PRELIMINARY INVESTIGATION OF THE EXTENT OF SEDIMENT CONTAMINATION IN MUSKEGON LAKE

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Executive Summary

A preliminary investigation of the nature and extent of sediment contamination in Muskegon Lake was performed using Sediment Quality Triad methodology. Sediment chemistry, solid-phase toxicity, and benthic macroinvertebrates were examined at 15 locations. In addition, three core samples were evaluated using radiodating and stratigraphy to assess sediment stability and contaminant deposition. High levels of cadmium, copper, chromium, lead, and mercury were found in the Division Street Outfall area. These levels exceeded the Probable Effect Concentrations (PECs) for current sediment quality guidelines. Most of the heavy metals were found in the top 80 cm of the core samples. Deeper layers of contamination were found only near the former Teledyne foundry and down stream from Ruddiman Creek. High concentrations of PAH compounds were found at a lakeshore industrial area formerly occupied by a manufactured gas facility, an iron foundry, commercial shipping docks, a rail yard, and a coal storage facility. These levels also exceeded PEC guidelines. Sediment toxicity was observed at two stations in the Division Street Outfall area and at the lakeshore industrial site. These locations had the highest concentrations of metals and PAH compounds respectively. Benthic macroinvertebrate communities throughout Muskegon Lake were found to be indicative of organically enriched conditions. The locations in the Division Street Outfall area were significantly different than reference sites with respect to fewer numbers and a smaller population of detritivores.

Sediment Quality Triad diagrams were prepared and significant correlations were obtained between chemistry and toxicity and chemistry and diversity ($p < .01$). Toxicity and diversity also were positively correlated ($p < .05$). Based on the results of this investigation, the Division Street Outfall and the location down gradient from the lakeshore industrial site are priority areas for further investigation and potential remediation due to adverse ecological effects, toxicity, and high contaminant levels.

Stratigraphy and radiodating analyses conducted on sediment cores provided important information related to depositional history. Ruddiman Creek appears to have a significant influence on the deposition of heavy metals in the southwestern part of Muskegon Lake. A peak in metals deposition was found that corresponded to the 100+ year flood that occurred in 1986. The historical deposition was considerably higher than current rates. The deep zone off the Car Ferry Dock was not found to be an area that accumulates sediments. High inventories of ^{210}Pb were found near the bottom of this 80 cm core, indicating active mixing and movement of sediments. The presence of elevated metals in the deeper strata plus the high ^{210}Pb inventories suggest that contaminated sediments are moved from the eastern part of Muskegon Lake to this location where they are mixed and made available for resuspension by the currents traveling along the old river channel. The core from the Division Street Outfall showed relatively stable sediments in the top 20 cm followed by a stable zone of heavy accumulation after 1960. Based on these results it is apparent that the removal of contaminated sediments from Ruddiman Creek and the lagoon would reduce the loading of heavy metals to western Muskegon Lake. The areas of high sediment contamination in the eastern part of the lake also appear to be mixed and subject to transport.

1.0 Introduction

Muskegon Lake, Michigan is a large drowned river mouth lake (4,150 acres) that is directly connected to Lake Michigan by a navigation channel. It is part of the Muskegon River watershed which has a drainage basin of 2,634 square miles. Muskegon Lake functions as a significant fishery and recreational area in this region of the Great Lakes and provides an important transition zone between the open waters of Lake Michigan and the estuary/riverine environments associated with the Muskegon River. Historically, significant anthropogenic activity has impacted the water and sediment of the lake. Prior to 1973, industrial and municipal wastes were directly discharged into the waters of Muskegon Lake. These discharges included effluents from petrochemical, organic chemical, metal finishing, and manufactured gas facilities. The International Joint Commission designated Muskegon Lake as an Area of Concern (AOC) because of severe environmental impairments related to these discharges. A map of Muskegon Lake is provided in Figure 1.1. In 1973, a state of the art wastewater treatment facility was constructed and the direct discharge of waste effluents was eliminated. While the water quality has improved considerably over the years, contaminated sediments remain in the lake. In addition, diffuse sources of contamination continue to enter the lake from tributaries, local runoff, and impacted groundwater plumes. Previous investigations of Muskegon Lake have identified areas of sediment contamination and depauperate benthic communities. High levels of lead (1400 mg/kg), chromium (1000 mg/kg), polycyclic aromatic hydrocarbon (PAH) compounds (10 mg/kg), and mercury (3.6 mg/kg) were found in sediment samples collected along the southern shoreline in 1982 (West Michigan Shoreline Regional Development Commission 1982). The same investigation also found high levels of PNAs (500 mg/kg) near an abandoned landfill located on the banks of the Muskegon River.

A recent investigation (EPA 1995) in the Division Street Outfall area found high levels of lead (700 mg/kg) and mercury (2 mg/kg) in several surface zone sediments (0-16 in). Higher levels were detected in the deeper strata. This outfall collected stormwater from a number of industrial facilities and was subject to historic discharges of untreated wastes. Since industrial discharges in this area were eliminated in 1973, the presence of high levels of metals in the zone of recent deposition suggests that the sediments at this location may be mobile and subject to resuspension. In consideration that many of the areas of contamination may be subject to the same physical phenomena, information related to sediment stability and mobility will be central to the development of remediation and restoration plans for the lake.

Since the last major assessment of the lake was conducted in the early 1980s, it is important to examine the current nature and extent of sediment contamination and the status of the health of the benthic community. This project utilized a series of sediment sampling stations that reflect deposition areas near historic industrial locations, wastewater treatment outfalls, and contamination sites. In addition, a group of sampling locations near the Division Street outfall were examined. The study protocol followed the sediment quality triad approach (Canfield 1998) and focused on sediment chemistry, sediment toxicity, and the status of the *in situ* benthic macroinvertebrate community. The information from this investigation will be important for the determination of areas that may require further delineation and the

prioritization of remedial action and habitat restoration activities. Additionally, these data will further our understanding of the ecological significance of sediments that are mobile and subject to resuspension in drowned river mouth systems.

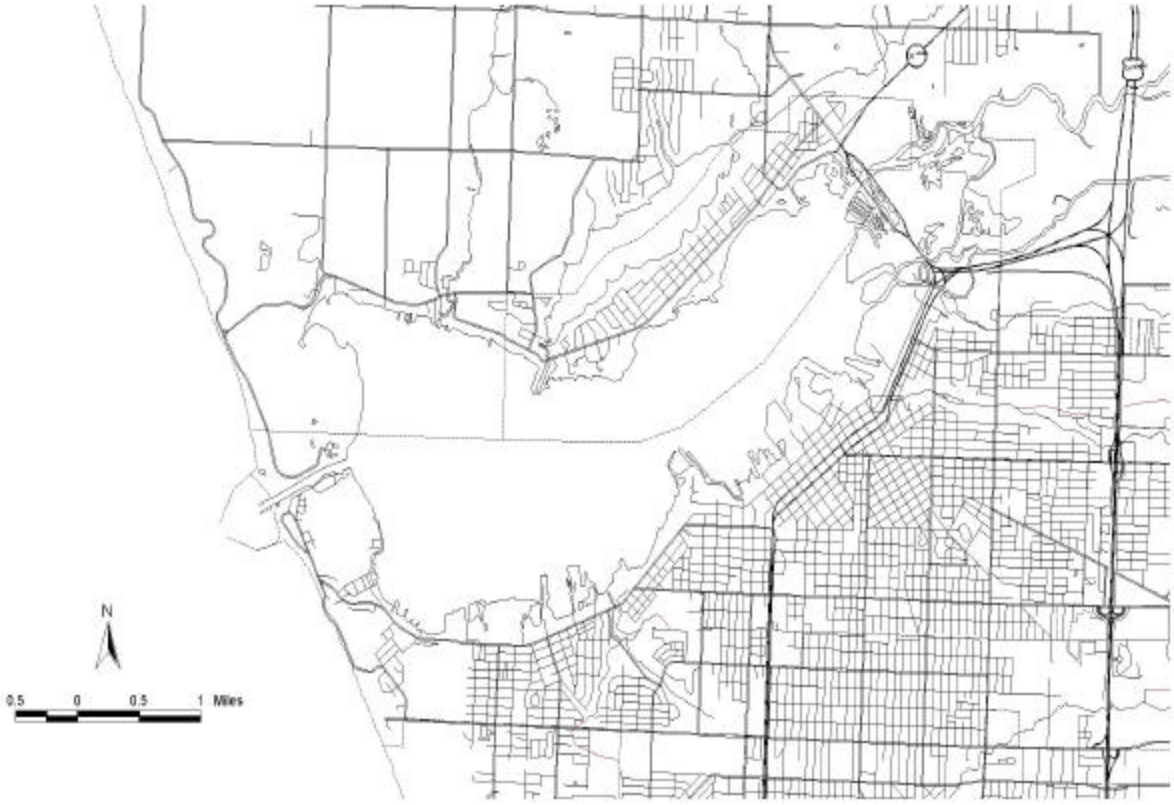


FIGURE 1.1 MUSKEGON LAKE

1.1 Summary Of Anthropogenic Activities In Muskegon Lake

The history of the Muskegon Lake and its watershed was described by Alexander (2000). Approximately 11,000 years ago, the glacial activity that formed the Great Lakes also created the Muskegon River watershed. Muskegon Lake was then formed as a drowned rivermouth by drastic fluctuations in Lake Michigan water levels and the closing of the channel by wind induced erosion of coastal sand dunes. During the 1700s, Native American tribes depended on the watershed's natural resources for food and transportation. They named the river the "Maskigon", which means river with marshes. In its natural state, the watershed was a continuous system of dense riparian forests, sprawling wetlands and marshes, inland lakes, and extensive riffle areas. The system was drastically changed in the 1800s when lumber barons harvested the region's timber resources and left behind a legacy of barren riparian zones and severe erosion. Saw mills were then constructed on the shoreline and much of the littoral zone was filled with sawdust, wood chips, timber wastes, and bark. Large deposits of

lumbering waste can still be found today in the nearshore zone of Muskegon Lake. The lumbering era was followed in the 1900s by an era of industrial expansion related to foundries, metal finishing facilities, petrochemical production, and shipping. Local dunes were extensively mined for foundry sand and the shoreline of Muskegon Lake had to be further modified to support heavy industry. Large quantities of waste foundry sand and slag were used as fill material in the remaining littoral zone.

The West Michigan Shoreline Regional Development Commission (1978) inventoried known and potential contamination sources for Muskegon Lake. The location of these sites is given in Figure 1.2. Ruddiman Creek served as a collection point for stormwater and waste discharges from several foundries, metal finishing facilities, and plating companies in addition to receiving contaminated groundwater from petrochemical storage tanks and transmission lines. The creek discharges over a shallow sandy zone of Muskegon Lake that rapidly drops off in a deep basin (45 ft). In addition, a large pulp and paper mill discharged effluent into this basin. Division Street Outfall also served as a collection point for industrial stormwater and waste discharges in addition to receiving metal laden effluents from Shaw Walker, Anaconda Copper, and Michigan Foundry Supply. High levels of heavy metals (copper, lead, cadmium, and mercury) were found in the sediments at these locations in previous investigations (West Michigan Shoreline Regional Development Commission 1982 and EPA 1995).

Moving further east along the shoreline, the downtown waterfront was impacted by a coal gasification facility (MichCon) that produced illumination gas from the early 1870s to 1950. High levels of coal tar related wastes were found on site in addition to a contaminated groundwater plume that was moving towards Muskegon Lake. The site was partially remediated in the 1990s and the amount of contaminated groundwater entering the lake was never determined. In addition to the MichCon site, this section of Muskegon Lake also was the location of two major shipping ports, an iron foundry (part of the former Lakey Foundry Complex), a coal storage operation, rail yards, and a wastewater treatment outfall. The area was also impacted by dredging and disposal related to the maintenance of commercial shipping ports. Because of the many potential sources of anthropogenic contamination, this location will be referred to as the lakeshore industrial area in this report. Sediment contamination in this area was not investigated in previous studies.

The area east of the downtown waterfront and bordered by Ryerson Creek was the location of the Lakey and Teledyne Foundries. Foundry sand, slag, and metal scrap were commonly used as fill materials in this area. High concentrations of heavy metals were found at this location in 1982 in addition to moderate concentrations of PAH compounds.

The South Branch and North Branch of the Muskegon River enter the lake along the eastern end. A large metal scrap yard was located on Muskegon Lake between the South Branch and Ryerson Creek. The wastewater discharge for the City of Muskegon also was located on the South Branch near the river mouth. Further upstream, a municipal waste landfill (1 mile) and

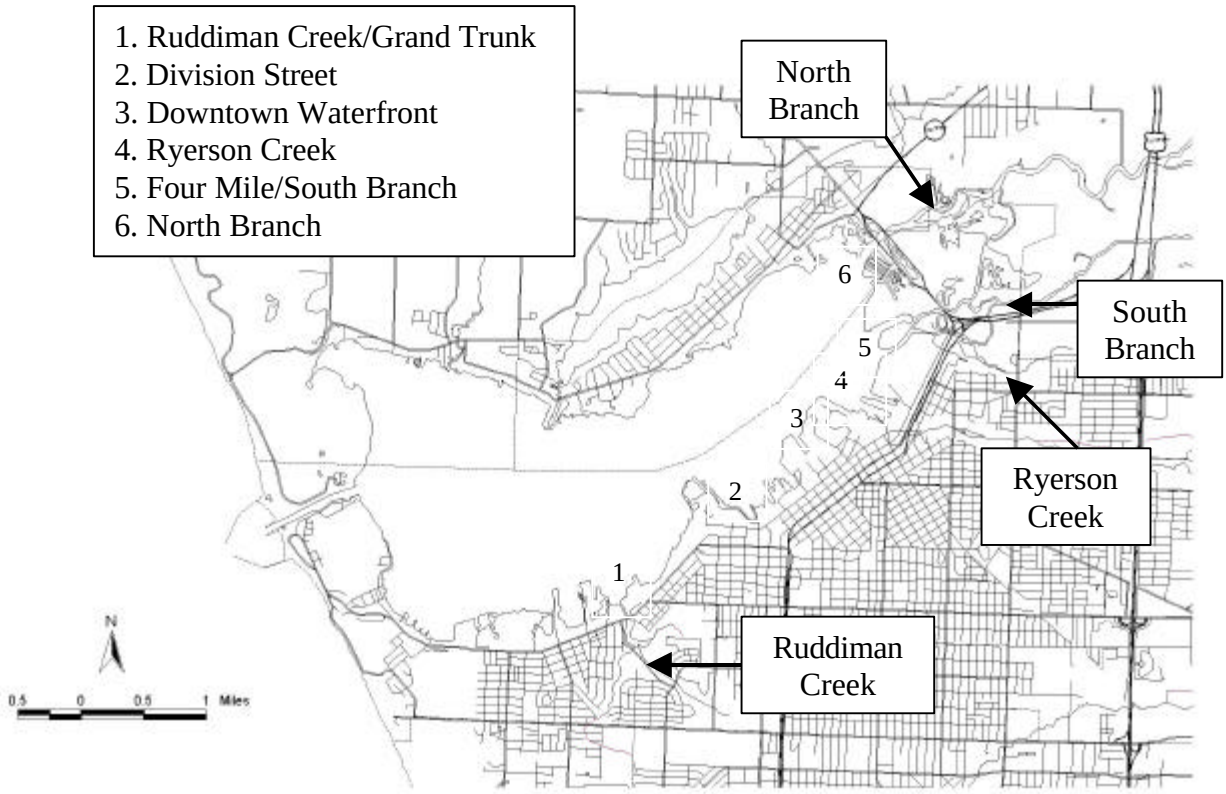


FIGURE 1.2. AREAS OF SEDIMENT CONTAMINATION IDENTIFIED IN MUSKEGON LAKE.

the NPDES discharge for Teledyne Continental Motors (2 miles) are located on the river banks. The 1982 investigation found very high levels of PAH compounds (>500 mg/kg) and heavy metals near the Teledyne outfall. Contamination sources are also present near the mouth of the North Branch. A fuel unloading terminal, petroleum tank farms, and a large coal fired power plant are located in this area. No contamination was found near the mouth of the North Branch of the Muskegon River in 1982.

Evans (1992) summarized historical water quality and biological data for Muskegon Lake. Prior to the 1973 wastewater diversion, nuisance algal blooms, fish tainting problems, excessive macrophyte growth, winter fish kills, and oxygen depletion in the hypolimnion were common. Average sediment concentrations of total phosphorus and total nitrogen were 1,258 mg/kg and 8,180 mg/kg respectively. Benthic macroinvertebrate communities were dominated by pollution tolerant oligochaetes and chironomids. While ambient water quality

improved significantly by the mid 1980s, the composition of the benthic community remained similar due to persistent sediment contamination. It is important to note that five months prior to collection of samples for this project (April 1999), a sewer break resulted in the release of over 60 million gallons of raw sewage into the lake. The sewage was diverted to Ryerson and Ruddiman Creeks and was of sufficient magnitude to influence the benthic community in much of the study area.

1.2 Project Objectives And Task Elements

The objective of this investigation is to conduct a Category II assessment of sediment contamination in Muskegon Lake. Specific objectives and task elements are summarized below:

- Determine the nature and extent of sediment contamination in Muskegon Lake.
  - A preliminary investigation was conducted to examine the nature and extent of sediment contamination in Muskegon Lake. Core samples were collected to provide a historical perspective of sediment contamination. The investigation was directed at known sources of contamination in the lake and provided expanded coverage in the area of the Division Street Outfall. Arsenic, barium, cadmium, chromium, copper, lead, nickel, zinc, selenium, mercury, TOC, semivolatile organics, resin acids, and grain size were analyzed in all core samples.
  - Surface sediments were collected from Muskegon Lake with a Ponar dredge to provide chemical data for the sediments used in the toxicity evaluations and for the analysis of the benthic macroinvertebrate communities. The Ponar samples were analyzed for the same parameters as the sediment cores.
  - Critical measurements were the concentration of arsenic, barium, cadmium, chromium, copper, lead, nickel, zinc, selenium, mercury, semivolatile organics, and resin acids in sediment samples. Non-critical measurements were total organic carbon and grain size.
- Determine the depositional history and stability of selected sediments in Muskegon Lake.
  - Sediment samples were collected with a box core and a piston core in Muskegon Lake. Concentration vs. depth profiles of radioisotopes and heavy metals were determined in the sediment cores.
  - Critical measurements were the concentrations of lead, chromium, and the radioisotopes (^{210}Pb, ^{214}Bi, and ^{137}Cs).
- Evaluate the toxicity of sediments from sites in the lower Muskegon Lake area.
  - Sediment toxicity evaluations were performed with *Hyalella azteca* and *Chironomus tentans*.
  - Toxicity measurements in Muskegon Lake sediments were evaluated and compared to the two control locations. These measurements determined the presence and degree of toxicity associated with sediments from Muskegon Lake.
  - Critical measurements were the determination of lethality during the toxicity tests and the monitoring of water quality indicators during exposure (ammonia, dissolved oxygen, temperature, conductivity, pH, and alkalinity).

- Determine the abundance and diversity of benthic invertebrates in Muskegon Lake

- Sediment samples were collected with a Ponar in Muskegon Lake.
- The abundance and diversity of the benthic invertebrate communities were evaluated and compared to the two control locations.
- Critical measurements were the abundance and species composition of benthic macroinvertebrates.

1.3 Experimental Design

This investigation was designed to examine specific sites of possible contamination as well as provide an overall assessment of the nature and extent of sediment contamination in Muskegon Lake. This bifurcated approach allowed the investigation to focus on specific sites based on historical information in addition to examining the broad-scale distribution of contamination. To address contamination at specific sites, 12 core samples were collected from locations likely to have been impacted by significant anthropogenic activity. The locations were selected to target current and historical point sources and downstream sites from known industrial and municipal discharges. These sites were determined by the analysis of historical data and industrial site locations. Analysis of lake depositional areas was then used to select locations that would reflect the general distribution of contaminants.

Sediment samples were collected using the U.S. EPA Research Vessel *Mudpuppy*. The sediment cores were collected with a VibraCore device with core lengths ranging from 1 m - 2.4 m. The core samples were then sectioned for chemical analysis. In general, two 38 cm segments were removed for the top and middle sections. The remainder of the core length was designated as the bottom section. Section lengths were altered if changes in the strata were noted. Ponar samples also were collected at these locations to provide an assessment of the near surface zone sediments. For each core, the analytical parameters included a general series of inorganic and organic constituents as well as specific chemicals related to a particular source or area. The general chemical series for each core included the following heavy metals; arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc. Analytical methods were performed according to the protocols described in SW-846 3rd edition (EPA 1999). Chemistry data were then supplemented by laboratory toxicity studies that utilized standardized exposure regimes to evaluate the effects of contaminated sediment on test organisms. Standard EPA methods (1999) using *Chironomus tentans* and *Hyalella azteca* were used to determine the acute toxicity of sediments from the Ponar samples.

In addition to the above scope of work, an investigation of sediment deposition and stability was conducted using radiodating and detailed stratigraphy. Radiodating profiles were used to define annual deposition rates and directly reflect sediment stability (Appleby et al., 1983 and Schelske et al., 1994). In consideration of the effluent diversions that occurred in the early 1970s, heavy metal flux into Muskegon Lake has changed dramatically over the last 25 years. If the sediments are stable and not subject to resuspension, lower levels of heavy metals should be encountered in the surface strata. To help assess the stability and deposition of sediments in Muskegon Lake, two box cores from deep deposition zones and one piston core from a near shore location were collected and dated using ^{210}Pb and ^{137}Cs. Each core was analyzed for a target list of heavy metals at 2 cm intervals in order to develop a detailed stratigraphic profile. Radionuclide and heavy metal profiles in the near shore areas were used

to determine if the sediments are stable or mixed by wave action. Data from the deeper cores were used to assess the mobility of sediments in the lake. If the near shore sediments were subject to mixing, contaminated materials from historic discharges may be moved to the surface and result in a long term impairment of ecological conditions. These data along with the biological and toxicological studies discussed above will provide a technically sound basis for the development of remediation alternatives and restoration plans for Muskegon Lake.

1.4 References

Alexander, J. 2000. The Muskegon River Unnatural Wonder. Special Series of The Muskegon Chronicle. September 12-15 1999. Muskegon, MI. 20 pp.

Appleby, P.G. and F. Oldfield. 1983. The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. *Hydrobiologia* 103: 29-35.

Canfield, T.J., E.L. Brunson, and F.J. Dwyer. 1998. Assessing sediments from upper Mississippi River navigational pools using a benthic invertebrate community evaluation and the sediment quality triad approach. *Arch. Environ. Contam. Toxico.* 35 (2):202-212.

EPA 1994. Test Methods for Evaluating Solid Waste Physical/Chemical Methods. U.S. Environmental Protection Agency. SW-846, 3rd Edition.

EPA 1995. Muskegon Lake Area of Concern: Division Street Outfall, 1994 sediment assessment. EPA Technical Report. Great Lakes National Program Office, Chicago. 48 pp.

EPA 1999. Methods for Measuring the Toxicity and Bioaccumulation of Sediment-Associated Contaminants with Freshwater Invertebrates. 2nd Edition. EPA Publication EPA/600/R-99/064.

Evans, E.D. 1992. Mona, White, and Muskegon Lakes in Muskegon County, Michigan The 1950s to the 1980s. Michigan Department of Natural Resources. MI/DNR/SWQ-92/261. 91pp.

Schelske, C.L., A. Peplow, M. Brenner, and C.. Spencer. 1994. Low-background gamma counting: Applications for ^{210}Pb dating of sediments. *J. Paleolim.* 10:115-128.

West Michigan Shoreline Regional Development Commission. 1977. Point Source Inventory: Sourcebook for Water Quality Planning. 156 pp.

West Michigan Shoreline Regional Development Commission. 1982. The Muskegon County Surface Water Toxics Study. Toxicity Survey General Summary. 153 pp.

2.0 Sampling Locations

Sampling locations for the assessment of contaminated sediments in Muskegon Lake were selected based on proximity to potential point and non-point sources of contamination. The locations of these sites were determined by review of historical records. Sediment samples were collected in areas of fine sediment deposition. Samples from areas containing rubble and sand were excluded. A total of 12 locations were selected for the collection of core samples and 15 locations were selected for Ponar samples. Cores were not collected in the Division Street Outfall area (M-5, M-6, and M-7) because of the previous sampling event performed by the EPA (1995). In addition, three stratigraphy cores were collected. Two were collected from the same general location as M-1 (M-1S) and M-5 (M-5S). The third stratigraphy core was collected at the deepest location in the lake off the Car Ferry Dock (M-2S). The sampling locations are listed below and displayed on Figure 2.1. GPS coordinates, depths, and visual descriptions are included in Tables 2.1 and 2.2 respectively, for core and Ponar samples.

Core Identification	Potential Source
M-1 and M-1S	Ruddiman Creek/Paper Mill
M-2S	Deep Deposition Area off Car Ferry Dock
M-3 and M-4	Ruddiman Creek
M-5, M-5S, M-6, M-7	Division Street Outfall (Ponars)
M-8	Westran/Shaw Walker
M-9	Mart Dock Marina
M-10	Teledyne/Lakey Foundry
M-11	Teledyne/Lakey Foundry/Ryerson Creek
M-12	Ryerson Creek
M-13	Mouth of Muskegon River South Branch
M-14	Mouth of Muskegon River North Branch
M-15	Control
M-16	Lakeshore Industrial Area (MichCon/Lakey Foundry)

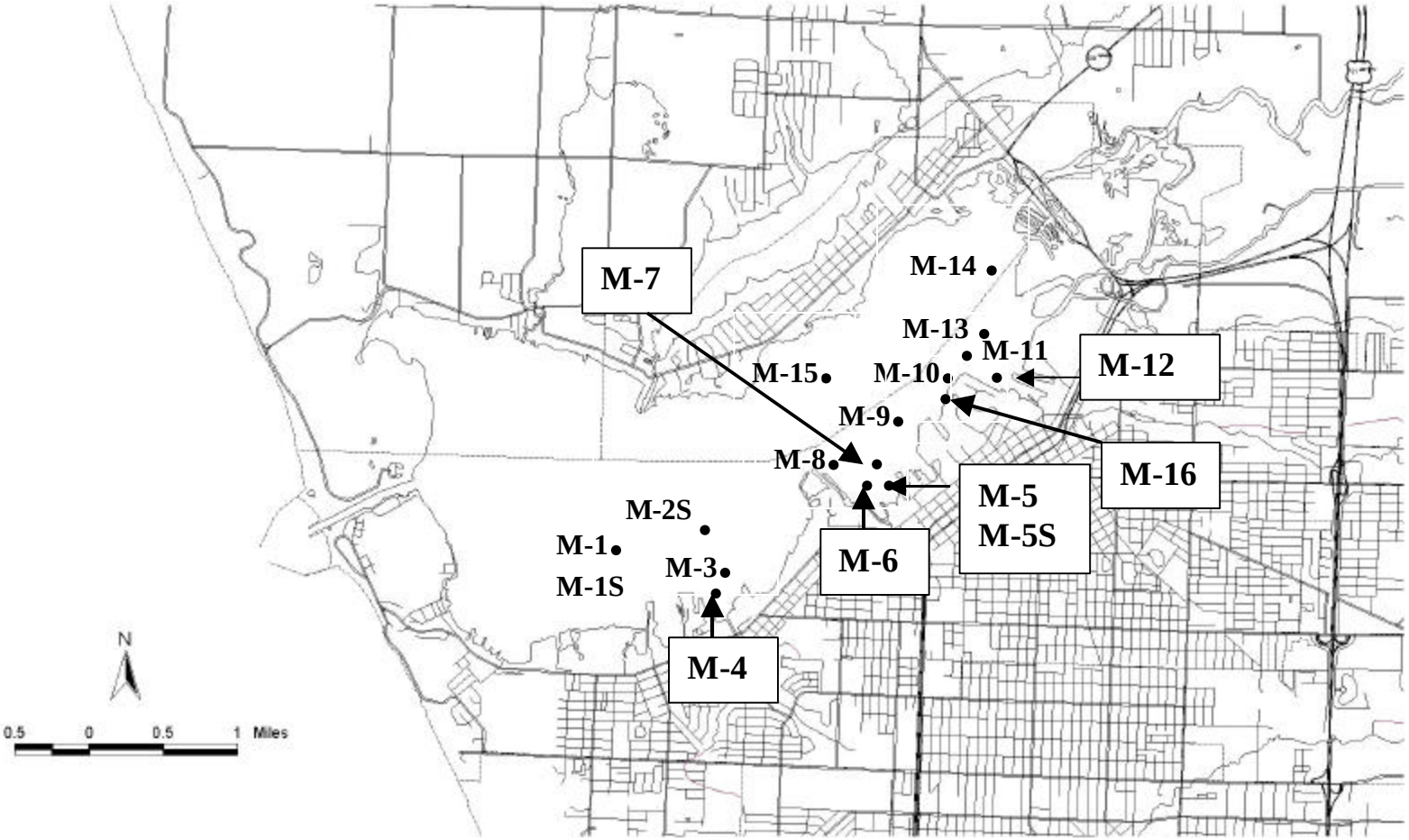


Figure 2.1 Muskegon Lake Core and PONAR Sampling Stations.

TABLE 2.1 MUSKEGON LAKE CORE SAMPLING STATIONS.

