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PART IX: Sediments

Chapter 24

CHEMICAL CHARACTERISTICS OF SEDIMENT OF THE LOWER HACKENSACK RIVER, NEW JERSEY

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ABSTRACT

The sediments of the Lower Hackensack River provide a record of contamination from ongoing and historical processes in a highly urbanized watershed in northern New Jersey. This estuarine river runs through suburban and small cities in its northern, freshwater reaches; passing south through 8,500 acres of wetlands known as the Hackensack Meadowlands to its mouth at Newark Bay. The goal of this review is to depict the environmental quality of this ecosystem using data derived from sediments collected in 2003 during a Fishery Resource Inventory. This study replicated a similar inventory conducted in 1988, allowing for elucidation of spatial and fifteen-year trends. In the sediments, heavy metal concentrations, grain size distribution and carbon content were analyzed.

Based on sediment guidelines published by NOAA in 1995, the estuary is in “poor” ecological condition; the average concentration of one contaminant, mercury, exceeds the ERM (ERM is the median concentration of a contaminant observed to have adverse biological effects in the literature values examined). It is also apparent that enrichment of mercury and other metals occurs in the Hackensack River north of the mouth of Berry’s Creek, a major tributary known for its legacy of industrial contamination. In addition to this spatial trend, a good predictor of metal concentrations in the sediments appears to be the amount of organic matter present; preservation of organic matter in the river increases as tidal influence is diminished. The sulfate/sulfide cycle, driven by the reaction between seawater and the organic matter, appears to be the primary mechanism.

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Between 1988 and 2003, the average sediment concentrations were reduced significantly for cadmium (71%), chromium (63%), copper (73%) and lead (22%); zinc concentrations remained approximately the same (mercury was not analyzed in 1988). These results suggest a natural attenuation process at work, as burial preserves sulfide rich contaminated sediments.

Keywords: contamination, estuary, organic matter, sediments

1. INTRODUCTION

In 1987 the Hackensack Meadowlands Development Commission (HMDC) initiated a two-year fishery study of the lower Hackensack River. The purpose of the study was to provide an inventory of the fishery resources within the boundaries of the Hackensack Meadowlands District. The data was used to assess the fish population that was using the River, and to determine the extent to which the River and its tributaries provided habitat and refuge for those species. The data from the 1987-88 study was presented in the HMDC's 1989 fishery resource inventory report (HMDC, 1989), which is frequently requested by the State and Federal resource agencies, environmental consultants and the public (Bragin et al., 2005).

The HMDC, which was renamed the New Jersey Meadowlands Commission (NJMC) on August 29, 2001 had always envisioned repeating the fishery inventory periodically to determine whether the fish community would respond to perceived water quality improvements that were occurring within the District. Therefore, in 2001, the NJMC began a new fishery resource inventory of the Hackensack River, the goal of which was to repeat the earlier study and compare the results.

Rather than simply repeat the inventory, the NJMC decided that additional studies would be beneficial. The additional studies included: an investigation of selected contaminants in fish tissue; a study of the reproductive health of the white perch; a food habits study of the white perch; an investigation of the benthic invertebrates that live in and on the river bottom; and a chemical and textural analysis of the river bottom sediments. The results of each of these companion studies are reported under separate cover, and can be obtained from the MERI library.

1.1 Study Design

A total of 21 sampling locations were established during the 1987-1988 fisheries study (HMDC, 1989). The locations were selected with the assistance of the New Jersey Department of Environmental Protection (NJDEP) Bureau of Marine

Fisheries. Sites were selected based on their spatial distribution along the River (within the HMD) and the suitability of deploying and retrieving each of the gear types in order to sample subtidal and shallow inshore areas of the River. The gear types were selected to match what the NJDEP Bureau of Marine Fisheries used in making collections for other fisheries studies in estuarine waters around the State.

The locations sampled during the 2001-2003 fisheries study depicted in Figure 1 replicated the 1988 sites. Due to changes in site conditions during the intervening 13 years, two sampling sites, T9 and TN1, were slightly re-located from their original 1987-1988 locations. Sediment samples were collected by the MERI fisheries team once from each sampling location during the study. Three replicate samples were collected from each location, for a total of 78 sediment samples (river trawl locations were sampled at the shallow and deep end). Table 1 lists the sediment sampling sites, indicating lower Hackensack River segment, river mile or tributary, and fisheries gear type used at each location.

This report focuses solely on the chemical and textural analysis of the river bottom sediments. Sediments were characterized by parameters helpful for measuring ecological-risk and for making comparisons between sampling locations. In the sediments, heavy metal concentrations, grain size distribution and total organic carbon content were analyzed. “These data confirm whether samples were collected in depositional zones, as indicated by relatively higher carbon values and a higher percentage of fine-grained particles, and provide a qualitative indication of bioavailability. Depositional zones are areas of highest potential contamination” (Frasco, 1997). The metals arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel and zinc were analyzed in all sediment samples.

2. MATERIALS AND METHODS

2.1 Field Methods

Sediment samples were collected using a standard 316-stainless steel Ponar grab sampler (sampling area of 0.05 m², weight ~50 lbs.), deployed from a 21 foot Privateer work skiff via a davit equipped with a battery-operated winch. The collection of sediments for chemistry and textural analyses occurred over six days between July and December of 2003, with the majority of the samples collected in December. The first step of the sediment collection process was to anchor the boat above the sampling location. Water depth was ascertained using a Garmin model 160 Blue depthfinder. Next, the Ponar grab was arranged in the open position and it was slowly lowered through the water column using a sufficient length of 5/8 inch line until it contacted the sediment. Once the Ponar grab was on the bottom,

the line was allowed to go slack, and was then given a sharp tug to release the closing mechanism. As the Ponar grab closed, it scooped up approximately 8.2 liters of sediment (i.e., for a full grab in soft sediments). At locations where the substrate was clay or hard-packed sediments, the Ponar was dropped from a

Table 1. Sediment Sampling Sites

	River Mile	Sampling Site	Net Type
Upper River	12.5	TN 6	Trap Net
	12.0	GN 3	Gill Net
	10.9	T5-S	Trawl Shallow
	10.9	T5-D	Trawl Deep
	10.9	TN 5	Trap Net
	10.6	S 3	Seine
	9.3	T4-S	Trawl Shallow
	9.3	T4-D	Trawl Deep
	9.2	TN 4	Trap Net
Middle River	7.4	S 2	Seine
	7.1	TN 3	Trap Net
	7.0	T3-S	Trawl Shallow
	7.0	T3-D	Trawl Deep
	6.8	GN 2	Gill Net
Lower River	5.4	T2-S	Trawl Shallow
	5.4	T2-D	Trawl Deep
	3.8	T1-S	Trawl Shallow
	3.8	T1-D	Trawl Deep
	3.6	TN 1	Trap Net
	3.5	S 1	Seine
	3.0	GN 1	Gill Net
Tributary	Sawmill	T6	Trawl
	Sawmill	TN2	Trap Net
	Berry's	T7	Trawl
	Mill	T8	Trawl
	Cromakill	T9	Trawl

height of one to two feet above the sediment surface in an attempt to collect a sufficient volume of material for the required laboratory analyses in one grab). The winch was then used to raise the Ponar grab containing the collected sediment to the surface. The davit was swung over the deck of the boat and the

Ponar grab was slowly lowered into a laboratory cleaned plastic tub (18.5 inches long x 14 inches wide x 7 inches high). Water overlying the sediment sample (if any) was slowly decanted through the screens at the top of the Ponar grab sampler and was discarded. The Ponar grab was then opened, releasing the collected sediments into the plastic tub. Any sediment adhering to the walls of the Ponar grab were scraped into the tub using a plastic scoop. The sediments were homogenized using the same plastic scoop, and were transferred to properly labeled, pre-cleaned, three-liter glass jar with a Teflon lid, and placed on ice in coolers for transfer to the Meadowlands Environmental Research Laboratory (MERI) laboratory. Three replicate samples were collected at each sampling location. Details regarding the collection location, date and time of sample collection, water depth, observations related to the sediments collected in each replicate sample, and any other pertinent observations were recorded in a field notebook, and are summarized in Table 2.

Table 2. Sediment Sampling

SITE	Date Sampled	Water Depth (ft)	Visual Description of Sediment	Additional Notes
GN1	12/04/03	~15	grey sandy mud (Rep 2 produced a sheen)	Rep. 1 required 3 grabs, and Rep 2 required 2 grabs
GN2	12/29/03	9	sticky grey clay	Needed 2 grabs for each replicate
GN3	08/05/03	8.4	very soft black mud (consistency of mayonnaise)	Each replicate was a full grab
S1	12/04/03	4	mud underlain by sand & gravel (mud produced a sheen)	Replicate 1 required 3 grabs
S2	12/04/03	3	sandy mud	Replicate 1 required 3 grabs
S3	12/12/03	2.5	soft black mud w/ thin brown surface layer	Each replicate was a full grab
T1 deep	12/18/03	16	stiff blackish-grey clay w/ a thin brown surface layer w/ sand & shell hash	Amphipods noted in samples
T1 shallow	12/18/03	11	stiff grey clay	Each replicate was between 1/2 to 3/4 full
T2 deep	12/18/03	19	brown mud w/ some sand. Rep. 1 produced a slight sheen	Replicates 2 & 3 required 2 grabs each
T2 shallow	12/18/03	11	brown sandy mud w/ organic matter & silvery sheen	Each replicate was ~1/4 full
T3 deep	12/18/03	15	soft black mud w/ thin (~1.5 - 2 inch thick) brown surface layer	Each replicate was a full grab

Table 2. Sediment Sampling (continued)

