalene, C_1 and C_2 alkylated homologues of naphthalene, fluorene, and phenanthrene. These low molecular weight PAHs are ubiquitous trace-level laboratory contaminants. Naphthalene contamination is often introduced from floor waxes, polyvinyl chloride tubing, and other laboratory equipment. Evidence of ultra-trace naphthalene contamination from the laboratory also is derived from the fact that all samples were affected and similar concentrations were detected in the corresponding method blanks. Fluorene and phenanthrene are ubiquitous PAHs found in all petroleum and its products, and in combusted fuels. Ultra-trace concentrations detected in otherwise uncontaminated samples, such as those collected at Liza and Sorubim, are often introduced from laboratory analytical equipment (i.e., cross-contamination).

Table 3-4. Summary results for hydrocarbons in Liza and Sorubim water samples. Results reported in µg L^{-1}, except where noted.

Analyte	No. of Detects	Mean	Standard Deviation	Minimum	Maximum
Liza (n=12)					
Total PAH (ng L^{-1})	12	31.56	6.44	18.0	43.32
Total SHC	3	36.38	66.42	<13	230
Total Unresolved SHC	3	21.3	27.87	<13	87
Total Resolved SHC	3	20.05	39.1	<13	143
Sorubim (n=9)					
Total PAH (ng L^{-1})	9	40.42	5.27	31.39	47.82
Total SHC	1	17.89	34.17	<13	109
Total Unresolved SHC	1	16.89	31.17	<13	100
Total Resolved SHC	1	6.78	0.83	<13	9

Note: ½ of the detection limit was used for non-detect results in all statistical calculations

4 SEDIMENT PHYSICAL AND CHEMICAL RESULTS

Analytical results, consisting of total organic carbon, particle size, hydrocarbons, and metals are presented for ten Liza and eight Sorubim sediment samples. Results for key chemical parameters were evaluated for spatial distribution at Liza and Sorubim, and for variability in relation to water depth and sediment physical characteristics. Results from diagnostic tools to identify potential hydrocarbon sources also are discussed. All results are reported on a dry weight basis.

4.1 Background

Sediment particle size characteristics are emphasized for their controlling influence upon sedimentary community dynamics, and because they often correlate with biologically meaningful variables such as sediment porosity, compaction, oxygen tension, water content and retention of organic matter. Particle size can be equally important in controlling sediment chemical concentrations due to the increase in adsorptive capacity with finer-grained particles. Because many contaminants co-occur with fine-grained particles, there is a potential for contaminant accumulation in deep-water areas, including the continental slope depths of the Stabroek Block.

Guyana coastal sediment is characterized by very thick deposits of transported Amazon mud and high volumes of fluvial mud from erosion in its coastal waters. These ultra-fined grained sediments move down the shelf edge towards the seaward basins, including the area of Liza and Sorubim. In the study area, sediments also are broadcast offshore by the Essequibo River, which empties southwest of the two exploration sites. Although the Guyana coastline has four major rivers that flow through a region of high terrestrial biodiversity, associated rates of detrital carbon flux to the deep seabed (> 1000m) from coastal and overlying water column sources are low, typical of low-productivity tropical habitats.

4.2 Sediment Grain Size and Total Organic Carbon

Sediment particle size (grain size) was reported for four major classes: gravel, sand, silt, and clay based on the percent composition of each class. Fines are the sum of silt and clay fractions, and represent the proportion of particles with diameters <0.0625 mm. Descriptions and corresponding ranges in size (based on the Wentworth scale, Folk 1980) are summarized in **Table 4-1**.

Particle size characteristics are summarized in **Table 4-2**. The majority of sediment samples are categorized as poorly to moderately sorted fine-grained material, comprised of approximately equal portions of silt and clay. All 18 stations had sediment containing greater than 59% fines, with gravel-sized particles absent from all samples and sand contributing no more than 40% in any sample. Results indicate fairly uniform, primarily fine-grained sediment comprised of a fairly narrow range of class sizes based on the Wentworth scale, typical of offshore depositional areas.

In general, significant relationships between key particle size parameters and sample depth were observed at Liza, but not at Sorubim. At Liza, percent fines (p= -0.85, z = 0.021) and TOC (p = -0.93, z = 0.0001) decreased significantly with water depth, but no such relationships were observed at Sorubim (z > 0.05). These results are likely due to the wider range of water depths at Liza compared with Sorubim, rather than differences in bottom sediment physical conditions. Concentrations of TOC were much lower than those of typical depositional sediments, with results less than 1% at all stations.

The respective distributions of percent fines and TOC at Liza and Sorubim are illustrated in **Figures 4-1** and **4-2**, in which both parameters display trends of higher concentrations in the southwest portion of the site, which is closer to shore.

Table 4-1. Sediment particle size descriptions (adapted from Folk 1980).

Sediment Type	Wentworth Scale (mm diameter)	Description
Gravel	>2 to 64	Very Fine Gravel to Gravel
Sand	>0.0625 to 2	Very Fine Sand to Very Coarse Sand
Silt	>0.0039 to 0.0625	Very Fine Silt to Coarse Silt
Clay	>0.00098 to 0.0039	Medium Clay to Coarse Clay

Table 4-2. Summary results for sediment particle size class and TOC. Results reported as percent (%) dry weight.

Parameter	Mean	Minimum	Maximum	Standard Deviation	Station with Minimum	Station with Maximum
Liza (n=10)						
Gravel	0	0	0	0	NA	NA
Sand	17.83	2.09	40.50	12.81	L10	L05
Silt	39.34	20.42	55.56	11.86	L05	L08
Clay	42.83	32.36	57.96	7.11	L07	L06
Fines	82.17	59.5	97.91	12.81	L05	L10
Graphic Sorting (Phi)	2.78	1.47	3.59	0.69	L10	L05
TOC	0.52	0.3147	0.8685	0.16	L05	L09
Sorubim (n=8)						
Gravel	0	0	0	0	NA	NA
Sand	28.88	14.63	38.92	8.92	S03	S09
Silt	31.97	24.17	37.30	4.78	S02	S08
Clay	39.15	24.74	56.37	11.36	S09	S03
Fines	71.12	61.08	85.37	8.92	S09	S03
Graphic Sorting (Phi)	3.37	2.69	3.77	0.39	S03	S02
TOC	0.37	0.2333	0.4939	0.08	S09	S03

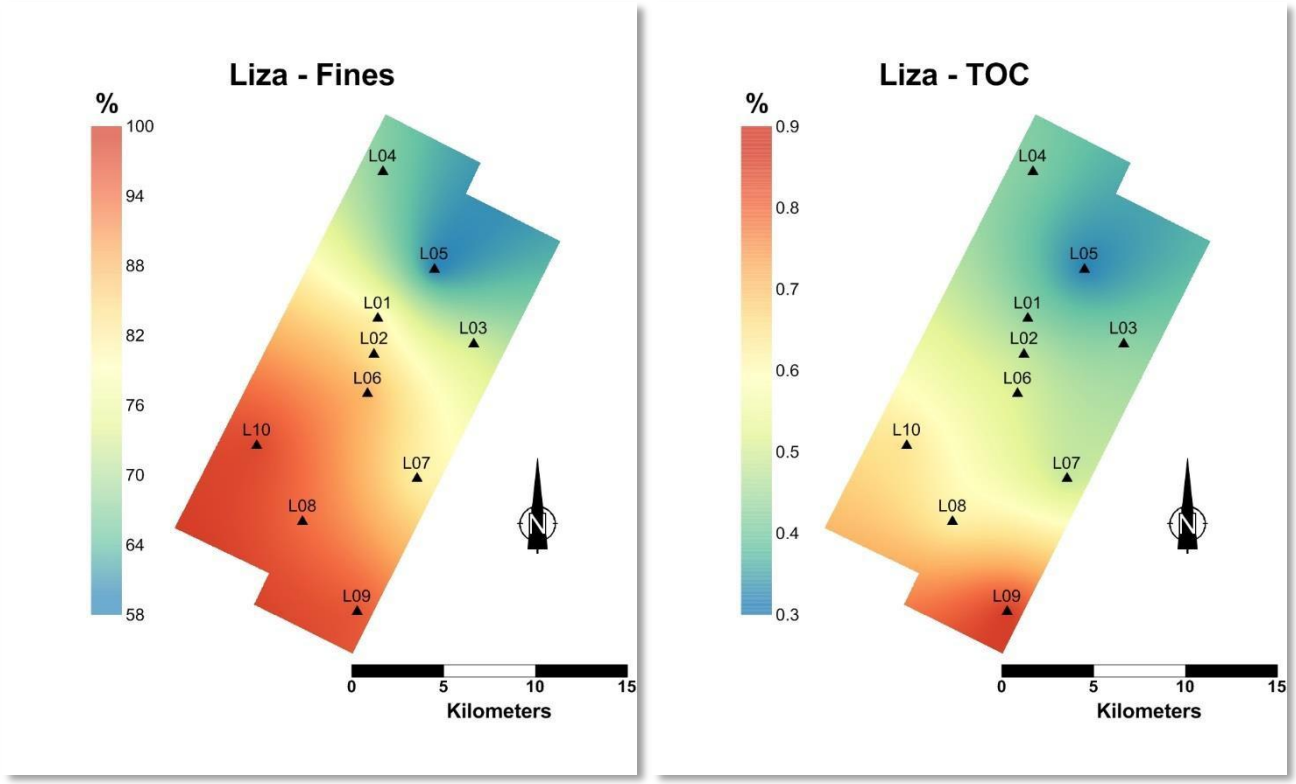

Figure 4-2. Spatial distribution of percent fines (silt + clay) and total organic carbon (TOC) at Liza.