Muskegon Lake Core Sampling Stations.							
Station	Sample ID	Date	Depth to Core	Depth of Core	Latitude	Longitude	Description
			m	cm	N	W	
M-1		10/26/99	12.0	91	43° 13.39'	86° 1869'	
	Muskegon 1 Top		12.0	0-30			Black silt oil sheen
	Muskegon 1 Middle		12.0	30-61			Black silt
	Muskegon 1 Bottom		12.0	61-91			Hard sandy black clay
M-3		10/26/99	12.2	152	43° 13.42'	86° 17.22'	
	Muskegon 3 Top		12.2	0-30			Black silt oil sheen
	Muskegon 3 Middle		12.2	30-91			Black silt
	Muskegon 3 3-4		12.2	91-122			Black silt
	Muskegon 3 4-5		12.2	122-152			Black sand with wood chips
M-4		10/28/99	12.8	84	43° 13.36'	86° 17.34'	
	Muskegon 4 Top		12.8	0-30			Black silt with wood chips
	Muskegon 4 Bottom		12.8	30-84			Loose sand with silt
M-8		10/28/99	8.2	198	43° 14.08'	86° 16.26'	
	Muskegon 8 Top		8.2	0-38			Black-brown silt with oil sheen and hydrocarbon odor
	Muskegon 8 2		8.2	38-76			Black silt with oil sheen
	Muskegon 8 3		8.2	76-137			Brown silt
	Muskegon 8 4		8.2	137-198			Brown silt and grey sandy clay with shells
M-9		10/27/99	7.5	81	43° 14.38'	86° 15.78'	
	Muskegon 9 Top		7.5	0-41			Grey Sand
	Muskegon 9 Bottom		7.5	41-81			Black sand with wood chips and shells, hydrocarbon odor
M-10		10/27/99	7.4	122	43° 14.63'	86° 15.56'	
	Muskegon 10 Top		7.4	0-38			Black-brown silt with oil sheen and hydrocarbon odor
	Muskegon 10 Middle		7.4	38-76			Black sandy silt w/ wood chips and oil drops
	Muskegon 10 Bottom		7.4	76-122			Grey-brown sand
M-11		10/27/99	8.8	183	43° 14.72'	86° 15.39'	
	Muskegon 11 Top		8.8	0-38			Black-brown silt with oil drops and hydrocarbon odor
	Muskegon 11 2		8.8	38-76			Brown silt
	Muskegon 11 3		8.8	76-114			Brown silt
	Muskegon 11 Bottom		8.8	114-183			Brown silt

TABLE 2.1 (CONTINUED) MUSKEGON LAKE CORE SAMPLING STATIONS (*FIELD DUPLICATE SAMPLE)

Muskegon Lake Core Sampling Stations.							
Station	Sample ID	Date	Depth to Core	Depth of Core	Latitude	Longitude	Description
			m	cm	N	W	
M-11 Dup*		10/27/99	8.9	147			Black-brown silt with oil drops
	Muskegon 11D Top		8.9	0-38			Brown silt
	Muskgeon 11D 2		8.9	38-76			Brown silt
	Muskgeon 11D 3		8.9	76-114			Brown silt
	Muskegon 11D Bottom		8.9	114-147			Brown silt
M-12		10/27/99	4.2	165	43° 14.56'	86° 14.96'	
	Muskegon 12 Top		4.2	0-84			Grey sand with hydrocarbon odor
	Muskegon 12 Middle		4.2	84-122			Sandy, dark silt with hydrocarbon odor
	Muskegon 12 Bottom		4.2	122-165			Damp clay silt
M-13		10/28/99	9.6	198	43° 14.90'	86° 15.18'	
	Muskegon 13 Top		9.6	0-38			Black silt
	Muskegon 13 2		9.6	38-76			Black silt
	Muskegon 13 3		9.6	76-137			Grey Peate
	Muskegon 13 Bottom		9.6	137-198			Sandy clay with wood chips
M-14		10/27/99	8.6	170	43° 15.04'	86° 15.11'	
	Muskegon 14 Top		8.6	0-38			Black silt
	Muskegon 14 2		8.6	38-76			Black sandy silt
	Muskegon 14 3		8.6	76-114			Black sandy clay silt
	Muskegon 14 Bottom		8.6	114-170			Black clay silt
M-15		10/27/99	9.6	160	43° 14.60'	86° 16.46'	
	Muskegon 15 Top		9.6	0-38			Black silt
	Muskegon 15 Middle		9.6	38-84			Black silt
	Muskegon 15 Bottom		9.6	84-160			Sand
M-16A		10/29/99	5.9	76	43° 14.46'	86° 15.48'	
	Muskegon 16A Top		5.9	0-38			Black coal tar, very strong solvent odor
	Muskegon 16A Bottom		5.9	38-76			Sand, tar/coal flecks, solvent odor

TABLE 2.2 MUSKEGON LAKE PONAR SAMPLING STATIONS (*FIELD DUPLICATE SAMPLE)

Muskegon Lake Ponar Sampling Stations.						
Station	Sample ID	Date	Depth to Sediment	Latitude	Longitude	Description
			m	N	W	
M-1-P	M-1-P	10/29/99	12.0	43° 13.37'	86° 18.69'	Black silt, oil sheen
M-3-P	M-3-P	10/29/99	12.2	43° 13.42'	86° 17.21'	Sandy silt
M-4-P	M-4-P	10/29/99	12.8	43° 13.36'	86° 17.34'	Sandy silt
M-5-P	M-5-P	10/29/99	6.4	43° 13.95'	86° 15.92'	Black silt with oil sheen, hydrocarbon odor
M-6-P	M-6-P	10/29/99	4.1	43° 13.99'	86° 15.92'	Black silt with oil sheen, hydrocarbon odor
M-7-P	M-7-P	10/29/99	7.9	43° 14.01'	86° 15.92'	Black silt
M-8-P	M-8-P	10/29/99	8.2	43° 14.01'	86° 16.27'	Sandy silt
M-8-P Dup*	M-8-P	10/29/99	8.2	43° 14.01'	86° 16.27'	Sandy silt
M-9-P	M-9-P	10/28/99	7.5	43° 14.39'	86° 15.71'	Black silt with organic matter and zebra mussels
M-10-P	M-10-P	10/28/99	7.4	43° 14.64'	86° 15.56'	Sand with hydrocarbon odor
M-11-P	M-11-P	10/28/99	8.8	43° 14.72'	86° 15.38'	Sandy silt
M-12-P	M-12-P	10/28/99	4.2	43° 14.57'	86° 14.95'	Sandy silt
M-13-P	M-13-P	10/29/99	9.6	43° 14.89'	86° 15.18'	Black silt, hydrocarbon odor
M-14-P	M-14-P	10/29/99	8.6	43° 15.04'	86° 15.12'	Black silt
M-15 P	M-15 P	10/29/99	9.6	43° 14.61'	86° 16.46'	Black silt
M-16A P	M-16A P	10/29/99	5.4	43° 14.47'	86° 15.52'	Sand/gravel, hydrocarbon odor and tar/coal flecks

TABLE 2.3 MUSKEGON LAKE STRATIGRAPHY SAMPLING STATIONS

Station	Date	Depth to Sediment	Latitude	Longitude
		m	N	W
M-1S	03/29/2000	12.1	43° 13.37'	86° 18.69'
M-2S	03/29/2000	22.5	43° 13.48'	86° 17.83'
M-5S	10/292000	6.4	43° 13.95'	86° 15.92'

3.0 Methods

3.1 Sampling Methods

Sediment and benthos samples were collected using the U.S. EPA Research Vessel *Mudpuppy*. Vibra Core methods were used to collect sediment cores for chemical analysis. A 4-inch aluminum core tube with a butyrate liner was used for collection. A new core tube and liner was used at each location. The core samples were measured and sectioned into three equal segments corresponding to top, middle, and bottom. Each section was then homogenized in a polyethylene pan and split into sub-samples. The visual appearance of each segment was recorded along with the water depth and core depth.

Ponar samples were collected for toxicity testing, sediment chemistry, and benthic macroinvertebrates. For sediment chemistry and toxicity testing, a standard Ponar sample was deposited into a polyethylene pan and split into sub-samples. The Ponar was washed with water in between stations. A petite Ponar was used for the collection of benthic macroinvertebrates. Three replicate grabs were taken at each of the sites and treated as discrete samples. All material in the grab was washed through a Nitex screen with 500 μm openings and the residue preserved in buffered formalin containing rose bengal stain.

GPS system coordinates were used to record the position of the sampling locations. Since the core and Ponar samples were collected on different days, some variation in the location may have occurred.

3.1.2 Sample Containers, Preservatives, And Volume Requirements

Requirements for sample volumes, containers, and holding times are listed in Table 3.1.
All sample containers for sediment chemistry and toxicity testing were purchased, precleaned, and certified as Level II by I-CHEM Inc.

TABLE 3.1 SAMPLE CONTAINERS, PRESERVATIVES, AND HOLDING TIMES

				Hold Times	
Matrix	***Parameter***	***Container***	***Preservation***	***Extraction***	***Analysis***
Sediment	Metals	250 mL Wide Mouth Plastic	Cool to 4°C	---	6 months, Mercury-28 Days
Sediment	TOC	250 mL Wide Mouth Plastic	Freeze -10^{0}C	---	6 months
Sediment	Semi-Volatile Organics	500 mL Amber Glass	Cool to 4°C	14 days	40 days
Sediment	Grain Size	1 Quart Zip-Lock Plastic Bag	Cool to 4°C	---	6 months
Sediment	Toxicity	4 liter Wide Mouth Glass	Cool to 4°C	---	45 days
Water	Semi-Volatile Organics and Resin Acids	1000 mL Amber Glass	Cool to 4°C	14 days	40 days
Culture	Alkalinity	250 mL Wide Mouth Plastic	Cool to 4°C	---	24 hrs.
Water	Ammonia Hardness Conductivity pH	250 mL Wide Mouth Plastic	Cool to 4°C	---	24 hrs.

3.2 Chemical Analysis Methods For Sediment Analysis

A summary of analytical methods and detection limits is provided in Table 3.2.1. Instrumental conditions and a summary of quality assurance procedures are provided in the following sections.

TABLE 3.2.1 ANALYTICAL METHODS AND DETECTION LIMITS

SEDIMENT MATRIX

Parameter	Method Description	Analytical Method	Detection Limit
Arsenic, Lead, Selenium, Cadmium	Arsenic-Graphite Furnace	7060[1] 3051[1] Digestion	0.10 mg/kg
Barium, Chromium, Copper, Nickel, Zinc	Inductively Coupled Plasma Atomic Emission Spectroscopy	6010[1], 3052[1] Digestion	2.0 mg/kg
Mercury	Mercury Analysis of Soils, Sludges and Wastes by Manual Cold Vapor Technique	7471[1], Prep Method in 7471[1]	0.10 mg/kg
Grain Size	Wet Sieve	WRI Method PHY-010	1 %
Total Organic Carbon	Combustion/IR	9060[1]	0.1%
USEPA Semivolatiles	Solvent Extraction and GC/MS analysis	8270[1], 3550[1] Extraction	Table 3.2.2

[1] - SW846 3rd. Ed. EPA 1994.

3.2.1 Sample Preparation For Metals Analysis

For aluminum, arsenic, barium, calcium, cadmium, chromium, copper, iron, magnesium, manganese, nickel, lead, selenium, and zinc analysis, sediment samples were digested according to a modified version of EPA SW-846 method 3052 “Microwave Assisted Acid Digestion of Sediments, Sludges, Soils and Oils”. Samples were air-dried prior to digestion. A Questron (Mercerville, NJ) Q-4000 microwave system was used. The system provided a controlled temperature and pressure in each digestion vessel. Approximately 0.25 g of sediment was weighed into a Teflon liner. 4 mL Type 1 deionized water, 3 mL of concentrated nitric acid, 6 mL of concentrated hydrochloric acid, and 4 mL of hydrofluoric acid was added to each sample. Vessels then were capped and placed into the microwave cavity. The program was set to raise the temperature inside the vessels to 200°C for 20.0 minutes. After completion of the run, vessels were cooled and vented. Then 15 mL of saturated boric acid was added to each sample in place of using hydrogen peroxide. The vessels were recapped and placed into the microwave cavity. The program was set to raise the temperature inside the vessels to 180°C for 15.0 minutes. After completion of the second run, the vessels were cooled and vented. The contents were transferred into 50 mL centrifuge

tubes and brought up to 50 mL with Type I deionized water. Samples were centrifuged for 5 minutes at 3000 rpm before analysis. For every batch of 20 samples at least one set of the following quality control samples was prepared:

Method Blank (4 mL of Type 1 deionized water, 3 mL of nitric acid and 6 mL of hydrochloric acid);
Laboratory Control Spike (Blank Spike);
Matrix Spike;
Matrix Spike Duplicate.

For determining total mercury the samples were prepared by EPA SW-846 method 7471A, "Mercury in Solid and Semisolid Waste". Approximately 0.2 g of wet sediment was weighed into a 50 mL centrifuge tube. 2.5 mL of Type I deionized water and 2.5 mL of aqua regia were then added to the tube. Samples were heated in a water bath at 95°C for 2 minutes. After cooling, the volume of the samples was brought up to 30 mL with Type I deionized water. Then 7.5 mL of 5% potassium permanganate solution was added to each sample, samples were mixed, and the centrifuge tubes were returned in the water bath for a period of 30 minutes. Three mL of 12% hydroxylamine chloride solution was added to each sample after cooling. Finally, the samples were mixed and centrifuged for 5 minutes at 3,000 rpm. Calibration standards were digested along with the samples. Quality control samples were prepared as stated previously for every batch of 10 samples or less.

3.2.2 Arsenic Analysis By Furnace

Arsenic was analyzed in accordance with the EPA SW-846 method 7060A utilizing the Graphite Furnace technique. The instrument employed was a Perkin Elmer 4110ZL atomic absorption spectrophotometer. An arsenic EDL Lamp was used as a light source at wavelength of 193.7 nm. The instrument utilized a Zeeman background correction that reduces the non-specific absorption caused by some matrix components. The temperature program is summarized below:

Step	Temp,° C	Time, sec.		Gas Flow, ml/min	Read
		Ramp	Hold		
1	110	1	35	250	
2	130	15	37	250	
3	1300	10	20	250	
4	2100	0	5	0	X
5	2500	1	3	250	

A Pd/Mg modifier was used to stabilize As during pyrolysis step. The calibration curve was constructed from four standards and a blank. Validity of calibration was verified with a check standard prepared from a secondary source. This action was taken immediately after calibration, after every 20 samples, and at the end of each run. At least 1 post-digestion spike was performed for every analytical batch of 20 samples.

3.2.3 Cadmium Analysis By Furnace

Cadmium was analyzed in accordance with the EPA SW-846 method 7060A utilizing the Graphite Furnace technique. The instrument employed was a Perkin Elmer 4110ZL atomic absorption spectrophotometer. A hollow cathode lamp was used as a light source at wavelength of 228.8 nm. The instrument utilized a Zeeman background correction that reduces the non-specific absorption caused by some matrix components. The temperature program is summarized below:

Step	Temp,° C	Time, sec.		Gas Flow, ml/min	Read
		Ramp	Hold		
1	110	1	40	250	
2	130	15	45	250	
3	500	10	20	250	
4	1550	0	5	0	X
5	2500	1	3	250	

A Pd/Mg modifier was used to stabilize Cd during pyrolysis step. The calibration curve was constructed from four standards and a blank. Validity of calibration was verified with a check standard prepared from a secondary source. This action was taken immediately after calibration, after every 20 samples, and at the end of each run. At least 1 post-digestion spike was performed for every analytical batch of 20 samples.

3.2.4 Lead Analysis By Furnace

Lead was analyzed in accordance with the EPA SW-846 method 7060A utilizing the Graphite Furnace technique. The instrument employed was a Perkin Elmer 4110ZL atomic absorption spectrophotometer. A lead EDL Lamp was used as a light source at wavelength of 283.3 nm. The instrument utilized a Zeeman background correction that reduces the non-specific absorption caused by some matrix components. The temperature program is summarized below:

Step	Temp,° C	Time, sec.		Gas Flow, ml/min	Read
		Ramp	Hold		
1	120	1	20	250	
2	140	5	40	250	
3	200	10	10	250	
4	850	10	20	250	
5	1900	0	5	0	X
6	2500	1	3	250	

A Pd/Mg modifier was used to stabilize Pb during pyrolysis step. The calibration curve was constructed from four standards and a blank. Validity of calibration was verified with a check

standard prepared from a secondary source. This action was taken immediately after calibration, after every 20 samples, and at the end of each run. At least 1 post-digestion spike was performed for every analytical batch of 20 samples.

3.2.5 Selenium Analysis By Furnace

Selenium was analyzed in accordance with the EPA SW-846 method 7060A utilizing the Graphite Furnace technique. The instrument employed was a Perkin Elmer 4110ZL atomic absorption spectrophotometer. An arsenic EDL Lamp was used as a light source at wavelength of 196.0 nm. The instrument utilized a Zeeman background correction that reduces the non-specific absorption caused by some matrix components. The temperature program is summarized below:

Step	Temp,° C	Time, sec.		Gas Flow, ml/min	Read
		Ramp	Hold		
1	120	1	22	250	
2	140	5	42	250	
3	200	10	11	250	
4	1300	10	20	250	
5	2100	0	5	0	X
6	2450	1	3	250	

A Pd/Mg modifier was used to stabilize Se during pyrolysis step. The calibration curve was constructed from four standards and a blank. Validity of calibration was verified with a check standard prepared from a secondary source. This action was taken immediately after calibration, after every 20 samples, and at the end of each run. At least 1 post-digestion spike was performed for every analytical batch of 20 samples.

3.2.6 Metal Analysis By ICP

Aluminum, barium, calcium, chromium, copper, iron, magnesium, manganese, nickel, and zinc were analyzed in accordance with EPA SW-846 method 6010A by Inductively Coupled Plasma Atomic Emission Spectroscopy. Samples were analyzed on a Perkin Elmer P-1000 ICP Spectrometer with Ebert monochromator and cross-flow nebulizer. The following settings were used:

Element Analyzed	Wavelength, nm
Al	308.2
Ba	233.5
Ca	315.9
Cr	267.7
Cu	324.8
Fe	259.9

Element Analyzed	Wavelength, nm
Mg	279.1
Mn	257.6
Ni	231.6
Zn	213.9

RF Power: 1300 W

Matrix interferences were suppressed with internal standardization utilizing Myers-Tracy signal compensation. Interelement interference check standards were analyzed in the beginning and at the end of every analytical run and indicated absence of this type of interferences at the given wavelength. The calibration curve was constructed from four standards and a blank, and was verified with a check standard prepared from a secondary source.

3.2.7 Mercury

After the digestion procedure outlined in 3.2.1, sediment samples were analyzed for total mercury by cold vapor technique according to SW-846 Method 7471. A Perkin Elmer 5100ZL atomic absorption spectrophotometer with FIAS-200 flow injection accessory was used. Mercury was reduced to an elemental state with stannous chloride solution, and atomic absorption was measured in a quartz cell at an ambient temperature and a wavelength of 253.7 nm. A mercury electrodeless discharge lamp was used as a light source. The calibration curve consisted of four standards and a blank, and was verified with a check standard prepared from a secondary source.

3.2.8 Total Organic Carbon

Total Organic Carbon analysis of sediments was conducted on a Shimadzu TOC-5000 Total Organic Carbon Analyzer equipped with Solid Sample Accessory SSM-5000A. Samples were air dried and then reacted with phosphoric acid to remove inorganic carbonates. The samples were allowed to air dry again prior to analysis. Calibration curves for total carbon were constructed from three standards and a blank. Glucose was used as a standard compound for Total Carbon Analysis (44% carbon by weight).

3.2.9 Grain Size Analysis

Grain size was performed by wet sieving the sediments. The following mesh sizes were used: 2 mm (granule), 1 mm (very coarse sand), 0.85 mm (coarse sand), 0.25 mm (medium sand), 0.125 mm (fine sand), 0.063 (very fine sand), and 0.031 (coarse silt). After sieving, the fractions were dried at 105^{o}C and analyzed by gravimetric methods to determine weight percentages.

3.2.10 Semivolatiles Analysis

Sediment samples were extracted for semivolatiles analysis using SW-846 Method 3050. The sediment samples were dried with anhydrous sodium sulfate to form a free flowing powder. The samples were then serially sonicated with 1:1 methylene chloride/acetone and concentrated to a 1 mL volume.

The sample extracts were analyzed by GC/MS on a Finnigan GCQ Mass Spectrometer according to Method 8270. Instrumental conditions are itemized below:

MS operating conditions:

- Electron energy: 70 volts (nominal).
- Mass range: 40-450 amu.
- Scan time: 820 amu/second, 2 scans/sec.
- Source temperature: 190° C
- Transfer line temperature: 250°C

GC operating conditions:

- Column temperature program: 45°C for 6 min., then to 250°C at 10°C/min, then to 300°C at 20°C/min hold 300°C for 15 min.
- Injector temperature program: 250°C
- Sample volume: 1 ul

A list of analytes and detection limits is given in Table 3.2.2. Surrogate standards were utilized to monitor extraction efficiency. Acceptance criteria for surrogate standards are given in Table 3.2.3. The GC/MS was calibrated using a 5-point curve. Instrument tuning was performed by injecting 5 ng of decafluorotriphenylphosphine and meeting method acceptance criteria. The MS and MSD samples were analyzed at a 5% frequency.

TABLE 3.2.2 ORGANIC PARAMETERS AND DETECTION LIMITS

	Sediment (mg/kg)
Semi-Volatile Organic Compounds (8270)	
Phenol	0.33
Bis(2-chloroethyl)ether	0.33
2-Chlorophenol	0.33
1,3-Dichlorobenzene	0.33
1,4-Dichlorobenzene	0.33
1,2-Dichlorobenzene	0.33
2-Methylphenol	0.33
4-Methylphenol	0.33
Hexachloroethane	0.33
Isophorone	0.33
2,4-Dimethylphenol	0.33
Bis(2-chloroethoxy)methane	0.33
2,4-Dichlorophenol	0.33
1,2,4-Trichlorobenzene	0.33
Naphthalene	0.33
Hexachlorobutadiene	0.33
4-Chloro-3-methylphenol	0.33
2-Methylnaphthalene	0.33
Hexachlorocyclopentadiene	0.33
2,4,6-Trichlorophenol	0.33
2,4,5-Trichlorophenol	0.33
2-Chloronaphthalene	0.33
Dimethylphthalate	0.33
Acenaphthylene	0.33
Acenaphthene	0.33
Diethylphthalate	0.33
4-Chlorophenyl-phenyl ether	0.33
Fluorene	0.33
4,6-Dinitro-2-methylphenol	1.7
4-Bromophenyl-phenyl ether	0.33

TABLE 3.2.2 ORGANIC PARAMETERS AND DETECTION LIMITS (CONTINUED)

	Sediment (mg/kg)
Semi-Volatile Organic Compounds (8270)	
Hexachlorobenzene	0.33
Pentachlorophenol	1.7
Phenanthrene	0.33
Anthracene	0.33
Di-n-butylphthalate	0.33
Fluoranthene	0.33
Pyrene	0.33
Butylbenzylphthalate	0.33
Benzo(a)anthracene	0.33
Chrysene	0.33
Bis(2-ethylhexyl)phthalate	0.33
Di-n-octylphthalate	0.33
Benzo(b)fluoranthene	0.33
Benzo(k)fluoranthene	0.33
Benzo(a)pyrene	0.33
Indeno(1,2,3-cd)pyrene	0.33
Dibenzo(a,h)anthracene	0.33
Benzo(g,h,i)perylene	0.33
3-Methylphenol	0.33

TABLE 3.2.3 DATA QUALITY OBJECTIVES FOR SURROGATE STANDARDS CONTROL LIMITS FOR PERCENT RECOVERY

Parameter	Control Limit
Nitrobenzene-d_5	30%-97%
2-Fluorobiphenyl	42%-99%
o-Terphenyl	60%-101%
Phenol-d_6	43%-84%
2-Fluorophenol	33%-76%
2,4,6-Tribromophenol	58%-96%

3.3 Chemical Analysis Methods For Water Analysis

The parameters, methods, and detection limits for the measurements performed on the culture water used in the sediment toxicity tests are listed in Table 3.3.1. All methods were performed according to procedures outlined in Standard Methods 14th Edition (1996).

TABLE 3.3.1 ANALYTICAL METHODS AND DETECTION LIMITS FOR CULTURE WATER

Parameter	Method	Detection Limit
Specific Conductance	Standard Methods 2510 B.	NA
Alkalinity	Standard Methods 2320	10 mg/l
Temperature	Standard Methods 2550	NA
Dissolved Oxygen	Standard Methods 4500-O G.	0.5 mg/l
Ammonia Electrode	Standard Methods 4500-NH_3 F.	0.05 mg/l
Hardness	Standard Methods 2340 C.	10 mg/l

3.4 Sediment Toxicity

The evaluation of the toxicity of the Muskegon Lake sediments was conducted using the ten-day survival test for the amphipod *Hyalella azteca* and the dipteran *Chironomus tentans*. The procedures followed are contained in EPA/600/R-94/024, Methods for Measuring the Toxicity and Bioaccumulation of Sediment-associated Contaminants with Fresh Water Invertebrates. All sediments were stored at 4°C prior to analysis.

3.4.1 Laboratory Water Supply

A moderately hard well water for *H. azteca* and *C. tentans* cultures and maintenance was employed.

3.4.2 Test Organisms

The original stock of *H. azteca* was obtained from the Great Lakes Environmental Research Laboratory in Ann Arbor, Michigan. The *H. azteca* culture was maintained in four 20 L glass aquaria using maple leaves as a substrate and as a food source. The food source was supplemented with a suspension of Tetramin® fish food. The original stock of *C. tentans* was obtained from the University of Michigan Department of Environmental Health in Ann Arbor,

Michigan. The culture of *C. tentans* was maintained in 36 L glass aquaria using shredded paper toweling as a substrate and was fed a suspension of Tetrafin® goldfish food.

3.4.3 Experimental Design

For the November testing, eight replicates per sediment were set up for both *H. azteca* and *C. tentans* exposures, with the sediment from site M-15P designated as the control. In all tests, moderately hard well water was utilized as the overlying water. The experimental conditions outlined in Tables 3.4.1 and 3.4.2 were used for the toxicity evaluations.

One day prior to the start of the test (day -1), the sediment from each site was mixed thoroughly and a 100 mL aliquot was transferred to each of the eight test chambers. Additionally, visual observations of the sediments were made. Moderately hard well water also was added at this time. On day 0, the overlying water was renewed once before the test organisms were introduced into each of the glass beakers. Measurement of water quality parameters also was initiated on this day. Ten, 7-14 day old *H. azteca* and 10 third instar *C. tentans* larvae were randomly added to their respective test chambers. At this time the organisms were fed 1.5 mL of Tetrafin®. The glass beakers were placed in a rack and transferred to a temperature controlled room ($23 \pm 1^{o}C$). The light cycle was 16 hours on and 8 hours off. Temperature and dissolved oxygen measurements were taken from one randomly selected beaker for each sediment sample every 12 hours, after which the overlying water was renewed in all the beakers. Feeding with the Tetrafin® suspension occurred after the morning renewal. This procedure was repeated daily through day 10, at which point the test was terminated. On day 0, the overlying water from the beakers was composited from each sediment sample and 250 mL were retained for alkalinity, pH, conductance, hardness and ammonia analysis. On the last day the same procedure was carried out. On day 10, the sediments were sieved, and the surviving test organisms were removed and counted. The biological endpoint for these sediment tests was mortality. The validity of the test was based on EPA (1994) criteria of greater than 80% survival in the control treatment for *H. azteca* and greater than 70% survival in the control treatment for the *C. tentans*. In addition, EPA (1994) recommended that the hardness, alkalinity, pH, and ammonia in the overlying water within a treatment should not vary by more than 50% over the duration the test.

TABLE 3.4.1 TEST CONDITIONS FOR CONDUCTING A TEN DAY SEDIMENT TOXICITY TEST WITH *HYALELLA AZTECA*

1.	Test Type:	Whole-sediment toxicity test with renewal of overlying water
2.	Temperature (°C):	23 ± 1°C
3.	Light quality:	Wide-spectrum fluorescent lights
4.	Illuminance:	About 500 to 1000 lux
5.	Photoperiod:	16 h light, 8 h darkness
6.	Test chamber size:	300 mL high-form lipless beaker
7.	Sediment volume:	100 mL
8.	Overlying water volume:	175 mL
9.	Renewal of overlying water:	2 volume additions per day (i.e., one volume addition every 12 hours)
10.	Age of test organisms:	7 to 14 days old at the start of the test
11.	Number of organisms per chamber:	10
12.	Number of replicate chambers per treatment:	8
13.	Feeding:	Tetramin® fish food, fed 1.5 mL daily to each test chamber
14.	Aeration:	None, unless dissolved oxygen in overlying water drops below 40% of saturation
15.	Overlying water:	Reconstituted water
16.	Overlying water quality:	Hardness, alkalinity, conductivity, pH, and ammonia measured at the beginning and end of a test. Temperature and dissolved oxygen measured daily.
17.	Test duration:	10 days
18.	End point:	Survival, with greater than 80% in the control

Test Method 100.1. EPA Publication 600/R-94/024 (July 1994).