SITE	Date Sampled	Water Depth (ft)	Visual Description of Sediment	Additional Notes
T3 shallow	12/18/03	4	soft black mud w/ thin brown surface layer	Each replicate was a full grab
T4 deep	12/12/03	14	hard sticky grey clay	Needed 2 grabs for each replicate
T4 shallow	12/12/03	~7	soft black mud	Each replicate was a full grab
T5 deep	07/11/03	16.8	brownish-black mud (consistency of mayonnaise) (no odor)	Each replicate was a full grab
T5 shallow	07/11/03	8.3	black mud (consistency of mayonnaise) (with a slight chemical odor)	Replicates 1&2 were full grabs, Rep 3 was 3/4 full
T6	12/04/03	12 to 15	hard grey clay	~6 grabs needed for each replicate
T7	12/29/03	18	soft black mud w/ thin brown surface layer, anaerobic odor, Phrag stalks	Each replicate was a full grab
T8	12/29/03	9.8	brownish-grey soft mud w/ many Phragmites stalks, anaerobic odor	Amphipods and chironomid larvae noted
T9	12/29/03	10	very soft black mud (consistency of mayonnaise) w/ worm tubes on surface	Each replicate was a full grab
TN1	08/05/03	4.2	brownish-grey clayey mud	Each replicate was ~3/4 full
TN2	08/05/03	5.1	greyish-black mud with thin brown layer on top	Each replicate was a full grab
TN3	12/04/03	5	blackish-grey mud w/ thin brown surface layer	Each replicate was a full grab
TN4	12/12/03	3	sticky black mud	Each replicate was between 1/2 to 3/4 full
TN5	12/12/03	4	sticky black mud w/ a very soft top layer	Each replicate was a full grab
TN6	08/05/03	2	soft black mud (consistency of mayonnaise) (no odor or sheen)	Each replicate was a full grab

The Ponar grab sampler was cleaned using site water and a hard-bristle scrub brush to remove any visible sediment before the next replicate sample was collected. After the third replicate sediment sample was collected at a particular sampling location, the Ponar grab sampler was decontaminated using a triple-step wash procedure that included an initial wash and scrub using site water, followed by an Alconox detergent wash/scrub and distilled water rinse, followed by a 10% nitric acid rinse, distilled water rinse, and finally an acetone rinse followed by a final distilled water rinse. The Ponar grab was then placed in a laboratory cleaned plastic tub, ready to be used at the next sediment collection location.

2.2 Physical Properties of Sediment

Sediment texture (particle-size), percent moisture and organic matter were determined for each sample in order to characterize the sediment and to help clarify the difference between site metal concentrations. Statistics performed to discern differences between sites normalized metal concentrations to the percentage of fine material contained in each sample. The American Society for Testing and Materials and (ASTM 2003) standard methods D 422 (particle-size) and D 2974 (moisture and organic matter) were utilized.

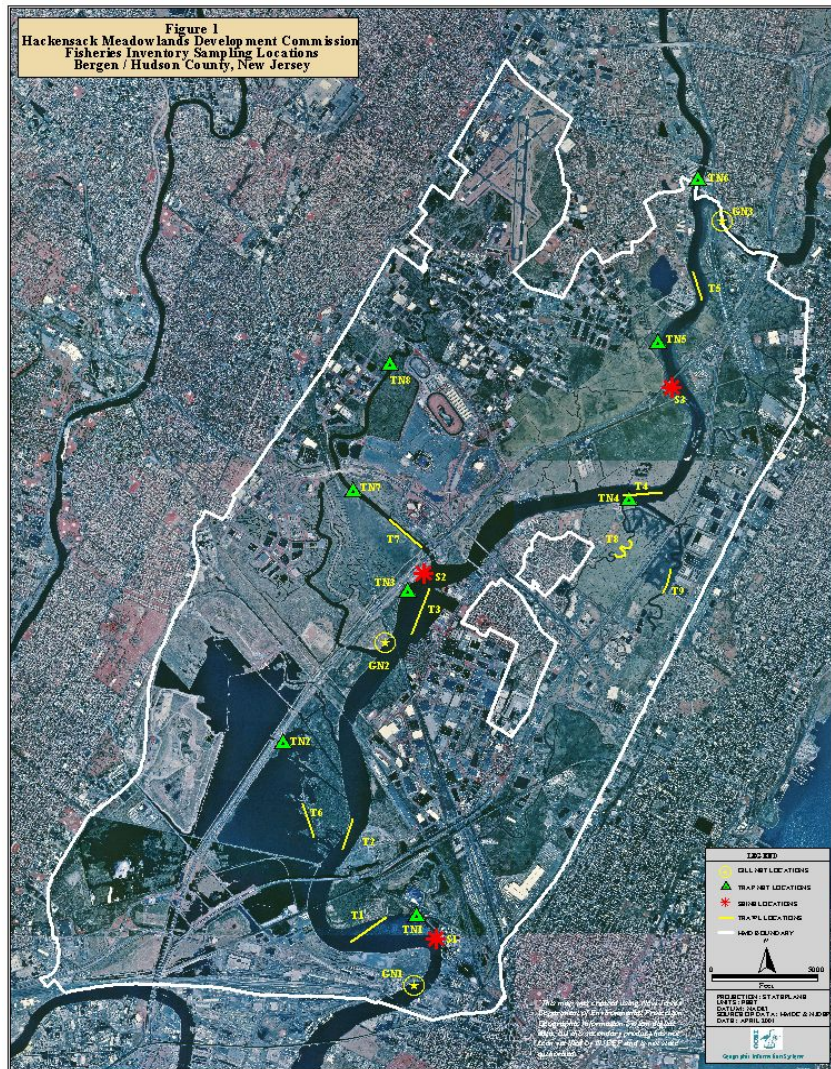


Figure 1. Map of Fisheries Inventory Sampling Locations

Appendix 1 contains the standard operating procedure for particle-size analysis. In summary:

1. The soil sample is dried at room temperature.
2. Sieve the ground sample through a No. 10 (2 mm) sieve using the Rotasift for 5 minutes. This material when weighed is the coarse fraction.
3. The material passing through the sieve is mixed with a dispersing agent until homogenized.
4. Transfer soil-water slurry (sample in dispersing agent) from its beaker into a glass sedimentation cylinder and fill to 1000mL with DI/distilled water.
5. Record both hydrometer (specific gravity) and temperature readings at intervals of 2, 5, 15, 30, 60, and 150 minutes after sedimentation begins.
6. When the hydrometer/temp readings are finished, pour the cylinder through a No. 230 (63 μ m) sieve. Dry the material retained on the No. 230 sieve at 105° C.
7. Once dried, break up aggregations and perform a final sieve analysis of the material through a No. 40 (425 μ m), No. 60 (250 μ m), and a No. 120 (125 μ m) sieve (simultaneously) for 20 minutes. Weigh and record the mass of material retained on each sieve and the material that passed through all three sieves. This is the mass of sandy material.

A calculator using Excel (Appendix 2 contains a sample spreadsheet) was devised to convert hydrometer readings to grain size classifications. This is necessary to distinguish between clay and silt size material (collectively referred to as % fines).

Table 3. Grain Size Classes

Sieve	Grain Size	Classification
4	4.75 mm	Pebble
10	2.00 mm	Granule
40	425 μ m	Coarse Sand
60	250 μ m	Medium Sand
120	125 μ m	Fine Sand
230	62.5 μ m	Very Fine Sand
<230	5 μ m	Silt
	<5 μ m	Clay

ASTM Method D 2974 describes the gravimetric determination of both moisture content and organic matter. Percent moisture was determined by drying

the sample for 16 hours at 105° C. Organic matter (ash content) was determined by igniting the oven dried sample from moisture content in a muffle furnace at 550 °C.

2.2 Metals Analysis

A sufficient amount of sediment (1-2 g wet weight, yielding 0.4-0.8 g dry weight) was oven-dried, weighed, and mineralized in 10 ml Trace Metal Grade HNO₃ in Teflon bombs in a microwave digester. The resultant mineralized solution was boiled off to near dryness, restored to 25 ml volume with 1% HNO₃, and divided. Twenty ml were used by the MERI laboratory for analysis of Cr, Cu, Cd, Fe and Pb by flame atomic absorption spectrophotometry (AAS). The remaining 5 ml were used by UMDNJ for Hg analysis by cold-vapor AA in a Bacharach MAS-50D mercury analyzer and for As analysis by hydride generation AA in a Perkin-Elmer 603 spectrophotometer. All metal analyses in 1988 were performed in the HMDC Laboratory (now MERI Laboratory) using AAS. Instrumentation in the MERI laboratory was upgraded in 2001.

One Standard Reference Material (SRM) was analyzed with every ten samples. Table 4 is a summary of the percent recovered, which ranged from 72.4% for Chromium to 103% for Cadmium in 2003, and 69.9% for Zinc to 120% for Cadmium in 1988. Arsenic, Mercury and Iron were not analyzed in 1988.

Table 4. Summary of SRM Recovery

Metal	% Recovery	
	1988	2003
Arsenic		75.7
Cadmium	120	103
Chromium	105	72.4
Copper	92.4	99.7
Mercury		91.2
Lead	108	95.9
Nickel	115	95.6
Zinc	69.9	82.0
Iron		81.9

3. RESULTS AND DISCUSSION

3.1 Sediment Texture

Table 5 summarizes the average percent fine material (sum of the silt and clay fractions), organic matter (OM) and moisture content grouped by net type. On

average, the seine locations had the least amount of fine sediment. This is an artifact of the manner in which the sites were selected. Since the seine net was walked through the water and the net hauled up onto the shoreline at each seine location, sites that could not be easily traversed (i.e., those with thick mud) were not selected. Areas chosen as seine collection locations generally had a firm bottom (i.e., were lacking in fines). On the other hand, the trap net sites were selected to sample nearshore areas which were too muddy to seine. The trap nets were staked into mudflats at the selected locations that were close to shore, hence the high average percentage of fine material in the trap net samples. Intermediate between the seine and trap net locations were the gill net and trawl locations, which were generally located in deeper waters of the Hackensack River, or in the tributaries. The higher energy of the flowing river at some locations does not allow for the settlement of much fine material (e.g., GN1 and T2), while other sampling locations were clearly in areas of lower energy which were depositional in nature (e.g., T1 and T5).