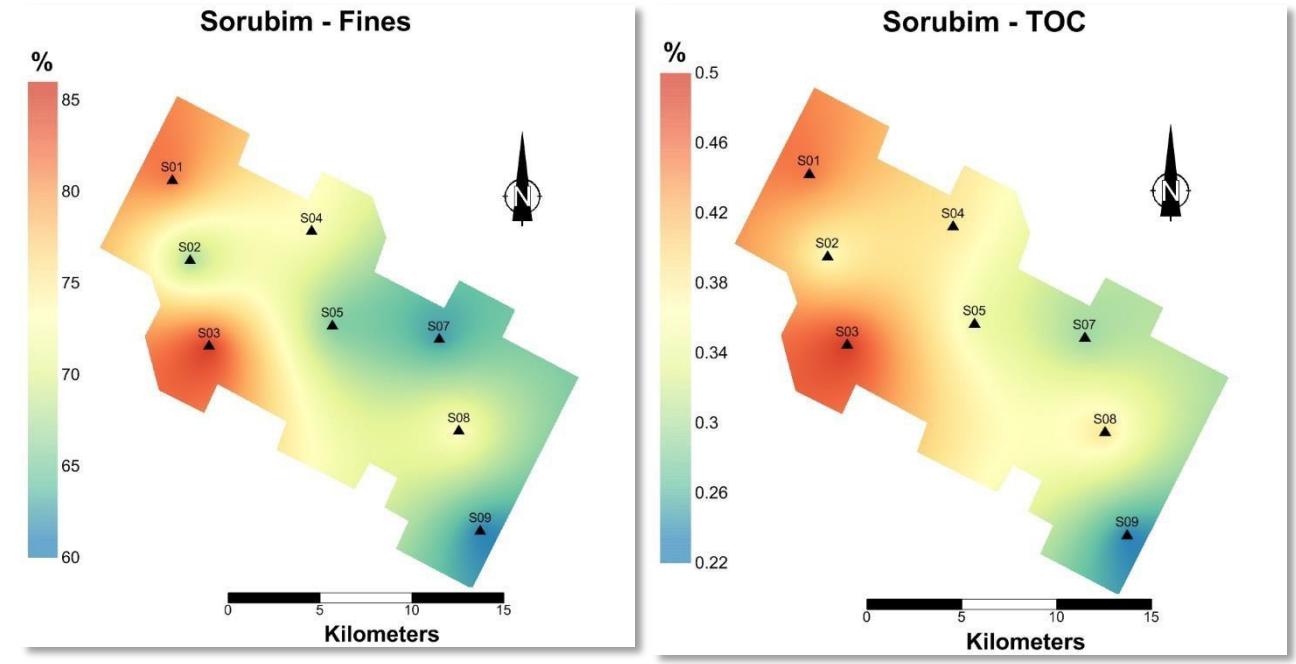

Figure 4-2. Spatial distribution of percent fines (silt + clay) and total organic carbon (TOC) at Sorubim.

4.3 Metals

Twelve metals were measured to determine general patterns of distribution within each site and to assess potential contamination from any nearby pollution sources. Ten metals commonly associated with anthropogenic sources, consisting of arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, vanadium and zinc were analyzed. Two additional metals, aluminum and iron, were analyzed to provide geological source information. Mean metal concentrations and associated statistics for Liza and Sorubim sediments are shown in **Table 4-3**. In general, concentrations of all metals were slightly lower at Sorubim compared with Liza; however, there were no statistically significant differences ($\alpha = 0.05$) between mean concentrations of any metal between the two sites. Concentrations of most metals were similar to or less than mean concentrations reported for the upper continental crust, except for arsenic, which had mean concentrations more than three times higher. Arsenic can become naturally enriched from arsenic-rich igneous and sedimentary rocks, and arsenic-bearing minerals, including arsenopyrite (AsFeS), realgar (AsS) and orpiment (As_2S_3). Elevated arsenic also is a byproduct of gold-mining, a staple of Guyana's economy. The Guyana Geology and Mines Commission (GGMC) oversees the mining industry and has implemented modern mining practices and codes of operation.

Table 4-3. Summary results for sediment metals for Liza and Sorubim. Reported in µg g^{-1} dry weight.

Parameter	Mean	Minimum	Maximum	Standard Deviation	Station with Minimum	Station with Maximum	Mean Background[1]
			Liza (n=10)				
Aluminum	11495	8100	15000	2322	L05	L10	77440
Arsenic	6.06	4.51	11.4	2.07	L01	L09	2.0
Barium	98.92	57.4	159	27.5	L05	L10	668
Cadmium	0.13	0.102	0.165	0.02	L05	L09	0.102
Chromium	14.95	8.57	21.1	4.34	L05	L09	35
Copper	13.11	9.86	16.5	1.84	L05	L10	14.3
Iron	19130	13500	25300	3879	L05	L09	30890
Lead	11.55	8.33	15.6	2.21	L05	L10	17
Mercury	0.042	0.0263	0.0624	0.012	L05	L10	0.056
Nickel	21.44	14.1	32.3	4.9	L05	L10	18.6
Vanadium	23.54	18.1	28.3	3.8	L05	L09	53
Zinc	45.51	26.9	63.7	12.5	L05	L10	52
			Sorubim (n=8)				
Aluminum	8779	7040	11800	1767	S05	S03	77440
Arsenic	6.78	3.86	14.1	3.17	S07	S02	2.0
Barium	76.53	37.8	119	25.8	S09	S01	668
Cadmium	0.13	0.0872	0.15	0.02	S09	S04	0.102
Chromium	12.44	8.38	16.9	2.63	S07	S03	35
Copper	14.53	9.63	19.6	3.12	S09	S01	14.3
Iron	14825	11300	19700	3092	S07	S02	30890
Lead	10.52	8.42	12.3	1.32	S09	S03	17
Mercury	0.034	0.022	0.0457	0.008	S09	S01	0.056
Nickel	18.29	13.8	22.9	2.9	S09	S01	18.6
Vanadium	25.03	17.4	35.8	5.3	S07	S02	53
Zinc	37.14	30.6	46.3	6.4	S07	S03	52

[1]Mean concentration in upper continental crust (Wedepohl 1995)

Pearson correlation coefficients for metals with water depth, percent fines, and/or TOC are shown in **Table 4-4** for Liza and Sorubim sediments. Barium, which can be introduced to the marine environment as barite in drilling muds, increased significantly with percent fines (z<0.001) at both sites. Most metal concentrations increased significantly with increasing TOC and fine-grained sediment (percent fines). Significant changes in these relationships along with increased concentrations of certain metals may be used as an indication of anthropogenic activities. For example, post-exploration changes in the strong positive correlation between percent fines and barium may indicate effects from drilling. In addition to TOC, barium also was strongly correlated with aluminum (p = 0.83, z = 0.003 at Liza; p = 0.82, z = 0.01 at Sorubim), which is apparent in **Figure 4-3**.

Table 4-4. Pearson correlation results (p) for key chemical and selected physical parameters at Liza and Sorubim. Significant correlations (z < 0.05) are shown in **bold.**

Metal	Water Depth	Percent Fines	Percent TOC
Liza (n = 10)			
Aluminum	**-0.79**	**0.91**	**0.80**
Arsenic	**-0.82**	**0.64**	**0.91**
Barium	-0.57	**0.83**	0.55
Cadmium	-0.61	**0.65**	**0.79**
Chromium	**-0.94**	**0.95**	**0.91**
Copper	-0.17	0.59	0.29
Iron	**-0.84**	**0.94**	**0.90**
Lead	**-0.81**	**0.94**	**0.86**
Mercury	**-0.86**	**0.93**	**0.84**
Nickel	-0.54	**0.82**	0.56
Vanadium	**-0.90**	**0.90**	**0.87**
Zinc	**-0.88**	**0.96**	**0.89**
Sorubim (n = 8)			
Aluminum	0.29	**0.90**	**0.86**
Arsenic	-0.02	-0.07	0.09
Barium	0.57	**0.93**	**0.93**
Cadmium	0.64	0.68	0.68
Chromium	0.01	**0.87**	**0.83**
Copper	0.69	**0.83**	**0.88**
Iron	-0.02	0.41	0.43
Lead	0.51	**0.71**	**0.83**
Mercury	0.60	**0.93**	**0.96**
Nickel	0.56	**0.92**	**0.93**
Vanadium	-0.09	0.18	0.26
Zinc	0.34	**0.85**	**0.87**

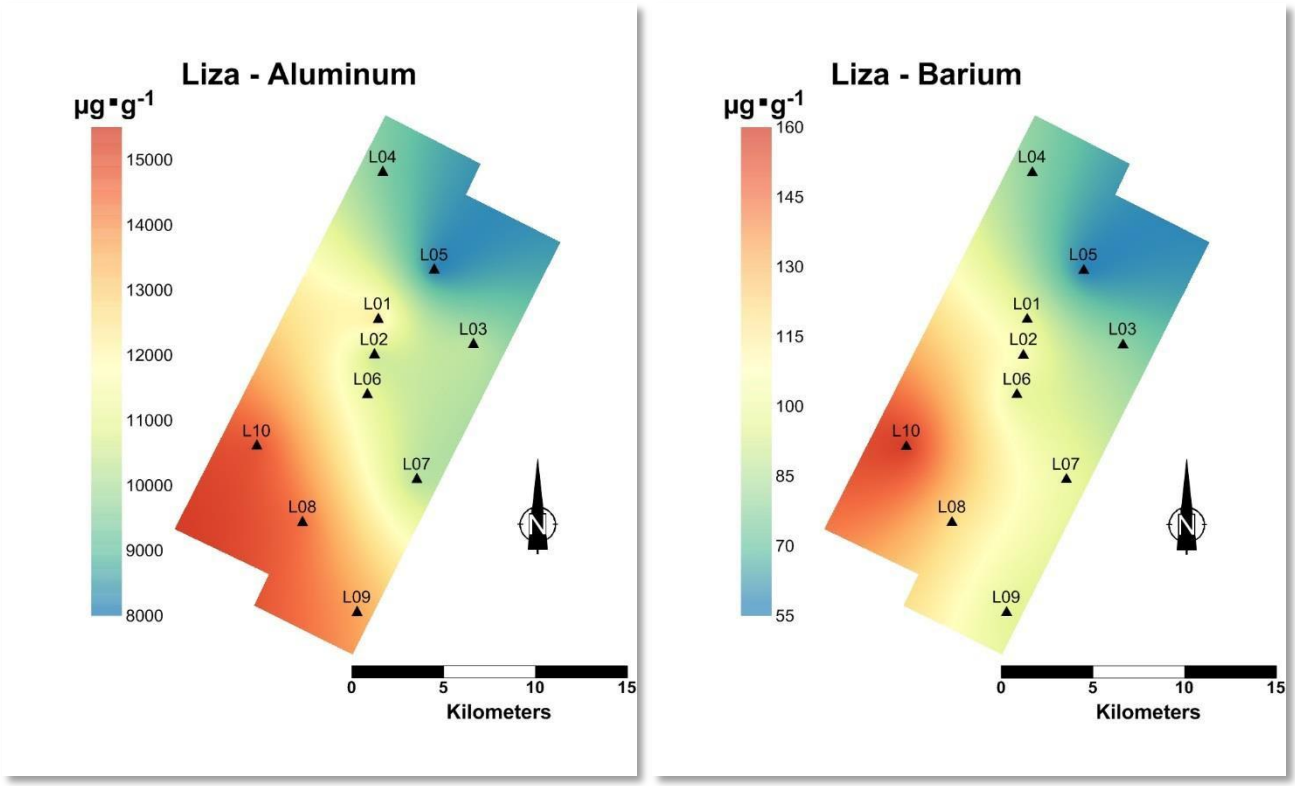

Figure 4-3. Spatial distribution of aluminum and barium in surface sediment at Liza.