TABLE 3.4.2 RECOMMENDED TEST CONDITIONS FOR CONDUCTING A TEN DAY SEDIMENT TOXICITY TEST WITH *CHIRONOMUS TENTANS*

1.	Test Type:	Whole-sediment toxicity test with renewal of overlying water
2.	Temperature (°C):	23 ± 1°C
3.	Light quality:	Wide-spectrum fluorescent lights
4.	Illuminance:	About 500 to 1000 lux
5.	Photoperiod:	16 h light, 8 h darkness
6.	Test chamber size:	300 mL high-form lipless beaker
7.	Sediment volume:	100 mL
8.	Overlying water volume:	175 mL
9.	Renewal of overlying water:	2 volume additions per day (i.e., one volume addition every 12 hours)
10.	Age of test organisms:	Third instar larvae (All organisms must be third instar or younger with at least 50% of the organisms at third instar)
11.	Number of organisms per chamber:	10
12.	Number of replicate chambers per treatment:	8
13.	Feeding:	Tetrafin® goldfish food, fed 1.5 mL daily to each test chamber (1.5 mL contains 4.0 mg of dry solids)
14.	Aeration:	None, unless dissolved oxygen in overlying water drops below 40% of saturation
15.	Overlying water:	Reconstituted water
16.	Overlying water quality:	Hardness, alkalinity, conductivity, pH, and ammonia measured at the beginning and end of a test. Temperature and dissolved oxygen measured daily.
17.	Test duration:	10 days
18.	End point:	Survival, with greater than 70% in the control.

Test Method 100.2. EPA Publication 600/R-94/024 (July 1994).

3.4.4 Statistical Analysis

Survival data for the toxicity testing were analyzed first for normality with Chi Square and then for homogeneity using Bartlett's Test. All data passed the normality and homogeneity tests without transformation. The data were then examined using Dunnett's Procedure to determine whether there was a significant difference in survival between the designated control sediment and those sediments containing pollutants. The TOXSTAT® 3.5 Computer Program was used for the statistical evaluations.

3.5 Benthic Macroinvertebrate Analysis

Samples were washed with tap water to remove formalin and extraneous debris through a USGS #30 mesh screen. The retained portion was poured into a white enamel pan from which the organisms were picked into two groups. These were oligochaetes and "other". The worms were preserved with 4% formalin and later identified to the lowest practical level. The worms were mounted separately and examined under 100X and 400X. The "other" group was preserved in 70% ethanol. Midges were removed from this group and a head mount of each midge was made and examined under 100X and 400X. The number and taxa were reported. The remainder of the organisms were identified and enumerated utilizing a 60X dissecting microscope.

3.6 Radiometric Dating

Radiometric measurements were made using low-background gamma counting systems with well-type intrinsic germanium detectors (Schelske et al. 1994). Dry sediment from each section was packed to a nominal height of 30 mm in a tared polypropylene tube (84 mm high x 14.5 mm outside diameter, 12 mm inside diameter). Sample height was recorded and tubes were weighed to obtain sample mass. Samples in the tubes were then sealed with a layer of epoxy resin and polyamine hardener, capped, and stored before counting to ensure equilibrium between ^{226}Ra and ^{214}Bi. Activities for each radionuclide were calculated using empirically derived factors of variation in counting efficiency with sample mass and height (Schelske et al. 1994). Total ^{210}Pb activity was obtained from the 46.5 kev photon peak, and ^{226}Ra activity was obtained from the 609.2 kev peak of ^{214}Bi. ^{226}Ra activity was assumed to represent supported ^{210}Pb activity. Excess ^{210}Pb activity was determined from the difference between total and supported ^{210}Pb activity and then corrected for decay from the coring date. The 661.7 kev photon peak is used to measure ^{137}Cs activity.

Sediments were aged using activity measurements of the above radioisotopes in the sediment samples. The method was based on determining the activity of total ^{210}Pb (22.3 yr half-life), a decay product of ^{226}Ra (half-life 1622 yr) in the ^{238}U decay series. Total ^{210}Pb represents the sum of excess ^{210}Pb and supported ^{210}Pb activity in sediments. The ultimate source of excess ^{210}Pb is the outgassing of chemically inert ^{222}Rn (3.83 d half-life) from continents as ^{226}Ra incorporated in soils and rocks decays. In the atmosphere, ^{222}Rn decays to ^{210}Pb which is deposited at the earth's surface with atmospheric washout as unsupported or excess ^{210}Pb. Supported ^{210}Pb in lake sediments is produced by the decay of ^{226}Ra that is deposited as one fraction of erosional inputs. In the sediments, gaseous ^{222}Rn produced from ^{226}Ra is trapped

and decays to ^{210}Pb. By definition, supported ^{210}Pb is in secular equilibrium (production rate matches decay rate) with sedimentary ^{226}Ra and is equal to total ^{210}Pb activity at depths where excess ^{210}Pb activity is not measurable due to decay. Because the decay of excess ^{210}Pb activity in sediments provides the basis for estimating sediment ages, it is necessary to make estimates of total and supported ^{210}Pb activities so excess ^{210}Pb activity can be determined by difference. Excess ^{210}Pb activity was calculated either by subtracting ^{226}Ra activity from total ^{210}Pb activity at each depth or by subtracting an estimate of supported ^{210}Pb activity based on measurements of total ^{210}Pb activity at depths where excess ^{210}Pb activity was negligible.

Sediment ages were calculated using a CRS model (Appleby and Oldfield 1983). This model calculates ages based on the assumption that the flux of excess ^{210}Pb to the lake was constant and therefore that variation in ^{210}Pb activity from a pattern of exponential decrease with depth depends on variation in rate of sedimentation. The age of sediments at depth x is given by:

$$t = (1/k) [\ln (Ao/A)]$$

where t is time in yr, k is 0.03114 (the ^{210}Pb decay constant), Ao is the total residual excess ^{210}Pb activity in the sediment core, and A is the integrated excess ^{210}Pb activity below depth x. Calculations for each depth provide a continuous profile of ages as a function of depth. Mass sedimentation rate (MSR) at depth x was determined by :

$$MSR = m/t$$

where m is dry mass of sediment (g /cm^2) for the sampling interval. Errors in age and mass sedimentation rate were propagated using first-order approximations and calculated according to Binford (1990).

3.7 References

Appleby, P. G. and F. Oldfield. 1983. The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103: 29-35.

Binford, M. W. 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. J. Paleolim. 3:253-267.

EPA 1994. Methods for Measuring the Toxicity and Bioaccumulation of Sediment-Associated Contaminants with Freshwater Invertebrates. EPA Publication 600/R-94/024.

Schelske, C. L., A. Peplow, M. Brenner, and C. N. Spencer. 1994. Low-background gamma counting: Applications for ^{210}Pb dating of sediments. J. Paleolim. 10:11128.

4.0 Results And Discussion

The results and discussion section is organized according to 6 sections that present and summarize the information related to the following topics:

Section 4.1	Sediment Chemistry Results
Section 4.2	Stratigraphy and Radiodating Results
Section 4.3	Toxicity Testing Results
Section 4.4	Benthic Macroinvertebrate Results
Section 4.5	Sediment Quality Triad Analysis
Section 4.6	Summary and Conclusions

The sediment chemistry results are presented for the core and Ponar samples (Section 4.1) and include metals, semivolatiles, and physical parameters. A discussion is also included related to the comparison of the data with published sediment quality guidelines. The stratigraphy and radiodating results are presented in Section 4.2 and include the results of radioisotopes and the target list of metals (chromium and lead). Toxicity and Benthic Macroinvertebrate results are presented in Sections 4.3 and 4.4, respectively. Statistical analyses of the data and comparisons to related chemical and biological data are also discussed. Finally, Section 4.5 provides a discussion of all the data using the Sediment Quality Triad to assess the significance of the sediment contamination in Muskegon Lake. The project summary and conclusions are provided in section 4.6.

The project data were reviewed for compliance with the Data Quality Objectives outlined in the Quality Assurance Project Plan. Low matrix spike recoveries were obtained on one sample for semivolatiles and one sample for metals. Acceptable recoveries were obtained in the for the laboratory control sample, indicating that the problem was matrix related. The data was not qualified due to the fact that the project was a preliminary investigation. The results of the Quality Assurance reviews are summarized in Appendix A.

4.1 Sediment Chemistry Results

The results of sediment grain size fractions, percent solids and TOC for the core and PONAR samples are presented in Tables 4.1.1 and 4.1.2, respectively. The sediments from most of the core samples can be characterized as having fine grain size (> 70% of particles < 63 *u*m) and moderate in total organic carbon (TOC 1% - 4%) in the top 40 cm. Grain size distributions changed to include a greater sand fraction (125-500 *u*m range) in the next 40 cm section. Most cores contained > 50% sand in depths beyond 80 cm. This pattern is consistent with historical industrial development of the shoreline. Much of the lake shoreline was filled with foundry sand during the 1930s-1950s. Erosion of the fill material probably resulted in a sand layer being deposited throughout the near shore area. The presence of the finer grained material is consistent with the recent history of a more stable shoreline and eutrophic conditions present in the lake. Cores from stations M-4, M-9, M-12, and M-16 did not fit this pattern. M-4 was collected near an aggregate storage area and in the deposition zone of Ruddiman Creek. Erosion inputs from both of these sources would increase the sand fraction

present in the core. Station M-9 was collected near a peninsula that once contained an abandoned metal finishing facility. The site has limited vegetation and is also subject to wave induced erosion. Station M-12 was different than the other cores in that a fine grained silt layer was found below 80 cm of sandy sediment. This site was located near an abandoned foundry, an aggregate storage area, and the mouth of Ryerson Creek. The core from M-16 was the only location that contained a significant gravel fraction that may have been the result of historical dredging or filling in the area. The sediments at this station also contained flecks of coal tar/coal and had a strong odor of aromatic hydrocarbons. Since the particle size and TOC characteristics of sediments will influence their ability to retain metals and organic chemicals, these data will be important in explaining the distribution of anthropogenic contaminants.

Very little difference was noted between the grain size and TOC content of the PONAR samples (Table 4.1.2) and the top core sections (Table 4.1.1). PONARS collected from M-4, M-9, M-12, and M-16 were all found to contain a higher fraction of sandy sediments. Since these samples were used for chemical analysis in addition to the assessment of sediment toxicity and benthic invertebrate diversity, the influence of particle size and TOC content will also be an important factor in the evaluation of the project data.

The results of sediment metals analyses are presented for the core and PONAR samples in Tables 4.1.3 and 4.1.4 respectively. The results of PAH analyses for the same sample groupings are given in Table 4.1.5. Figures 4.1.1, 4.1.2, and 4.1.3, 4.1.4, and 4.1.5 illustrate the spatial distribution of chromium, cadmium, copper, lead, and PAH compounds, respectively, in core samples collected from western Muskegon Lake. This section of the lake is located down stream from the historical industrial activity found along the southeast shore and in the deposition zone of Ruddiman Creek. Low levels of metals were found at M-4. As discussed earlier, this station contained sandy sediment that would not accumulate heavy metals. The highest levels of chromium, cadmium, copper, and lead were found in the top 30 cm layer of the core from M-1. Levels decrease dramatically as depth increased, indicating the source of contaminants is relatively recent. In contrast, the concentrations of the same metals were higher in the middle 30-60 cm section than the top layer of the M-1 core. Very little change was noted in the bottom core section, as all metals remained elevated. This pattern suggests that the near shore environment is subject to mixing and resuspension from wind and wave induced currents. Station M-1 was located in the middle of the lake and outside the influence of near shore currents. Since deposition from Ruddiman Creek would influence both locations and no industrial activity was present along the local shoreline, sediment mixing at M-3 in combination with the advection of contaminants along the old river channel would account for the pattern of deposition observed at the locations.

Figures 4.1.6, 4.1.7, and 4.1.8, 4.1.9, and 4.1.10 present the spatial distribution of chromium, cadmium, copper, lead, and PAH compounds, respectively, in core samples collected from eastern Muskegon Lake. The southern shoreline of this part of the lake was heavily industrialized and also extensively backfilled with foundry sand. Only station M-9 did not contain elevated levels of heavy metals. The core from this location had a large sand fraction and would have a limited capacity to retain metals. Three depositional patterns were noted in

TABLE 4.1.1 RESULTS OF SEDIMENT GRAIN SIZE FRACTIONS, TOC, AND PERCENT SOLIDS FOR MUSKEGON LAKE CORE SAMPLES, OCTOBER 1999.

Sample ID	<2000 *u*m Weight %	1000-2000 *u*m Weight %	850-1000 *u*m Weight %	500-850 *u*m Weight %	125-500 *u*m Weight %	63-125 *u*m Weight %	<63 *u*m Weight %	Solids Weight %	TOC Weight %
M-1-top	0.0	0.3	0.1	0.8	6.4	6.6	86	16	4.2
M-1 mid	0.3	0.8	0.4	3.7	35	3.5	56	30	2.1
M-1 bot	1.9	1.7	0.7	5.1	70	1.1	19	77	<0.5
M-3 top	1.0	0.1	0.0	0.2	5.2	9.0	85	16	5.1
M-3-mid	0.1	0.1	0.0	0.3	3.9	5.4	90	17	3.9
M-3 3-4'	0.1	0.1	0.1	0.4	9.9	6.8	83	19	2.6
M-3 4-5'	0.1	0.1	0.1	1.1	61	3.5	34	45	1.1
M-4 top	4.6	0.6	0.2	0.7	45	7.5	41	49	1.2
M-4 bot	2.7	0.5	0.1	0.9	67	3.9	25	55	<0.5
M-8 top	0.0	0.1	0.0	0.3	14	0.2	86	20	4.7
M-8-2	0.7	0.2	0.1	0.9	17	4.6	76	28	3.4
M-8-3	0.0	0.0	0.0	9.1	0.4	7.8	83	31	5.2
M-8-bot	0.8	0.6	0.3	3.2	36	16	43	58	<0.5
M-9 top	2.4	0.2	0.5	10	65	1.9	20	89	<0.5
M-9 bot	3.7	2.1	0.8	6.0	65	3.5	19	77	<0.5
M-10 top	0.5	0.2	0.1	0.4	10	12	76	28	1.5
M-10 mid	6.6	4.1	1.8	7.2	46	3.2	32	54	<0.5
M-10 bot	0.2	0.4	0.2	2.6	79	2.4	15	83	<0.5
M-11 top	0.1	0.1	0.1	0.2	3.2	8.0	88	24	4.3
M-11 2	0.1	0.0	0.0	0.3	6.1	12	81	29	3.2
M-11 3	0.3	0.1	0.0	0.2	5.9	11	82	34	1.3
M-11 bot	0.5	0.1	0.1	0.4	8.5	7.5	83	34	<0.5
M-11D top	0.0	0.1	0.0	0.1	4.6	9.2	86	24	4
M-11D 2	0.0	0.0	0.0	0.6	5.7	8.6	85	29	3.1
M-11D 3	0.0	0.0	0.0	0.2	3.9	8.9	87	34	1.8
M-11D bot	0.1	0.1	0.0	0.2	6.8	9.1	84	37	<0.5

TABLE 4.1.1 (CONTINUED) RESULTS OF SEDIMENT GRAIN SIZE FRACTIONS, TOC, AND PERCENT SOLIDS FOR MUSKEGON LAKE CORE SAMPLES, OCTOBER 1999.

Sample ID	<2000 *u*m Weight %	1000-2000 *u*m Weight %	850-1000 *u*m Weight %	500-850 *u*m Weight %	125-500 *u*m Weight %	63-125 *u*m Weight %	<63 *u*m Weight %	Solids Weight %	TOC Weight %
M-12 top	3.4	1.3	0.7	8.4	65	4.7	17	91	<0.5
M-12 mid	0.6	0.5	0.3	2.1	49	15	33	68	<0.5
M-12 bot	0.3	0.3	0.2	0.7	15	9.7	74	50	<0.5
M-13 top	0.2	0.0	0.0	0.1	3.8	9.3	87	34	2.7
M-13 2	0.0	0.0	0.0	0.1	4.7	12	83	37	1.9
M-13 3	0.1	0.1	0.0	0.1	4.9	9.2	86	39	2.6
M-13 bot	2.8	1.1	0.2	1.0	20	8.4	67	44	4.0
M-14 top	0.4	0.1	0.1	0.2	8.5	13	78	28	2.4
M-14 2	0.9	0.1	0.0	0.3	23	16	60	46	1.5
M-14 3	0.3	0.1	0.1	0.3	23	16	60	45	1.1
M-14 bot	0.0	0.4	0.1	0.4	6.0	9.2	84	38	<0.5
M-15 top	0.0	0.1	0.0	0.1	2.1	3.7	94	18	2.2
M-15 mid	0.0	0.0	0.0	0.3	9.8	7.5	82	28	1.6
M-15 Bot	0.4	0.2	0.0	1.3	85	1.3	11	88	<0.5
M-16 top	9.0	1.8	0.4	2.2	61	6.8	18	78	0.8
M-16 mid	2.6	0.3	0.3	3.0	73	0.8	20	81	<0.5
M-16A top	2.9	0.5	0.3	1.2	34	8.6	53	39	1.9
M-16A bot	7.8	4.0	1.7	11	64	1.4	10	88	<0.5

TABLE 4.1.2 RESULTS OF SEDIMENT GRAIN SIZE FRACTIONS, TOC, AND PERCENT SOLIDS FOR MUSKEGON LAKE PONAR SAMPLES, OCTOBER 1999.

Sample ID	<2000 *u*m Weight %	1000-2000 *u*m Weight %	850-1000 *u*m Weight %	500-850 *u*m Weight %	125-500 *u*m Weight %	63-125 *u*m Weight %	<63 *u*m Weight %	Solids Weight %	TOC Weight %
M-1P	0.9	0.0	-0.1	0.2	6.2	2.1	91	15	4.5
M-3P	0.5	0.2	0.0	0.2	6.9	9.0	83	18	5.5
M-4P	5.6	0.5	0.1	1.6	73	4.2	15	72	<0.5
M-5P	0.2	0.1	0.0	0.3	7.2	11	81	22	4.1
M-6P	0.3	0.2	0.0	0.2	11	13	75	23	5.3
M-7P	0.9	0.1	0.0	0.2	7.9	15	76	20	8.0
M-8P	0.0	0.0	0.0	0.3	6.4	10	83	16	5.2
M-8PD	0.0	0.1	0.0	0.2	4.5	7.7	87	17	4.5
M-9P	1.3	1.1	0.6	5.9	74	2.2	15	66	<0.5
M-10P	0.5	0.0	-0.0	0.1	3.2	7.5	89	22	1.1
M-11P	0.0	0.1	0.0	0.0	2.9	8.4	89	23	4.3
M-12P	17	2.7	1.2	8.9	53	1.7	15	85	<0.5
M-13P	0.9	0.2	0.1	0.3	7.1	13	79	25	4.2
M-14P	0.9	0.2	0.1	0.2	6.5	12	81	25	2.3
M-15P	2.9	0.1	0.0	0.1	9.7	4.5	83	19	2.5
M-16AP	8.8	1.8	0.3	1.8	67	9.6	11	65	1.4

TABLE 4.1.3 RESULTS OF SEDIMENT METALS ANALYSES FOR MUSKEGON LAKE CORE SAMPLES (MG/KG DRY WEIGHT), OCTOBER 1999.

Sample ID	Total Arsenic mg/kg	Total Barium mg/kg	Total Cadmium mg/kg	Total Chromium mg/kg	Total Copper mg/kg	Total Nickel mg/kg	Total Lead mg/kg	Total Zinc mg/kg	Total Mercury mg/kg	Total Selenium mg/kg
M 1 Top	15	150	12	440	85	27	150	360	0.65	0.24
M 1 Middle	7.8	94	3.4	160	31	15	62	140	0.29	<0.10
M 1 Bottom	10	18	0.11	8.4	2.2	3.1	5.1	23	<0.10	<0.10
M 3 Top	12	130	3.7	130	65	24	120	270	0.39	0.50
M 3 Middle	10	140	11	420	90	29	170	380	0.69	0.55
M 3 3-4	14	150	10	230	87	24	170	300	1.2	0.58
M 3 4-5	2.7	36	0.21	11	6.0	6.4	6.8	27	<0.10	<0.10
M 4 Top	5.4	45	0.88	38	21	8.8	42	82	0.12	0.29
M 4 Bottom	7.9	32	1.4	48	16	6.4	35	71	0.11	<0.10
M 8 Top	7.3	140	11	290	100	33	180	420	0.82	0.45
M 8 2	9.1	130	20	78	150	29	160	290	1.8	0.49
M 8 3	8.7	85	0.76	25	17	17	19	77	0.23	0.30
M 8 4	7.3	38	0.13	7.5	3.5	5.0	2.6	20	<0.10	<0.10
M 9 Top	1.2	10	0.66	8.2	7.0	2.5	7.5	21	<0.10	<0.10
M 9 Bottom	4.4	28	0.35	8.0	4.5	4.1	10	26	<0.10	<0.10
M 10 Top	10	100	5.5	110	68	24	110	240	0.41	<0.10
M 10 Middle	12	65	2.8	27	19	7.3	45	87	0.19	<0.10
M 10 Bottom	5.5	16	0.12	2.8	1.5	1.2	1.9	9.8	<0.10	<0.10
M 11 Top	7.6	110	2.7	63	50	20	68	170	0.26	0.41
M 11 2	10	130	5.3	160	81	38	120	300	0.37	0.45
M 11 3	7.6	150	12	150	100	34	160	270	0.58	0.44
M 11 Bottom	6.7	92	1.6	27	25	17	51	99	0.26	0.31
M 11D Top	6.1	100	2.8	66	50	20	71	170	0.28	0.42
M 11D 2	8.9	130	5.4	170	81	39	130	320	0.40	0.46
M 11D 3	7.3	140	9.5	240	94	36	140	300	0.54	0.43
M 11D Bottom	9.0	130	10	86	82	25	150	220	0.59	0.38

TABLE 4.4.3 (CONTINUED) RESULTS OF SEDIMENT METALS ANALYSES FOR MUSKEGON LAKE CORE SAMPLES (MG/KG DRY WEIGHT), OCTOBER 1999.

Sample ID	Total Arsenic mg/kg	Total Barium mg/kg	Total Cadmium mg/kg	Total Chromium mg/kg	Total Copper mg/kg	Total Nickel mg/kg	Total Lead mg/kg	Total Zinc mg/kg	Total Mercury mg/kg	Total Selenium mg/kg
M 12 Top	0.90	9.5	0.17	4.8	9.4	2.3	12	18	<0.10	<0.10
M 12 Middle	5.1	45	1.5	28	34	8.7	73	120	0.32	<0.10
M 12 Bottom	11	140	8.5	210	130	31	320	450	0.84	0.52
M 13 Top	6.8	99	5.0	140	40	21	77	200	0.30	0.40
M 13 2	5.9	110	7.6	160	49	20	70	200	0.41	0.41
M 13 3	7.5	94	4.0	42	31	16	110	120	0.37	0.36
M 13 Bottom	5.1	59	0.24	18	9.9	12	10	44	<0.10	<0.10
M 14 Top	7.4	88	1.0	34	32	16	42	110	0.14	0.39
M 14 2	5.8	66	2.4	69	26	15	70	140	0.19	0.31
M 14 3	5.5	58	1.1	18	17	11	100	62	0.15	0.28
M 14 Bottom	6.7	87	0.42	24	16	19	16	71	<0.10	0.33
M 15 Top	8.3	140	10	190	72	26	160	300	0.60	0.82
M 15 Middle	5.8	120	1.4	33	24	20	48	110	0.26	0.47
M 15 Bottom	5.0	12	<0.10	3.8	<0.10	1.8	1.5	14	<0.10	<0.10
M 16A Top	8.4	90	7.4	47	58	16	140	180	0.72	0.46
M 16A Bottom	1.8	13	0.15	4.0	1.5	2.1	4.6	12	<0.10	<0.10

TABLE 4.1.4 RESULTS OF SEDIMENT METALS ANALYSES FOR MUSKEGON LAKE PONAR SAMPLES (MG/KG DRY WEIGHT), OCTOBER 1999.

Sample ID	Total Arsenic mg/kg	Total Barium mg/kg	Total Cadmium mg/kg	Total Chromium mg/kg	Total Copper mg/kg	Total Nickel mg/kg	Total Lead mg/kg	Total Zinc mg/kg	Total Mercury mg/kg	Total Selenium mg/kg
M 1P	10	130	3.9	250	63	24	120	260	0.38	0.72
M 3P	6.1	130	2.0	71	52	19	83	190	0.20	0.44
M 4P	5.2	14	0.13	4.8	4.0	2.0	5.8	13	<0.10	<0.10
M 5P	11	180	12	210	260	38	270	600	1.7	0.49
M 6P	9.5	180	7.9	160	260	38	280	640	1.7	0.53
M 7P	11	120	4.2	120	100	29	140	290	0.56	0.48
M 8P	8.2	120	4.2	95	78	24	120	240	0.50	0.54
M 8PD	5.1	140	4.6	120	89	27	130	270	0.55	0.83
M 9P	5.6	20	0.38	9.6	6.8	3.4	12	30	<0.10	<0.10
M 10P	6.2	110	2.9	77	58	22	89	200	0.34	0.58
M 11P	6.8	110	2.3	61	49	20	67	160	0.26	0.59
M 12P	5.2	10	0.1	2.8	3.4	2.6	6.2	14	<0.10	<0.10
M 13P	10	97	3.1	80	39	19	63	160	0.25	0.38
M 14P	5.2	88	1.1	30	33	14	31	100	0.14	0.38
M 15P	5.8	120	2.5	68	46	19	64	160	0.26	0.42
M 16AP	3.7	33	1.3	20	16	6.8	31	67	0.14	<0.10

TABLE 4.1.5 RESULTS OF SEDIMENT PAH ANALYSES FOR MUSKEGON LAKE CORE AND PONAR SAMPLES (MG/KG DRY WEIGHT), OCTOBER 1999.

Sample ID	Naphthalene	2-Methyl-naphthalene	Acenaph-thylene	Acenaph-thene	Dibenzofuran	Fluorene	Phenanthrene	Anthracene	Carbazole	Fluor-anthene
M 1 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 1 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 1 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 3 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 3 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 3 3-4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 3 4-5	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 4 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 4 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8 4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 9 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 9 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 10 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 10 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0.34
M 10 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11D Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11D 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0.66
M11D 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11D Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 12 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 12 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 12 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 13 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 13 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 13 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 13 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 14 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 14 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 14 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 14 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 15 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 15 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 15 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 16A Top	320	450	39	390	40	220	640	200	4.7	250
M 16A Bot	1.5	3.3	0.60	5.7	0.53	3.1	8.6	2.9	< 0.33	3.8
M 1P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 3P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 4P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 5P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0.82
M 6P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	1.3
M 71P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 8PD	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 9P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 10P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 11P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 12P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 13P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 14P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 15P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33
M 16AP	0.87	< 0.33	3.8	8.8	0.74	6.7	30	11	< 0.33	16

TABLE 4.1.5 (CONTINUED) RESULTS OF SEDIMENT PAH ANALYSES FOR MUSKEGON LAKE CORE AND PONAR SAMPLES (MG/KG DRY WEIGHT), OCTOBER 1999.