Table 5. Net Type Averages of Physical Properties

Net Type	# of Locations	% Fines	% OM	% Moisture
Seines	3	40	7.7	50
Gill Nets	3	61	7.9	51
Trawls	14	70	9.8	60
Trap Nets	6	82	12.0	65

The surface area of particles increases as the size of particles decreases; as organic matter is often found as coatings on particles, it is reasonable for fine material and organic matter to co-vary as demonstrated by the net type averages. The moisture content of samples introduces the notion that opportunities for interchange between solid and liquid phases in the benthic environment are plentiful. In fact, the complexity of the system described by these parameters plays a strong role in the metal concentrations found in our samples.

Table 6 describes the texture of material sampled in the current and previous studies. Overall, the percentage of fines in the samples has remained relatively consistent; averaging 72% in 1988 and 69% in 2003. A plot of the data in Figure 2 reveals the temporal relationship in better detail. At Site T5 Deep, for example, fine material was relatively depleted in 1988 compared to 2003. This site is located in the channel of the River opposite the PSE&G Bergen Generating Station power plant; between 1988 and 2003 the cooling regime for this plant was converted from using river water to self contained cooling towers. This removed a thermal discharge plume which likely scoured the fine material from the river channel, providing a possible explanation for this change. Site S1 is also relatively depleted in fine material. The site is located along the bank of the river where a

strong current provides persistent scouring; but no change in conditions has occurred to explain the difference between the intervening years. Figure 2 also illustrates that one goal in the sampling design was met; collection sites were successfully replicated. This conclusion is supported by calculation of the population correlation coefficient between the two data sets: $r = 0.73$.

Table 6. Comparison of Fine Material Collected, 1988/2003

Sample Site	1988	2003	Difference
GN1	11.5%	19.1%	7.6%
GN2	73.0%	73.7%	0.7%
GN3	98.2%	89.0%	-9.2%
S1	41.5%	1.80%	-39.7%
S2	40.3%	27.7%	-12.6%
S3	97.3%	91.3%	-6.0%
T1 (deep)	55.1%	70.6%	15.5%
T1 (shallow)	56.4%	74.6%	18.2%
T2 (deep)	17.6%	19.5%	1.9%
T2 (shallow)	11.0%	40.2%	29.2%
T3 (deep)	92.8%	87.5%	-5.3%
T3 (shallow)	91.0%	81.2%	-9.8%
T4 (deep)	88.9%	60.9%	-28.0%
T4 (shallow)	93.9%	68.6%	-25.3%
T5 (deep)	14.8%	84.7%	69.9%
T5 (shallow)	96.7%	79.6%	-17.1%
T6	94.8%	76.6%	-18.2%
T7	94.6%	84.6%	-10.0%
T8	91.4%	84.0%	-7.4%
T9	92.5%	86.4%	-6.1%
TN1	76.3%	83.6%	7.3%
TN2	94.8%	86.5%	-8.3%
TN3	96.0%	78.6%	-17.4%
TN4	89.4%	76.7%	-12.7%
TN5	77.6%	80.1%	2.5%
TN6	84.8%	85.6%	0.8%
Average	72.0%	68.9%	-3.1%

The percentage of fine material helps describe the sedimentary character of the estuary, both spatial and temporal. The sampling sites covered nine miles of the river and the major tributaries that are within the Hackensack Meadowlands

District. Grouping the river sampling sites spatially can reveal differences between the lower, middle and upper part of the river within the District. Refer to Table 1 for the grouping of sites. Note that each river segment is separated by at least 1.5 river miles. Because of the strong influence of net type on sediment characteristics, an attempt was made to include a sampling from each net type in each segment. Exceptions are the absence of a gill net in the upper part of the river and a seine in the tributaries.

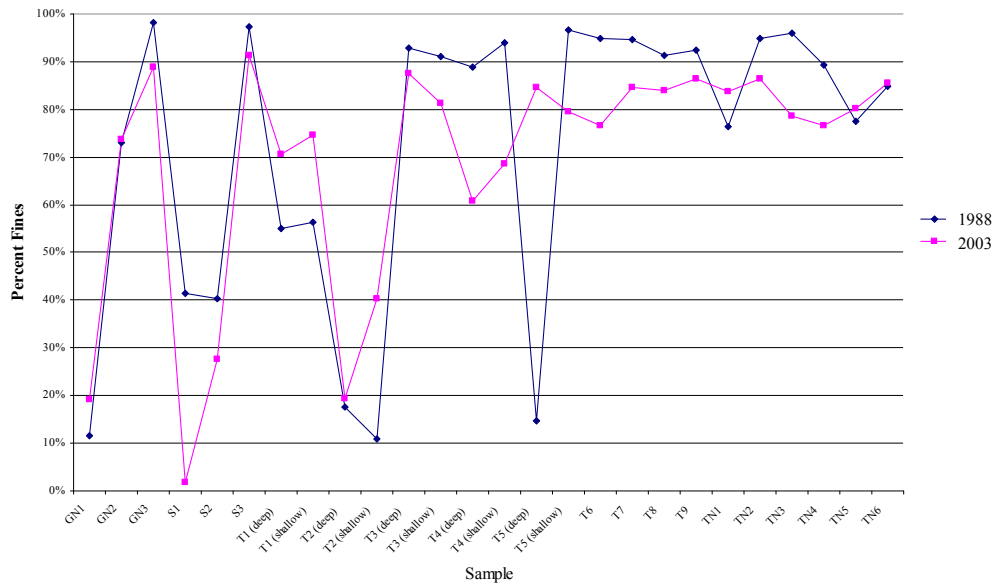


Figure 2. Plot of Site Textures

Figure 3A compares the average of fine percentages found in the tributaries and river in 1988 and 2003: Tributaries contain finer material than the river; the river hasn't changed during the 15 year interval between sampling; and there has been a 12% reduction in the percentage of fine material found in tributary samples. The composition of fine material is a function of hydrodynamics. As energy in the water column dissipates, finer material is deposited. The River would naturally have higher energy, with finer material being carried until deposition occurs in mudflats, along the shorelines and in the tributaries. Because the relative amount of fine material is very dynamic, it is difficult to draw conclusions from this data; for example, the increased energy from storm events can redistribute fine material in the short term that would mask long term changes in the River.

Figure 3B is a comparison between the average of fine percentages found in the three segments of the river in 1988 and 2003: The average percentage found in

the lower river has increased 13%; the middle part of the river has decreased by 13%; and the upper part of the river has remained relatively unchanged (2% decrease). Appendices 3 and 4 contain the complete grain size analysis for sediments collected in 1988 and 2003.

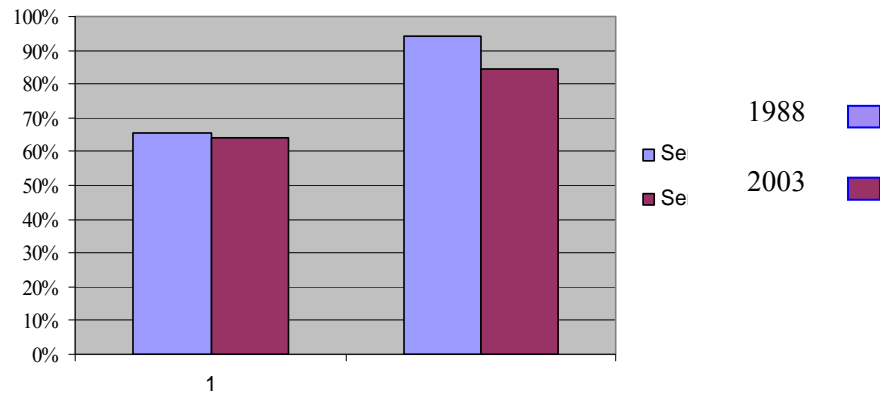


Figure 3A. Spatial Distribution of Percent Fines: River vs. Tributaries

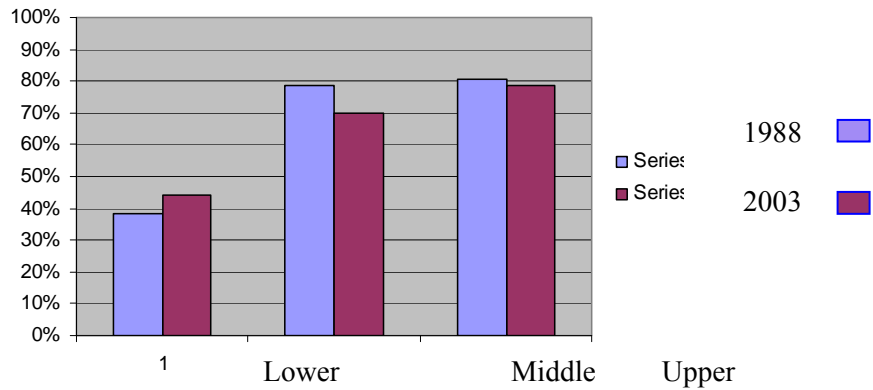


Figure 3B. Spatial Distribution of Percent Fines: River Segments

3.2 METALS

The metals and organic chemicals selected for analysis are contaminants known to bioaccumulate. The organics and mercury bioconcentrate, i.e., accumulating to higher levels (typically an order of magnitude) with each trophic level, making them of special concern (Weis 2005). The discussion which follows will include a description of the spatial distribution of metal concentrations collected in 2003

and the factors affecting that distribution; and a comparison between data collected in 2003 and 1988 using sediment quality criteria as a measure of ecosystem quality. A complete listing of concentrations obtained in 2003 and 1988 appears in Appendices 5 and 6.