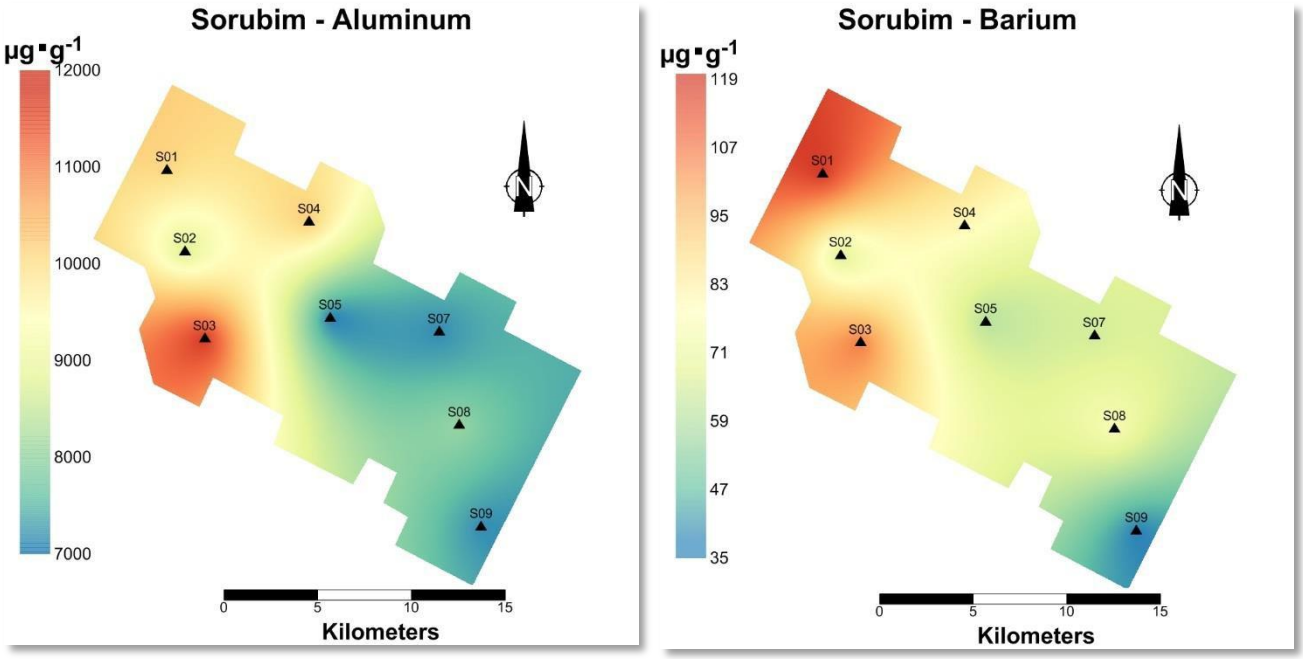

Figure 4-4. Spatial distribution of aluminum and barium in surface sediment at Sorubim.

4.4 Hydrocarbons

Hydrocarbon data describe background conditions as a precursor to future oil and gas development, with the objective of establishing a statistically reliable database for assessment of potential impacts and predictive capacity for projected environmental perturbations. Specifically, the EBS study objectives focus on defining existing chemical concentrations in sediment within the Liza and Sorubim exploration sites. Two classes of organic chemicals consisting of polycyclic aromatic hydrocarbons (PAH) and saturated hydrocarbons (SHC) were emphasized since they are important indicators of age and source of petroleum-related hydrocarbons in sediments. Polycyclic aromatic hydrocarbons analyzed included 20 parent (unalkylated) compounds and 23 alkylated homologues, consisting of two- to six-ring PAH compounds and dibenzothiophenes (sulfur containing compounds). Laboratory data also included results for biphenyl, several hopanes, and several furans, which were not included or interpreted in the EBS. These compounds are rarely addressed in published studies of environmental hydrocarbons, and are not required for the interpretation of hydrocarbon type and potential source in offshore Guyana sediment.

Extremely low concentrations of hydrocarbons were measured in sediments collected at both sites. Total PAH (43 analytes) concentrations ranged from 16.48 to 53.36 ng g^{-1} (nanograms per gram; parts-per-billion) dry weight. Concentrations of total SHC (39 nC_9-nC_{40} analytes, including 7 isoprenoids) also were extremely low, ranging from 1.2 to 14 µg g^{-1} (micrograms per gram; parts-per-million) (mean=9.5 µg g^{-1}), with resolved hydrocarbons comprising the majority of SHC in most samples. There was no significant correlation between total PAH and total SHC (apparent in **Figure 4-5** for Liza), indicating non-petroleum related sources for these extremely low hydrocarbon concentrations.

Hydrocarbon concentrations measured at both sites were lower than those reported for coastal sediments adjacent to relatively unpopulated or non-industrialized regions that receive minor hydrocarbon inputs, such as undeveloped coastal California, the south Baltic Sea, the North Atlantic continental slope and the Gulf of Finland, which all have total aliphatic hydrocarbon (SHC) concentrations ranging from 70 to 500 µg g^{-1} and total PAH concentrations <1 µg g^{-1} (i.e., 1000 ng g^{-1}) (Kennish 1997).

Table 4-5. Summary results for hydrocarbons. Reported in dry weight.

Analyte	Mean	Minimum	Maximum	Standard Deviation	Minimum at Station	Maximum at Station
			Liza (n=10)			
Total PAH (ng g^{-1})	38.61	24.58	53.36	10.99	L05	L08
Total SHC (µg g^{-1})	10.64	8	14	1.92	L06	L05
Total Unresolved SHC (µg g^{-1})	6.97	3	12	2.87	L09	L05
Total Resolved SHC (µg g^{-1})	3.68	2	8.9	2.07	L01	L09
			Sorubim (n=8)			
Total PAH (ng g^{-1})	31.50	16.48	48.05	11.05	S09	S01
Total SHC (µg g^{-1})	8.05	2.6	9.4	2.28	S09	S05
Total Unresolved SHC (µg g^{-1})	5.93	1.2	8.5	2.44	S09	S05
Total Resolved SHC (µg g^{-1})	2.11	0.9	4	1.23	S05	S02

Several key hydrocarbon parameters displayed significant correlations with water depth, grain size parameters, and/or TOC (see **Table 4-6)**; however, results were inconsistent between sites, likely due to the extremely low concentrations measured and the relatively narrow depth range sampled. The positive correlations between total PAH and TOC for both sites is due almost entirely to perylene, a biogenic PAH, which comprised >80% of total PAH concentration in most samples.

Table 4-6. Pearson correlation results (*p*) for key hydrocarbon parameters at Liza and Sorubim. Significant correlations ($z < 0.05$) are shown in **bold.**

Hydrocarbon	Water Depth	Percent Fines	Percent TOC
	Liza (n = 10)		
Total PAH	**-0.86**	**0.82**	**0.71**
Total SHC	0.13	-0.52	-0.14
Total Unresolved SHC	**0.65**	**-0.77**	**-0.71**
Total Resolved SHC	**-0.81**	0.60	**0.88**
	Sorubim (n = 8)		
Total PAH	0.46	**0.89**	**0.93**
Total SHC	**0.78**	0.24	0.46
Total Unresolved SHC	0.48	0.01	0.19
Total Resolved SHC	0.53	0.42	0.47

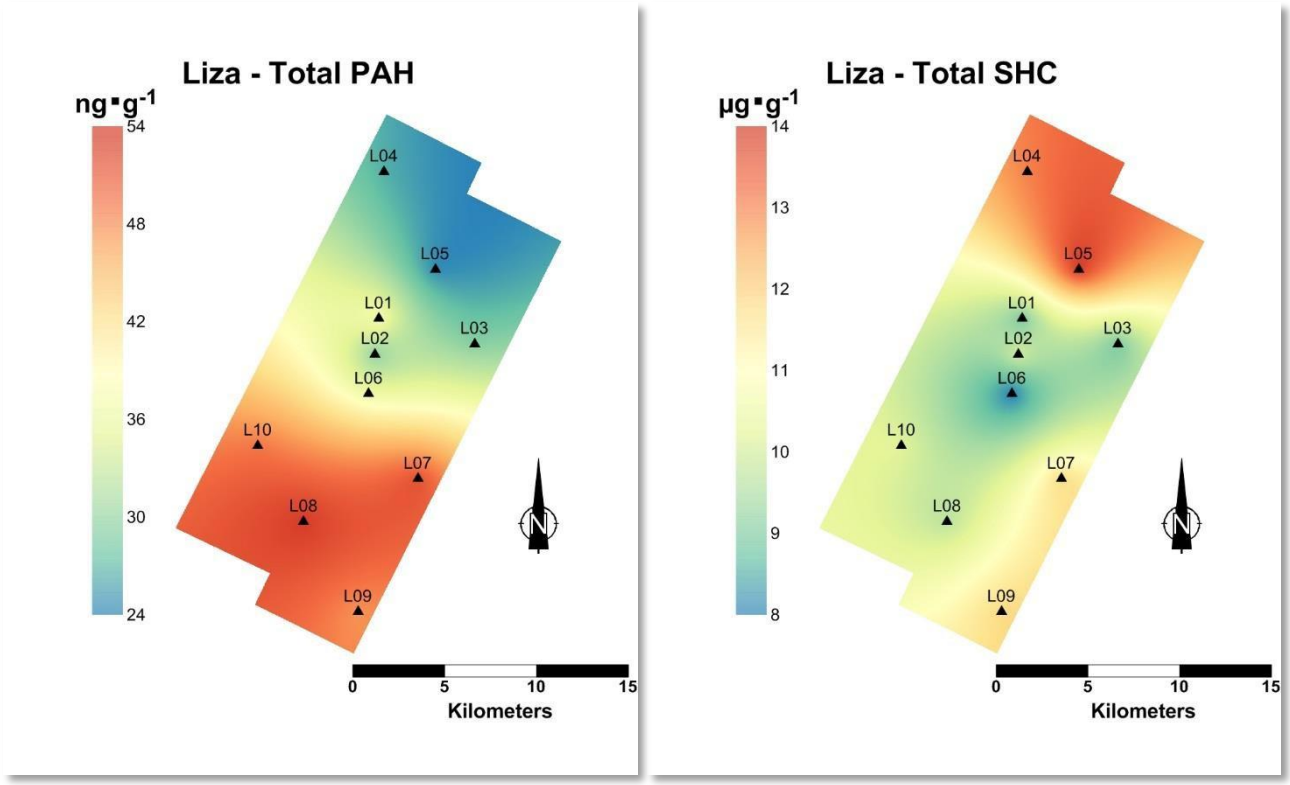

Figure 4-5. Spatial distribution of total PAH and total SHC in surface sediment at Liza.