Sample ID	Pyrene	Benzo(a) anthracene	Chrysene	Benzo(b) fluoranthene	Benzo(k) fluoranthe	Benzo(a) pyrene	Indeno(1,2,3-cd) pyrene	Dibenzo(a,h) anthracene	Benzo(g,h,i) perylene	Total PAH
M 1 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 1 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 1 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 3 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 3 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 3 3-4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 3 4-5	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 4 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 4 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8 4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 9 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 9 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 10 Top	1.9	1.7	1.8	< 0.33	< 0.33	2.2	< 0.33	< 0.33	< 0.33	8
M 10 Mid	0.47	< 0.33	0.36	< 0.33	< 0.33	0.45	< 0.33	< 0.33	< 0.33	2
M 10 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11D Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11D 2	0.76	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	1
M11D 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11D Bot	1.4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	1
M 12 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 12 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 12 Bot	1.4	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	1
M 13 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 13 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 13 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 13 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 14 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 14 2	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 14 3	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 14 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 15 Top	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 15 Mid	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 15 Bot	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 16A Top	290	110	100	88	53	97	13	4.4	10	3319
M 16A Bot	4.6	1.7	1.6	1.4	< 0.33	1.4	0.43	< 0.33	0.42	42
M 1P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 3P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 4P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 5P	0.83	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	2
M 6P	1.1	< 0.33	0.81	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	3
M 71P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 8PD	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 9P	0.34	< 0.33	0.33	< 0.33	< 0.33	0.36	< 0.33	< 0.33	< 0.33	1
M 10P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 11P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 12P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 13P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 14P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 15P	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	< 0.33	0
M 16AP	20	9.6	9.1	5.2	7.0	9.6	2.2	0.72	1.8	143

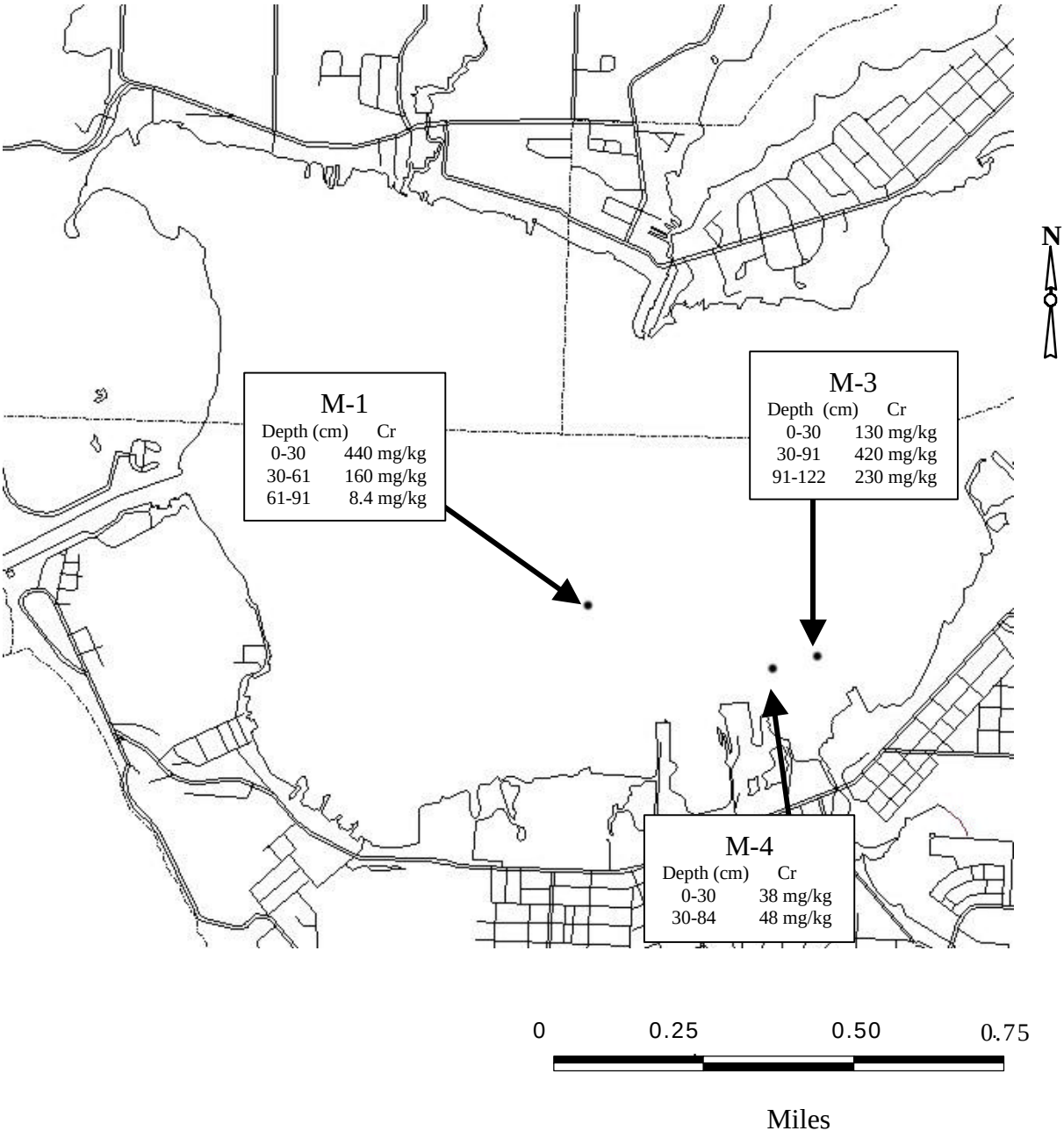


FIGURE 4.1.1 CHROMIUM IN CORE SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999.

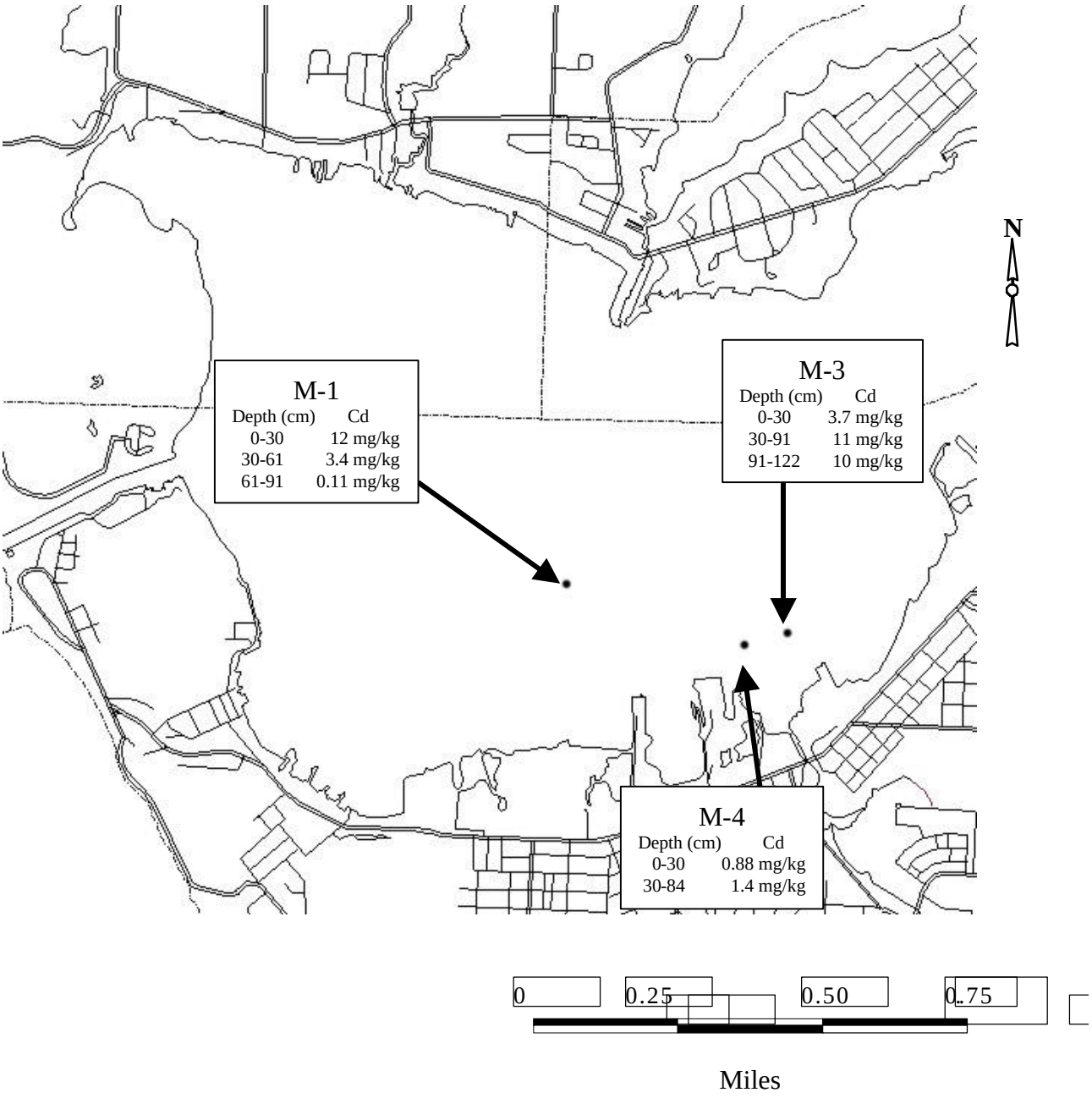


FIGURE 4.1.2 CADMIUM IN CORE SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999.

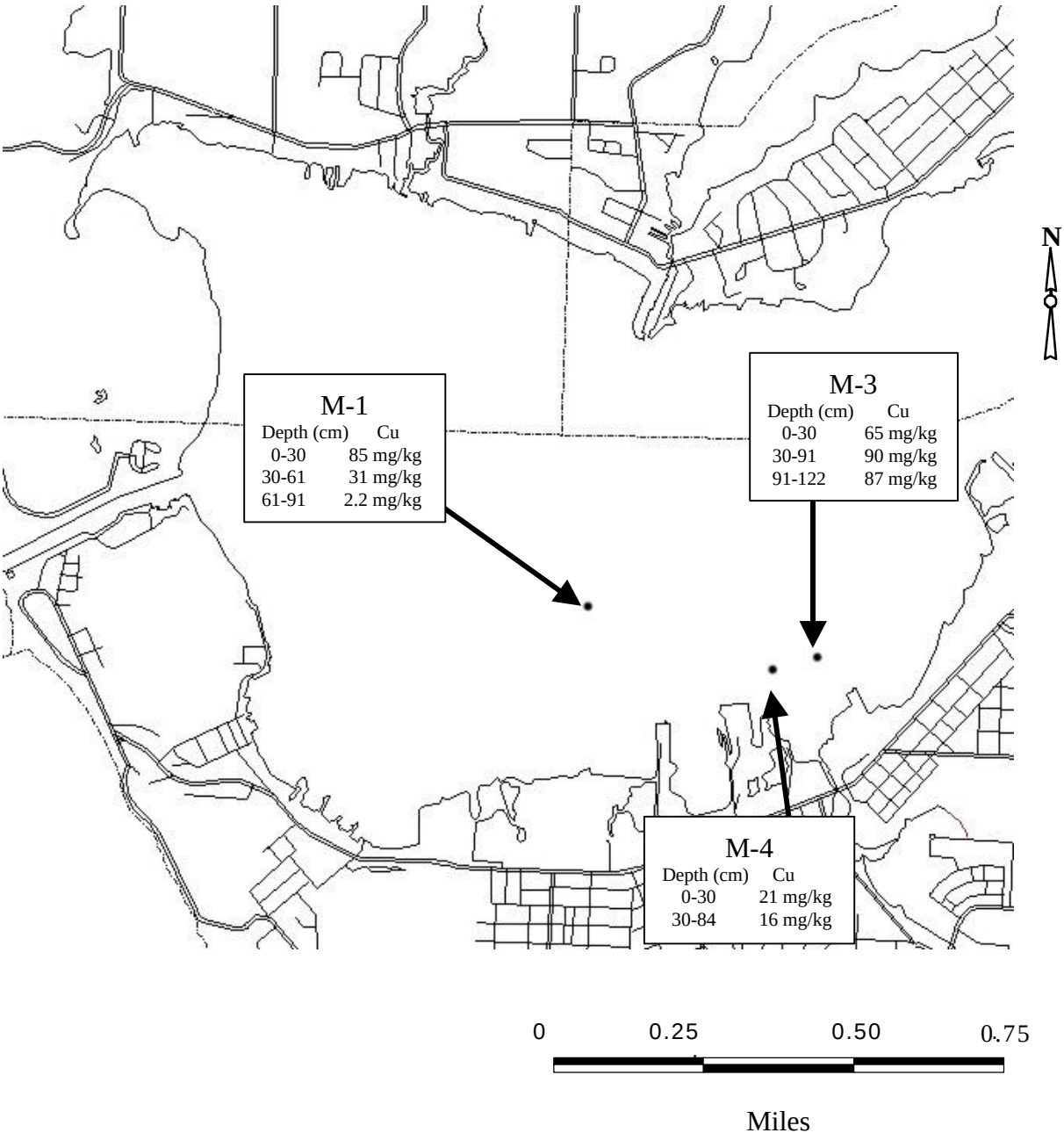


FIGURE 4.1.3 COPPER IN CORE SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999.

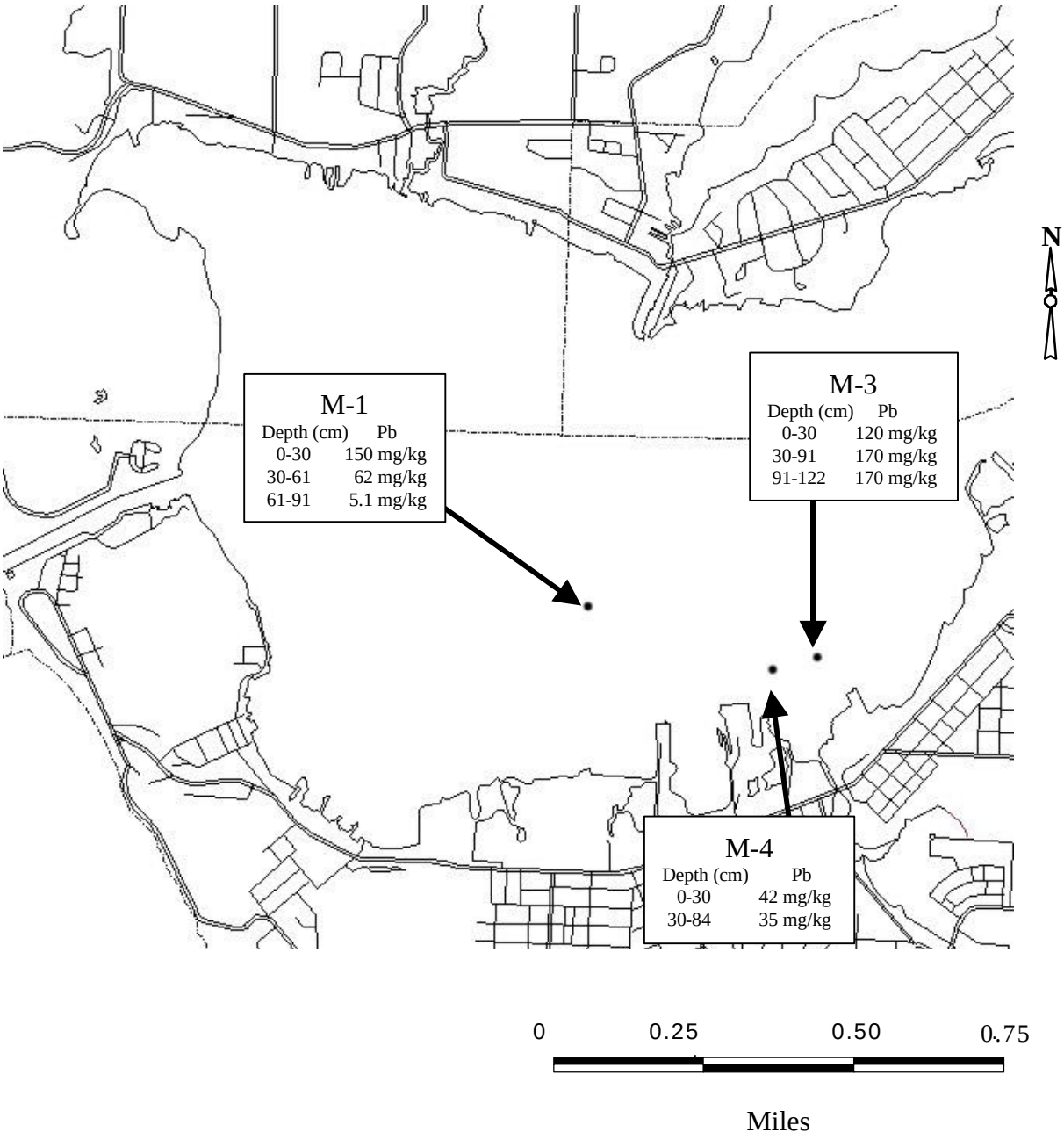


FIGURE 4.1.4 LEAD IN CORE SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999.

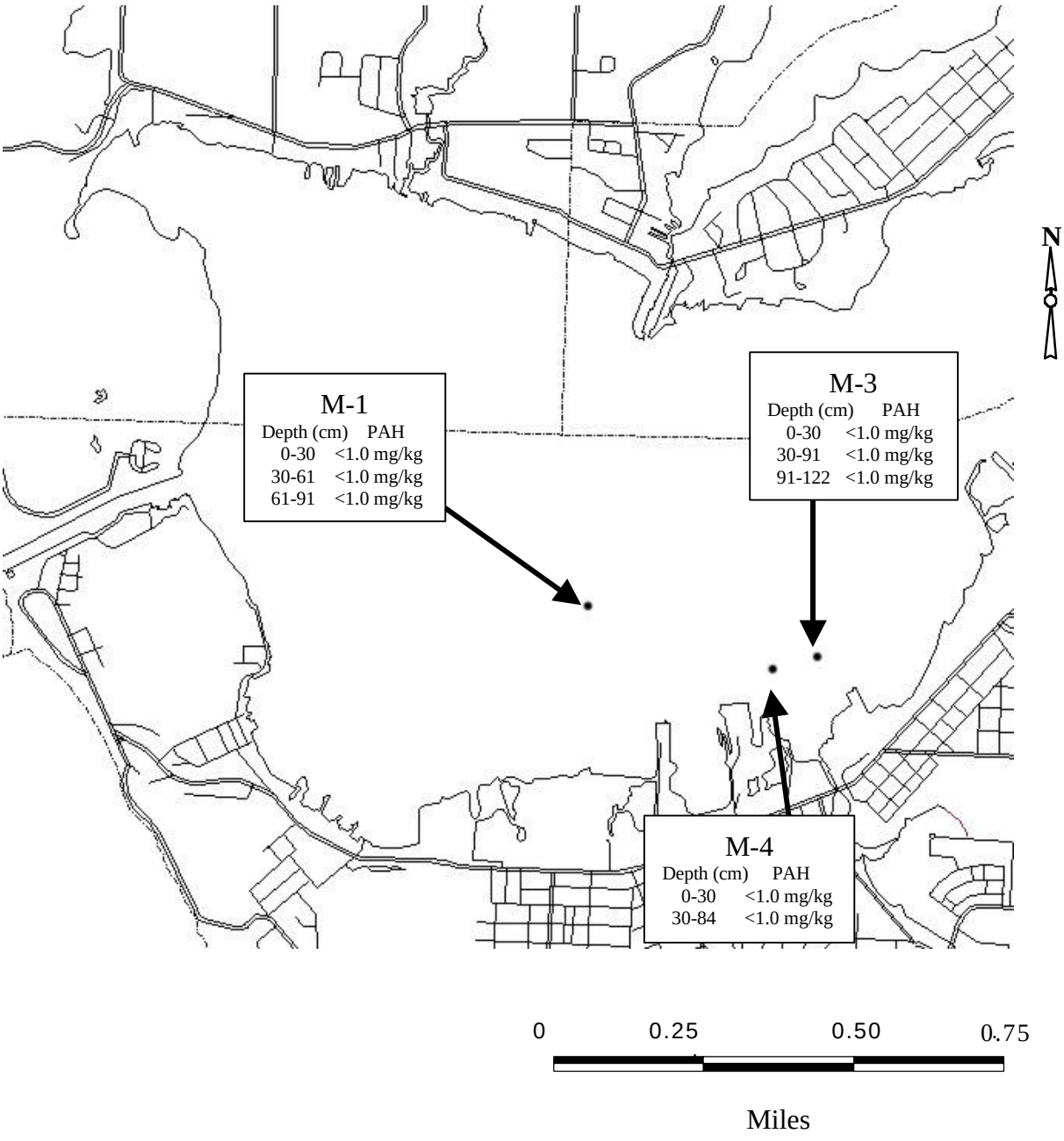


FIGURE 4.1.5 TOTAL PAH COMPOUNDS IN CORE SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999.

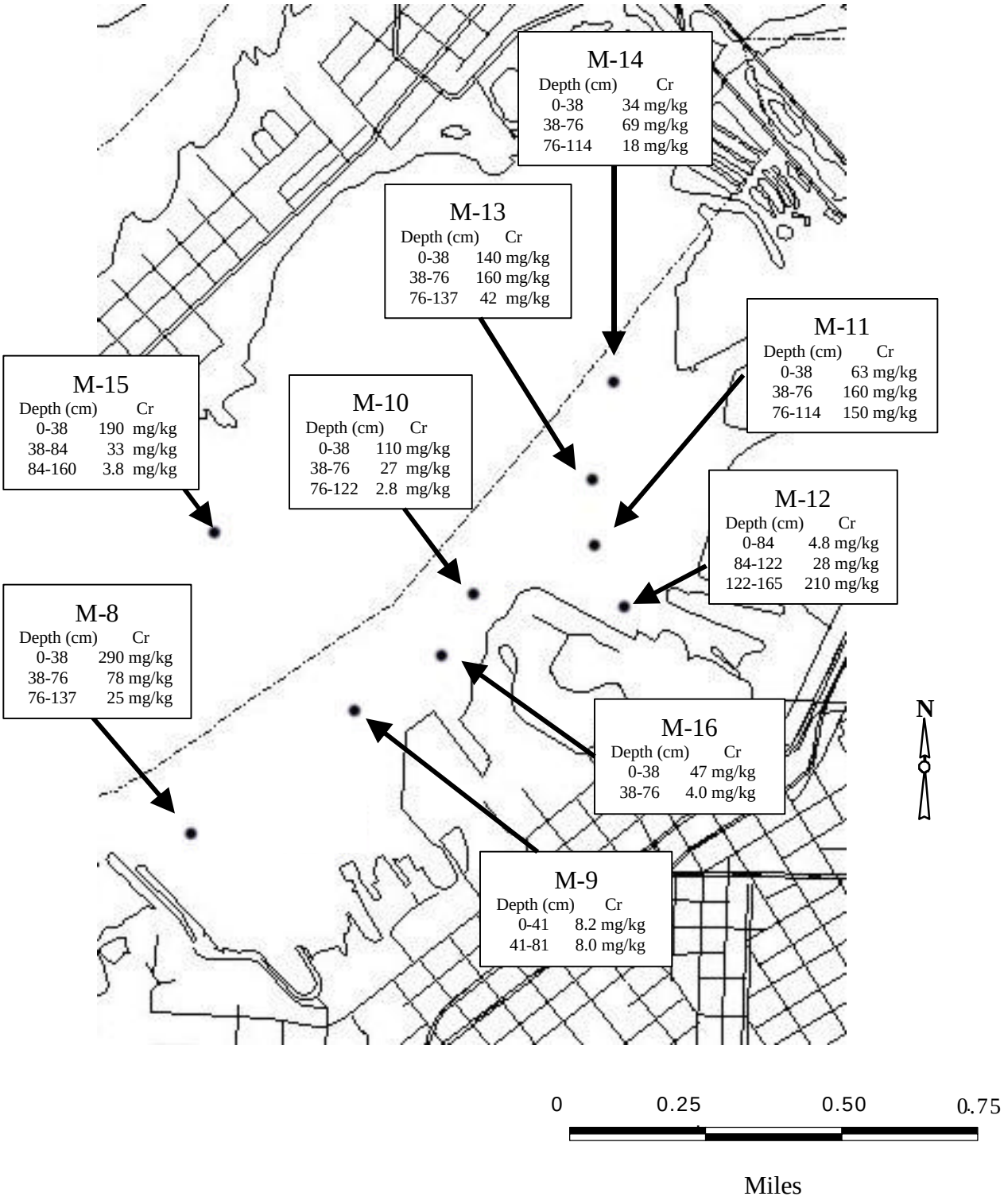


FIGURE 4.1.6 CHROMIUM IN CORE SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999.

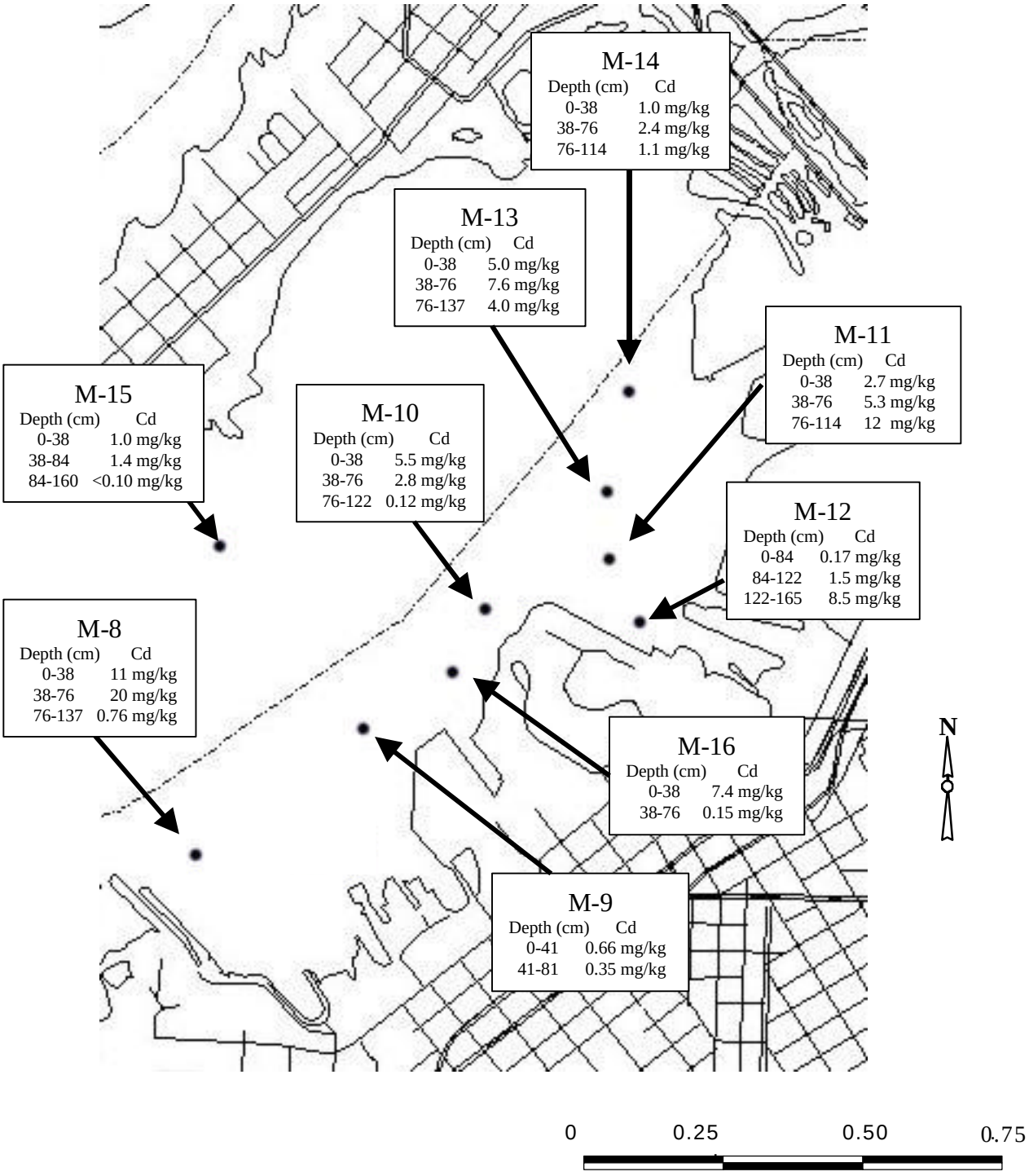


FIGURE 4.1.7 CADMIUM IN CORE SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999.

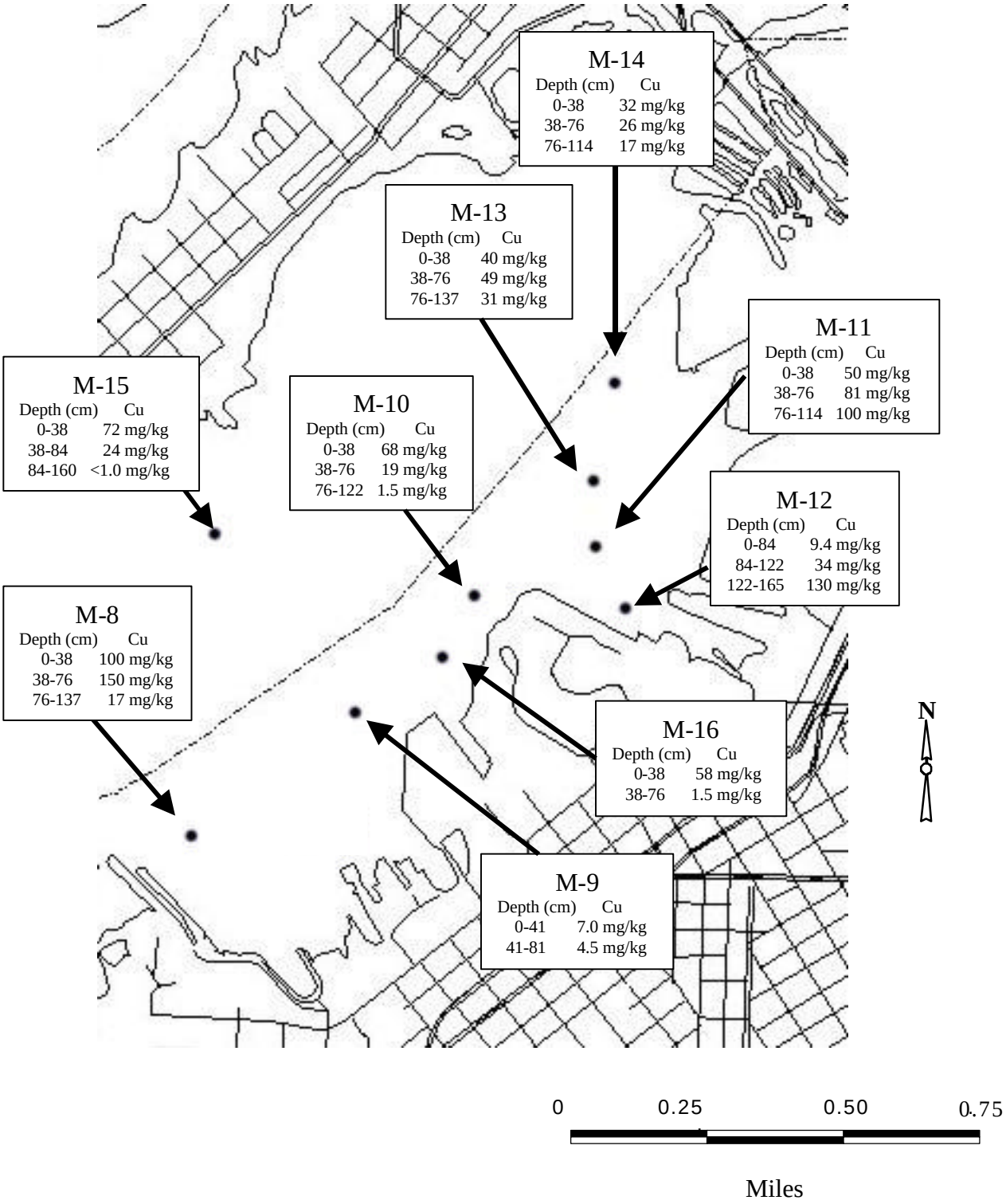


FIGURE 4.1.8 COPPER IN CORE SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999.