There are no absolute chemical concentrations that correspond to sediment toxicity, but “Effects Range Low” (ERL) and “Effects Range Median” (ERM) values are used as guidelines in assessing sediment contamination. ERM is the median concentration of a contaminant observed to have adverse biological effects in the literature studies examined (Long et al 1995). A more protective indicator of contaminant concentration is the ERL criteria, which is the 10th percentile concentration of a contaminant represented by studies demonstrating adverse biological effects in the literature. Ecological effects are not likely to occur at contaminant concentrations below the ERL criterion (USEPA 2004, p. 12).

Table 7 describes qualitative ratings for sites based on ERM and ERL criteria. Based on the EPA’s sediment contamination assessment criteria, the ecological condition of the Hackensack River estuary sediments in 2003 was Poor; the average concentration of one contaminant, mercury, exceeds the ERM. Table 8 provides a comparison of average metal concentrations obtained in 1988 and 2003 to the ERM and ERL criteria. Metals which exceeded the ERM criteria are printed in red. In 1988, three additional metals cadmium, copper and nickel exhibited concentrations that would have exceeded the ERM criteria. The improvement in sediment quality in the 15 years between studies is depicted in the table as the high concentrations of cadmium, copper and nickel are no longer experienced in these estuarine sediments.

Table 7. Criteria for Assessing Sediment Contaminants by Site (USEPA 2004, p. 17)

Rating	Criteria
Good	No ERM concentrations are exceeded, and less than five ERL concentrations are exceeded.
Fair	Five or more ERL concentrations are exceeded
Poor	An ERM concentration is exceeded for one or more contaminants.

Six of the 21 river samples, collected primarily at sites below the mouth of Berrys Creek, exhibit Good sediment quality: the mercury ERM is not exceeded and less than five ERLs are exceeded (See Table 9). None of the tributary sites meet this criteria. Other contaminants that exceed ERM criteria in individual samples are cadmium, lead, nickel and zinc. The average concentration of all of the metals exceed ERL criteria; 60% of the sampling sites exceed more than five ERLs.

It is apparent that the sediments can be considered contaminated by all of the metals studied. Superimposing a semi-qualitative stacked bar graph on the map of the estuary, Figure 4, reinforces this spatial trend. In this urban estuary, multiple sources for the metals are likely; Newark Bay, the Passaic River, historical industrial discharges, hazardous waste sites, landfills, power plant emissions and run-off from combined sewer outfalls and transportation arteries contribute.

Table 8. Hackensack River: Average Metal Concentrations (As and Hg were not analyzed in 1988)

ERM and ERL Guidance Values in Sediments (Long et al., 1995)				
Constituent	ERL mg/kg	ERM mg/kg	Hackensack Estuary Mean	
			1988	2003
Arsenic	8.2	70		8.89
Cadmium	1.2	9.6	10.5	3.0
Chromium	81	370	347	130
Copper	34	270	429	115
Mercury	0.15	0.71		3.55
Lead	47	218	164	128
Nickel	21	52	110	42.9
Zinc	150	410	243	263

The sediments are mobile, capable of absorbing contaminants anywhere in the estuary, carrying their load of metals until being deposited.

The distribution of the mercury in the sediments of the estuary is depicted in Figure 5. The maximum concentration of the mercury occurs in Berry's Creek. It is apparent that enrichment occurs in the Hackensack River above the mouth of Berry's Creek Canal (Site T7). A chemical processing plant located at the head of the tidal portion of Berry's Creek operated from 1929 until 1974. Although the Ventron/Velsicol facilities were abandoned and demolished in 1974, contaminants still remain on site and potential pathways for migration are re-distribution of sediments, groundwater and air. Discharges from the facility are known to have contaminated the Creek with mercury and other chemicals. Mercury levels in the sediment adjacent to the property are among the highest known in freshwater ecosystems nationwide. (USEPA 2006). It is clear that the mercury contamination is no longer confined to Berry's Creek. Statistical analysis supports the conclusion that there is no significant difference between mercury concentrations found throughout lower, middle and upper river segments (Filipiak and Johnson 2007).

Table 9 represents the average metal concentration of three replicates collected at each site. The organization of the table by river miles and tributaries with coloration of concentrations exceeding the ERL sediment criteria (See Table 8), allows for a visual representation of spatial trends. The distribution of ERL exceedences (five or more per site) suggests that with two exceptions, S-2 at mile 7.4 and T-4 Deep at mile 9.3, the river north of mile 7.0 is likely to suffer negative ecological effects.

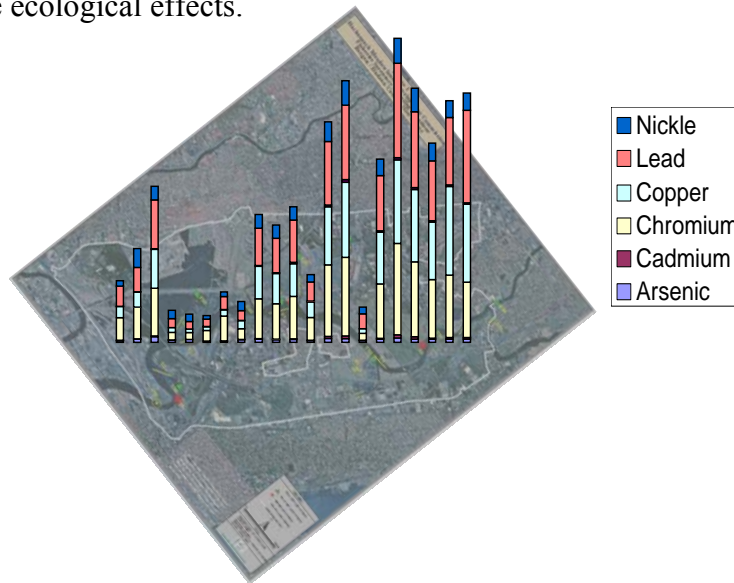


Figure 4. Visual Depiction of metal spatial trend

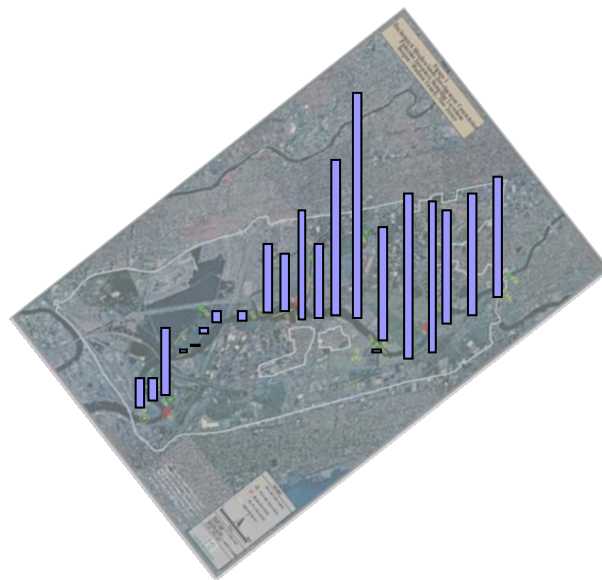


Figure 5. Visual Depiction of mercury spatial trend

Table 9. Hackensack River metal concentrations obtained in 2003
 Values exceeding the ERL are typed in boldface; values exceeding the ERM are bolded and italicized.

		Metals (mg/kg)								
		Arsenic	Cadmium	Chromium	Copper	Mercury	Lead	Nickel	Zinc	Iron
	ERL	8.2	1.2	81	34	0.15	47	21	150	
	ERM	70	9.6	370	270	0.71	218	52	410	
Sampling Sites	River Mile									
GN 1	3.0	5.13	0.80	68.9	33.9	<i>1.11</i>	61.5	16.2	101	12472
S 1	3.5	10.4	0.42	96.1	46.6	<i>0.85</i>	73.7	57.8	113	34720
TN 1	3.6	17.1	2.48	145	118	<i>2.57</i>	148	41.7	230	29198
T1-S	3.8	7.01	0.14	23.2	14.5	0.09	27.3	25.2	59.2	26463
T1-D	3.8	8.76	0.13	20.6	11.2	0.05	22.6	22.6	56.4	27471
T2-S	5.4	3.68	0.29	32.4	11.8	0.20	22.7	10.8	54.7	11997
T2-D	5.4	3.58	0.46	76.0	19.5	0.43	39.4	14.0	68.6	12139
GN 2	6.8	8.26	0.34	33.3	24.9	0.38	29.1	28.1	82.0	34512
T3-S	7.0	9.65	1.69	121	99.1	<i>2.65</i>	113	41.9	213	33966
T3-D	7.0	8.16	1.45	108	92.5	<i>2.22</i>	105	40.2	210	30418
TN 3	7.1	8.92	1.62	130	99.3	<i>4.19</i>	129	40.5	236	34945
S 2	7.4	5.68	0.90	69.1	47.4	<i>2.86</i>	58.0	22.4	130	19859
TN 4	9.2	11.8	5.95	218	177	<i>5.99</i>	193	59.8	390	36687
T4-S	9.3	11.1	8.43	240	228	<i>8.65</i>	227	74.3	437	38166
T4-D	9.3	5.79	0.36	21.3	13.8	0.09	45.3	20.2	61.2	24987
S 3	10.6	9.64	2.95	165	158	<i>4.36</i>	168	49.9	359	37232
T5-S	10.9	13.4	9.88	278	255	<i>6.34</i>	287	76.2	660	35524
T5-D	10.9	9.87	7.28	228	220	<i>5.79</i>	231	71.8	522	36034
TN 5	10.9	9.11	3.90	178	175	<i>4.35</i>	182	53.8	384	36923
GN 3	12.0	9.63	5.30	190	270	<i>4.67</i>	205	51.2	527	37760
TN 6	12.5	10.1	5.08	168	237	<i>4.65</i>	282	52.3	494	37772
TN2	Sawmill	9.33	2.03	190	270	<i>2.06</i>	205	51.2	527	37760
T6	Sawmill	6.36	0.13	123	106	0.20	130	41.1	244	32817
T7	Berry's	13.8	<i>13.05</i>	23	13	<i>20.8</i>	22	25.8	66	29304
T8	Mill	22.8	1.93	297	237	<i>3.41</i>	227	73.4	536	38060
T9	Cromakill	11.6	2.19	170	133	<i>3.28</i>	141	52.2	283	38843