4.4.1 Hydrocarbon Source

The within sample distribution of individual PAH compounds provides information for a range of hydrocarbon sources, whereas SHC compounds are used primarily to distinguish between biogenic and petroleum-derived sources. Relatively high concentrations of low molecular weight PAH (2-, 3-, and several 4-ring PAH) are typically associated with petrogenic (petroleum-derived) sources. Increased concentrations of high molecular weight PAH (4-, 5- and 6-ring PAH) indicate either pyrogenic (fossil fuel combustion) sources or possibly heavier, more degraded crude oils, depending on their relative distributions. Pyrogenic sources typically display increased concentrations of fluoranthene and pyrene relative to their corresponding alkylated homologues, while heavier crude oils generally display a fuller suite of alkylated compounds that are elevated relative to their parent compounds. The degree of hydrocarbon weathering generally increases as the ratio of naphthalene homologues to phenanthrene/anthracene homologues decreases. Interpretation of values for this ratio (i.e., N/P) and other diagnostic indices used to identify hydrocarbon source and degree of weathering are shown in **Table 2-3** (Section 2); results for diagnostic parameters for the 18 EBS sediment samples are shown in **Table 4-7**.

The distribution of n-alkanes in mature crude oil and distillates typically does not exhibit odd-even carbon preference. Terrestrial plants synthesize n-alkanes almost exclusively with an odd number of carbon atoms in the nC_{25} to nC_{37} range, whereas marine plants synthesize odd-numbered carbon chains in the nC_{15} to nC_{21} range (Hunt 1995). The ratio of pristane to phytane concentrations in sediment also is a useful diagnostic parameter, because phytane is mainly derived from petroleum, whereas both petroleum and biological sources typically contribute pristane to marine sediment. In addition, reduction in concentrations of low molecular weight alkanes (i.e., nC_9 to nC_{20}) and the ratio of heptadecane (nC_{17}) to pristane are commonly related to evaporative and biological weathering of hydrocarbons in sediment.

Table 4-7. Values for key diagnostic parameters indicating hydrocarbon source.

Analyte	Mean	Minimum	Maximum	Standard Deviation	Minimum at Station	Maximum at Station
			Liza (n=10)			
Petrogenic/Pyrogenic	3.36	2.14	4.65	0.97	L04	L07
CPI	1.97	1.47	3.27	0.50	L10	L09
C16/(C15+C17)	0.40	0.24	0.51	0.10	L09	L05
Pristane/Phytane:	1.34	0.67	1.8	0.42	L01	L09
			Sorubim (n=8)			
Petrogenic/Pyrogenic	2.66	1.94	3.37	0.60	S04	S02
CPI	1.99	1.24	3.22	0.59	S07	S02
C16/(C15+C17)	0.36	0.25	0.54	0.09	S08	S09
Pristane/Phytane:	1.05	0.33	2.0	0.51	S03	S01

*see Section 2.3.4 for a description of diagnostic parameters; CPI=carbon preference index

Chromatograms for all 18 sediment samples exhibited a noticeable predominance of odd-carbon-number over even-carbon-number n-alkanes, with a Carbon Preference Index (CPI) value >2 in most samples, indicating primarily biogenic sources of these low concentration hydrocarbons. A strong odd-carbon-number preference in the nC_{25} to nC_{37} range also was observed, indicating that the majority of hydrocarbons in sediment are derived primarily from plant (biogenic) material. Similarly, the low ratio (<1) of nC_{16} over the sum of nC_{15} + nC_{17} for all samples, indicates relatively low inputs of marine algae to these sediments, consistent with the low observed organic carbon content.

Analysis of the aromatic fractions revealed the presence of a full suite of 2-, 3-, 4-, 5- and 6-ring PAH compounds in most samples, with a notable absence of the sulfur-containing benzofurans. In general, sample distributions were dominated by the low molecular weight PAHs, naphthalenes and anthracene-phenanthrenes. High concentrations of perylene relative to other PAH compounds also were observed for all samples. Perylene is a biogenic compound formed during early diagenesis in marine and lacustrine sediments, usually associated with terrestrial plants (Tan and Heit 1981; LaFlamme and Hites 1978), and has been reported as the dominant PAH in clean sediments sampled offshore Brazil. A study by Krauss et al. (2005) indicated that naphthalenes and phenanthrenes (2- and 3-ring PAH) from plant biogenesis provided the majority of PAH measured in sediments and soils in a Brazilian rainforest with low overall PAH concentrations (i.e., <1 µg g^{-1}). In particular, phenanthrene had elevated concentrations (12-60 ng g^{-1}) in bark and twigs of Vismia trees, of which several species (e.g., *Vismia guyana, Vismia baccifera)* are native to Guyana.

The relative absence of combustion-related PAH in all sediment samples, as evidenced in petrogenic/pyrogenic ratios greater than 1 (**Table 4-7**), further indicates that biogenic or natural material, rather than combustion-related compounds, are the primary source of low level hydrocarbons measured in Guyana offshore sediment.

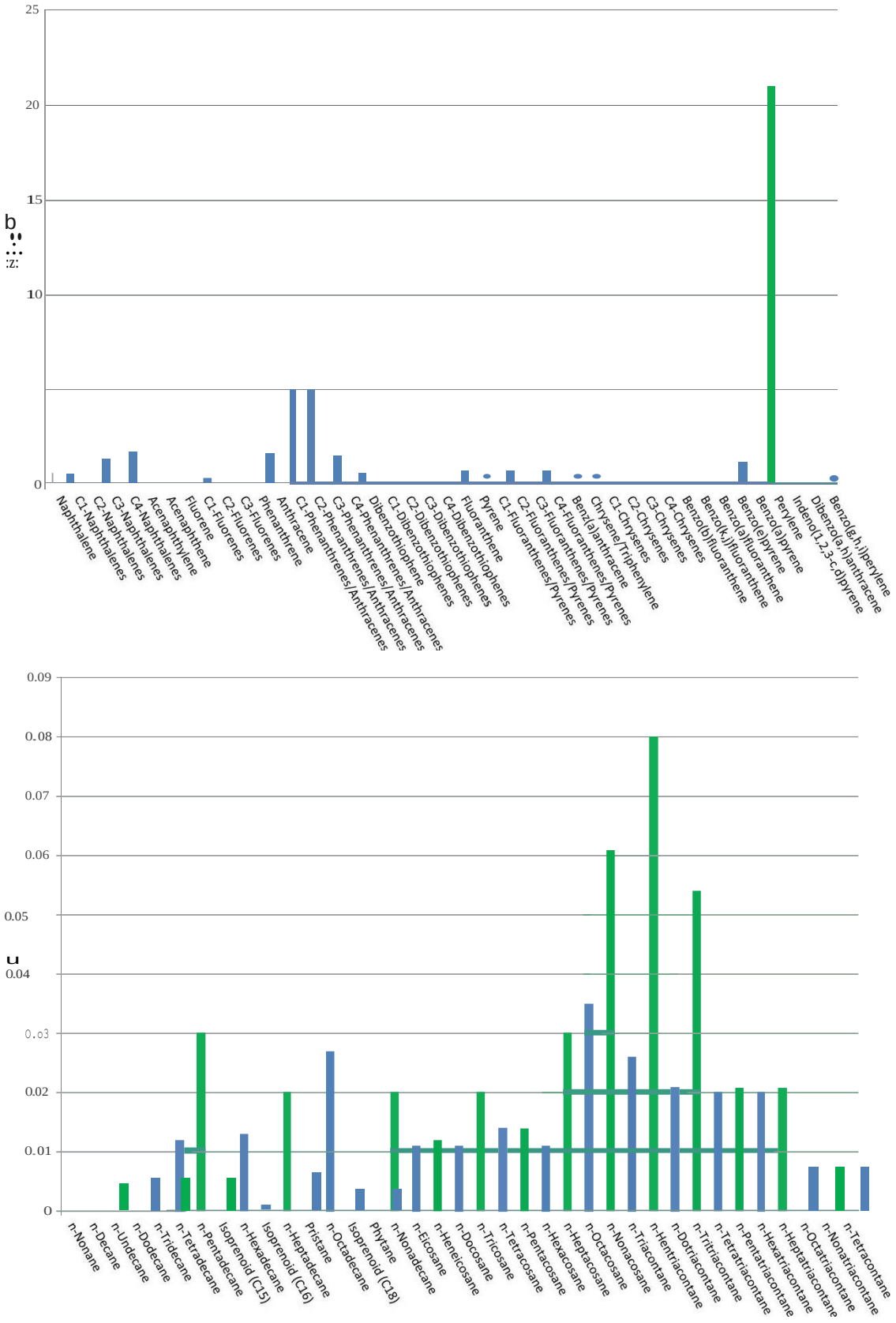

Figure 4-6. Distributions of individual PAH (top) and SHC (bottom) analytes in a representative sediment sample (station L08).

5 BENTHIC MACROFAUNA RESULTS

Benthic macrofauna results are presented for ten Liza and eight Sorubim sediment samples, consisting of patterns of total abundance, abundance of major taxonomic groups, taxonomic diversity, and taxonomic dominance. Presented results include mean values, maxima and minima, and coefficients of variation of data for each of the two sites. Correlations of the biota with depth, sediment grain size and organic content also are examined, spanning the entire range of sediment conditions and depth (877–2327m).

The two sites were sampled at mid- to outer continental slope depths (see Section 1). A stainless steel box corer insert with a sampling surface area of 0.1 m² was used to collect the samples, which were sieved through a 0.5 mm screen and preserved for analysis. Abundance data were respectively transformed and reported as the number of organisms per square meter, which is consistent with conventionally reported benthic literature. Complete field sampling procedures and analytical methods are described in Section 2.

Information on species diversity is constrained by the lack of taxonomic refinement in identification of organisms from deep sediments in general, and particularly from areas such as offshore Guyana (see Levin et al. 2001). Due to the relatively unknown nature of the deep-water biota from this region, taxonomic diversity is discussed in a broader context that is not directly related to the species concept of diversity. Instead, discussion is focused on biological diversity at the family level, which has been shown to be effective in delineating pollution impacts upon the diversity of benthic macrofauna (Ferraro and Cole 1990; Dauvin et al. 2003; Gomez Gesteira et al. 2003).