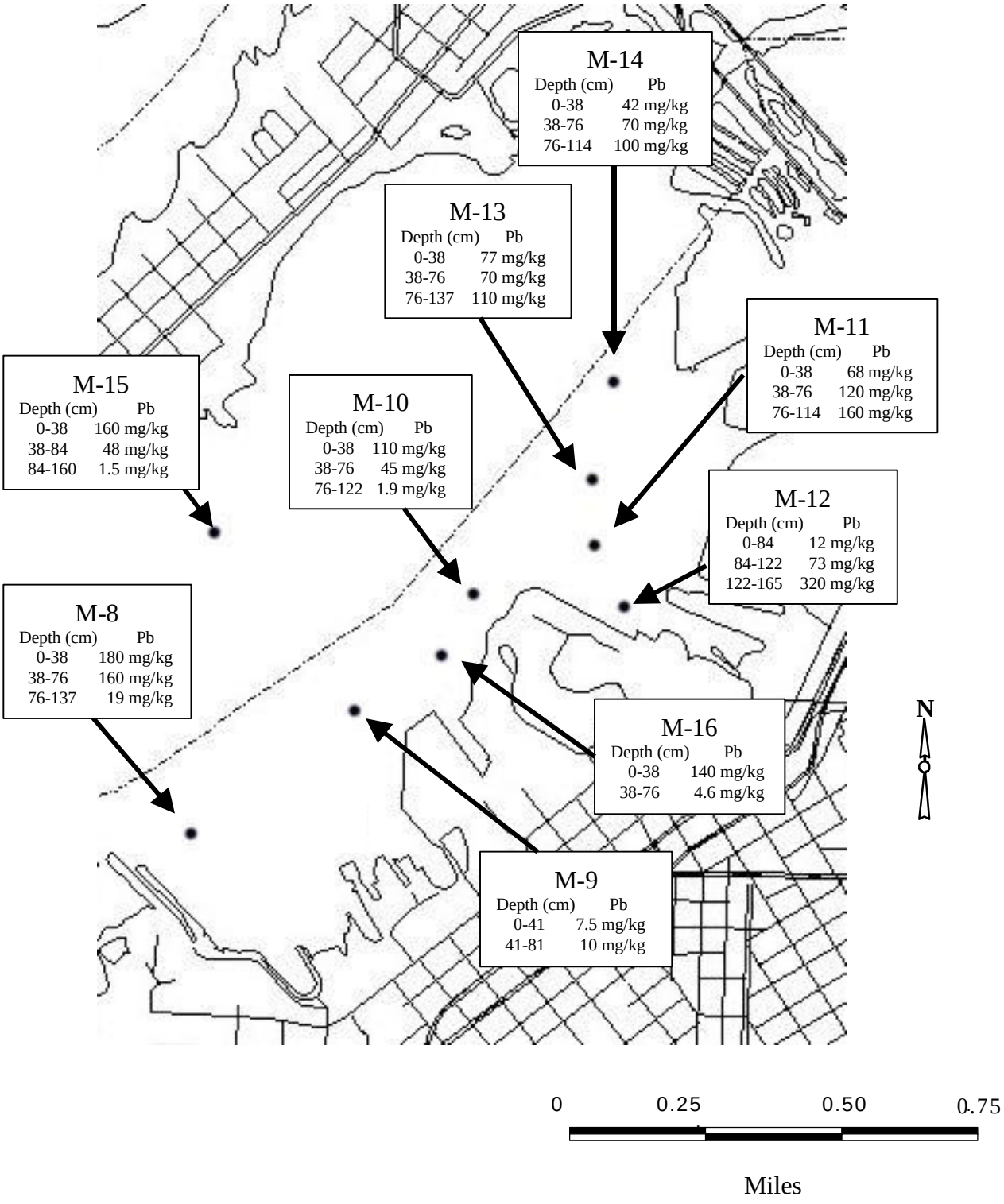


FIGURE 4.1.9 LEAD IN CORE SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999.

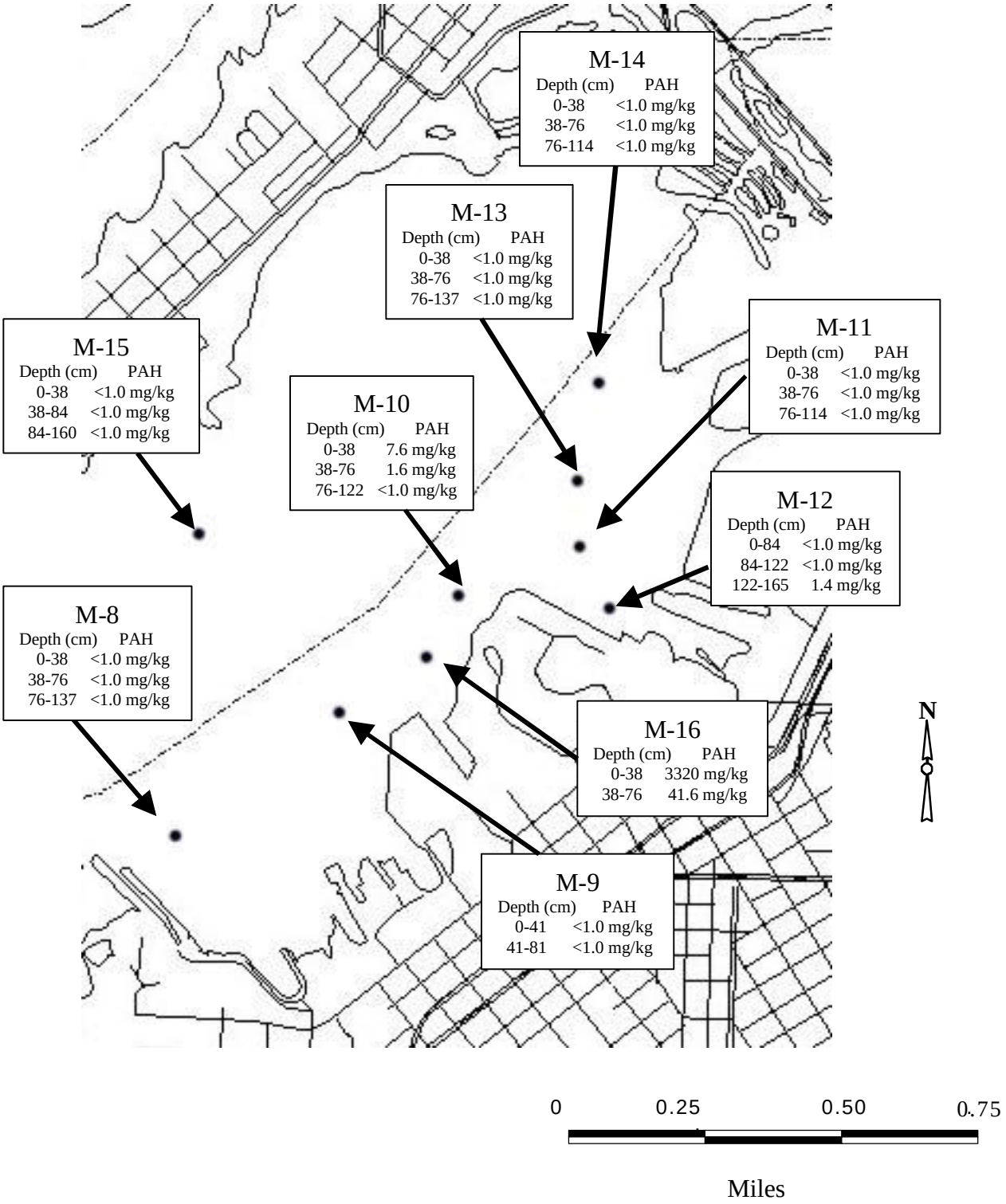


FIGURE 4.1.10 TOTAL PAH COMPOUNDS IN CORE SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999.

the remaining cores. Cores collected between the inlet of Ryerson Creek and the south branch of the Muskegon River had higher levels of metals in the deeper strata. This area was subject to the recent influx of sand from the Muskegon River (Rediske 2000) and from erosion along Ryerson Creek. Sources at these locations include the abandoned Teledyne Foundry, a historic landfill, and a metal scrap yard. A second type of deposition pattern was observed in the cores collected at M-8, M-10, and M-15. At these locations, the highest concentrations of chromium and lead were observed in the top 40 cm. Higher levels of cadmium and copper were noted in the 40-80 cm section. Since most of the industrial activity occurred prior to the 1970s, sediment resuspension and advection are major influences in the eastern section of the lake.

The third pattern of deposition was related to the distribution of PAH compounds. A concentrated and localized source of PAH compounds was found at M-16 (Fig 4.1.10). Total PAH compounds in excess of 3,000 mg/kg were found in the top 30 cm of the sediment core. Concentrations were reduced to 41.6 mg/kg in the second 30 cm section. The migration of these compounds was not noted in the down stream cores (M-15 and M-8). The presence of significant levels of PAH compounds in a near surface zone is suggestive of a groundwater source entering the lake or a deposit of contaminated materials from historic dredging/filling operations. A Manufactured Gas facility, coal yards, commercial shipping docks, and a foundry all operated in this area for over 80 years and may be the logical source of this material. Lower concentrations of PAH compounds also were detected in the top and middle 30 cm sections at M-10 and bottom 120-160 cm section at M-12. These locations are near the historic Lakey/Teledyne foundry complex and may also be the result of groundwater influx. In consideration of the high levels found at M-16, an additional investigation of sediment contamination is recommended in this area.

The results of all the core sections for cadmium, chromium, lead, copper, and PAH compounds are shown in Figures 4.1.11, 4.1.12, 4.1.13, 4.1.14, and 4.1.15, respectively. Cadmium in excess of 5 mg/kg was found in the top sections of cores collected at M-1, M-8, M-10, and M-16 (Fig 4.1.11). The highest cadmium concentration was found at M-1, which was located in the depositional area down stream from Ruddiman Creek. A similar level of 11 mg/kg was also found near the Division Street Outfall at M-8. Although surface contamination with cadmium was not noted at M-12, this location had the highest concentration of all stations in the bottom core section (8 mg/kg). Chromium (Fig 4.1.12) followed a similar distribution with the highest concentrations being detected at M-1 and M-8 (440 mg/kg and 290 mg/kg, respectively). Significant enrichment of chromium was noted only in the bottom core section at M-12 (210 mg/kg).

Copper and lead (Figs 4.1.13 and 4.1.14) followed a different distribution pattern as the highest concentration of both elements was observed in the bottom core section at M-12 (130 mg/kg and 320 mg/kg, respectively). Station M-8 contained the highest concentration of both metals (100 mg/kg and 180 mg/kg) followed by M-1 (85 mg/kg and 150 mg/kg). Contamination with PAH (Fig 4.1.15) compounds was limited to only 4 locations with the highest concentrations found at M-16. While diffuse sources such as stormwater runoff and

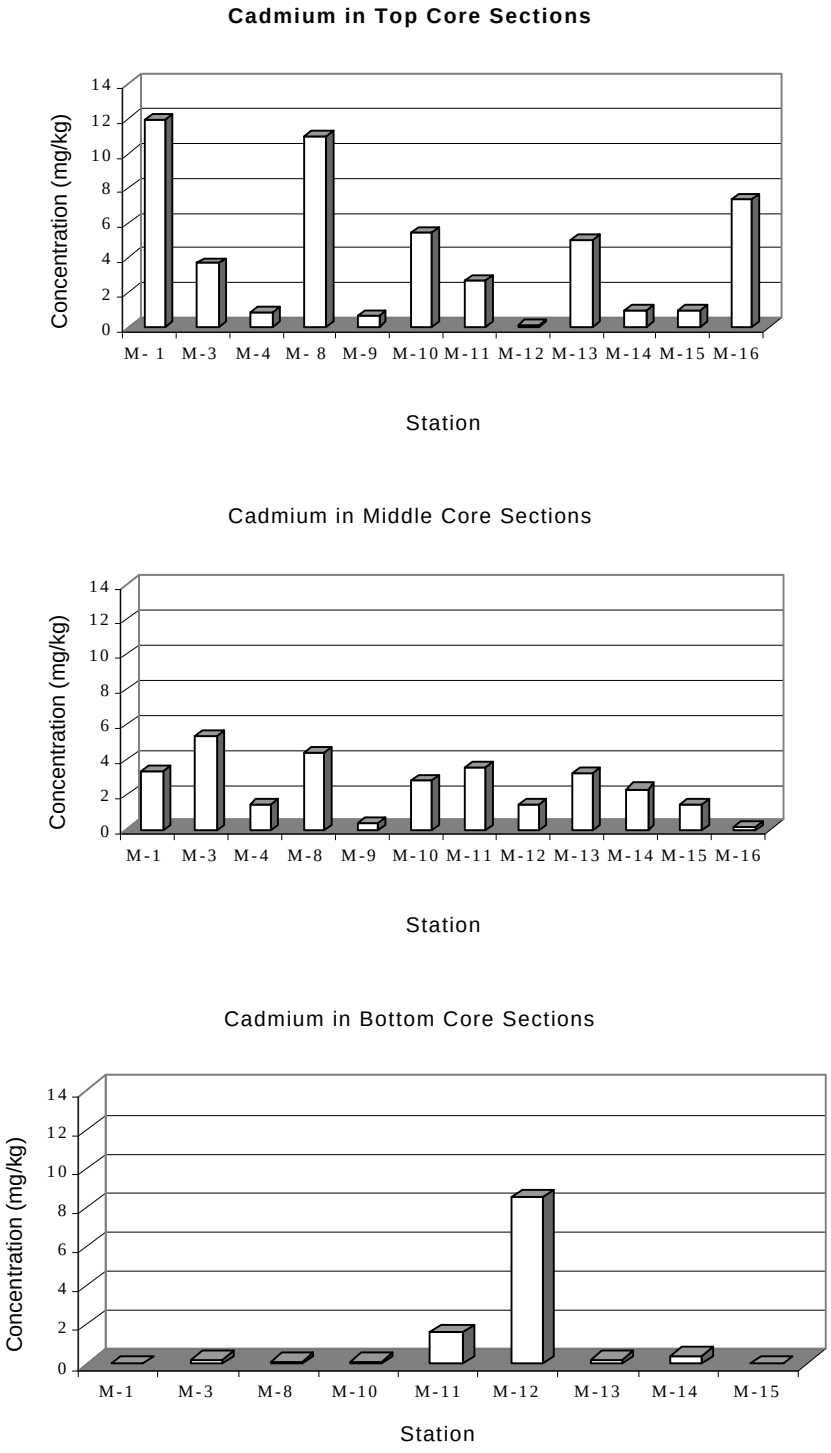


FIGURE 4.1.11 TOTAL CADMIUM IN CORE SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. (AVERAGE DEPTHS: TOP SECTION 0-38 CM, MIDDLE SECTION 38-76 CM, BOTTOM SECTION > 76 CM. DEPTHS GIVEN IN TABLE 4.1.2.)

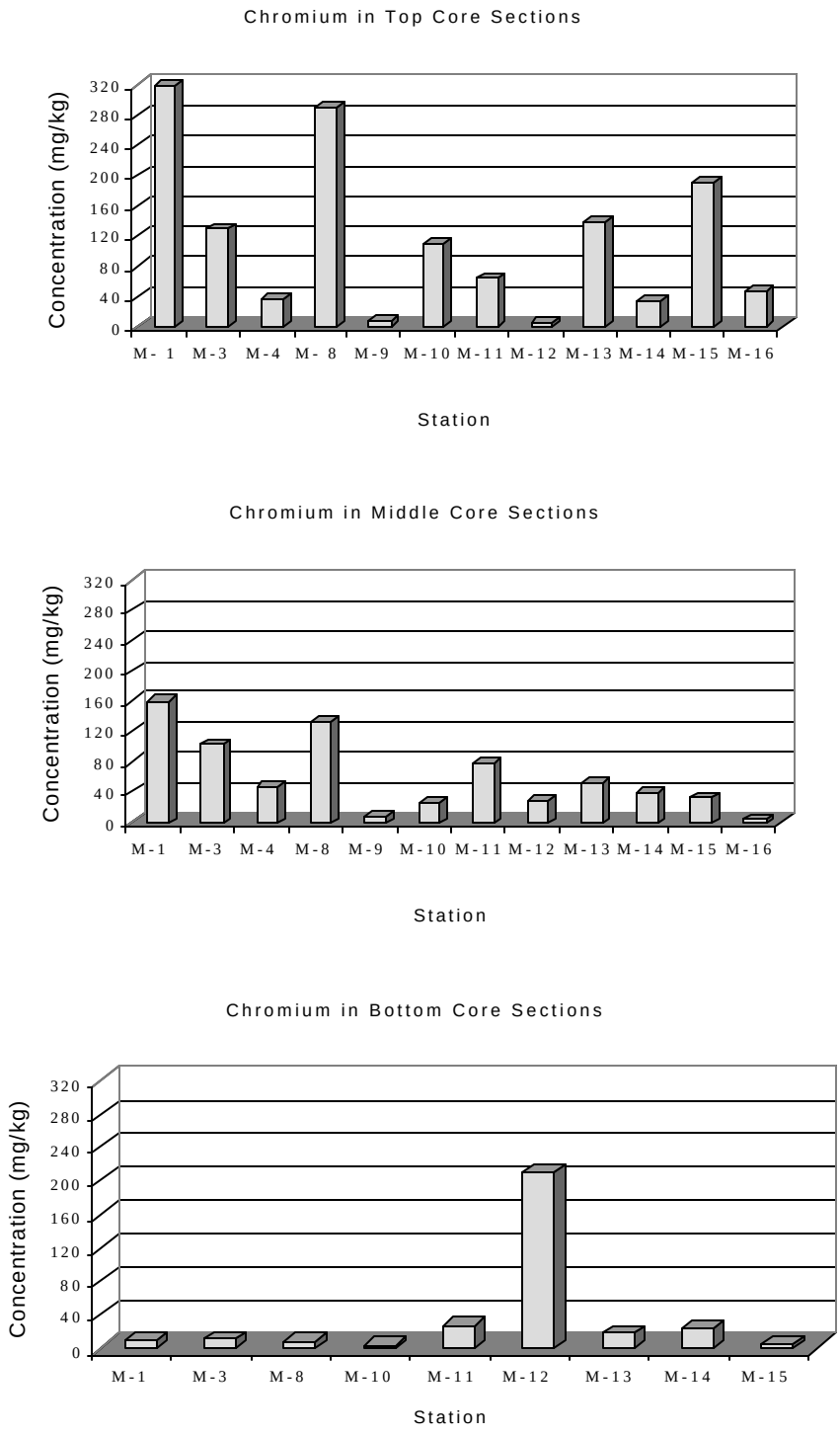
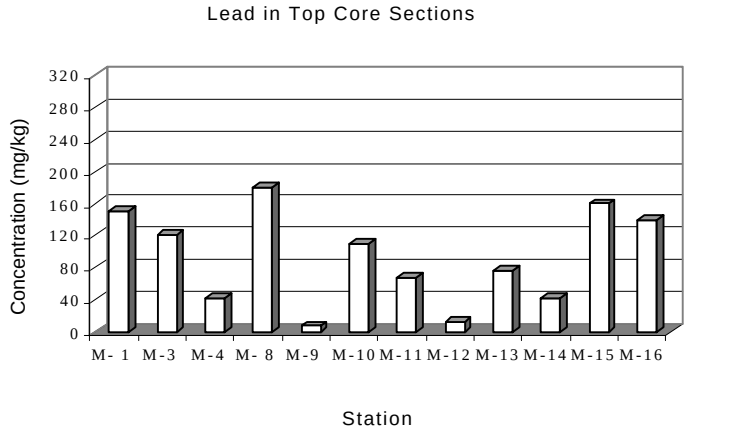
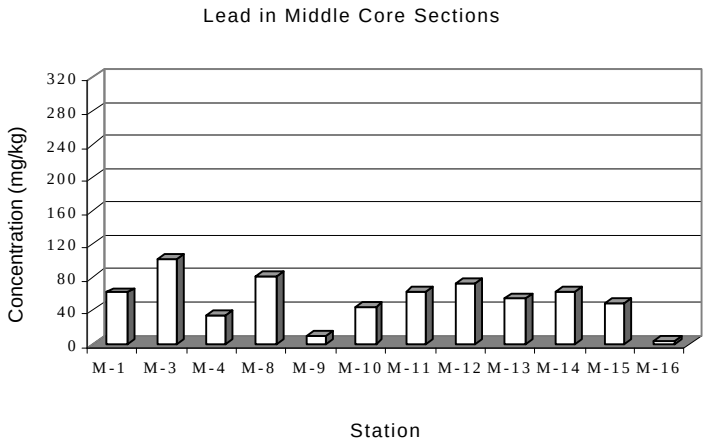


FIGURE 4.1.12 TOTAL CHROMIUM IN CORE SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. (AVERAGE DEPTHS: TOP SECTION 0-38 CM, MIDDLE SECTION 38-76 CM, BOTTOM SECTION > 76 CM. DEPTHS GIVEN IN TABLE 4.1.2.)





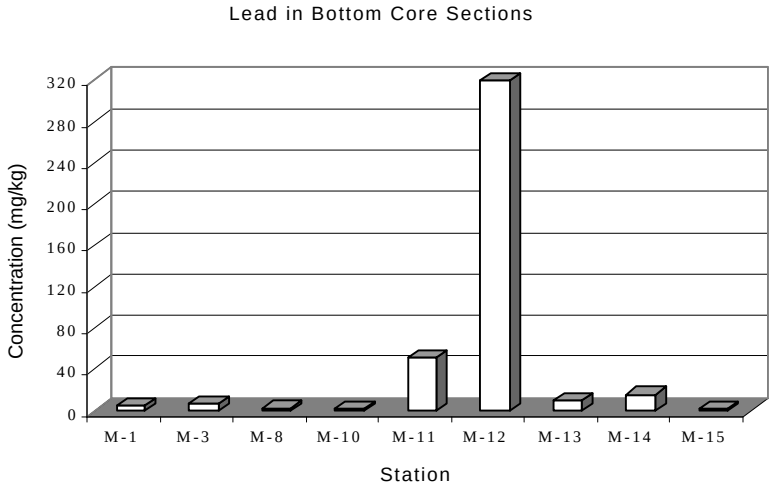


FIGURE 4.1.13 TOTAL LEAD IN CORE SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. (AVERAGE DEPTHS: TOP SECTION 0-38 CM, MIDDLE SECTION 38-76 CM, BOTTOM SECTION > 76 CM. DEPTHS GIVEN IN TABLE 4.1.2.)

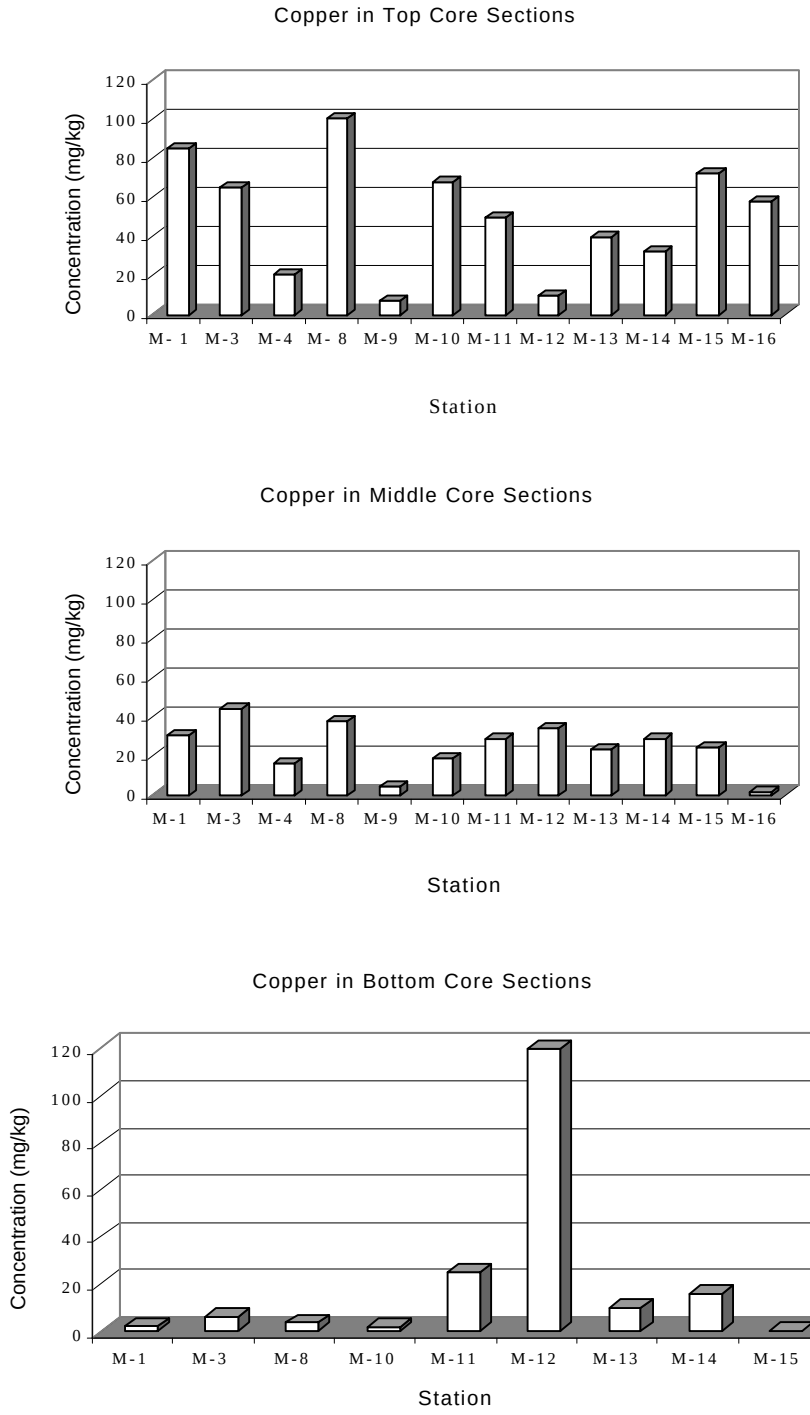


FIGURE 4.1.14 TOTAL COPPER IN CORE SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. (AVERAGE DEPTHS: TOP SECTION 0-38 CM, MIDDLE SECTION 38-76 CM, BOTTOM SECTION > 76 CM. DEPTHS GIVEN IN TABLE 4.1.2.)

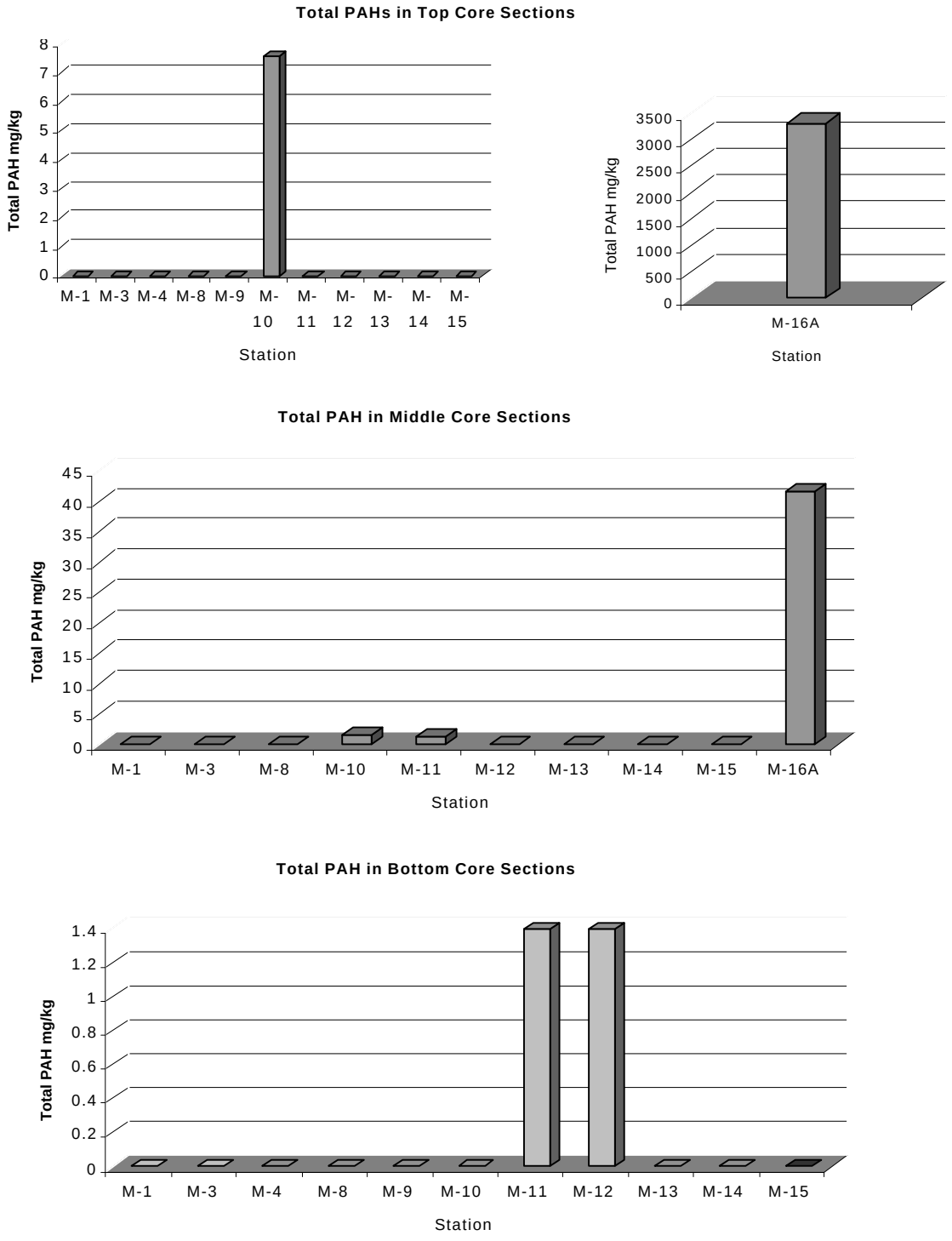


FIGURE 4.1.15 TOTAL PAH COMPOUNDS IN CORE SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. (AVERAGE DEPTHS: TOP SECTION 0-38 CM, MIDDLE SECTION 38-76 CM, BOTTOM SECTION > 76 CM. DEPTHS GIVEN IN TABLE 4.1.2.)

releases from shipping can account for the presence of PAH compounds in sediment, the result of this type of activity would reflect a more broad distribution of contamination. When high levels of contaminants are located adjacent to known sources of anthropogenic activity, the sediment contamination may be linked to the venting of contaminated groundwater, erosion of contaminated soils, and/or dredging/filling operations.