3.3 Sediment Metal Behavior

We can look to the relative concentration of total carbon and fine grained particles to discern why the metals reside where they do. Concentration distributions presented to show patterns of regional contaminant distributions and metal co-variances imply common sources or behaviors (Mecray et al 2001). Table 10 displays the Pearson product-moment coefficient (R^2) which depicts the strength of the correlation of the values of independent variables obtained at each sampling

site. With the exception of iron and arsenic, the sediment correlation matrix displays the close affinity of all of the metals. A general linear model was used to measure the relationship between each of the metals as independent or predictor variables and other metal as dependent or criterion variable (Filipiak and Johnson 2007). The significant model equations for each of the metals confirmed the strong interaction between the metals (Filipiak and Johnson 2007). Because correlation does not imply causation, it cannot be inferred from this information that the metals share a common source. It is more likely that their observed distributions result from the influence of hydrodynamics reflected by sediment texture and organic content.

Table 10. Sediment Correlation Matrix (R^2)
* Correlation coefficients > 0.77

	Arsenic	Cadmium	Chromium	Copper	Iron	Lead	Mercury	Nickel	Zinc	River mile	% Fines
Cadmium	0.47										
Chromium	0.58	0.93*									
Copper	0.50	0.91*	0.92*								
Iron	0.63	0.55	0.63	0.66							
Lead	0.56	0.91*	0.94*	0.96*	0.65						
Mercury	0.43	0.89*	0.93*	0.88*	0.60	0.90*					
Nickel	0.67	0.80*	0.87*	0.78*	0.83*	0.82*	0.76*				
Zinc	0.47	0.94*	0.93*	0.99*	0.65	0.97*	0.89*	0.80*			
River mile	0.13	0.77*	0.71	0.85*	0.62	0.79*	0.81*	0.60	0.85*		
% Fines	0.55	0.54	0.54	0.65	0.70	0.62	0.58	0.47	0.63	0.61	
% TOC	0.62	0.85*	0.89*	0.92*	0.79*	0.95*	0.87*	0.82*	0.92*	0.80*	0.79*

Particulate size and resulting total surface area available for adsorption are both important factors in adsorption processes... smaller particles can both be more widely dispersed by water and can also serve as sites of enhanced adsorption (John and Leventhal 1995 p. 13). In this estuary dominated by the tidal regime, depositional environments occur when energy dissipates. One would expect the percent of fine material to increase as the distance increases from the mouth of the river; a moderate correlation ($R^2 = 0.61$) between % fines (silt and clay fraction) and river mile does exist. The strength of the correlation between the metals and % fines is moderate as well (average $R^2 = 0.59$). A confounding factor which diminishes the strength of the river mile/ percent fines correlation relates to the differing substrate requirements for the four net-types used for sampling fish which provided the sites for sediment collections as well (Table 5).

A better predictor of metal concentrations in the sediments appears to be the amount of organic matter present in the sediments. In organic carbon-rich sediments, trapped interstitial fluids can commonly form a strongly reducing (anoxic) environment. The sediment samples in this study averaged almost 60% water. Low redox potential in this environment can promote sulfate reduction and sulfide mineral deposition. During diagenesis, much of the potentially toxic metals, such as arsenic, cadmium, copper, mercury, lead, and zinc, can form insoluble sulfides; a change to an oxidizing environment caused by disturbance of the sediment and exposure to the atmosphere or with the influx of oxygenated (sea) water can result in rapid reaction of this anoxic sediment and thereby release significant proportions of these metals (John and Leventhal 1995 p. 13). The sulfate/sulfide mechanism appears to effect metal concentrations, helping to explain the enrichment in the upper reaches of the river and depletion as oxygenated sea water interacts the organic matter in sediments.

3.4 1988/2003 Comparison

Between 1988 and 2003, the average sediment concentration of cadmium, chromium, copper, lead and nickel was reduced by between 22% and 71%; zinc concentrations remained relatively constant (8% increase). This dramatic improvement suggests a natural attenuation process is burying contaminated sediments with cleaner material. Perhaps the naturally high background concentration of zinc found in this region provides a continuous supply of this metal to the sediments.

Table 11. Metal Comparison 1988/2003

Average Metal Concentrations (mg/kg)			
Metal	1988	2003	Difference
Cadmium	10.5	3.0	-71%
Chromium	347	130	-63%
Copper	429	115	-73%
Lead	164	128	-22%
Nickel	110	42.9	-61%
Zinc	243	263	+8%

Statistical analysis was performed on the sediment metal concentrations as well (Filipiak and Johnson 2007). Three sites, S1, S3 and TN5, were not included in the year to year comparison. S3 was excluded because there was no data in 1988; it had been identified as S4. S1 and TN5 were excluded as the site identification was recorded incorrectly. To test whether there were significant different between studies done in 1987-88 and 2003 a paired t test was used. The justification for using the paired t experimental design was the methodology of having samples collected at approximately the same geographical locations where

the only factor is the time in between collections (Filipiak and Johnson 2007).

Significant difference in concentrations was found for the following metals in sediments when comparing 1987-88 and 2003 using a paired t-test:

- Cadmium (Cd), levels higher for 1987-88
- Chromium (Cr), levels higher for 1987-88
- Copper (Cu), higher for 1987-88
- Lead (Pb), higher for 1987-88.

When the sites were grouped according to their location in the main river or tributaries, the following metals exhibited significant differences in the main river:

- Cadmium (Cd), higher for 1987-88
- Copper (Cu), higher for 1987-88
- Lead (Pb), higher for 1987-88

The main river levels of Chromium, Nickel and Zinc did not have a statistically significant change between 1987-88 and 2003. In the tributaries, there were no significant differences for any of the metals studied.

Statistics were also applied to the Lower, Middle and Upper segments of the Hackensack River (see Table 1 and Figure 1). The only statistically significant result was the higher value of cadmium concentrations in the Lower River in 1987-88 compared to 2003.

4. CONCLUSIONS

Sampling and analytical methods applied to the sediment study of 2003 successfully replicated the 1988 effort, allowing for spatial and temporal comparisons between physical and chemical properties. The ecological quality of the Hackensack River Estuary was discerned using guidance criteria applied to metal concentrations.

The texture of bottom sediments has not changed greatly during the 15 year interval between studies and the sediment quality has clearly improved. Between 1988 and 2003, the average sediment concentration of cadmium, chromium, copper, lead and nickel was reduced by between 22% and 71%. However, since 60% of the sampling sites exceed more than five ERLs the estuary continues to exhibit metal contamination.

Mercury concentrations once thought to be confined to Berry's Creek, have now reached all parts of the estuary. Since Mercury was not determined in the 1989 study, it was not possible to determine trends over time.

Finally, the majority of the metals seem to be correlated. This correlation however does not conclusively show that they share a common source. The study indicates that their observed distributions are also closely related to sediment texture and organic content.

5. REFERENCES

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APPENDIX 1. Grain-Size Analysis SOP

Standard Test Method for Particle-Size Analysis of Soils, D422-63(2002). ASTM International, 2003.

(Nicole Quinn, MERI)

Procedure:

Expose the soil sample (about 130g out of jar for silt/clay soils, about 200g for sandy soils) to air at room temperature until dry. Use the blower under the hood. This could take 2-7 days.

Break up aggregations in a mortar with a rubber-covered pestle, trying not to crush the grains.

Sieve the ground sample through a No. 10 (2 mm) sieve using the Rotasift for 5 minutes.

Break up aggregations retained on No. 10 sieve, using mortar and pestle. Sieve the ground material again through the No. 10 sieve for 5 minutes.

After sieving the sample twice through the No. 10 sieve, remove the sieve and wash with DI/distilled water anything retained on the sieve. Put this sieve in the oven to dry at a temp. of 100 – 105 degrees Celsius. This is the coarse material.

Get a 250mL beaker and a spatula and measure out 50g into the beaker for silt/clay soils and 100g for sandy soils. Use at least 32g for silt/clay and 82g for sandy soils. Use the PB3002-S DeltaRange scale.

Add 125mL of the dispersing solution (40g/L sodium hexametaphosphate) to the beaker and stir until homogenized. Cover with parafilm, label, and leave for at least 16 hours.

To make more dispersing solution, measure 40g of sodium hexametaphosphate and add to about 800mL DI/distilled water in a 1000mL beaker. Place on stir plate, and using stir bar, mix for about 20 minutes or until homogenized.

Remove the sieve with the coarse material from oven when the sample is dry and sieve it for 5 minutes through both a No. 10 and a No. 4 sieve, simultaneously. Weigh and record the masses for each sieve. These are the masses of coarse material for the sample. Use the PB221S Sartorius scale.

After 16 hours, begin the hydrometer readings for the samples. Use the same 151H hydrometer that was used throughout this project, for which a composite correction has already been made.