5.1 Background

The benthic boundary layer serves as a repository for sinking particles containing both organic and inorganic matter, hosting a biologically active and complex trophic food web in continental slope sediments. Benthic infaunal organisms are described as those residing on and in the sediments. They are collected by grab or core sampling, and have conventionally been designated as macrofauna at sizes larger than 0.5 mm (Holme and McIntyre 1971). Most macrofauna live within the upper 10 cm of sediment and are small, averaging only a few milligrams in weight and usually numbering from several hundred to several thousand per m^2 (m^{-2}). Peak values may reach several tens of thousands m^{-2} when a smaller sieve screen (e.g., 0.3mm) is utilized. Many of the increased numbers retained on the smaller screen are isopod and tanaid crustaceans.

The most common invertebrate macrofaunal groups found in marine shelf and continental slope sediments are polychaetous annelid worms, peracarid crustaceans and mollusks (Rex 1981; Grassle et al. 1990; Gage and Tyler 1991). Polychaetes typically comprise about half of the numbers and a third of the macrofaunal species from deep-water marine habitats. Beyond the continental shelf, conventionally defined as exceeding 150 m in depth, macrofaunal biomass and average body size typically decrease with depth, usually ascribed to decreasing food availability and reduced temperature (Rowe et al. 1991; Levin et al. 2000).

Macrofauna communities are known to be strongly influenced by bathymetric gradients in factors such as temperature, dissolved oxygen, and food availability, with depth strongly correlated to shifts of benthic community composition. Relationships of these environmental factors with macrofaunal benthic diversity have been summarized by Levin and Gage (1998) from 40 sites ranging from shelf to abyssal depths of the Atlantic, Pacific and Indian Oceans. Depth, latitude, sediment total organic carbon content (TOC) and bottom water oxygen concentration were determined to be the most significant factors affecting four indices of diversity and community structure, accounting for 52% to 87% of observed variation. Sediment grain size factors were relatively insignificant. When depth and latitude effects were removed, oxygen and organic carbon accounted for 32% to 67% of variation in the four indices.

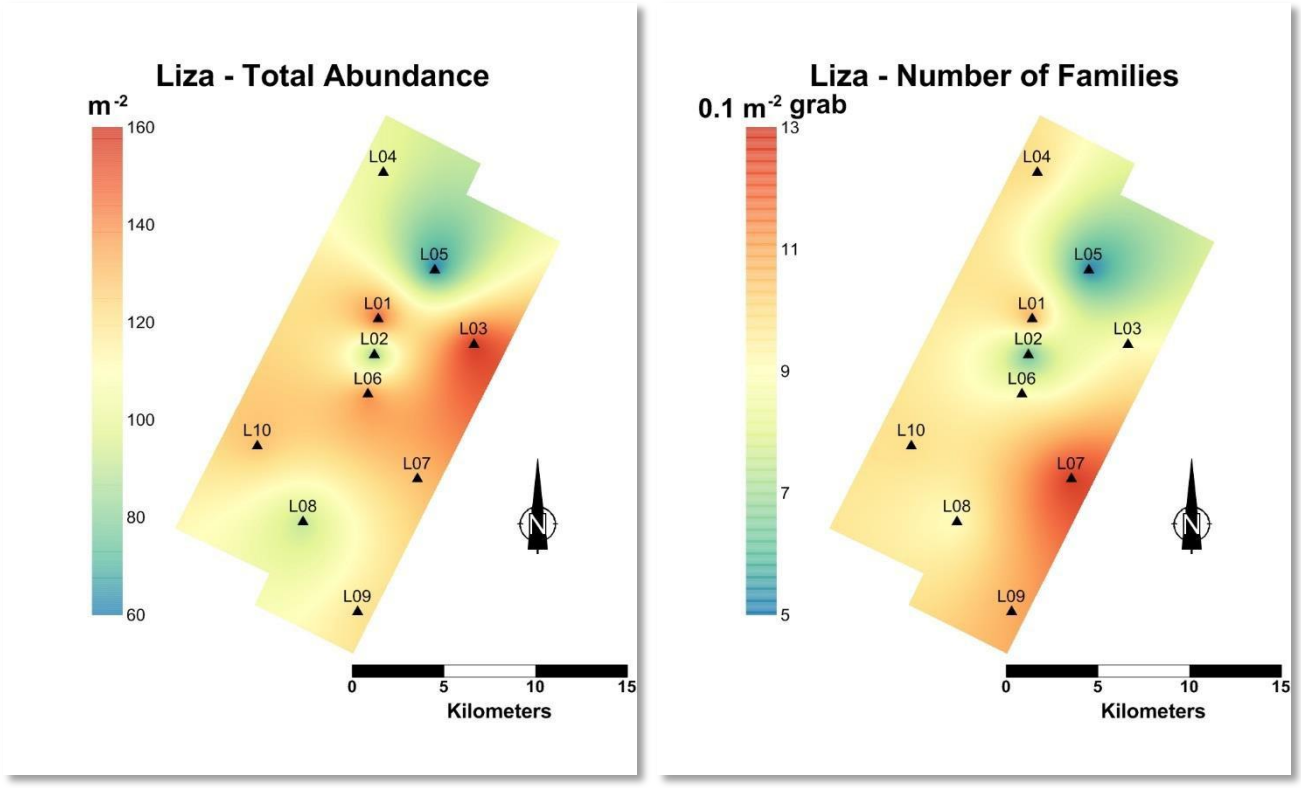

Figure 5-1. Spatial distribution of macrofauna total abundance and family diversity at Liza.

At depths greater than 500 m, seasonal variation in physical parameters (e.g. temperature, salinity) is minimal (Thistle 2003). The absence of significant upwelling phenomena offshore Guyana and little or no seasonal variation in surface productivity in offshore tropical waters suggest that no, or minimal, seasonal variation would be predicted for the benthos in the Liza and Sorubim sampling areas.

Studies of macrofaunal community diversity and abundance have not been conducted on the continental slope offshore Guyana, nor from adjacent areas within several hundred kilometers. This reflects the dearth of information from deep water sites in the southern hemisphere, especially from the western Atlantic Ocean (see Levin and Gooday 2003). From the broader region, studies in the Venezuelan Basin have indicated a macrofaunal abundance of 678 organisms m^{-2} and biomass carbon levels of less than 0.01 grams m^{-2} (Tietjen 1992). Sediments from this region may contain high levels of biogenic carbonate (up to 75%) from Foraminifera tests and may harbor distinctive faunal elements (Briggs 1985).

5.2 Liza – Abundance and Diversity

Ten stations, with a total sampling area of 1.0 m^2, contained 116 organisms, represented by 50 distinct families. General patterns of abundance and diversity, and correlations with sediment parameters and depth follow.

5.2.1 Abundance

Average total macrofaunal abundance was 116 m^{-2}, ranging from 60 to 160 m^{-2}. This population density is at the lower end of macrofaunal densities reported from continental slope sediments around the world (see Rowe et al. 1982; Gage and Tyler 1991). Levels of sediment organic carbon were extremely low in Liza sediments, averaging only 0.52% of sediment dry weight (see Section 4.1). Low sediment TOC suggests limited input of organic food sources sinking to the bottom and does not appear to be sufficient to maintain an abundant macrofauna. Abundance statistics are summarized in **Table 5-1**. Spatial distribution of the abundance of all organisms is illustrated in **Figure 5-1**. Total abundance was not significantly correlated with water depth or sediment physical parameters.

Table 5-1. Summary statistics for benthic macrofauna at Liza (*n*=10). Reported as organisms m^{-2} except where noted.

Parameter	Mean	Standard Deviation	CV	Minimum	Maximum	Station with Minimum	Station with Maximum
Number of Families[1]	9.3	2.4	25.4	5	13	L05	L07
Total Abundance	116	32.4	27.9	60	160	L05	L03
Crustacea	20	14.9	74.5	0	50	L10	L01
Mollusca	29	20.2	69.8	0	60	L05	L03
Polychaeta	47	22.6	48.2	20	90	L04	L01
Other Minor Phyla	11	11	100	0	30	L01	L10

[1]reported as distinct taxa per 0.1 m^2 grab sample; CV=coefficient of variation

The most abundant major taxonomic group was polychaete worms, averaging 47 m^{-2}, comprising 41% of total abundance, followed by mollusks (29 m^{-2}, 25%) and crustaceans (20 m^{-2}, 16%). Collectively they comprised 83% of total macrofaunal numbers. These major taxa are the predominant macrofaunal components of continental slope sediments worldwide. Several other taxonomic groups made up the remaining 18%, including four of the five major classes of echinoderms (brittle stars, starfish, sea-cucumbers, sea urchins), along with nemerteans (ribbon worms), nematodes (round worms), sponges, pycnogonids (sea-spiders) and sipunculids (peanut worms). Dominant families, collectively exceeding 50% of total macrofaunal abundance, are listed in **Table 5-2**.

Table 5-2. Dominant families of macrofauna collectively comprising >50% of total abundance at Liza (*n*=10).

Family	Major Taxon	Percent of total abundance	Frequency of Occurrence (%)
Oweniidae	Polychaete	14.7	70
Tindariidae	Bivalve Mollusk	7.8	40
Apseudidae	Tanaid Crustacean	4.3	50
Arcidae	Bivalve Mollusk	4.3	30
Maldanidae	Polychaete	3.4	30
Golfingiidae	Sipunculid	3.4	30
Phyllodocidae	Polychaete	2.6	30
Chaetopteridae	Polychaete	2.6	20
Ampharetidae	Polychaete	2.6	20
Eusiridae	Amphipod Crustacean	2.6	30
Bairdiidae	Ostracod Crustacean	2.6	20

Polychaete worms were present in all 10 samples and were the numerically dominant taxonomic group, comprising 41% of total abundance (47 m^{-2}), varying by a factor 4.5 between samples.

Predominance of polychaetes is characteristic of continental slope sediments (Knox 1977; Gage and Tyler 1991). Nineteen polychaete families were identified, of which five collectively comprised more than 75% of total polychaete abundance (Oweniidae, 17 m^{-2}; Maldanidae, 4 m^{-2}; Chaetopteridae, 3 m^{-2}; Phyllodocidae, 3 m^{-2}; Ampharetidae, 3 m^{-2}). These families are common and cosmopolitan in distribution from continental slope sediments.

Oweniid polychaetes were the most abundant family of macrofauna, comprising 14.7% of total organisms sampled. These sedentary tube dwelling polychaetes feed on surface deposits and filter suspended particulate matter. Other families such as Capitellidae, Spionidae and Cirratulidae which typify deep sediments with higher organic content (see Pearson and Rosenberg 1978; Bellan 1984) were present, but in lower numbers. Polychaete abundance was not significantly correlated with depth, mean grain size or TOC.

Mollusks were collected at nine of the ten stations. Abundance averaged 29 m^{-2}, comprising 25% of the total macrofauna. Eleven families were collected, of which eight were pelecypods (bivalves). Other molluscan taxa included gastropods (snails), scaphopods (tusk shells) and chaetodermatids. Mollusk abundance was not significantly correlated with depth, TOC or sediment grain size parameters.