The spatial distribution of contaminants in the PONAR samples is given in Figures 4.1.16-4.1.19. Since the PONAR collects samples from the biologically active zone of 0-20 cm, the results can be compared to sediment quality guidelines to evaluate ecological effects. For this purpose, levels exceeding the Probable Effect Concentrations (PECs) (MacDonald et al. 2000) are listed in bold print. PECs are consensus based guidelines that indicate a >75% probability that adverse ecological effects may be observed when the concentrations are exceeded. PEC concentrations and the stations where exceedences are observed are itemized

TABLE 4.1.6 SUMMARY OF PONAR SAMPLING LOCATIONS IN MUSKEGON LAKE THAT EXCEED CONSENSUS BASED PEC GUIDELINES (MACDONALD ET AL. 2000).

Contaminant	**Consensus-Based PEC mg/kg**	**Location in Muskegon that Exceed the PEC**
Arsenic	33.0	None
Cadmium	4.98	M-5 and M-6
Chromium	111	M-1, M-5 M-6, M-7, and M-8
Copper	149	M-5 and M-6
Lead	128	M-5 M-6, and M-7
Mercury	1.06	M-5 and M-6
Nickel	48.6	None
Zinc	459	M-5 and M-6
Total PAH Compounds	22.9	M-16

in Table 4.1.6. In the western part of Muskegon Lake (Figs 4.1.16 and 4.1.17), only chromium at M-1 (250 mg/kg) exceeds the PEC of 111 mg/kg. In contrast, a number of locations exceeded PEC guidelines in the eastern section of the lake (4.1.18 and 4.1.19). Stations M-5 and M-6 had concentrations of chromium, mercury, cadmium, lead, copper, and zinc that exceeded PEC guidelines. Lead and chromium at M-7 also exceeded the PECs. The only station with total PAH compounds above the PEC guideline was M-16.

Figures 4.1.20-4.1.22 provide a relative comparison of metals and PAH compounds in the PONAR samples. The Division Street Outfall area (M-5, M-6, M-7, and M-8) contains the highest concentrations of most elements and exceeds the PEC guidelines with the greatest frequency. The Ruddiman Creek area ranks second with respect to heavy metal contamination; however only exceeds the PEC guideline for chromium. Levels of heavy metals in the foundry area were similar in concentration to the remaining stations and did not

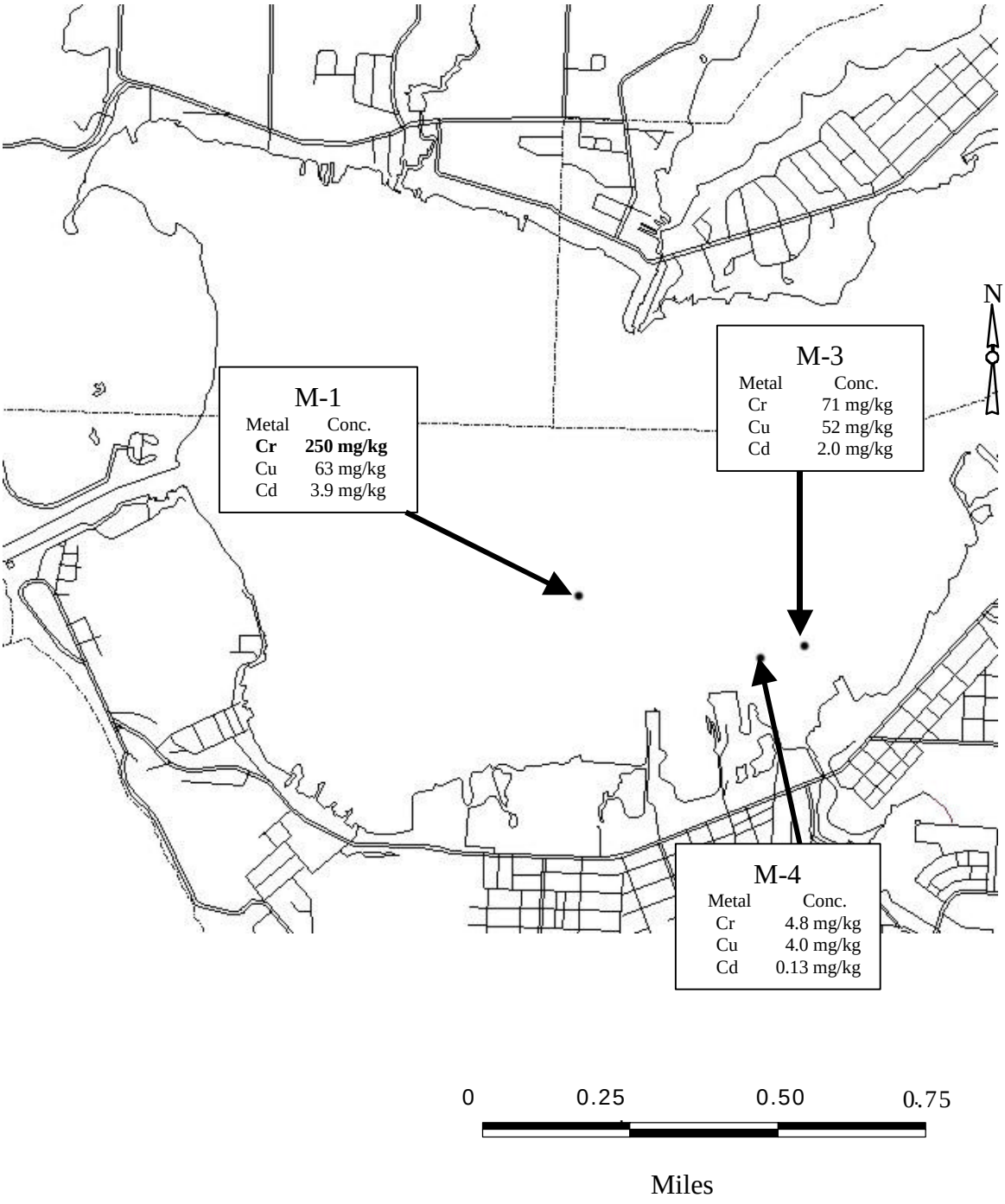


FIGURE 4.1.16 CHROMIUM, COPPER, AND CADMIUM IN PONAR SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999. BOLD VALUES EXCEED PROBABLE EFFECT CONCENTRATIONS (PECS).

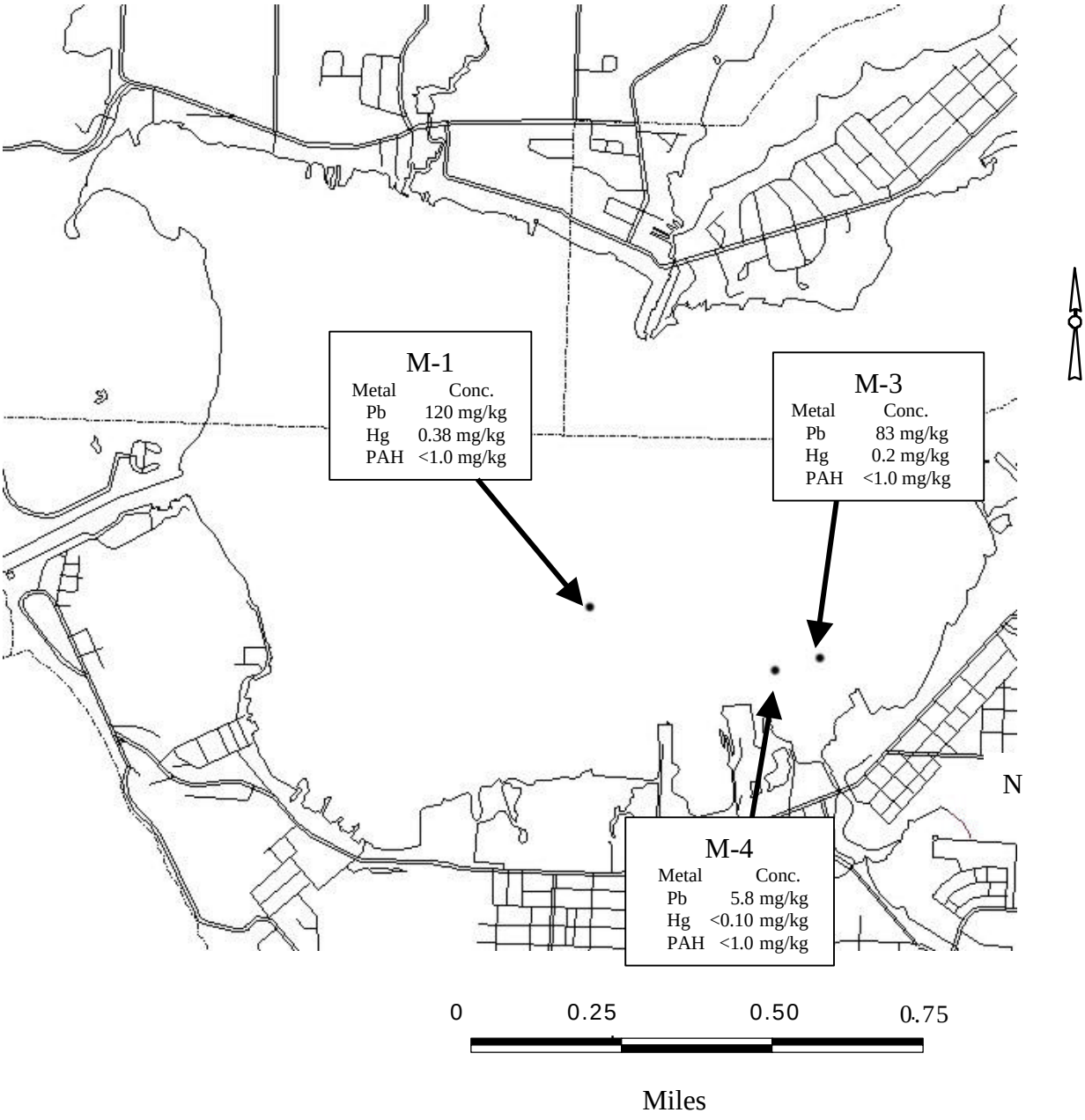


FIGURE 4.1.17 LEAD, MERCURY, AND TOTAL PAH COMPOUNDS IN PONAR SAMPLES COLLECTED FROM EASTERN MUSKEGON LAKE, OCTOBER 1999. ALL VALUES BELOW PROBABLE EFFECT CONCENTRATIONS (PECS).

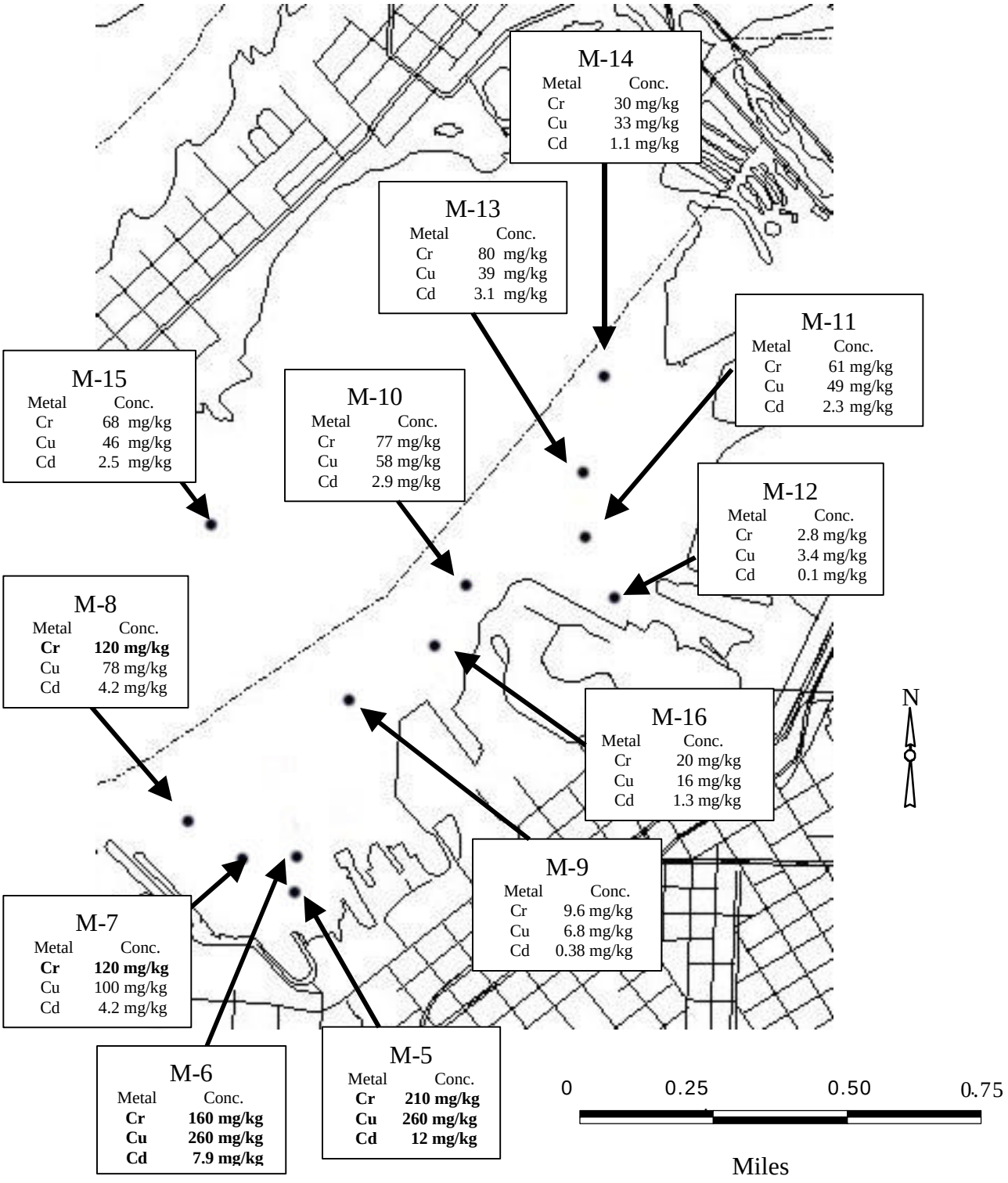


FIGURE 4.1.18 CHROMIUM, COPPER, AND CADMIUM IN PONAR SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999. BOLD VALUES EXCEED PROBABLE EFFECT CONCENTRATIONS (PECS).

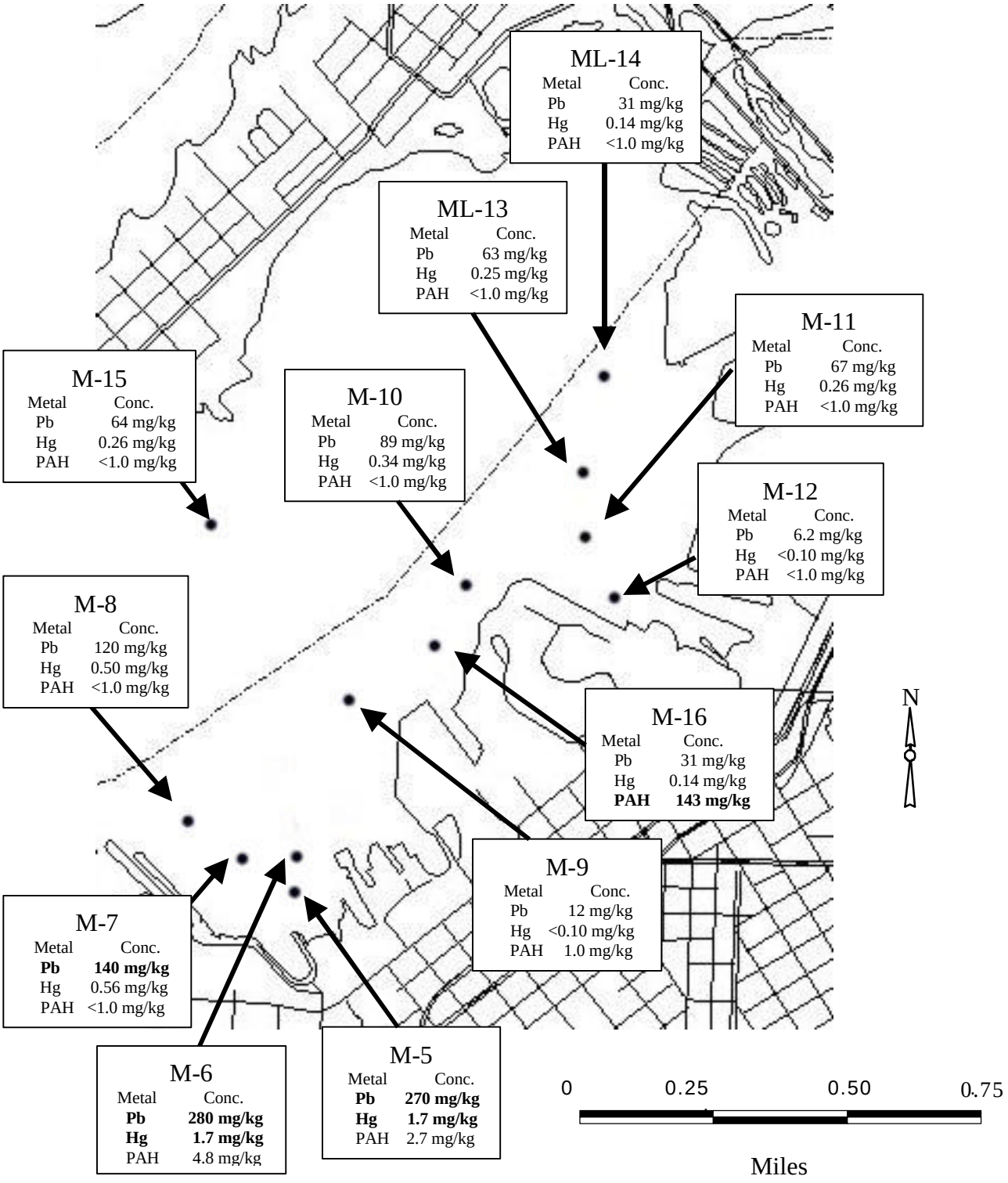


FIGURE 4.1.19 LEAD, MERCURY, AND TOTAL PAH COMPOUNDS IN PONAR SAMPLES COLLECTED FROM WESTERN MUSKEGON LAKE, OCTOBER 1999. BOLD VALUES EXCEED PROBABLE EFFECT CONCENTRATIONS (PECS).

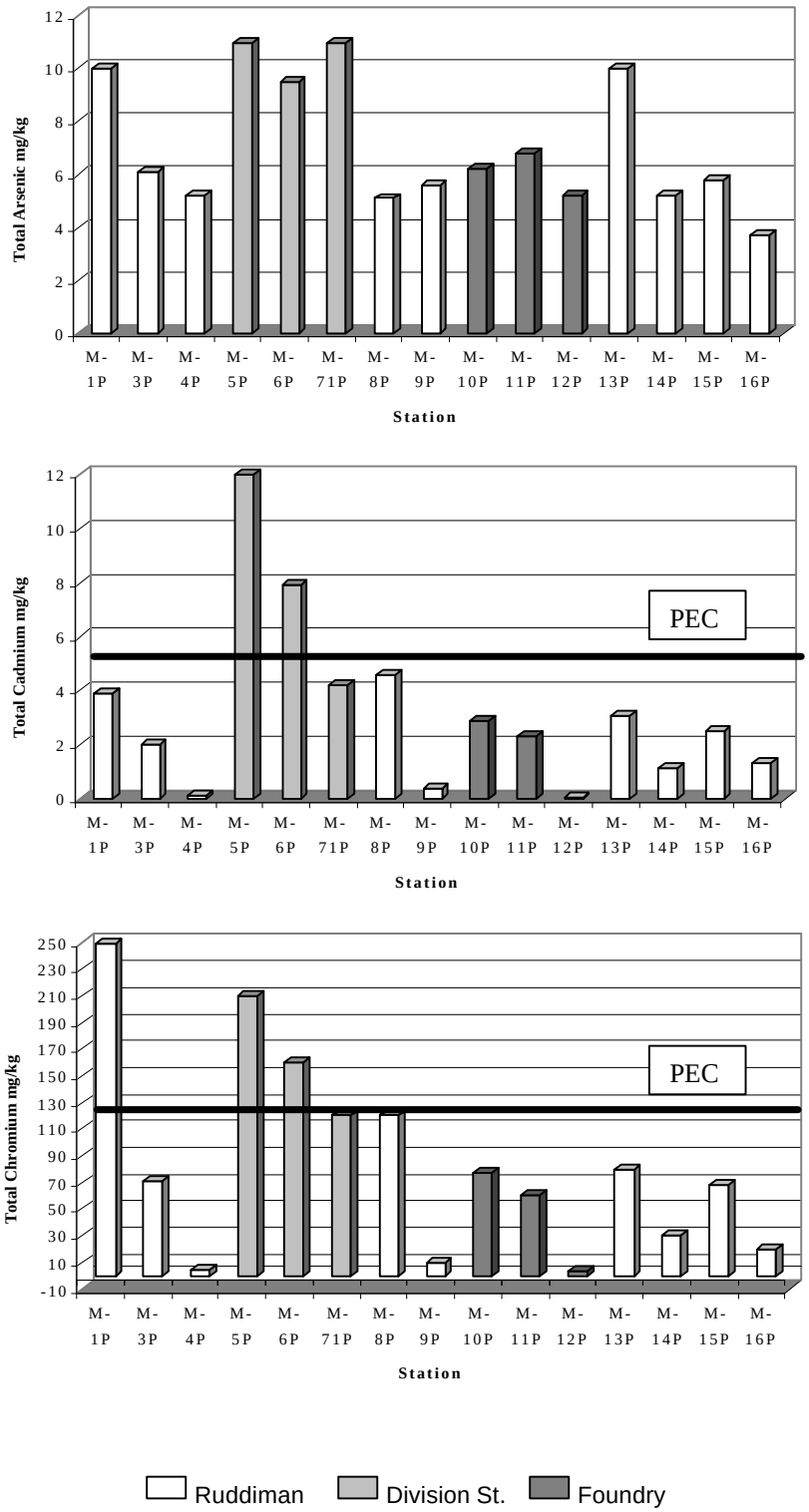


FIGURE 4.1.20 TOTAL ARSENIC, CADMIUM, AND CHROMIUM IN PONAR SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. PATTERNS DENOTE REGIONS OF MUSKEGON LAKE. BOLD LINES IDENTIFY PEC LEVELS.

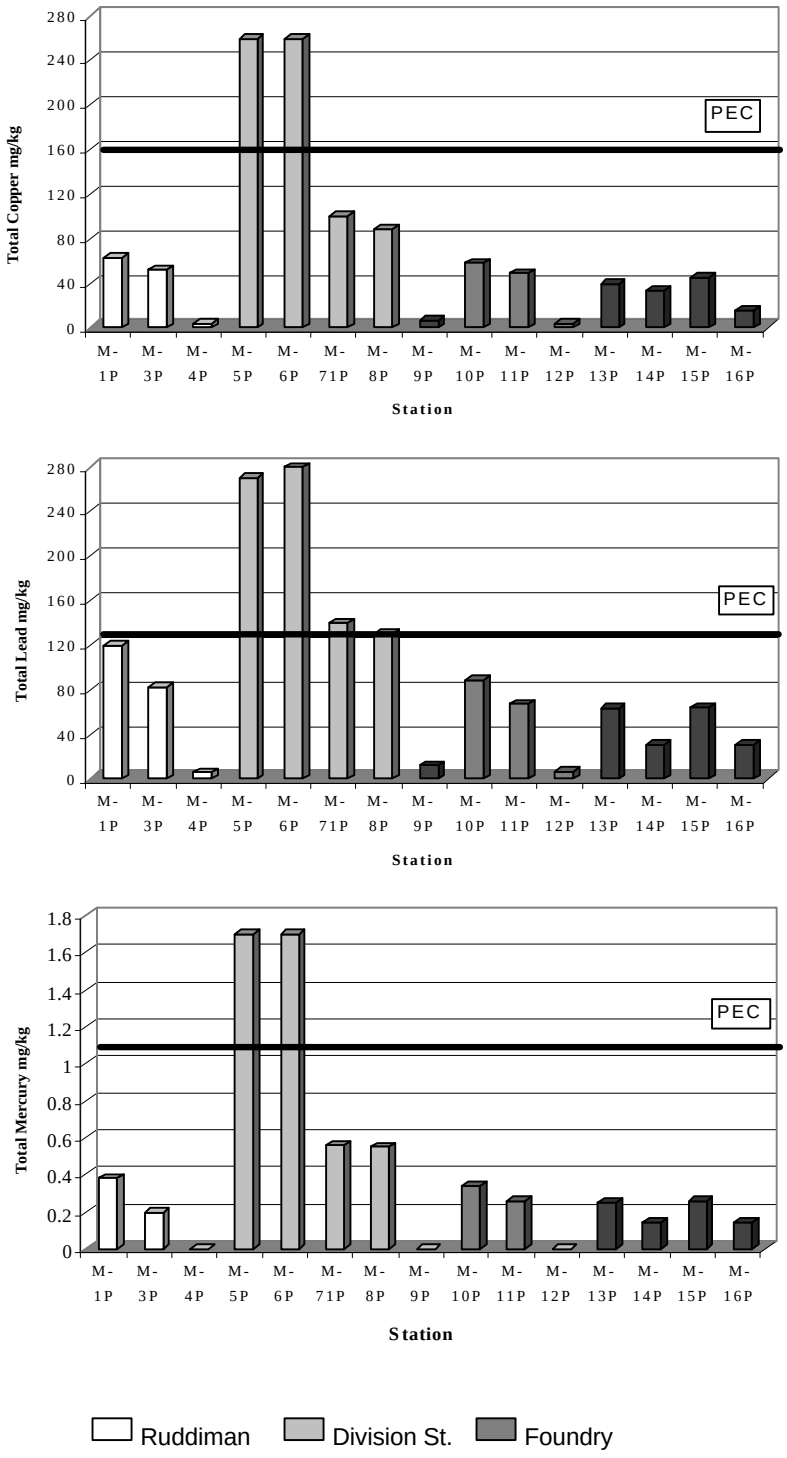


FIGURE 4.1.21. COPPER, LEAD, AND MERCURY IN PONAR SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. PATTERNS DENOTE REGIONS OF MUSKEGON LAKE. BOLD LINES IDENTIFY PEC LEVELS.

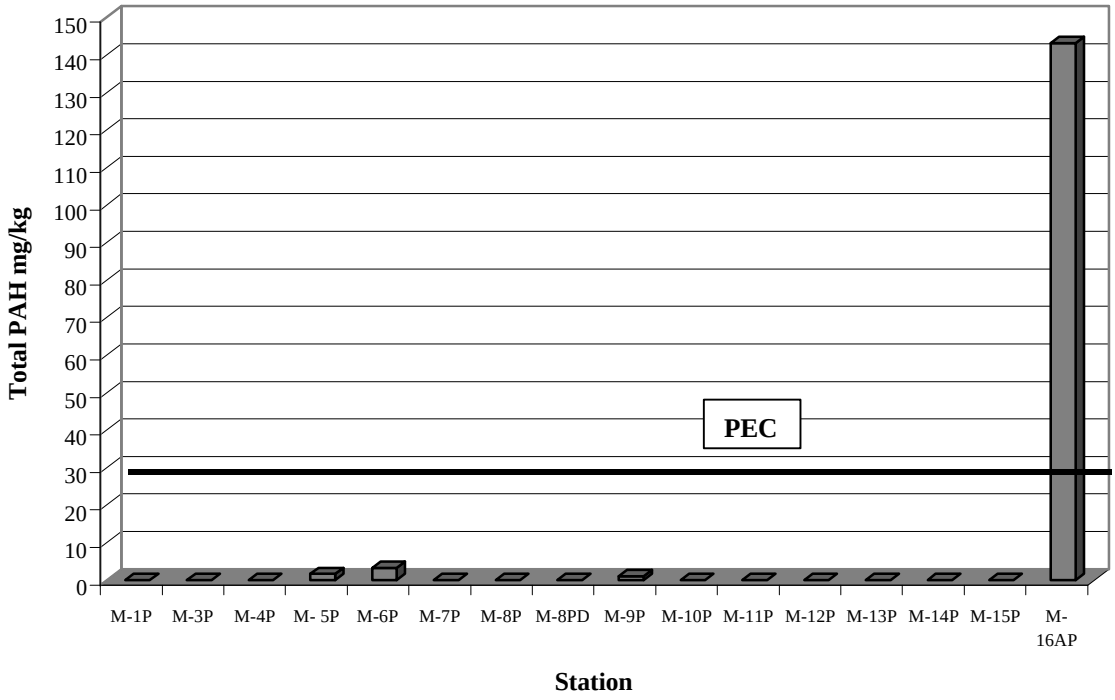


FIGURE 4.1.22. TOTAL PAH COMPOUNDS IN PONAR SAMPLES COLLECTED FROM MUSKEGON LAKE, OCTOBER 1999. BOLD LINES IDENTIFY PEC LEVELS.

exceed PEC guidelines. The station down gradient from the former lakeshore industrial area (M-16) was the only location to exceed the PEC for total PAH compounds. The sediment concentration of total PAH compounds at this location was 143 mg/kg compared to the PEC of 22.9 mg/kg. PAH compounds were also found at the Division Street Outfall locations M-5 and M-6 (2.7 mg/kg and 4.8 mg/kg, respectively).