Transfer soil-water slurry (sample in dispersing agent) from its beaker into a glass sedimentation cylinder and fill to 1000mL with DI/distilled water. Rinse all soil from beaker into cylinder. Label the cylinders. Only two tests can be run at a time, and it is possible to finish four in a day.

Use a rubber stopper to cap the cylinder. Record both hydrometer (specific gravity) and temperature readings at intervals of 2, 5, 15, 30, 60, and 150 minutes after sedimentation begins. Hold both ends of the cylinder and mix for one minute. Setting down the cylinder is the beginning of sedimentation. Record your start time.

When you have finished the hydrometer/temp readings for the sample, pour the cylinder through a No. 230 (63 μm) sieve over the sink and run tap water through it until clear. Dry the material retained on the No. 230 sieve in an aluminum weighing dish in the oven at 105 degrees Celsius. This will take about 1.5 – 2 days for most samples to completely dry.

Once dried, break up aggregations in mortar with rubber-covered pestle. Perform a final sieve analysis of the material through a No. 40 (425 μm), No. 60 (250 μm), and a No. 120 (125 μm) sieve (simultaneously) for 20 minutes. Weigh (on the Sartorius scale) and record the mass of material retained on each sieve and the material that passed through all three sieves. This is the mass of sandy material.

APPENDIX 2. GRAIN-SIZE CALCULATOR

**PARTICLE-SIZE ANALYSIS OF
SOILS ASTM D 422**

Start by recording data from notebook
or worksheet.

Hit [F9] to calculate.

Save to a new file name and
repeat.

Sample #	78816
	GN2-
Location	3
Weight (g)	50.0
Temperature	
C	21.0
K	0.014

Sieve Analysis	
Sieve	Weight (g)
4	0.000
10	0.124
40	0.000
60	2.681
120	2.013
230	0.000
<230	45.18

Size Classification and %	
Pebble	0.00%
Granule	0.25%
Coarse	
Sand	0.00%
Medium	
Sand	5.36%
Fine Sand	4.03%
Very Fine	
Sand	0.00%
Silt	62.6%
Clay	27.8%

Time (T)	Hydrometer reading	Hydrometer Analysis		L/T	Diameter (D)	Ln D
		% in Suspension	Depth L			
2	1.020	65.0%	11.0	5.500	0.032	-
5	1.017	55.2%	11.8	2.360	0.021	-
15	1.014	45.5%	12.6	0.840	0.013	-
30	1.012	39.0%	13.1	0.437	0.009	-
60	1.011	35.7%	13.4	0.223	0.006	-
150	1.009	29.2%	13.9	0.093	0.004	-
		Silt diameter	Ln		Trend Coefficient	
		0.005	5.298		0.308	

APPENDIX 3. SEDIMENT SAMPLE TEXTURES 2003

Location	Pebble 4 MM	Granule 2 MM	Coarse Sand 0.5 MM	Medium Sand 0.25 MM	Fine Sand 0.125 MM	Very Fine Sand 0.0625 MM	Silt 0.005 MM	Clay < 0.005 MM
TN1-1	0.72%	0.31%	0.96%	1.37%	0.03%	21.0%	33.3%	42.4%
TN1-2	0.34%	0.71%	0.00%	0.00%	0.00%	0.00%	47.5%	51.4%
TN1-3	0.00%	0.33%	0.45%	2.07%	0.03%	20.8%	38.0%	38.3%
S1-1	16.4%	11.3%	33.8%	17.5%	0.01%	18.2%	1.76%	1.01%
S1-2	29.5%	12.1%	31.3%	9.21%	0.06%	17.4%	0.31%	0.18%
S1-3	21.7%	19.4%	17.1%	9.78%	0.02%	29.6%	1.31%	1.06%
GN1-1	0.02%	0.50%	1.50%	12.9%	15.9%	50.6%	9.15%	9.54%
GN1-2	1.13%	1.07%	2.51%	13.6%	0.01%	65.1%	9.87%	6.65%
GN1-3	0.05%	0.67%	2.92%	12.8%	0.01%	61.4%	12.0%	10.2%
T1-1 Deep	6.85%	2.11%	1.17%	3.68%	0.02%	35.4%	25.8%	24.9%
T1-2 Deep	0.00%	0.00%	0.46%	1.97%	0.01%	25.4%	21.4%	50.8%
T1-3 Deep	0.00%	0.00%	2.95%	3.29%	5.00%	0.0%	42.3%	46.5%
T1-1 Shallow	0.00%	0.00%	0.36%	2.46%	0.03%	11.9%	26.3%	58.9%
T1-2 Shallow	1.01%	2.52%	3.29%	2.33%	0.06%	15.5%	28.5%	46.7%
T1-3 Shallow	7.41%	2.15%	3.22%	3.46%	0.02%	20.5%	23.3%	40.0%
TN2-1	0.00%	0.06%	1.17%	1.93%	3.06%	13.0%	29.6%	51.3%
TN2-2	0.00%	0.04%	0.17%	0.36%	0.00%	4.39%	35.2%	59.9%
TN2-3	0.00%	0.15%	0.72%	1.40%	0.09%	14.1%	25.2%	58.3%
S2-1	13.3%	5.55%	6.26%	10.2%	0.04%	23.6%	22.2%	18.9%
S2-2	27.4%	8.64%	0.00%	27.0%	18.8%	12.2%	3.4%	2.62%
S2-3	27.4%	8.14%	8.22%	5.85%	1.53%	12.9%	12.1%	23.9%
GN2-1	5.43%	0.70%	1.42%	8.90%	0.03%	17.4%	21.3%	44.8%
GN2-2	0.00%	0.35%	0.61%	3.45%	0.02%	30.9%	27.8%	36.9%
GN2-3	0.00%	0.25%	0.00%	5.36%	4.03%	0.00%	23.9%	66.4%
T2-1 Deep	11.9%	1.89%	10.2%	26.7%	0.01%	49.1%	0.17%	0.07%
T2-2 Deep	4.07%	2.55%	9.79%	12.7%	0.02%	16.8%	42.2%	11.9%
T2-3 Deep	3.69%	1.87%	21.9%	30.4%	0.05%	38.0%	3.17%	0.88%
T2-1 Shallow	0.11%	0.51%	8.30%	2.39%	0.01%	83.7%	3.6%	1.44%
T2-2 Shallow	2.48%	0.75%	0.55%	2.10%	0.01%	69.4%	16.8%	7.92%
T2-3 Shallow	0.00%	0.01%	1.64%	2.56%	0.02%	86.5%	8.22%	1.10%
TN3-1	0.00%	0.07%	12.3%	9.87%	6.94%	21.0%	28.2%	21.5%
TN3-2	0.60%	0.02%	0.36%	0.37%	0.00%	5.29%	31.7%	61.7%
TN3-3	0.99%	0.17%	0.37%	0.38%	0.00%	5.43%	15.8%	76.9%

Location	Pebble 4 MM	Granule 2 MM	Coarse Sand 0.5 MM	Medium Sand 0.25 MM	Fine Sand 0.125 MM	Very Fine Sand 0.0625 MM	Silt 0.005 MM	Clay < 0.005 MM
S3-1	0.00%	0.30%	0.42%	1.02%	0.01%	3.34%	18.7%	76.2%
S3-2	0.07%	0.56%	1.39%	2.76%	0.01%	6.03%	31.9%	57.3%
S3-3	0.00%	0.48%	1.24%	2.92%	0.03%	5.57%	25.5%	64.2%
GN3-1	0.00%	0.00%	11.6%	0.79%	0.05%	1.66%	45.7%	40.2%
GN3-2	0.00%	0.18%	3.22%	0.64%	0.00%	1.55%	51.0%	43.4%
GN3-3	0.00%	0.00%	7.02%	1.10%	0.04%	5.25%	42.1%	44.4%
T3-1 Deep	0.00%	0.00%	2.21%	3.22%	0.08%	17.4%	20.1%	57.0%
T3-2 Deep	0.00%	0.29%	0.27%	0.29%	0.00%	6.47%	26.8%	65.9%
T3-3 Deep	0.22%	0.07%	0.19%	0.33%	0.02%	6.55%	22.7%	69.9%
T3-1 Shallow	0.00%	12.6%	0.16%	0.39%	0.03%	6.04%	25.4%	55.4%
T3-2 Shallow	0.00%	0.14%	0.26%	0.42%	0.02%	7.15%	27.3%	64.7%
T3-3 Shallow	0.00%	0.00%	1.50%	3.88%	0.03%	23.7%	28.4%	42.6%
TN4-1	0.00%	0.01%	1.76%	0.87%	0.02%	4.31%	26.3%	66.8%
TN4-2	0.00%	0.02%	13.7%	0.84%	0.23%	4.08%	27.1%	54.0%
TN4-3	0.00%	0.00%	3.74%	8.69%	0.07%	31.5%	19.7%	36.3%
T4-1 Deep	0.00%	0.18%	0.19%	1.53%	0.03%	36.6%	24.9%	36.6%
T4-2 Deep	0.00%	0.13%	1.90%	2.23%	0.04%	46.7%	22.1%	26.9%
T4-3 Deep	0.19%	0.05%	0.22%	1.95%	0.02%	25.5%	30.2%	41.8%
T4-1 Shallow	0.00%	0.00%	5.41%	8.22%	0.06%	30.2%	14.0%	42.1%
T4-2 Shallow	0.00%	0.11%	3.04%	0.98%	0.01%	4.83%	32.0%	59.0%
T4-3 Shallow	0.00%	0.00%	8.01%	6.98%	0.08%	26.3%	18.6%	40.1%
TN5-1	0.00%	0.00%	9.64%	6.26%	0.13%	26.9%	18.6%	38.4%
TN5-2	0.00%	0.00%	0.00%	8.85%	2.07%	0.00%	23.8%	65.3%
TN5-3	0.00%	0.07%	3.68%	1.84%	0.47%	0.00%	34.4%	59.6%
T5-1 Deep	0.00%	0.00%	5.14%	1.02%	0.01%	5.10%	45.0%	43.7%
T5-2 Deep	0.00%	0.06%	1.10%	1.12%	0.01%	8.29%	34.8%	54.6%
T5-3 Deep	0.00%	0.21%	4.45%	2.81%	0.09%	16.6%	28.1%	47.8%
T5-1 Shallow	0.00%	1.95%	1.46%	1.68%	0.17%	6.93%	41.6%	46.2%
T5-2 Shallow	0.00%	0.00%	8.96%	3.26%	0.26%	14.4%	32.0%	41.1%
T5-3 Shallow	0.00%	0.07%	7.61%	1.99%	0.01%	12.4%	35.8%	42.2%
TN6-1	1.47%	0.08%	9.00%	2.38%	0.02%	6.80%	35.1%	45.2%
TN6-2	0.00%	0.06%	1.21%	0.79%	0.29%	5.82%	27.0%	64.8%
TN6-3	0.01%	0.25%	3.14%	4.04%	0.24%	7.54%	41.1%	43.7%
T6-1	0.00%	0.96%	6.29%	4.34%	1.76%	0.00%	22.9%	63.7%
T6-2	2.98%	1.90%	6.82%	10.1%	0.02%	20.3%	20.3%	37.5%
T6-3	0.00%	0.06%	0.03%	2.04%	0.02%	12.4%	11.5%	74.0%