Pelecypods had an average abundance of 25 m^{-2}, comprising 86% of mollusk numbers and 22% of total macrofaunal abundance. Tindariids (9 m^{-2}) and Arcids (5 m^{-2}) were the most abundant pelecypod families. Only a single gastropod (snail) was collected (from station L07). Scaphopods of the family Dentaliidae were represented by single specimens from Stations L08 and L10. A single chaetodermatid was collected at station L10.

Crustaceans were present in nine of the ten samples. Abundance averaged 20 m^{-2}, comprising 16% of the total macrofauna. The coefficient of variation between stations (74.5) was the highest of the major taxonomic groups. Crustacean abundance was not significantly correlated with depth, TOC, or sediment grain size parameters.

The most abundant crustaceans were amphipods and tanaidaceans (6 and 5 m^{-2}, respectively). Cumaceans, ostracods, and isopods comprised the remaining crustacean fauna (collectively 5 m^{-2}). Typically, tanaidaceans and isopods are the numerically dominant crustacean groups in slope sediments.

Crustaceans were represented by 10 families, each typically absent from the majority stations or represented by a single individual. Only the tanaidacean family Apseudidae was present at the majority of stations, from which only single individuals were collected. With the exception of three ostracod specimens, all crustaceans (amphipods, isopods, cumaceans, tanaidaceans) were members of the Pericarida super-order, a group of crustaceans that brood their young, generally are of small body size, and are highly successful in deep marine sediments (Sanders 1977; Brandt 1997).

Grouped Minor Phyla, the remaining Liza macrofauna, consisting of a variety of major taxa, collectively comprised 18% of total abundance. Of these, echinoderms (9 m^{-2}) and sipunculids (6 m^{-2}) were most abundant. None of the remaining major taxa exceeded 2 m^{-2} in average abundance.

5.2.2 Diversity and Dominance

The number of families per sample (also referred to as family diversity) can provide an assessment of species habitat suitability. A diversity of families indicates relatively unstressed conditions, with habitat factors that are central to the tolerance ranges of a relatively high number of potential recruits. Low family diversity may reflect environmentally stressed or marginal conditions unsuitable for successful settlement and subsequent growth of recruits. Dominance is defined as the number of species comprising 50% or more of total infaunal abundance. Herein, it is applied to the number of families.

Fifty families of marine organisms were identified from the 10 boxcore samples. Areal (spatial) distribution of family diversity is shown in **Figure 5-1**. The average number of families per grab was 9.3, ranging from 5 to 13, with a CV of 25.4. This is a high number of families given the low total number (n = 116) of organisms retrieved from ten samples. The average number of organisms per family was only 2.3, indicating a low level of dominance by any specific family. This indicates conditions of low physical-chemical stress at the sediment boundary, thereby providing adequate habitat for a diverse biota, but with low flux of detrital food material reaching the bottom to support a larger population.

It is noteworthy that over half of the 50 families were represented by either one or two individuals from the ten samples. This proportion of families represented by few individuals indicates that much more sampling is required to adequately represent the family diversity either locally or regionally (see Grassle and Maciolek 1992).

5.3 Sorubim – Abundance and Diversity

Eight stations from the Sorubim site, with a total sampling area of 0.8 m^2 contained 80 organisms, represented by a 41 families. General patterns of abundance, diversity and their correlations with sediment parameters and depth are discussed below.

5.3.1 Abundance

Average total macrofaunal abundance was 100 m^{-2}. This population density is at the lower end, but within the range, of macrofaunal densities reported from continental slope sediments around the world (see Rowe et al. 1982; Gage and Tyler 1991). Levels of sediment organic carbon were low in sediments, averaging only 0.37% of sediment dry weight (Section 3.3.1), indicating a general limitation of organic food sources reaching bottom sediments to maintain an abundant macrofauna. The only significant correlation (z < 0.05) between abundance and depth, TOC or sediment grain size parameters was a positive correlation between bivalve abundance and percent fines.

Abundance statistics are summarized in **Table 5-3**. Dominant families, collectively exceeding 50% of total macrofaunal abundance, are listed in Table 5-4. Spatial distribution is illustrated in **Figure 5-2**.

Table 5-3. Summary statistics for benthic macrofauna at Sorubim (*n*=8). Reported as organisms m^{-2} except where noted.

Parameter	Mean	Standard Deviation	CV	Minimum	Maximum	Station with Minimum	Station with Maximum
Number of Families[1]	8	3.4	42.8	4	14	S01	S05
Total Abundance	100	40	40	40	150	S01	S03
Crustacea	15	20	133.3	0	50	S01	S05
Mollusca	37.5	29.2	77.7	0	100	S01	S03
Polychaeta	28.8	27	93.8	0	90	S09	S07
Other Minor Phyla	13.8	14.1	102.4	0	40	S01	S08

[1]reported as distinct taxa per 0.1 m^2 grab sample; CV=coefficient of variation

Table 5-4. Dominant families of macrofauna collectively comprising >50% of total abundance at Sorubim (*n*=8).

Family	Major Taxon	Percent of total abundance	Frequency of Occurrence (%)
Tindariidae	Bivalve Mollusk	12.5	37.5
Oweniidae	Polychaete	7.5	20
Nuculidae	Bivalve Mollusk	7.5	27.5
Silicea*	Sponge	3.8	12.5
Chrysopetalidae	Polychaete	3.8	12.5
Spionidae	Polychaete	3.8	25
Cirratulidae	Polychaete	3.8	37.5
Nematoda*	Round Worm	3.8	37.5
Eusiridae	Amphipod Crustacean	2.5	25

*Unidentified family

Mollusks were the most abundant major taxonomic group, averaging 37.5 m^{-2}, comprising 37.5% of total abundance, followed by polychaete worms (28.8 m^{-2}, 29%) and crustaceans (15 m^{-2}, 15%). Collectively they comprised 81% of total macrofaunal numbers. These major taxa are the predominant macrofaunal components of continental slope sediments, worldwide. Several other taxonomic groups made up the remaining 18.5%, including four of the five major classes of echinoderms (brittle stars, starfish, sea-cucumbers, sea urchins), along with hydrozoans, sea-anemones, nemerteans, nematodes and sponges.

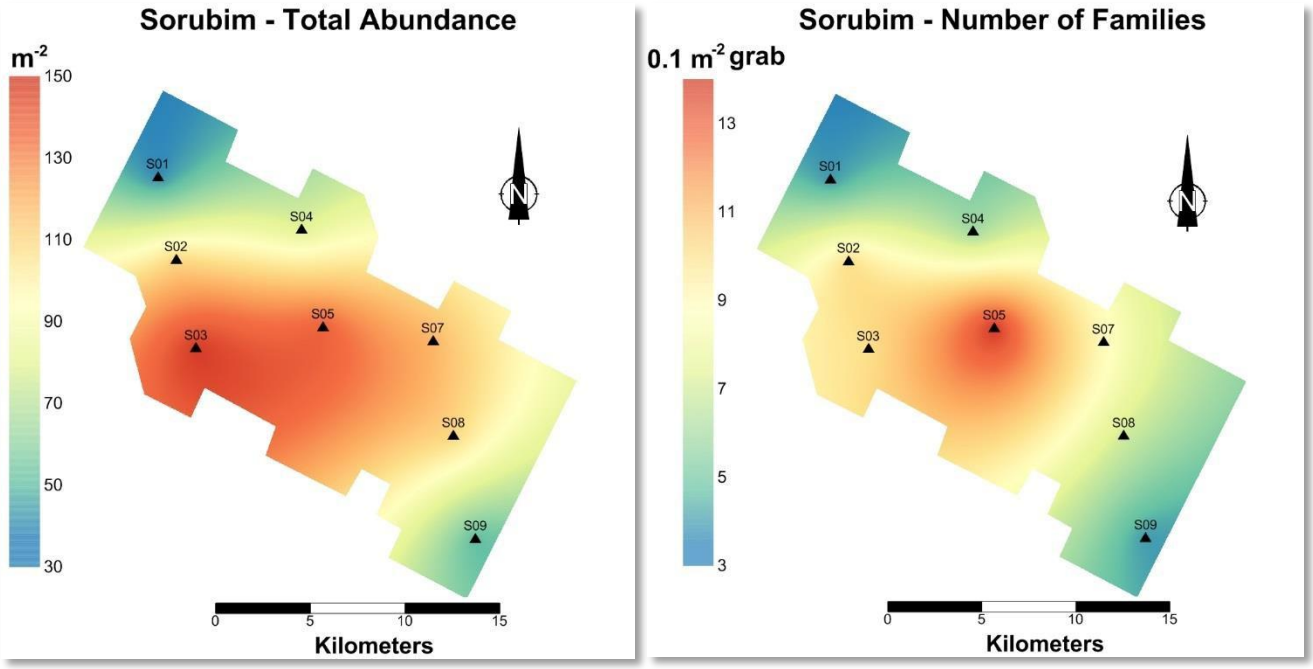

Figure 5-2. Spatial distribution of macrofauna total abundance and family diversity at Sorubim.

Mollusks were collected at seven of the eight sampling stations. Abundance averaged 37.5 m^{-2}, comprising 37.5% of the total macrofauna. Eleven families were collected, of which nine were pelecypods (bivalves). Other molluscan taxa included gastropods (snails) and scaphopods (tusk shells).

Pelecypods had an average abundance of 32.5 m^{-2}, comprising 87% of mollusk numbers and 32.5% of total macrofaunal abundance. Tindariidae (12.5 %) and Nuculidae (7.5 %) were the most abundant pelecypod families (**Table 5-4**). Both of these families are members of the bivalve Order Nuculoida, which contains several families that are dominant members of continental slope macrofaunal communities. Only two gastropods (snails) were collected (from stations S05 and S07). Scaphopods of the family Laevidentaliidae were represented by single specimen from station S03.

Pelecypod abundance exhibited a positive correlation with fine (silt + clay) sediments ($p = 0.837$, $z = 0.019$). Correspondingly, they had a significant negative correlation with the larger sand fraction. Correlations with depth and TOC were insignificant.

Polychaete worms were present in seven of the eight samples, with an average abundance of 28.8 m^{-2}, comprising 29% of total abundance, with a CV of 93.8 between samples. Polychaetes typically represent a higher fraction of total abundance in slope sediments.

Eleven polychaete families were identified, of which oweniids (7.5 m^{-2}) were the most abundant. Other representative families (see **Table 5-4**) are common and cosmopolitan in distribution from continental slope sediments. These sedentary tube dwelling polychaetes feed on surface deposits and filter suspended particulate matter. Other families such as Capitellidae, Spionidae and Cirratulidae which typify deep sediments with higher organic content (see Pearson and Rosenberg 1978; Bellan 1984) were present, but in lower numbers. Polychaete abundance was not significantly correlated with depth, mean grain size or TOC.