In summary, the core show that heavy metal contamination is present in the 0-80 cm zone at most stations. The only core samples with significant levels of heavy metals at > 80 cm were near the former Teledyne foundry and near the confluence of Ruddiman Creek. High levels of PAH compounds were found in only one location that was located downgradient from the former lakeshore industrial area. Near surface zone sediments in the Division Street Outfall were contaminated with a variety of heavy metals at concentrations above the PEC guidelines. PEC guidelines for total PAH compounds were exceeded at the location downgradient from the former lakeshore industrial area. The most significant area of sediment heavy metal contamination was in the vicinity of the Division Street Outfall. The deposition basin down stream from Ruddiman Creek ranked second with respect to heavy metal enrichment.

4.2. Stratigraphy and Radiodating

Three cores were collected for radiodating and the analysis of detailed stratigraphy for chromium and lead. The first core (M-1S) was collected at station M-1 and would reflect contributions from Ruddiman Creek and the general westerly movement of sediment in Muskegon Lake. The second core (M-2S) was collected at the deepest location in Muskegon Lake and would provide an indication of sediment movement from the industrialized shoreline located to the east. The final core (M-5S) was collected at station M-5 in the Division Street Outfall area. This location would provide an indication of depositional history and sediment stability in this heavily contaminated area. The results of each core are presented in the following sections.

4.2.1 Core M-1S

Stratigraphy and radiodating results for M-1S are presented in Table 4.2.1. Profiles of depth and concentration for chromium and lead are shown on Figure 4.2.1 along with the calculated dates from the ^{210}Pb deposition model. Chromium and lead followed different depositional patterns. Concentrations in the top 10 cm for both elements were relatively uniform. Excess ^{210}Pb inventories were also uniform over the same interval, indicating that some degree of mixing occurs in this region. Below this level, two peaks in concentration were observed for chromium. The first peak corresponds to 1988 and contained a concentration of 440 mg/kg. The second peak corresponded to 1964 and contained 560 mg/kg. In contrast, the stratigraphy for lead only showed one peak of 200 mg/kg in approximately 1988. Increasing concentrations were noted for both elements beginning in the 1920s. It is interesting to note that a catastrophic flood occurred in the Muskegon River watershed during 1986. Rainfall in excess of the 100 year flood fell and several dam failures occurred. The presence of depositional peaks for both elements during this time frame suggests the strong influence of storm events on the system. Ruddiman Creek has a lagoon located near the confluence with Muskegon Lake. A recent investigation by the U.S. Army Corps of Engineers (ACOE 2000) found that the lagoon sediments were highly contaminated with heavy metals including chromium and lead. Thus, the results suggest the storm event of 1986 may have mobilized contaminated sediments from the Ruddiman Lagoon and deposited them in this region of Muskegon Lake.

4.2.2 Core M-2S

Stratigraphy and radiodating results for M-2S are presented in Table 4.2.2. Station M-2S is located at the deepest point in Muskegon Lake and within the flow path of the old river channel. Profiles of depth and concentration for chromium and lead are shown on Figure 4.2.2. This location was originally thought to be a depositional area due to its depth (70 ft).

TABLE 4.2.1 RESULTS OF STRATIGRAPHY AND RADIODATING RESULTS FOR CORE M-1S COLLECTED FROM MUSKEGON LAKE, MARCH 2000.

Depth (cm)	Total Chromium mg/kg	Total Lead mg/kg	Total Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)	Date at Given Depth
2	141	125					
4	108	110	22.548	3.935	1.841	18.613	1998
6	123	113					
8	123	120	23.607	4.518	1.337	19.089	1996
10	131	125					
12	170	168	25.890	6.107	1.601	19.783	1992
14	220	175					
16	440	200	23.139	5.297	1.600	17.842	1988
18	260	150					
20	220	95	20.603	3.981	1.592	16.622	1984
22	380	120					
24	380	120	20.801	4.668	1.483	16.133	1979
26	480	140					
28	420	120	19.510	4.256	1.762	15.254	1974
30	440	120					
32	400	100	17.851	3.281	3.321	14.570	1968
34	560	130					
36	460	110	17.037	3.053	8.406	13.983	1962
38	98	48					
40	72	33	16.293	2.994	4.567	13.299	1954
42	58	39					
44	48	32	9.951	2.430	2.995	7.521	1947
46	52	29					
48	62	32	8.000	2.222	1.926	5.778	1941
50	64	29					
52	60	33	7.877	2.596	1.860	5.281	1935
54	76	29					
56	46	20	7.353	2.354	2.196	4.999	1925
58	42	20					
60	10	9	5.360	2.583	1.584	2.777	1917
62	8	9					
64	11	10	4.107	2.643	1.231	1.465	1912

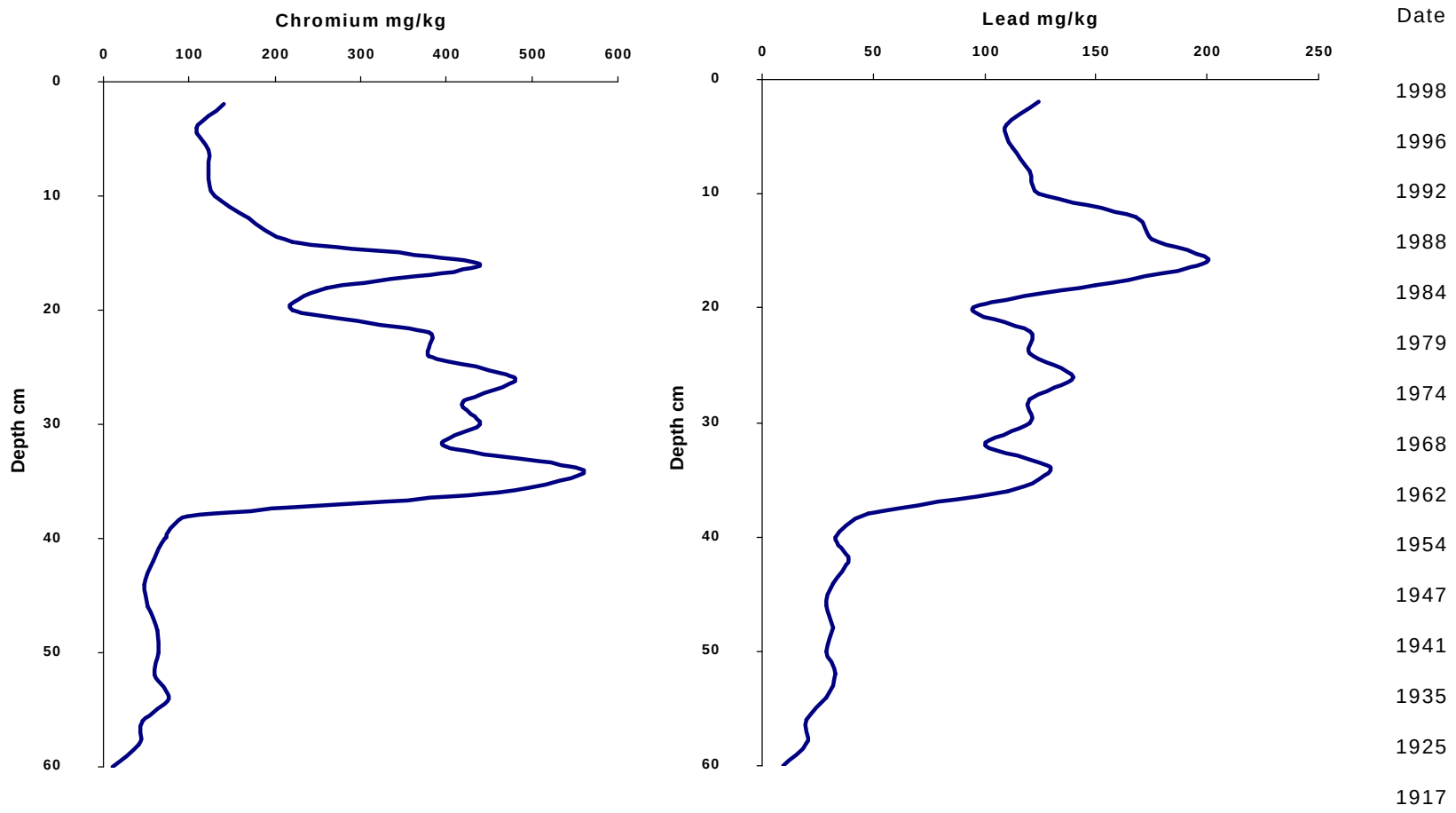


FIGURE 4.2.1 DEPTH AND CONCENTRATION PROFILES FOR CHROMIUM AND LEAD AT STATION M-1S, MUSKEGON LAKE, MARCH 2000. SEDIMENT DATES CALCULATED BY RADIODATING WITH PB-210

TABLE 4.2.2 RESULTS OF STRATIGRAPHY AND RADIODATING RESULTS FOR CORE M-2S COLLECTED FROM MUSKEGON LAKE, MARCH 2000.

DEPTH cm	Total Chromium mg/kg	Total Lead mg/kg	Total Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)
0-4	52	58	22.018	5.180	1.056	16.84
4-8	58	62	21.944	5.492	1.023	16.45
8-12	52	62	20.419	4.891	-0.067	15.53
12-16	80	87	21.208	5.133	1.364	16.08
16-20	98	103	14.030	3.282	0.915	10.75
20-24	124	128	9.771	4.222	1.583	5.55
24-28	130	135	9.658	3.833	1.434	5.82
28-32	135	140	12.705	3.524	1.628	9.18
32-36	155	140	8.543	3.066	1.236	5.48
36-40	200	135	8.188	3.255	1.178	4.93
40-44	250	140	7.455	3.926	1.886	3.53
44-48	265	135	9.299	3.849	2.284	5.45
48-52	285	130	9.131	3.986	2.265	5.14
52-56	335	130	8.170	4.904	2.595	3.27
56-60	330	115	6.143	2.796	0.101	3.35
60-64	285	95	8.579	3.151	2.740	5.43
64-68	380	120	9.625	3.466	2.512	6.16
68-72	360	115	9.470	3.495	0.433	5.98
72-76	325	100	5.632	3.623	2.768	2.01
76-80	275	105	6.509	3.292	2.368	3.22
80-84	235	115	8.830	3.828	2.086	5.00
84-88	255	125	6.324	3.105	2.176	3.22
88-92	315	130	6.636	3.723	2.775	2.91

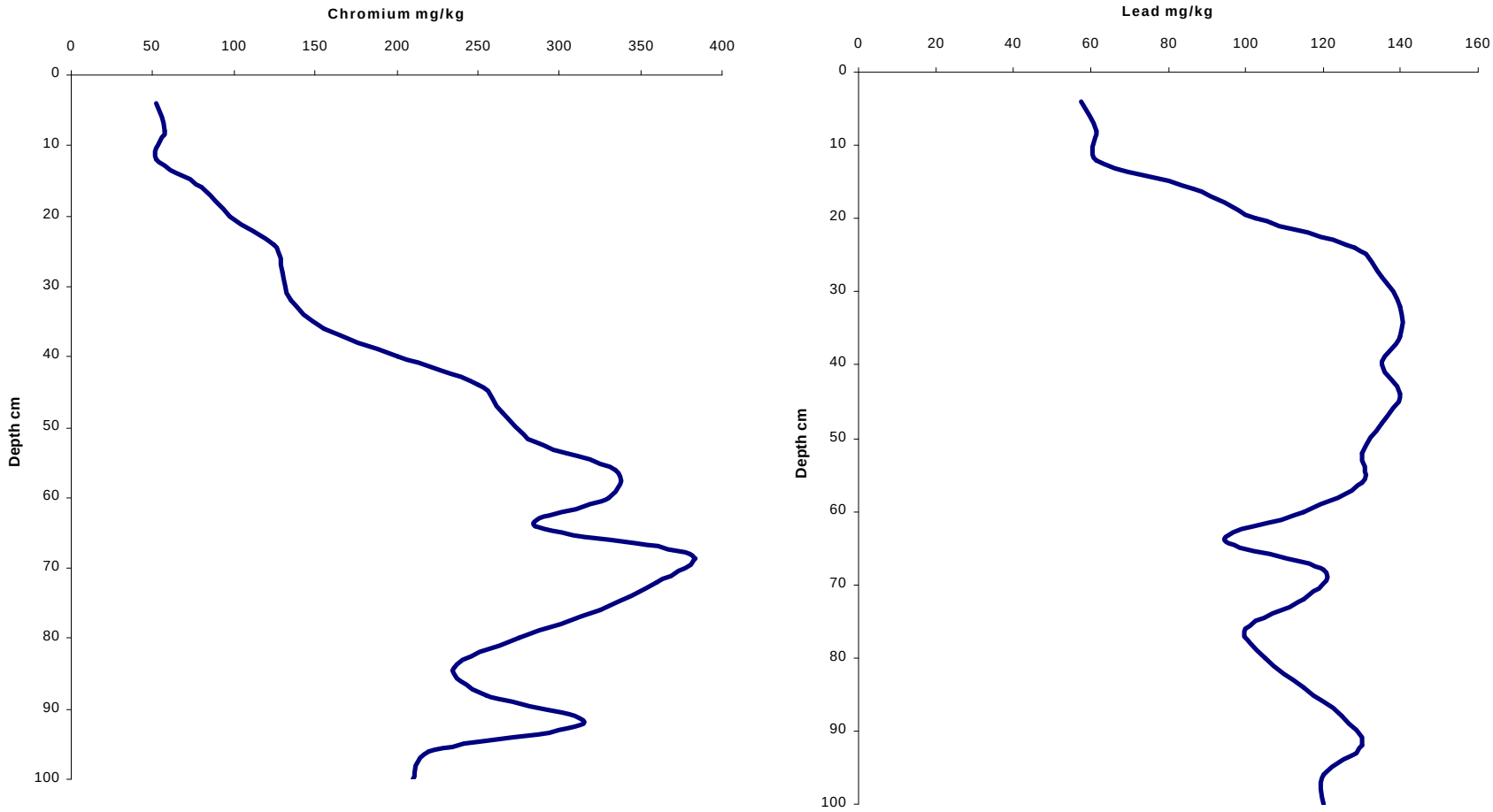


FIGURE 4.2.2 DEPTH AND CONCENTRATION PROFILES FOR CHROMIUM AND LEAD AT STATION M-2S, MUSKEGON LAKE, MARCH 2000.

The radiodating results show however that stable sediments were not accumulating at this location. The accumulation of stable sediments would result in a ^{210}Pb profile that exhibits an exponential decay of the radioisotope (Robbins and Herche 1993) similar to core M-1S. No exponential decay pattern is visible in core M-2S (Table 4.2.1). Instead, a mixed layer with uniform ^{210}Pb inventories was observed for the first 16 cm followed by a pattern of sections with increasing and decreasing ^{210}Pb concentrations ranging from 2.01 dpm to 6.16 dpm. The presence of excess ^{210}Pb throughout the core indicates a continuous influx of sediment and frequent movement out of the location. Based on the increasing and decreasing pattern, it appears that episodic events such as storms act to remove varying amounts of sediment from the location. The depositional patters of chromium and lead also have sporadic changes in concentration indicating the influence of episodic events. Concentrations of chromium peak at 64 cm – 70 cm while lead peaks at 28 cm – 44 cm. These data suggest that that the source of chromium is older than the source of lead. The rapidly decreasing concentrations of chromium noted in the top 40 cm indicates that the advection and deposition of this metal has declined in recent history. In contrast, peak lead deposition appears to occur more recently, with a smaller peak near the base of the core. Since lead contamination may originate from both point and nonpoint sources, the smaller peak near the bottom of the core may be related to industrial discharges from foundry and metal finishing operations. The more recent peak of lead deposition may be from the erosion of contaminated soils (from shoreline development) and the use of leaded fuels. The presence of currents at M-2S plus the fact that it is located downstream from the areas of contaminated sediments such as the Division Street Outfall suggests that resuspension and transport mechanisms are moving contaminants to the deeper zones of Muskegon Lake.

4.2.3 Core M-5S

Stratigraphy and radiodating results for M-5S are presented in Table 4.2.3. Profiles of depth and concentration for chromium and lead are shown on Figure 4.2.3 along with the calculated dates from the ^{210}Pb deposition model. Elevated concentrations of chromium and lead continue beyond the estimated date of 1894, which indicates that the CRS model did not yield credible results. The sediment layers below 30 cm from this core were fibrous in nature with strands that appeared to resemble fiberglass. The fibrous material continued down to 90 cm. It is likely that excessive historical inputs of waste materials diluted out the ^{210}Pb inventory in the deeper sections. The presence of a measurable ^{137}Cs horizon at 18 cm indicated that the dating of the upper sections of the core were accurate. No evidence of mixing in the upper sediment layers was visible as the ^{210}Pb inventories decay in the expected manner. Very high levels of chromium (850 mg/kg) and lead (890 mg/kg) were found in the deeper sections of the core (> 20 cm). Concentrations of both elements declined near the bottom however one section (96 cm) contained 600 mg/kg of chromium. This section appeared to have some metallic particles mixed with the sediment. Surficial sediments were contaminated above PEC levels for chromium and lead. This core was collected in the near shore area of the bay that contains the Division Street Outfall and may be protected from erosional forces from wave-induced currents. Locations further from shore and in the marina area may be subject to advection from boat traffic and currents.

TABLE 4.2.3 RESULTS OF STRATIGRAPHY AND RADIODATING RESULTS FOR CORE M-5S COLLECTED FROM MUSKEGON LAKE, MARCH 2001.

DEPTH cm	Total Lead mg/kg	Total Chromium mg/kg	Total Pb-210 Activity (dpm/g)	Ra-226 Activity (dpm/g)	Cs-137 Activity (dpm/g)	Excess Pb-210 Activity (dpm/g)	Date at Given Depth
2	330	110	26.472	2.547	1.128	24.260	2000
4	330	110	19.997	1.797	0.992	17.667	1996
6	410	130	16.288	2.340	1.988	13.890	1991
8	490	170	11.395	2.529	1.438	8.904	1986
10	500	160	11.640	1.962	2.116	9.160	1981
12	540	180	10.049	2.384	1.992	7.538	1977
14	570	210	9.832	2.572	4.178	7.319	1971
16	640	670	7.205	2.359	8.801	4.637	1966
18	720	850	7.972	2.992	10.080	5.422	1960
20	680	680	4.815	2.980	5.181	2.198	1958
22	660	660	5.870	2.339	3.576	3.277	1954
24	780	480	7.564	2.612	2.070	5.012	1947
26	500	360	6.845	2.169	1.770	4.279	1940
28	540	200	4.929	2.612	2.055	2.318	1935
30	540	210	4.222	2.614	2.203	1.595	1932
32	620	130	3.611	2.090	2.384	0.970	1930
34	590	270	5.967	2.342	2.904	3.385	1922
36	580	250	5.721	1.839	2.261	3.133	1910
38	560	260	5.198	2.187	2.466	2.598	1894
40	620	260	6.291	2.040	2.239	3.721	
42	750	280	6.308	2.205	1.932	0.000	
44	770	220	5.245	2.737	2.209	0.000	
46	720	190	6.051	2.272	1.759	0.000	
48	750	200	3.741	3.260	1.037	0.000	
50	780	190	6.699	3.326	0.851	0.000	
52	890	200	8.922	3.093	0.759	0.000	
54	770	160	5.497	3.514	0.305	0.000	
56	820	180	2.352	2.890	-0.025	0.000	
58	830	210	6.181	2.446	-0.542	0.000	
60	680	120	3.538	2.737	-0.056	0.000	
62	510	150	3.191	2.637	-0.254	0.000	
64	450	140	5.833	3.869	-0.175	0.000	
66	350	110				0.000	
68	280	150				0.000	
70	260	110	3.863	2.526	-0.331	0.000	
72	230	96	5.148	2.856	-0.361	0.000	
74	220	110				0.000	
76	200	100				0.000	
78	190	82				0.000	
80	160	89	4.643	2.888	-0.306	0.000	
82	135	95	4.870	2.469	-0.055	0.000	
84	111	110				0.000	
86	99	100				0.000	
88	88	130	3.847	2.869	-0.495	0.000	
90	53	120					
92	41	130					
94	42	200					
96	33	600					
98	32	120					
100	30	89					

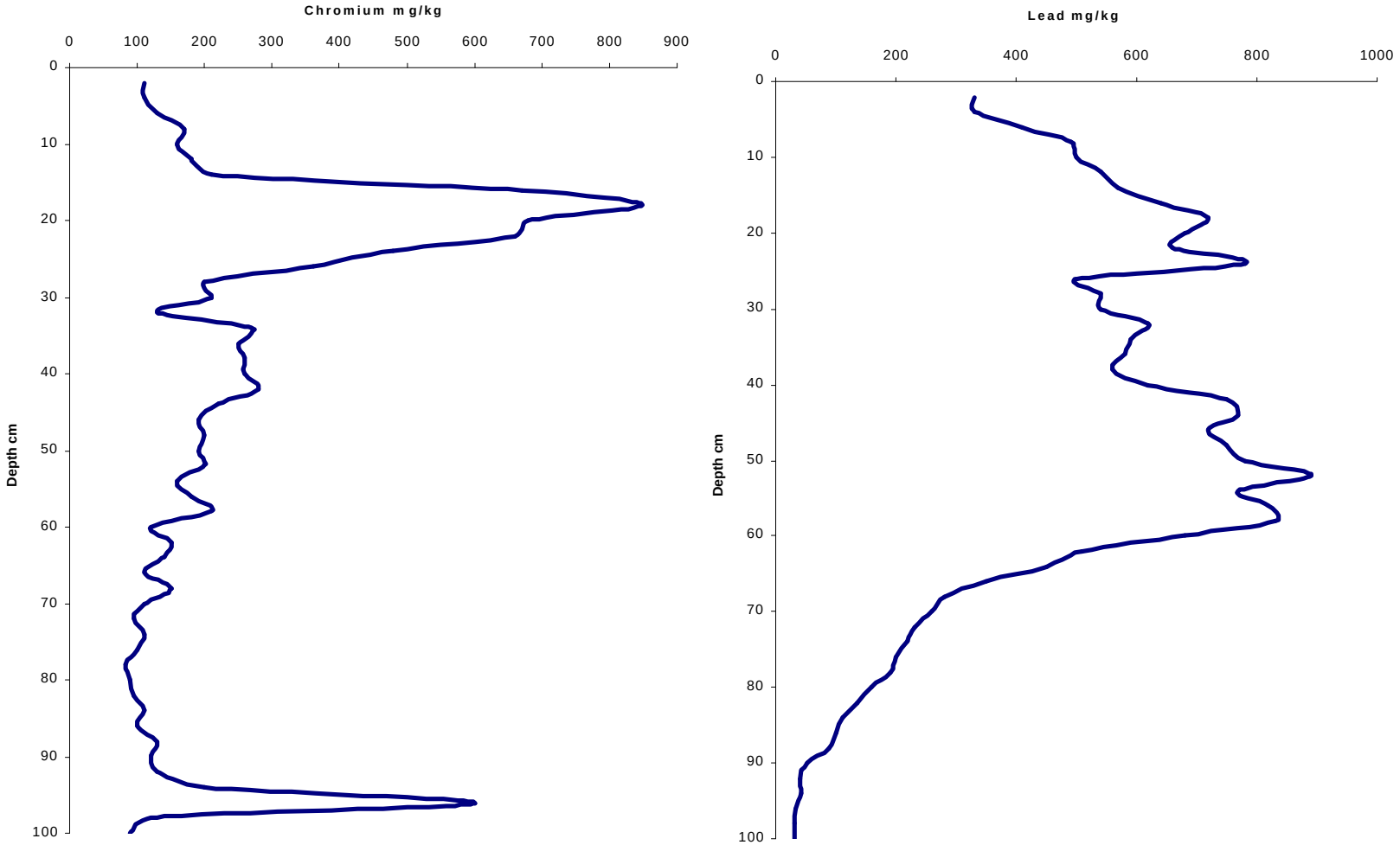


FIGURE 4.2.3 DEPTH AND CONCENTRATION PROFILES FOR CHROMIUM AND LEAD AT STATION M-5S, MUSKEGON LAKE, MARCH 2001.

4.2.4 Stratigraphy and Radiodating Summary

In examining the results of the three stratigraphy cores together, some important patterns in contaminant deposition are evident. Ruddiman Creek appeared to have a significant influence on the deposition of heavy metals in the southwestern part of Muskegon Lake. A peak in metals deposition was found that corresponded to the 100+ year flood that occurred in 1986. The historical deposition was considerably higher than current rates. The deep zone off the Car Ferry Dock was not found to be an area that accumulates sediments. High inventories of ^{210}Pb were found near the bottom of the 80 cm core, indicating active mixing and movement of sediments. The presence of elevated metals in the deeper strata plus the high ^{210}Pb inventories suggests that contaminated sediments are moved from the eastern part of Muskegon Lake to this location where they are mixed and made available for resuspension by the currents along the old river channel. The core from the Division Street Outfall showed relatively stable sediments in the top 20 cm followed by a zone of heavy accumulation after 1960. Based on these results it is apparent that the removal of contaminated sediments from Ruddiman Creek and the lagoon would reduce the loading of heavy metals to western Muskegon Lake. The areas of high sediment contamination in the eastern part of the lake also appear to be mixed and subject to transport.

4.3 Toxicity Testing Results

The toxicity evaluations of the Muskegon Lake sediments were performed during November 1999. Grab sediment samples collected from 14 different sites (14 samples with one additional field duplicate) were evaluated using the EPA (1994) solid phase testing protocol with *Hyalella azteca* and *Chironomus tentans*.

Conductivity, hardness, alkalinity, ammonia, and pH were determined on the culture water at the beginning and on the tenth day of each test (Appendix E: Tables E-1, E-3). With the exception of ammonia in most of the sediments and conductivity and hardness in M10-P, these parameters remained relatively constant. Variations of less than 50% from initial to final measurements for both test species were observed. Based on the initial pH values (all < 8.00) and the fact that the overlying water was exchanged prior to adding the organisms, toxicity related to unionized ammonia was not anticipated to be a factor in these experiments. Temperature and dissolved oxygen measurements were recorded daily throughout the duration of the tests (Appendix E: Tables E-2, E-4). Very little variation was noted with respect to temperature. The dissolved oxygen remained above 40% saturation in all of the test beakers.

4.3.1 *Hyalella azteca*

Survival data for solid phase toxicity tests with *Hyalella azteca* are presented in Table 4.3.1.1. The survival in the control (M-15P) treatments exceeded the required 80%. Un-transformed survival data were evaluated to determine whether they were consistent with data from a normal distribution with a mean and standard deviation equal to the sample distribution. The Chi-Squared distribution was used to compare the expected count of data values at the 10^{th}, 20^{th}, …, and 90^{th} percentiles with the observed count. The sample data was found to be consistent with those drawn from a normal population ($p > 0.01$). Dunnett's Test (Table 4.3.1.2) showed a statistically significant ($p < 0.05$) difference for the survival data compared to control site M-15P in 3 out of 15 sediments. Sediments from site M-5P, M-6P and M-16AP had significantly reduced survival compared to M-15P. Based on amphipod mortality, station M-16AP had the highest mortality followed in decreasing order by M-5P, M-6P, and M-12P. All remaining stations had amphipod survival ≥ 80%.