Location	Pebble 4 MM	Granule 2 MM	Coarse Sand 0.5 MM	Medium Sand 0.25 MM	Fine Sand 0.125 MM	Very Fine Sand 0.0625 MM	Silt 0.005 MM	Clay < 0.005 MM
T7-1	0.00%	0.04%	4.77%	0.92%	0.01%	5.24%	41.7%	47.4%
T7-2	1.52%	5.12%	9.30%	2.31%	0.02%	7.78%	46.7%	27.3%
T7-3	0.56%	0.53%	2.23%	1.04%	0.33%	4.47%	37.7%	53.1%
T8-1	2.38%	4.07%	2.44%	1.37%	0.04%	5.10%	40.2%	44.4%
T8-2	0.08%	1.03%	1.40%	1.74%	0.01%	8.56%	31.7%	55.4%
T8-3	3.34%	4.53%	4.38%	2.14%	0.47%	4.91%	51.0%	29.3%
T9-1	0.02%	0.07%	5.73%	2.43%	0.01%	6.64%	53.6%	31.5%
T9-2	0.19%	0.15%	2.72%	1.85%	0.01%	5.91%	44.4%	44.8%
T9-3	0.00%	0.14%	4.26%	2.10%	0.02%	8.70%	43.7%	41.1%

APPENDIX 4. SEDIMENT SAMPLE TEXTURES (PERCENTAGE) 1988

Location	Pebble 4 MM	Granule 2 MM	Very Coarse Sand 1 MM	Coarse Sand 0.5 MM	Medium Sand 0.25 MM	Fine Sand 0.125 MM	Very Fine Sand 0.0625 MM	Silt and Clay < 0.0625 MM
TN1	0	0.2	1.6	2.8	6.1	7.7	5.3	76.3
S1	8	6.4	6.2	10.4	12.8	12.2	4.6	39.4
GN1	0	0.3	0.3	0.7	22.2	58.5	6.5	11.5
T1 Deep	3.6	3.7	1.7	2	5.9	16.2	11.8	55.1
T1 Shallow	0.32	0.5	0.4	1.3	3.8	20.9	16.4	56.4
TN2	0	0.3	0.8	0	0.4	2.2	1.5	94.8
S2	0.7	1	2.2	4.4	8.8	24.4	18	40.3
GN2	0	0.7	0	0.8	10	8.6	6.7	73
T2 Deep	0.1	1.9	2	10.1	27.8	30.8	9.8	17.6
T2 Shallow	54.1	6.5	2.9	3.5	8.2	10.1	3.6	11
TN3	0	0.2	0.7	1.3	0.2	0.9	0.7	96
S3	0	0.1	0.5	0	0.2	1.3	0.5	97.3
GN3	0	0	0	0	0.2	0.1	1.5	98.2
T3 Deep	0	0	0.8	0	0.1	1.6	4.7	92.8
T3 Shallow	0	0.7	0.1	0	0.4	2.1	5.8	91
TN4	0	0.7	0.3	0	0	1.5	2.8	89.4
T4 Deep	0	0	0.4	0	0.2	2.1	8.3	88.9
T4 Shallow	0	0.7	0.3	0	0.1	1.7	3.3	93.9
TN5	0	0	0.7	0	1	14.8	5.8	77.6
T5 Deep	0	0.3	3.5	7.9	29.8	38.3	5.4	14.8
T5 Shallow	0	0.1	0	0	0.1	0.3	2.8	96.7
TN6	0	0.3	0.5	1.6	1	7.5	4.3	84.8
T6	0	0	0.6	0	0.5	2.1	2.1	94.8
T7	0	0.2	0.8	0.2	0.3	1.7	2.3	94.6
T8	0	0.1	0.3	0	0.4	5.8	2	91.4
T9	0	0.1	0.8	0.1	1	2.9	2.6	92.5

Note: Percentages reflect the results obtained from one sample collected at each location.

**APPENDIX 5. METAL CONCENTRATIONS OF SEDIMENTS
COLLECTED IN 2003 (MG/KG DRY WT.)**

Site - Rep. #	Collection Date	T.O.C. (%)	% Fines (silt & clay)	METALS (ug/g) Dry Weight								
				As	Cd	Cr	Cu	Hg	Pb	Ni	Zn	Fe
T5 Shallow-1	7/11/03	N.D.	87.8	12.3	7.36	134	203	4.64	230	52.0	469	37348
T5 Shallow-2	7/22/03	13.7	73.1	13.3	11.7	316	294	5.84	306	95.9	738	35332
T5 Shallow-3	7/22/03	13.2	77.9	14.5	10.6	384	268	8.55	327	80.6	773	33892
T5 Deep-1	7/22/03	14.3	88.7	10.0	4.22	142	189	4.28	185	55.1	436	37593
T5 Deep-2	7/22/03	15.9	89.4	9.3	6.18	145	197	4.43	202	63.3	453	38317
T5 Deep-3	7/22/03	15.9	75.8	10.3	11.4	398	274	8.66	306	96.8	675	32193
GN3-1	8/5/03	13.1	85.9	9.1	5.24	190	258	4.85	144	50.2	521	39472
GN3-2	8/5/03	12.8	94.4	8.4	5.03	198	261	4.46	221	47.3	505	35780
GN3-3	8/5/03	11.8	86.6	11.4	5.63	183	289	4.69	250	56.1	555	38029
TN6-1	8/5/03	16.4	80.3	10.0	5.58	174	234	4.56	239	55.2	510	38999
TN6-2	8/5/03	15.8	91.8	10.1	4.94	173	243	4.55	241	49.0	516	38106
TN6-3	8/5/03	13.6	84.8	10.2	4.71	159	234	4.83	366	52.7	455	36209
TN1-1	8/5/03	9.39	75.6	11.9	1.39	124	101	2.49	125	38.3	196	28208
TN1-2	8/5/03	10.3	99.0	18.0	3.92	146	114	2.58	161	43.0	244	27904
TN1-3	8/5/03	10.7	76.3	21.4	2.13	166	140	2.63	158	43.9	251	31481
TN2-1	8/5/03	9.42	80.8	9.40	1.63	119	104	1.77	115	37.8	239	32867
TN2-2	8/5/03	10.2	95.0	9.30	2.52	127	106	2.31	136	46.2	243	31953
TN2-3	8/5/03	9.65	83.6	9.30	1.96	123	109	2.11	139	39.2	251	33632
GN1-1	12/4/03	2.17	18.7	4.85	0.83	62.9	35.4	1.43	52.7	16.5	98	13214
GN1-2	12/4/03	4.50	16.5	4.50	0.71	72.1	26.1	0.73	51.5	13.1	86	10119
GN1-3	12/4/03	5.54	22.1	6.04	0.88	71.8	40.2	1.19	80.5	19.0	118	14085
S1-1	12/4/03	3.71	2.77	10.7	0.29	118	36.4	0.30	54.1	71.9	91	35598
S1-2	12/4/03	4.76	0.49	11.2	0.43	80.6	45.7	1.28	76.9	42.0	116	39712
S1-3	12/4/03	8.15	2.37	9.2	0.54	89.9	57.8	0.98	90.2	59.6	133	28849
T6-1	12/4/03	6.04	86.7	6.11	0.14	24.1	13.1	0.10	25.4	28.1	71.2	30114
T6-2	12/4/03	4.86	57.8	6.37	0.09	17.0	11.2	0.45	15.2	19.6	50.0	22551
T6-3	12/4/03	6.09	85.4	6.59	0.16	27.1	15.8	0.05	24.1	29.7	76.1	35248
S2-1	12/4/03	5.35	41.1	7.23	1.03	97.5	65.2	2.81	81.4	30.1	175	24612
S2-2	12/4/03	4.41	5.98	3.98	0.67	46.0	30.0	2.06	39.6	15.7	89.1	14593
S2-3	12/4/03	4.66	36.0	5.84	0.99	63.7	47.0	3.72	52.8	21.5	126	20371
TN3-1	12/4/03	10.5	49.7	8.38	1.61	125	98.3	5.03	117	38.8	225	33847
TN3-2	12/4/03	7.04	93.4	9.06	1.62	127	100	3.36	143	40.3	241	34899
TN3-3	12/4/03	10.6	92.7	9.32	1.62	137	99.3	4.18	126	42.2	242	36088
TN5-1	12/12/03	12.5	57.0	9.01	4.27	184	183	4.47	189	56.8	401	36467
TN5-2	12/12/03	12.7	89.1	9.16	3.24	163	162	3.79	170	50.4	386	38544
TN5-3	12/12/03	12.7	93.9	9.15	4.18	187	181	4.79	187	54.3	363	35759
S3-1	12/12/03	12.5	94.9	9.79	3.01	179	157	5.11	177	49.6	373	37568