Crustaceans were present at four of the eight stations. Abundance averaged 15 m^{-2}, comprising 15% of the total macrofauna. The coefficient of variation between stations (133.5) was the highest of the major taxonomic groups. Crustacean abundance was not significantly correlated with depth, TOC or sediment grain size parameters.

The most abundant crustaceans were amphipods (10 m^{-2}). Tanaidaceans and isopods each averaged 2.5 m^{-2}. They are typically found at higher population densities in slope sediments. Crustaceans were absent from half of the eight stations. Only a single crustacean family (Eusiridae), an amphipod, exceeded 2% of total macrofaunal abundance. All crustaceans were pericarids, which brood their young.

Grouped Minor Phyla; the remaining Sorubim macrofauna, consisting of a variety of major taxa collectively comprised 19% of total abundance. Of these, echinoderms (5 m^{-2}) and sponges (5 m^{-2}) were most abundant.

5.3.2 Diversity and Dominance

Forty-one families of marine organisms were identified from the eight stations. Spatial distribution of family diversity is shown in **Figure 5-2**. The average number of families per grab was 8.0, ranging from 4 to 14, with a CV of 42.8. This is a high number of families given the low total number of organisms (*n* = 80) obtained from the eight samples. The average number of organisms per family was only 1.95, indicating a low level of dominance by any specific family, suggesting conditions of low physical-chemical stress at the sediment boundary. While a diversity of families was present, none had large populations due to an apparent lack of food source as indicated by low TOC values, which averaged less than 0.4% of sediment dry weight.

6 EVALUATION OF DATA QUALITY

This section evaluates the quality of the collected and analyzed data to determine whether relevant program objectives identified in Section 1.1 were met. Specifically, elements of the study design, critical to meeting program objectives (restated below) were evaluated using EBS results (Section 6.1). Sections 6.2 and 6.3 evaluate quality control data for key chemical and biological parameters provided by the laboratories to ensure that data quality objectives, specified in method-specific Standard Operating Procedures (SOPs), were met. Detailed descriptions of analytical methods are presented in Section 2.

6.1 Evaluation of EBS Objectives

Results for key parameters were examined to determine whether the following program objectives (see Section 1) were met.

1. *Provide comprehensive, descriptive, and quantitative documentation of environmental conditions in the area of potential exploration within Liza and Sorubim exploration sites.*

2. *Gain information to assess the significance of environmental impacts to offshore Guyana sediment from potential existing sources such as atmospheric deposition.*

3. *Identify potential confounding factors that may interfere with the interpretation of sediment chemical and biological data to aid sampling design and interpretation of future environmental data.*

To meet the above objectives, sediment and water were sampled in Liza and Sorubim areas of planned petroleum exploration to determine environmental conditions prior to future drilling (see Figure 1-1, Section 1). A total of 18 sediment samples were collected: ten at Liza and eight at Sorubim. Water samples were collected at seven of the sediment stations: four at Liza and three at Sorubim. Samples were collected at three discrete depths (near-surface, at 25m depth, and near-bottom) to capture representative samples from the stratified water column. Water depths ranged from 877m to 2327m for the sampling area, which was located primarily downslope off the central coast of Guyana.

Results for key physical, biological, and chemical parameters (identified in Table 2-2, Section 2) were evaluated to provide estimates of variability and identify physical factors that may impact monitoring results. Potential physical confounding factors, including sediment particle size, water depth, and total organic carbon (TOC), also were measured. These factors are recognized for their strong influence on benthic community structure and sediment chemical characteristics, and can be important in the interpretation of data.

6.1.1 Study Objective 1

Variation within the data set, presented as coefficients of variation (CV), is shown for selected key parameters in **Table 6-1**. Coefficients of variation indicate the relative spread in population data, where the CV = standard deviation ⁄ the population mean x 100. The mean value ± 2 x CV (expressed as percent of mean) provides an approximation of the data envelope containing 95% of the individual data points. With the exception of percent sand at Liza, all key physical and chemical parameters had CV's <50 for sediment samples collected from each site, consistent with physically uniform, uncontaminated sediment. Echinodermata and Amphipoda abundance CV's were relatively high (>100) compared with other macrofauna results, likely due to very low numbers of individuals and patchy distribution. In general, variability is expected to decrease with decreasing distance between stations in future surveys.

Benthic macrofauna community results with CV's >100 are often reported in the literature, typically due to factors such as recruitment, availability of food, predation, environmental contamination, and organic enrichment.

Table 6-1. Coefficients of variation (CV) for mean results reported for selected key parameters for Liza and Sorubim.

Parameter	Liza (*n*=10)	Sorubim (*n*=8)
Sand	71.9	30.9
Silt	30.1	15.0
Clay	16.6	29.0
Fines	15.6	12.5
TOC	30.4	22.6
Depth	24.2	9.0
Aluminum	20.2	20.1
Arsenic	34.2	46.8
Barium	27.8	33.7
Cadmium	19.4	18.3
Chromium	29.0	21.1
Copper	14.0	21.5
Iron	20.3	20.9
Lead	19.1	12.5
Mercury	27.9	21.9
Nickel	23.0	15.9
Vanadium	16.0	21.2
Zinc	27.5	17.3
Total PAH(43)	28.5	35.1
Total SHC	18.0	28.3
Total Unresolved SHC	41.2	41.2
Total Resolved SHC	56.1	58.3
Total Abundance	27.9	40.0
Number of Families	25.4	42.8
Annelida	48.2	93.8
Crustacea	74.5	133.3
Mollusca	69.8	77.7
Other	100.0	102.4
Echinodermata	143.0	151.2
Amphipoda	161.0	141.4
Pelecypoda	76.0	73.1
Polychaeta	48.2	80.0

Low variability in key physical and chemical measurements indicates that post-exploration environmental impacts to study area sediments will be relatively easy to discern from existing conditions. For example, drilling-related discharges to the seafloor, including barium, cuttings (via grain size measurements), or hydrocarbons (e.g., adhered non-aqueous drilling mud), should produce significant differences from background at concentrations of approximately two times higher than EBS concentrations, which are very low based on results from this study. A prospective (a priori) power analysis should be performed prior to designing a post-drilling program to provide information on the number of samples needed to determine a defined difference between mean values for different areas (e.g., well site, reference), which is a standard approach used to quantify changes from drilling-related discharges.

6.1.2 Study Objective 2

Potential confounding factors were evaluated to satisfy Study Objective 2, and to aid sampling design of future studies. Pearson correlations were performed on measured parameters to identify physical characteristics that were significantly correlated with key chemical and biological results, and could therefore, potentially confound interpretation of results. Correlation results for physical parameters with key chemical and macrofauna parameters are presented in Sections 4 and 5, respectively.

Most metals (including barium) and several key hydrocarbon parameters displayed significant correlations with percent fines and TOC (z <0.05) at both sites. These results indicate that sediment grain size and/or TOC should be taken into account in the interpretation of chemical results in future studies.

There were no significant correlations between major macrofauna group abundances with sediment physical parameters or water depth for either site. This is an unusual situation that is likely due to the limited water depth range and consistently low levels of TOC observed at each site.

6.2 Analytical Chemistry Data Quality

Laboratory quality control results were evaluated to ensure that data of sufficient quality were produced to meet program objectives. Quality control objectives for batch analysis (≤20 field samples) are shown in **Table 6-2** for analysis of hydrocarbons and in **Table 6-4** for metals. Quality control results for PAH, SHC and metals data follow.

6.2.1 Hydrocarbons

B&B Analytical Laboratory quality control data packages demonstrated that initial calibration, continuing calibration and procedural blank data for polycyclic aromatic hydrocarbons (PAH) and saturated (aliphatic) hydrocarbons (SHC) met or exceeded data quality objectives listed in **Table 6-2**. Continuing calibration, procedural blanks, duplicate samples, and blank spike/blank spike duplicate pairs were analyzed with every batch of field samples.

PAH. Trace levels of several target compounds (primarily naphthalene, and C_1- and C_2-napthalenes) were detected in the procedural blanks for both sediment and water samples. All concentrations were below five times the corresponding method detection limits, and therefore, met quality control criteria for the method.

Surrogate standards were added to every field sample to monitor extraction efficiency. Surrogate standard recoveries were within the quality control limits specified in **Table 6-3** for all sediment and water samples.

Differences in analyte concentrations (>10x method detection limit) for duplicate samples, as well as concentrations of 100% of matrix spike/matrix spike duplicate analytes and all of the reference standard analytes were within acceptable limits (results not shown).

SHC. Initial calibration, continuing calibration, and procedural blank data for SHC analysis performed by B&B Analytical Laboratory met or exceeded data quality objectives for the method (US EPA 8015-modified). Continuing calibration, procedural blank, duplicate sample, blank spike/blank spike duplicate and standard reference material were analyzed with every batch of field samples. Surrogate standards were added to every field sample to monitor extraction efficiency. Differences in analyte concentrations (>10 x method detection limit) of duplicate samples were within acceptable limits, as were matrix spike and matrix spike duplicate analyte concentrations. Based on these results, SHC analysis satisfied the data quality objectives established for the program. Quality control results for surrogate spike recoveries for 18 sediment and 21 water samples for PAH and SHC are summarized in **Table 6-3**. All surrogate recoveries were within acceptable ranges for each method.

Table 6-2. Summary results for QC surrogate recovery for hydrocarbons (PAH and SHC) in sediment and water. Results reported as percent recoveries (%).

QC Parameter	QC Frequency	Acceptance Criteria	Corrective Action
Instrument Check	1 per analytical run	±15% recovery	Reanalyze or document justification.
Surrogate recovery	2-3 per sample	50-120% recovery	Reanalyze or document justification. Flag impacted data.
Procedural blank	1 per batch of 20 samples	No target analytes > 5X MDL	Reanalyze or document justification. Flag impacted data.
Laboratory Control Sample (Blank Spike)	1 per batch of 20 samples	70-120% recovery	Reanalyze or document justification. Flag impacted data.
Laboratory Sample Duplicate	1 per batch of 20 samples	±30% RPD for 90% of the target analytes that are present at concentrations >10x MDL	Review data to assess impact of matrix. Reanalyze or document justification. Flag impacted data.
Instrument Calibration – Initial Calibration	Initial 5-point prior to sample analysis	±25% RSD single compound average of 15%	Re-calibration or document justification.

MDL=method detection limit; RPD=relative percent difference; RSD=relative standard deviation.

Table 6-3. QC summary results for hydrocarbons (PAH and SHC) analyzed in water and sediment. Results reported as percent (%).

Surrogate	Mean	Minimum	Maximum	Standard Deviation	Acceptable
Sediment PAH (n=18)					
Acenaphthene-d10	86.66	83.67	91.64	2.44	Yes
Chrysene-d12	82.63	79.95	85.15	1.44	Yes
Naphthalene-d8	79.88	74.57	87.36	3.65	Yes
Perylene-d12	62.59	31.71	81.61	14.38	Yes
Phenanthrene-d10	84.30	81.49	87.84	1.67	Yes
Sediment SHC (n=18)					
n-Dodecane-d26	80.56	74.70	89.60	5.50	Yes
n-Eicosane-d42	90.44	83.30	97.20	4.81	Yes
n-Triacontane-d6	94.08	86.40	101.40	5.27	Yes
Water PAH (n=21)					
Naphthalene-d8	83.18	69.32	92.00	6.46	Yes
Acenaphthene-d10	90.41	80.65	105.00	6.64	Yes
Phenanthrene-d10	82.35	66.66	99.00	8.46	Yes
Chrysene-d12	86.74	74.00	94.00	6.01	Yes
Perylene-d12	86.05	74.00	92.00	5.78	Yes
Water SHC (n=21)					
n-Dodecane-d26	56.95	29.90	73.80	11.17	Yes
n-Eicosane-d42	92.11	78.80	98.00	5.51	Yes
n-Triacontane-d6	86.85	71.70	97.10	5.07	Yes

6.2.2 Metals

Quality control criteria and corresponding results for metals analysis are presented in **Tables 6-4** and **6-5,** respectively. Analysis of procedural blanks, matrix spikes, and sample duplicates performed by Albion Environmental Laboratory met all data quality objectives. A procedural blank was analyzed with each batch in order to monitor potential contamination resulting from laboratory reagents and processing procedures. A matrix spike sample (method of additions analysis) was analyzed to provide information on the extent of any signal suppression or enhancement due to the sample matrix. A sample duplicate was analyzed every 10 samples to verify method precision. Based on these results, analysis of metals satisfied the data quality objectives established for the program.

The heated, strong acid leach digestion used to extract metals is NOT a total digestion quantifying all of a given element present in the sediment matrix. The percentage of metal leached into solution for analysis varies by element. For example, for the more refractory metals (e.g., chromium, vanadium), only a relatively small percentage is extracted. For many other elements (including many pollutant metals) that are largely adsorbed onto the sediment particles, a much higher percentage is extracted. A sediment reference material (MESS-3) was used to estimate the percentage of each element leached into solution for analysis. The percentage released is compared to a historical percentage that is typically observed for such a heated strong acid leach. Results for the batch analysis of MESS-3 were within the normal range of historical data, indicating acceptable accuracy for the EBS metals analyzed (historical data not shown).

6-4. Data quality objectives for metals analyzed by ICP with mass detector.

QC Parameter	Acceptance Criteria	Corrective Actions
Mass Calibration	Must not differ by more than 0.1 amu from true value	Perform Instrument Maintenance. Re-calibrate
Resolution Checks	Less than 0.9 amu at full width at 10% peak height	Perform Instrument Maintenance. Re-check
Method Blank	< reporting limit	Notify project manager. Re-extract samples. Evaluate impact to data, discuss with manager, determine if corrective action is necessary
Laboratory Control Sample	80-120% recovery for aqueous and 75-125% recovery for solid	Evaluate impact to data, discuss with manager, determine if corrective action is necessary
Matrix Spike Duplicate (if requested)	75-125% recovery for solid and aqueous; and 20% RPD	Evaluate impact to data, discuss with manager, determine if corrective action is necessary
Initial and Continuing Calibration Verification	90-110% recovery	Perform Instrument Maintenance. Re-analyze affected samples. Notify project manager and justify.
Initial and Continuing Calibration Blank	< reporting limit	Perform Instrument Maintenance. Re-analyze affected samples. Notify project manager and justify.
ICSA and ICSAB Solution	80-120% recovery for spiked analytes	Evaluate impact to data, discuss with manager, determine if corrective action is necessary

amu=atomic mass unit; MDL=method detection limit; RPD=relative percent difference; RSD=relative standard deviation.

6-5. QC summary results for metals analyzed in water and sediment. Results reported as percent (%) unless noted.

QC Sample	Total QC Batch Samples	Minimum	Maximum	Acceptable
Sediment Samples (n=18)				
Matrix Spike Recovery	2	89 (V)	116 (Ba)	Yes
Laboratory Duplicate RPD	2	0.9 (V)	24 (Pb)	Yes
Reference Material Recovery	2	91 (V)	104 (Al, Fe)	Yes
Blank Spike Recovery	2	81 (Pb, Zn)	115 (As)	Yes
Method Blank (µg L^{-1})	2	<0.002 (Hg)	<20 (Al, Fe)	Yes
Water Samples (n=21)				
Matrix Spike Recovery	3	92 (Cd, Cu)	107 (As)	Yes
Reference Material Recovery	3	92 (V)	102 (Zn)	Yes
Blank Spike Recovery	3	95 (Zn)	115 (Ni)	Yes
Method Blank (µg L^{-1})	2	<0.0002 (Hg)	<0.5 (Pb, Zn, Ni, Cr)	Yes
Field Blank (µg L^{-1})	3	<0.0002 (Hg)	<0.5 (Pb, Zn, Ni, Cr)	Yes

6.3 Benthic Infauna

There are three major processes that affect the quality of benthic infaunal data: 1) field collection of samples, 2) laboratory removal and sorting of organisms, and 3) taxonomic identification. Quality control procedures and results used for each of these three major processes follow.

6.3.1 Collection of Benthic Infaunal Sediment Samples

Sample quality was controlled through a process of observation and measurement during the acquisition of sediments destined for infaunal analysis. All 18 EBS sediment samples collected met the following criteria:

1. Sampling device (e.g., 0.1-m^2 box core insert) was not overfilled with sediment
2. Sampling device was fully closed upon sample retrieval
3. Overlying water was not excessively turbid
4. Sampling device contained greater than 15 cm of sediment
5. Sieving/screening device was without tears and punctures for all samples

Infaunal sediment samples collected during the investigation that did not meet the above criteria were rejected and the station was re-sampled. Review of station occupation data taken from the field logs indicated that of the 21 stations sampled, two required more than one grab due to washed out, slumped, or disturbed sediment.

6.3.2 Laboratory Removal and Sorting of Organisms

Ten percent of all samples (i.e., 2 random samples) were re-sorted to provide assurance that >90% of infaunal organisms were removed from sample debris. Resorting was conducted by a quality control technician that did not perform the initial sorting task. The quality control technician sorted through previously processed material following procedures used during the initial removal/sorting process. The total number of newly discovered organisms from the second sorting effort was compared to the total number of organisms obtained from the initial processing task. If the resorted sample contained greater than 10 percent additional organisms, all samples processed by the initial processing technician were completely reprocessed.

Sorting QC results for two randomly selected samples follow. Sample S-EBC02 (station S02) passed, scoring 100%. Sample L-EBC07 (station L07) failed at 90%. An additional QC sample for the initial sorter was randomly chosen from their remaining eight samples. That sample (L-EBC03, station L03) passed, scoring 100%. Final QC results were 95% average sorting efficiency.

6.3.3 Identification and Enumeration of Benthic Macrofauna

Randomly selected 10% of all identifications were reviewed by a second taxonomist. Individual taxa were compared to an extensive in-house reference collection and a voucher collection of identified species was established. Additionally, names of identified species were compared to species reported from other investigations of Caribbean / southwest Atlantic macrofauna, and with the scientific literature for similar latitudes and water depths.

7 DISCUSSION AND CONCLUSIONS

The offshore Guyana EBS area is relatively isolated from coastal activities, and at present is removed from other offshore oil and gas operations. Potential impacts to the marine environment from offshore petroleum development are unlikely to be significant if they are restricted to the immediate development area. However, there is the potential for transport of drilling and operation-related substances into sensitive areas of nearshore shallow zones from the longshore North Brazil Current (NBC) that flows north along the northeastern coast of South America, as it passes Guyana. In addition, the environment may be vulnerable to offshore transport of substances from the Essequibo River, which could project a freshwater lens to Stabroek Block surface waters during periods of heavy flow. Metal and hydrocarbon concentrations in offshore sediments and water are some of the lowest reported worldwide. However, increased industrialization of onshore areas, or localized activities associated with oil and gas exploration and production could contribute to pollutants offshore.

The observed patterns of variance in key physical, chemical, and biological parameters have general implications for environmental monitoring design. Under observed conditions, minor chemical perturbations to the seafloor from drilling operations will be discerned in the local environment within Liza and Sorubim areas of the Stabroek Block. Based upon the current set of data, hydrocarbons (i.e., total PAH and total resolved SHC) are the best indicators of chemical impact. This is due to their potential source from drilling activities as well as their extremely low concentrations and strong positive correlations with fine-grained sediment and organic carbon content.

Benthic macrofauna at Liza and Sorubim are characterized by low abundances combined with high diversity, and low dominance by specific groups. Numerically prevalent groups include polychaete worms, pelecypod molluscs and pericarid crustaceans, as is typical of slope-depth sediments worldwide. The respective average abundances of 116 m^{-2} and 100 m^{-2} are amongst the lowest values reported from continental slope sediments. This result indicates low primary productivity in overlying surface waters, as indicated by corresponding sediment total organic carbon concentrations of approximately 0.5%.

While total abundances were similar between the sites, polychaetes were relatively more abundant at Liza, while mollusks prevailed at Sorubim. Crustaceans were more common and abundant at Liza. The 51 and 41 respective families identified at Liza and Sorubim are typical of continental slope habitats over wide geographic ranges of the world's oceans that are not limited by oxygen depletion, organic loading, or other unique conditions.

The majority of families were represented by no more than two individuals per station, suggesting a low level of group dominance, and indicating that higher sampling density would be required to adequately characterize local or regional diversity.

The results of the Liza and Sorubim site surveys did not indicate the presence of any unique or atypical habitat for the region under consideration. Thus, should any localized potential impact from drilling activities occur, they are unlikely to pose a significant threat to overall population maintenance of the resident biota in the region.

Based upon the current set of data, while abundances of major taxonomic and selected indicator species may be sensitive to drilling-related impacts, taxonomic diversity (e.g., family diversity) would likely provide the best indicator due to its conservative nature (low variability) and responsiveness to environmental perturbations.

Little information concerning temporal variability in macrofauna from this region is available. Therefore, direct comparison of pre- and post-drilling conditions to quantify impacts from exploration activities should be avoided. Instead, inference of drilling-related effects should be based on statistically-based gradient analysis between point sources and references sites that are removed from potential impacts.

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