Site - Rep. #	Collection Date	T.O.C. (%)	% Fines (silt & clay)	METALS (ug/g) Dry Weight								
				As	Cd	Cr	Cu	Hg	Pb	Ni	Zn	Fe
S3-2	12/12/03	12.7	89.2	9.33	3.31	158	169	4.32	163	51.0	347	36712
S3-3	12/12/03	12.8	89.8	9.79	2.52	159	147	3.66	163	49.2	356	37417
T4 Deep-1	12/12/03	6.52	61.5	6.28	0.20	19.7	13.1	0.11	27.6	22.2	58	24479
T4 Deep-2	12/12/03	5.74	49.0	7.90	0.18	19.8	12.9	0.15	30.5	17.0	54	26222
T4Deep-3	12/12/03	6.89	72.1	3.18	0.71	24.6	15.5	0.02	77.7	21.5	71	24260
T4 Shallow-1	12/12/03	13.0	56.1	10.7	8.01	241	248	9.58	232	74.6	426	39234
T4 Shallow-2	12/12/03	11.9	91.0	11.6	8.87	226	210	8.69	223	75.3	451	37175
T4Shallow-3	12/12/03	13.5	58.6	11.1	8.41	253	225	7.66	225	72.8	434	38090
TN4-1	12/12/03	13.6	93.0	11.7	5.38	214	185	5.23	187	60.2	396	37472
TN4-2	12/12/03	15.1	81.2	12.4	6.49	224	180	6.24	199	62.0	396	39010
TN4-3	12/12/03	11.1	56.0	11.2	5.97	217	165	6.49	193	57.1	377	33579
T1 Shallow-1	12/18/03	7.10	85.2	8.80	0.10	22.4	13.8	0.06	22.1	26.8	63.5	29156
T1 Shallow-2	12/18/03	5.10	75.3	6.71	0.20	27.2	16.3	0.16	36.4	25.6	64.6	24839
T1 Shallow-3	12/18/03	8.50	63.3	5.51	0.14	20.0	13.4	0.05	23.5	23.0	49.5	25396
T1 Deep-1	12/18/03	6.79	50.7	8.89	0.11	18.8	12.4	0.13	25.3	21.7	48.1	28642
T1 Deep-2	12/18/03	6.01	72.2	8.02	0.12	20.7	9.66	0.00	20.9	25.5	61.0	27684
T1 Deep-3	12/18/03	4.00	88.8	9.38	0.17	22.4	11.5	0.03	21.8	20.6	59.9	26087
T2 Shallow-1	12/18/03	2.48	5.03	3.44	0.30	34.9	10.9	0.20	14.9	10.3	52.6	11720
T2 Shallow-2	12/18/03	2.00	24.7	3.85	0.20	31.6	11.0	0.21	25.9	10.8	57.5	12256
T2Shallow-3	12/18/03	2.60	91.0	3.74	0.35	30.7	13.4	0.19	27.4	11.3	54.0	12015
T2 Deep-1	12/18/03	2.61	0.25	3.79	0.43	83.8	17.1	0.40	24.6	13.1	66.9	12197
T2 Deep-2	12/18/03	2.63	54.1	3.30	0.34	45.0	15.2	0.35	48.9	11.7	52.8	9580
T2 Deep-3	12/18/03	1.92	4.06	3.64	0.63	99.3	26.2	0.55	44.6	17.2	86.0	14639
T3 Shallow-1	12/18/03	9.05	80.8	9.41	1.68	113	96.6	2.53	111	42.6	206	35249
T3 Shallow-2	12/18/03	10.2	92.0	9.18	1.74	127	103	2.74	115	42.1	214	33548
T3 Shallow-3	12/18/03	10.6	70.9	10.3	1.65	124	97.8	2.69	114	41.1	220	33101
T3 Deep-1	12/18/03	10.4	77.1	8.47	1.29	109	97.3	1.83	104	40.2	224	30968
T3 Deep-2	12/18/03	10.2	92.7	7.62	1.46	104	88.6	2.29	99.2	38.6	197	28276
T3 Deep-3	12/18/03	9.88	92.6	8.39	1.60	111	91.5	2.56	112	41.9	208	32010
GN2-1	12/29/03	7.03	66.1	9.36	0.45	41.7	33.7	0.55	35.0	31.3	98.3	37439
GN2-2	12/29/03	4.78	64.6	10.1	0.27	23.7	17.2	0.30	25.4	29.1	76.7	34499
GN2-3	12/29/03	5.12	90.4	5.38	0.31	34.4	23.9	0.30	27.0	23.9	71.0	31598
T7-1	12/29/03	9.09	89.0	13.9	11.57	308	240	15.09	234	73.2	519	35445
T7-2	12/29/03	19.0	74.0	14.2	13.70	287	224	25.24	215	72.6	535	45747
T7-3	12/29/03	12.5	90.8	13.3	13.88	296	247	22.19	231	74.4	554	32987
T8-1	12/29/03	21.0	84.6	11.4	1.98	168	136	3.53	138	50.4	289	39307
T8-2	12/29/03	15.6	87.2	1.30	1.45	160	130	2.65	136	52.7	276	36831
T8-3	12/29/03	20.4	80.2	55.6	2.35	181	133	4.04	149	53.5	283	40390
T9-1	12/29/03	16.4	85.1	12.0	2.04	158	144	3.08	162	53.0	328	39216
T9-2	12/29/03	16.5	89.2	11.2	1.97	159	149	3.33	144	50.6	271	46105
T9-3	12/29/03	16.1	84.8	11.5	2.56	157	145	3.44	152	51.0	337	35251

	T.O.C. (%)	% Fines (silt & clay)	METALS (ug/g) Dry Weight									
			As	Cd	Cr	Cu	Hg	Pb	Ni	Zn	Fe	
MIN	1.92	0.25	1.30	0.09	17	10	0.00	15	10.3	48	9580	
MAX	21.01	99.0	55.6	13.9	398	294	25.2	366	96.8	773	46105	
AVG	9.78	68.9	9.64	3.05	130	115	3.55	128	42.9	263	31095	
ST DEV	4.69	28.1	6.26	3.47	87	88	4.30	86	20.3	185	8756	

* The T.O.C. values shown are the mean of two samples.

+ The T.O.C. value shown is the mean of three samples.

APPENDIX 6. METAL CONCENTRATIONS OF SEDIMENTS COLLECTED IN 1988 (MG/KG DRY WT.)

Sample	N	Ni	Cu	Pb	Cd	Zn	Cr
T1 (shallow)	4	37.3 ± 4.3	176 ± 10.8	151.3 ± 39.8	2.8 ± 0.5	140.5a	256.5 ± 26.1
T1 (deep)	2	49.5	371	28.5	1.7	114b	35
T2 (shallow)	2	86.5	1128.5	101	2.9	367b	71
T2 (deep)	2	127.5	836.5	196	3.7	402b	251
T3 (shallow)	2	22.5	121.5	116.5	2.9	96b	115
T3 (deep)	2	38	163.5	119.5	3.8	112b	145.5
T4 (shallow)	3	61.7 ± 2.4	303 ± 11.5	235.3 ± 46.5	8.9 ± 0.7	225b	430.3 ± 95.1
T4 (deep)	3	60.3 ± 6.3	271 ± 9.9	219.7 ± 25.2	8.0 ± 1.1	180a	302.7 ± 104.9
T5 (shallow)	2	92.5	235.5	212.5	13	307	313.5
T5 (deep)	3	306.3 ± 27.6	1063 ± 216.0	328.3 ± 88.3	8.7 ± 2.1	481.3 ± 59.7	821.3 ± 80.0
T6	3	71.0 ± 6.5	175.7 ± 9.0	23.7 ± 3.7	1.7 ± 0.3	109.7 ± 71.7	39.7 ± 27.1
T7	1	49	172	125	8.5	118	195
T8	1	52	110	25	2.8	75	25
T9	2	91.5	491	324	13.5	563.5	1196
GN1	3	502.3 ± 327.7	1917 ± 378.2	215.3 ± 40.4	4.2 ± 0.4	569.3 ± 78.2	920.3 ± 424.8
GN2	2	84	259.5	190.5	6.2	187	284.5
GN3	2	133	586.5	258	13.9	497.5	415.5
TN1	3	128.3 + 61.5	166 ± 7.1	115.7 ± 15.8	3.9 ± 1.0	100.7 ± 4.1	309.7 ± 136.7
TN2	2	63.5	156.5	100.5	4.7	134	189
TN3	1	61	156	106	4.9	129	198
TN4	1	52	151	97	4.7	123	151
TN5	5	124.2 ± 40.3	229.4 ± 16.8	174.6 ± 24.5	5.5 ± 1.1	171.4 ± 53.5	459 ± 175.9
TN6	2	133	350	233.5	9.2	276.5	366
SI	3	218 16.5	529 + 28.5	164.3 + 21.3	5.9 + 0	332.7 + 102.8	917.3 + 175.1
S2	2	124	424.5	154	8	271.5	285
S3/S4	1	87	602	249	120	241	334
MIN		22.5	110	23.7	1.70	75.0	25.0
MAX		502	1917	328	120	569	1196
AVG		110	429	164	10.5	243	347
ST DEV		100	412	82.5	22.6	153	299