4.3.2 *Chironomus tentans*

Survival data for solid phase toxicity tests with *Chironomus tentans* are presented in Table 4.3.2.1. The survival in the control treatments (M-15P) exceeded the required 70%. Un-transformed survival data were evaluated as described above with the Chi-Squared distribution. The sample data was found to be consistent with those drawn from a normal population ($p > 0.01$). Dunnett's Test (Table 4.3.2.2) showed a statistically significant ($p < 0.05$) difference for the survival data of M-16P compared to the control. Only 25 % survival was observed at this location. *Chironomus tentans* growth data is presented in Table 4.3.2.3. Un-transformed growth data were found to be consistent with a Chi-Squared distribution at

TABLE 4.3.1.1 SUMMARY OF *HYALELLA AZTECA* SURVIVAL DATA OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

Sample	N	#	Survival					
			MIN	MAX	MEAN	VARIANCE	SD	C.V. %
M-1	8	10	7	10	8.375	1.6964	1.3025	15.55
M-3	8	10	8	9	8.375	1.125	1.0607	12.67
M-4	8	10	8	10	9.375	0.2679	0.5175	5.52
M-5	8	10	5	7	6.000	0.5536	0.7440	12.40
M-6	8	10	5	8	6.500	0.5714	0.7559	11.63
M-7	8	10	6	10	8.000	1.1429	1.0690	13.36
M-8	8	10	7	10	8.625	1.7143	1.3093	15.18
M-8D	8	10	7	9	8.375	0.5714	0.7559	9.03
M-9	8	10	9	10	9.375	0.2679	0.5175	5.52
M-10	8	10	7	10	8.375	1.1250	1.0607	12.67
M-11	8	10	7	10	8.375	1.1250	1.0607	12.67
M-12	8	10	4	9	7.375	2.5536	1.5980	21.67
M-13	8	10	7	10	8.375	0.8393	0.9161	10.94
M-14	8	10	7	10	8.250	1.3571	1.1650	14.12
M-15	8	10	7	10	8.375	1.6964	1.3025	15.55
M-16	8	10	3	7	4.500	1.4286	1.1952	26.56

TABLE 4.3.1.2 SUMMARY OF DUNNETT'S TEST ANALYSIS OF *HYALELLA AZTECA* SURVIVAL FOR THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

ID	TRANS MEAN	ORIGINAL MEAN	T STAT	SIG 0.05
M-1	8.3750	8.3750	0.0000	
M-3	8.3750	8.3750	0.0000	
M-4	9.3750	9.3750	-2.0735	
M-5	6.0000	6.0000	4.9246	*
M-6	6.5000	6.5000	3.8878	*
M-7	8.0000	8.0000	0.7776	
M-8	8.6250	8.6250	-0.5184	
M-8D	8.0000	8.0000	1.1047	
M-9	9.3750	9.3750	-2.0735	
M-10	8.3750	8.3750	0.0000	
M-11	8.3750	8.3750	0.0000	
M-12	7.3750	7.3750	2.1330	
M-13	8.3750	8.3750	0.0000	
M-14	8.2500	8.2500	0.2041	
M-15	8.3750	8.3750		
M-16	4.5000	4.5000	6.3278	*

Dunnett's critical value = 2.4800. 1 Tailed, alpha = 0.05.

TABLE 4.3.2.1 SUMMARY OF *CHIRONOMUS TENTANS* SURVIVAL DATA OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

Sample	N	#	Survival					
			MIN	MAX	MEAN	VARIANCE	SD	C.V. %
M-1	8	10	7	9	8.3750	1.4107	1.1877	14.18
M-3	8	10	7	10	8.3750	1.4107	1.1877	14.18
M-4	8	10	8	10	9.4286	0.2679	0.5175	5.49
M-5	8	10	5	9	7.7500	2.7857	1.6690	21.54
M-6	8	10	6	9	7.7500	1.6429	1.2817	16.54
M-7	8	10	7	10	8.0000	2.0000	1.4142	17.68
M-8	8	10	8	10	8.6250	0.5536	0.7440	8.63
M-8D	8	10	7	9	8.0000	0.5714	0.7559	9.45
M-9	8	10	9	10	9.3750	0.2679	0.5175	5.52
M-10	8	10	7	10	8.3750	1.1250	1.0607	12.67
M-11	8	10	8	9	8.3750	1.1250	1.0607	12.67
M-12	8	10	6	8	8.0000	1.4286	1.0607	13.26
M-13	8	10	7	9	8.3750	1.1250	1.1952	14.27
M-14	8	10	7	10	8.2500	0.5000	1.0607	12.86
M-15	8	10	7	10	8.3750	0.5536	0.7440	8.88
M-16	8	10	1	4	2.5000	1.1429	1.0690	42.76

TABLE 4.3.2.2 SUMMARY OF DUNNETT'S TEST ANALYSIS OF SURVIVAL DATA *CHIRONOMUS TENTANS* OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

ID	TRANS MEAN	ORIGINAL MEAN	T STAT	SIG 0.05
M-1	8.3750	8.3750	0.0000	
M-3	8.3750	8.3750	0.0000	
M-4	9.4286	9.4286	-1.0000	
M-5	7.7500	7.7500	0.6250	
M-6	7.7500	7.7500	0.6250	
M-7	8.0000	8.0000	1.3750	
M-8	8.6250	8.6250	-0.2500	
M-8D	8.0000	8.0000	0.7579	
M-9	9.3750	9.3750	-1.2846	
M-10	8.3750	8.3750	0.0000	
M-11	8.3750	8.3750	0.0000	
M-12	8.0000	8.0000	0.7579	
M-13	8.3750	8.3750	0.0000	
M-14	8.2500	8.2500	0.2526	
M-15	8.3750	8.3750		
M-16	2.5000	2.5000	11.8743	*

Dunnett's critical value = 2.4800. 1 Tailed, alpha = 0.05

TABLE 4.3.2.3 SUMMARY OF *CHIRONOMUS TENTANS* DRY WEIGHT DATA OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

Sample ID	Rep	Pan Wt (g)	Pan + Sample Dry Wt (g)	Sample Dry Wt (g)	# Survivors	Mean wt (mg) per survivor	Sample Mean	Sample Std Dev
M-1	a	0.9884	0.9955	0.0071	10	0.7100	1.033	0.2564
	b	0.9883	0.9982	0.0099	8	1.2375		
	c	0.9888	0.9973	0.0085	8	1.0625		
	d	0.9977	1.0071	0.0094	10	0.9400		
	e	0.9989	1.0048	0.0059	9	0.6556		
	f	0.9994	1.0082	0.0088	8	1.1000		
	g	0.9995	1.0075	0.008	7	1.1429		
	h	0.9994	1.0093	0.0099	7	1.4143		
M-3	a	0.9928	1.0013	0.0085	10	0.8500	0.953	0.1862
	b	0.9964	1.0041	0.0077	9	0.8556		
	c	1.0024	1.0112	0.0088	8	1.1000		
	d	0.9957	1.0023	0.0066	6	1.1000		
	e	0.9972	1.0019	0.0047	8	0.5875		
	f	0.9993	1.0081	0.0088	9	0.9778		
	g	0.9960	1.0053	0.0093	8	1.1625		
	h	0.9974	1.0063	0.0089	9	0.9889		
M-4	a	1.0106	1.0211	0.0105	9	1.1667	0.945	0.1707
	b	1.0083	1.0167	0.0084	10	0.8400		
	c	1.0028	1.0126	0.0098	9	1.0889		
	d	1.0132	1.0225	0.0093	9	1.0333		
	e	1.0091	1.0162	0.0071	10	0.7100		
	f	1.0130	1.0202	0.0072	9	0.8000		
	g	1.0106	1.0180	0.0074	9	0.8222		
	h	1.0112	1.0200	0.0088	8	1.1000		
M-5	a	0.9996	1.0104	0.0108	7	1.5429	1.125	0.3711
	b	0.9898	1.0002	0.0104	9	1.1556		
	c	0.9898	0.9986	0.0088	8	1.1000		
	d	0.9970	1.0070	0.01	6	1.6667		
	e	0.9961	1.0016	0.0055	10	0.5500		
	f	0.9966	1.0029	0.0063	5	1.2600		
	g	1.0080	1.0152	0.0072	9	0.8000		
	h	0.9974	1.0048	0.0074	8	0.9250		
M-6	a	0.9973	1.0053	0.0080	7	1.1429	1.060	0.2806
	b	0.9928	1.0010	0.0082	6	1.3667		
	c	1.0101	1.0220	0.0119	8	1.4875		
	d	1.0036	1.0100	0.0064	6	1.0667		
	e	1.0036	1.0092	0.0056	9	0.6222		
	f	0.9938	1.0033	0.0095	9	1.0556		
	g	1.0062	1.0144	0.0082	9	0.9111		
	h	0.9953	1.0011	0.0058	7	0.8286		
M-7	a	1.0158	1.0260	0.0102	9	1.1333	1.107	0.2914
	b	1.0085	1.0155	0.0070	10	0.7000		
	c	1.0092	1.0174	0.0082	7	1.1714		
	d	1.0037	1.0096	0.0059	7	0.8429		
	e	1.0027	1.0166	0.0139	9	1.5444		
	f	1.0027	1.0092	0.0065	7	0.9286		
	g	0.9981	1.0069	0.0088	6	1.4667		
	h	0.9910	1.0006	0.0096	9	1.0667		
M-8	a	1.0225	1.0317	0.0092	10	0.9200	0.969	0.1499
	b	1.0155	1.0223	0.0068	8	0.8500		
	c	1.0165	1.0231	0.0066	8	0.8250		
	d	1.0083	1.0149	0.0066	8	0.8250		
	e	1.0037	1.0132	0.0095	9	1.0556		
	f	1.0022	1.0116	0.0094	9	1.0444		
	g	1.0151	1.0252	0.0101	8	1.2625		
	h	1.0087	1.0174	0.0087	9	0.9667		
M-8D	a	1.0037	1.0130	0.0093	9	1.0333	0.964	0.1479
	b	0.9789	0.9891	0.0102	10	1.0200		
	c	0.9879	0.9994	0.0115	9	1.2778		
	d	0.9883	0.9962	0.0079	9	0.8778		
	e	0.9868	0.9949	0.0081	9	0.9000		
	f	1.0039	1.0119	0.0080	10	0.8000		
	g	1.0069	1.0158	0.0089	10	0.8900		
	h	1.0020	1.0102	0.0082	9	0.9111		

TABLE 4.3.2.3 (CONTINUED) SUMMARY OF *CHIRONOMUS TENTANS* DRY WEIGHT DATA OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

Sample ID	Rep	Pan Wt (g)	Pan + Sample Dry Wt (g)	Sample Dry Wt (g)	# Survivors	Mean wt (mg) per survivor	Sample Mean	Sample Std Dev
M-9	a	1.005	1.0141	0.0092	9	1.0222		
	b	0.999	1.0086	0.0101	10	1.0100		
	c	1.000	1.0088	0.0090	10	0.9000		
	d	0.999	1.0063	0.0069	9	0.7667	0.927	0.1953
	e	1.006	1.0148	0.0085	9	0.9444		
	f	0.994	1.0000	0.0059	9	0.6556		
	g	0.996	1.0081	0.0117	9	1.3000		
	h	0.998	1.0058	0.0082	10	0.8200		
M-10	a	0.998	1.0068	0.0086	9	0.9556		
	b	0.997	1.0008	0.0040	10	0.4000		
	c	0.995	1.0052	0.0103	9	1.1444		
	d	0.996	1.0061	0.0106	8	1.3250	0.943	0.3389
	e	1.000	1.0042	0.0046	7	0.6571		
	f	0.994	1.0043	0.0103	9	1.1444		
	g	0.998	1.0079	0.0102	8	1.2750		
	h	0.999	1.0031	0.0045	7	0.6429		
M-11	a	0.998	1.0067	0.0084	7	1.2000		
	b	0.997	1.0052	0.0084	8	1.0500		
	c	0.992	1.0065	0.0149	8	1.8625		
	d	1.001	1.0068	0.0061	7	0.8714	1.003	0.3856
	e	1.000	1.0067	0.0063	9	0.7000		
	f	1.001	1.0083	0.0069	9	0.7667		
	g	0.996	1.0036	0.0073	9	0.8111		
	h	1.000	1.0076	0.0076	10	0.7600		
M-12	a	0.996	1.0065	0.0110	8	1.3750		
	b	0.998	1.0070	0.0093	7	1.3286		
	c	0.997	1.0026	0.0056	8	0.7000		
	d	0.994	0.9986	0.0050	8	0.6250	1.124	0.7015
	e	0.992	1.0080	0.0162	6	2.7000		
	f	0.995	1.0020	0.0069	9	0.7667		
	g	0.995	1.0018	0.0068	8	0.8500		
	h	0.996	1.0025	0.0065	10	0.6500		
M-13	a	1.000	1.0050	0.0051	9	0.5667		
	b	1.001	1.0104	0.0094	7	1.3429		
	c	1.001	1.0057	0.0049	8	0.6125		
	d	0.997	1.0040	0.0075	9	0.8333	0.836	0.2478
	e	1.000	1.0071	0.0074	8	0.9250		
	f	0.995	1.0011	0.0058	9	0.6444		
	g	0.995	1.0022	0.0068	8	0.8500		
	h	0.983	0.9915	0.0082	9	0.9111		
M-14	a	1.003	1.0081	0.0054	9	0.6000		
	b	0.999	1.0062	0.0068	7	0.9714		
	c	1.004	1.0116	0.0079	8	0.9875		
	d	1.003	1.0091	0.0063	9	0.7000	0.939	0.2386
	e	1.003	1.0130	0.0101	8	1.2625		
	f	1.001	1.0102	0.0096	8	1.2000		
	g	0.999	1.0058	0.0067	9	0.7444		
	h	0.991	0.9995	0.0084	8	1.0500		
M-15	a	0.997	1.0040	0.0068	9	0.7556		
	b	0.999	1.0062	0.0074	9	0.8222		
	c	0.996	1.0020	0.0059	9	0.6556		
	d	0.999	1.0119	0.0134	9	1.4889	0.988	0.2941
	e	0.998	1.0092	0.0110	8	1.3750		
	f	0.998	1.0050	0.0075	8	0.9375		
	g	1.018	1.0253	0.0069	7	0.9857		
	h	1.006	1.0128	0.0071	8	0.8875		
M-16	a	1.013	1.0141	0.0012	2	0.6000		
	b	1.007	1.0086	0.0017	3	0.5667		
	c	1.006	1.0088	0.0029	4	0.7250		
	d	1.005	1.0063	0.0017	3	0.5667	0.561	0.1237
	e	1.013	1.0148	0.0015	3	0.5000		
	f	1.000	1.0000	0.0003	1	0.3000		
	g	1.008	1.0081	0.0006	1	0.6000		
	h	1.004	1.0058	0.0019	3	0.6333		

$p > 0.01$. Dunnett's Test (Table 4.3.2.4) showed a statistically significant ($p < 0.05$) difference with the *Chironomus tentans* weight data for M-16 compared to the control. Weight data for the other locations were similar to the control.

TABLE 4.3.2.4 SUMMARY OF DUNNETT'S TEST ANALYSIS OF WEIGHT DATA FOR *CHIRONOMUS TENTANS* OBTAINED DURING THE 10 DAY TOXICITY TEST WITH MUSKEGON LAKE SEDIMENTS.

ID	TRANS MEAN	ORIGINAL MEAN	T STAT	SIG 0.05
M-1	1.0328	1.0328	-0.3370	
M-3	0.9528	0.9528	0.2716	
M-4	0.9451	0.9451	0.3295	
M-5	1.1250	1.1250	-1.0373	
M-6	1.0602	1.0602	-0.5445	
M-7	1.1067	1.1067	-0.8982	
M-8	0.9687	0.9687	0.1508	
M-8D	0.9640	0.9640	0.1332	
M-9	0.9274	0.9274	0.4645	
M-10	0.9430	0.9430	0.3453	
M-11	1.0027	1.0027	-0.0752	
M-12	1.1244	1.1244	-0.7194	
M-13	0.8357	0.8357	0.8086	
M-14	0.9394	0.9394	0.2597	
M-15	0.9885	0.9885		
M-16	0.5364	0.5364	2.5880	*

DUNNETT'S CRITICAL VALUE = 2.4800. 1 TAILED, ALPHA = 0.05

4.3.3 Sediment Toxicity Data Discussion

Statistically significant ($p < 0.05$) acute toxicity effects were observed in the sediments from sites M-5P, M-6P, and M-16AP for the amphipod, *H. azteca*. In addition, statistically significant ($p < 0.05$) mortality and growth were noted for the midge, *C. tentans* in sediment from site M-16. Sediment from station M-16AP was toxic to both organisms and had the highest level of total PAH compounds (143 mg/kg). Stations M-5P and M-6P had statistically significant ($p < 0.05$) mortality and contained the highest levels of chromium, cadmium, copper, lead, and zinc found in the near surface zone sediments. Concentrations of these elements were above PEC guidelines (MacDonald et al. 2000) as shown in Table 4.1.6. The remaining sites had levels of PAH compounds and heavy metals that did not exceed PEC guidelines. Statistically significant mortality was not observed at these locations in the solid phase toxicity tests for both organisms.

4.4 Benthic Macroinvertebrate Results

Triplicate PONAR grab samples were used to characterize the benthic macroinvertebrate populations at each of the investigative stations. The locations, depths, and physical characteristics of the sediments are given in Table 2.2. Benthic macroinvertebrate populations were assessed by three methods. These data were first analyzed for differences in taxa and total number of organisms and the results summarized in Section 4.4.1. A further analysis of these data using trophic indices and diversity metrics was then conducted and presented in Section 4.4.2. Finally, the individual replicates at selected stations were statistically analyzed in Section 4.4.3 to determine if there were differences between locations presumably impacted by the Division Street Outfall (M-5 through M-7) and stations influenced by the Lakey/Teledyne Foundry complex (M-10 and M-11).

4.4.1 Benthic Macroinvertebrate Results Of Individual Samples

The population composition and abundance data are summarized in Table 4.4.1.1 by mean and standard error for each station. The results for each replicate are presented in Appendix F, Table F-1. A total of 55 taxa were identified, with an average of 10 ± 2.498 taxa per station (range 6-15, Table 4.4.1.1). The general distribution of organisms is shown in Figure 4.4.1.1. Oligochaetes dominated the benthic macroinvertebrate assemblages at most stations. Zebra mussels dominated the stations with sandy substrates. Chironomids also were abundant at most stations. Benthic populations show an increase in both total numbers and species compared to the historic data reported by Evans (1992) for the 1980s. A summary of total organisms and taxometric groups is presented in table 4.4.1.2. Total density was generally high and ranged between 4,649/m^2 and 49,124/m^2 with 12 of 15 sites having >5000 organisms/m^2. Oligochaeta were the most abundant group at all but two of the sites sampled, comprising between 2.395/m^2 and 10,489/m^2. Immature tubificids were 72% of the total abundance of oligochaetes from all sampling sites; the remaining 28% included 18 positively identified taxa (Appendix F, Table F-1). Relative oligochaete density was variable (range 12% to 87%) and exceeded 50% at 12 of the 15 sites sampled. The proportion of oligochaetes was the lowest at sites, M-9 (26.9%) and M-12 (12.4%) where *Dreissena* exceeded 15,000/m^2. Three species, *Aulodrilus pigueti, Limnodrilus hoffmeisteri,* and *Quistadrilus multisetosus* were found at most sites (Table 4.4.1). One of the more pollution tolerant species, *L. hoffmeisteri,* was found at all but four sites (M-4, M-7, M-15, and M-16). This oligochaete was found in lower abundances than the other two species. Howmiller and Scott (1977) and Milbrink (1983) classified benthic macroinvertebrate assemblages dominated by these species as enriched with organic (nutrient) materials. Sites near the mouth of the Muskegon River (M-11, M-13, and M-14), Ruddiman Creek (M-1), and the northern shore (M-15) were indicative of the greatest degree of enrichment based on oligochaete densities of > 80% of the total benthic macroinvertebrate population. The deposition of organic matter from the Muskegon River and the eutrophic conditions present in the lake create an enriched environment which supports high oligochaete densities. The

TABLE 4.4.1.1 BENTHIC MACROINVERTEBRATE DISTRIBUTION IN MUSKEGON LAKE (#/M^2), OCTOBER 1999. MEAN NUMBER OF ORGANISMS (± STANDARD ERROR) REPORTED FOR EACH STATION.

Station	Musk-1	Musk-3	Musk-4	Musk-5	Musk-6	Musk-7	Musk-8	Musk-9
Taxa								
Turbellaria	14 ± 14	14 ± 14	43	144 ± 14	86 ± 25	57 ± 38	72 ± 52	1249 ± 1035
Oligochaeta								
Lumbriculidae								
Stylodrilus heringianus	0	0	0	0	0	0	14 ± 14	0
Naididae								
Arcteonais lomondi	14 ± 14	0	0	0	0	0	14 ± 14	0
Dero digitata	258 ± 66	14 ± 14	0	14 ± 14	0	14 ± 14	0	170 ± 170
Dero flabelliger	0	0	0	14 ± 14	0	0	0	0
Piguetiella michiganensis	0	0	0	0	0	0	0	0
Salvina appendulata	0	0	0	0	0	14 ± 14	0	114 ± 114
Tubificidae								
Aulodrilus americanus	0	0	0	0	14 ± 14	0	0	113 ± 113
Aulodrilus limnobius	172 ± 50	14 ± 14	81	14 ± 14	57 ± 57	86 ± 66	0	57 ± 57
Aulodrilus pigueti	359 ± 152	460 ± 51	570	1134 ± 288	1220 ± 546	344 ± 132	258 ± 114	2415 ± 1942
Aulodrilus pluriseta	1076 ± 305	0	4556	0	0	0	0	0
Ilyodrilus templetoni	14 ± 14	79 ± 59	81	0	0	0	0	0
Isocheatides freyi	86 ± 50	0	81	0	0	14 ± 14	0	0
Limnodrilus cervix variant	0	0	0	0	0	0	0	0
Limnodrilus hoffmeisteri	72 ± 14	76 ± 17	0	14 ± 14	29 ± 14	0	29 ± 14	29 ± 29
Limnodrilus maumeensis	0	14 ± 14	0	0	0	0	0	0
Limnodrilus udekemianus	0	0	0	0	0	0	0	0
Potamothrix moldaviensis	0	0	0	0	0	0	0	0
Quistadrilus multisetosus	14 ± 14	508 ± 216	163	14 ± 14	14 ± 14	57 ± 57	187 ± 38	1335 ± 1120
Immatures w/o hair chaetae	1378 ± 25	3752 ± 610	2115	990 ± 282	1033 ± 326	1938 ± 634	2411 ± 197	2422 ± 1003
Immatures w/hair chaetae	359 ± 63	1215 ± 299	814	201 ± 94	144 ± 63	273 ± 144	545 ± 94	243 ± 135
Polychaeta								
Manayunkia speciosa	0	0	0	0	0	0	0	0
Hirudinea								
Glossiphoniidae								
Alboglossiphonia heteroclita	0	0	0	0	0	0	0	0
Helobdella stagnalis	29 ± 14	0	0	0	0	0	0	0
Helobdella elongata	0	0	0	0	0	0	0	0
Mollusca								
Gastropoda								
Amnicola sp.	0	57 ± 38	0	57 ± 14	100 ± 52	100 ± 52	29 ± 14	144 ± 103
Bithynia sp.	0	0	0	14 ± 14	14 ± 14	0	0	29 ± 29
Valvata tricarinata	0	0	0	144 ± 38	187 ± 72	144 ± 52	57 ± 14	43 ± 43
Valvata sincera	0	0	0	0	0	0	0	0
Bivalvia								
Pisidium sp.	0	86 ± 50	0	1550 ± 224	646 ± 25	646 ± 132	431 ± 66	258 ± 114
Sphaerium sp.	0	29 ± 14	0	43 ± 25	0	244 ± 14	201 ± 80	57 ± 38
Musculium sp.	0	0	0	14 ± 14	0	14 ± 14	0	14 ± 14
Dreissena polymorpha	0	29 ± 14	0	359 ± 175	316 ± 123	316 ± 132	14 ± 14	15758 ± 15715
Isopoda								
Caecidotea	0	0	0	0	0	29 ± 29	43 ± 0	158 ± 137

TABLE 4.4.1.1 (CONTINUED) BENTHIC MACROINVERTEBRATE DISTRIBUTION IN MUSKEGON LAKE (#/M^2), OCTOBER 1999. MEAN NUMBER OF ORGANISMS (± STANDARD ERROR) REPORTED FOR EACH STATION.

Station	Musk-1	Musk-3	Musk-4	Musk-5	Musk-6	Musk-7	Musk-8	Musk-9
Taxa								
Amphipoda								
Gammarus sp.	14 ± 14	144 ± 29	1206	244 ± 87	330 ± 57	29 ± 14	57 ± 29	57 ± 38
Hyalella sp.	29 ± 14	0	43	43 ± 43	29 ± 29	0	0	86 ± 66
Echinogammarus sp.	0	0	0	0	0	0	0	57 ± 38
Diptera								
Ceratopogonidae*	0	0	0	0	0	0	0	0
Probezzia sp.	0	0	0	0	0	14 ± 14	14 ± 14	0
Chaoboridae								
Chaoborus sp.	115 ± 52	129 ± 75	0	29 ± 14	57 ± 38	57 ± 29	158 ± 29	86 ± 66
Chironomidae								
Chironominae								
Chironomus sp.	445 ± 29	1163 ± 197	474	14 ± 14	0	57 ± 38	230 ± 63	115 ± 29
Cladopelma sp.	0	0	86	0	0	0	0	0
Cryptochironomus sp.	0	57 ± 29	43	115 ± 76	144 ± 63	172 ± 25	115 ± 63	144 ± 29
Cryptochironomus digitatus	0	0	0	0	0	0	0	0
Dicrotendipes sp.	0	0	0	0	0	0	0	14 ± 14
Paratanytarsus sp.	0	0	0	0	0	0	0	0
Polypedilum spp.	0	0	0	0	0	0	0	0
Tanytarsus sp.	14 ± 14	0	0	0	0	0	0	0
Orthocladiinae								
Heterotrissocladius oliveri	0	0	0	0	0	0	0	0
Tanypodinae								
Ablabesmyia annulata	0	0	0	0	0	0	0	14 ± 14
Coelotanypus concinnus	0	14 ± 14	0	976 ± 486	474 ± 124	223 ± 57	144 ± 38	215 ± 86
Conchapelopia sp.	0	0	0	0	0	0	0	14 ± 14
Procladius sp.	187 ± 38	158 ± 63	43	144 ± 29	72 ± 72	100 ± 38	158 ± 38	187 ± 52
Ephemeroptera								
Caenis sp.	0	0	0	0	0	0	0	0
Tricoptera								
Ocetis sp.	0	0	0	14 ± 14	14 ± 14	29 ± 29	0	0
Neureclipsis sp.	0	0	0	0	0	0	0	14 ± 14

TABLE 4.4.1.1 (CONTINUED) BENTHIC MACROINVERTEBRATE DISTRIBUTION IN MUSKEGON LAKE (#/M^2), OCTOBER 1999. MEAN NUMBER OF ORGANISMS (± STANDARD ERROR) REPORTED FOR EACH STATION.

Station	Musk-10	Musk-11	Musk-12	Musk-13	Musk-14	Musk-15	Musk-16
Taxa							
Turbellaria	158 ± 38	29 ± 14	388 ± 179	0	330 ± 94	14 ± 14	201 ± 63
Oligochaeta							
Lumbriculidae							
Stylodrilus heringianus	0	0	0	0	0	0	0
Naididae							
Arcteonais lomondi	0	0	0	0	0	0	34 ± 34
Dero digitata	29 ± 14	79 ± 45	168 ± 120	14 ± 14	0	150 ± 82	0
Dero flabelliger	0	0	0	0	0	0	0
Piguetiella michiganensis	0	0	104 ± 104	0	0	0	0
Salvina appendulata	14 ± 14	0	0	0	0	0	0
Tubificidae							
Aulodrilus americanus	0	0	0	0	0	0	220 ± 79
Aulodrilus limnobius	14 ± 14	27 ± 27	27 ± 27	0	30 ± 30	157 ± 96	121 ± 80
Aulodrilus pigueti	445 ± 117	136 ± 72	725 ± 44	177 ± 91	834 ± 452	1601 ± 682	1611 ± 442
Aulodrilus pluriseta	0	53 ± 27	14 ± 14	43 ± 25	0	150 ± 82	0
Ilyodrilus templetoni	0	0	29 ± 29	0	0	0	0
Isocheatides freyi	0	0	0	0	0	55 ± 55	0
Limnodrilus cervix variant	0	26 ± 26	0	26 ± 26	14 ± 14	0	0
Limnodrilus hoffmeisteri	14 ± 14	106 ± 24	88 ± 47	137 ± 26	70 ± 50	0	0
Limnodrilus maumeensis	0	0	0	0	0	0	0
Limnodrilus udekemianus	0	0	0	0	0	0	30 ± 30
Potamothrix moldaviensis	0	0	14 ± 14	0	0	0	0
Quistadrilus multisetosus	187 ± 38	296 ± 99	14 ± 14	72 ± 38	620 ± 249	232 ± 122	216 ± 77
Immatures w/o hair chaetae	1507 ± 538	6404 ± 597	4654 ± 937	4247 ± 883	6335 ± 1082	6951 ± 1842	4192 ± 1209
Immatures w/hair chaetae	459 ± 100	1859 ± 354	274 ± 98	838 ± 289	1191 ± 254	1193 ± 466	250 ± 22
Polychaeta							
Manayunkia speciosa	14 ± 14	0	0	14 ± 14	0	0	0
Hirudinea							
Glossiphoniidae							
Alboglossiphonia heteroclita	0	0	0	0	0	0	0
Helobdella stagnalis	0	0	0	0	0	0	0
Helobdella elongata	0	43 ± 43	0	0	0	0	0
Mollusca							
Gastropoda							
Amnicola sp.	172 ± 75	0	115 ± 14	0	0	0	388 ± 188
Bithynia sp.	0	0	0	0	0	0	14 ± 14
Valvata tricarinata	43 ± 25	0	29 ± 14	0	0	29 ± 29	72 ± 29
Valvata sincera	0	0	0	0	0	0	29 ± 14
Bivalvia							
Pisidium sp.	1119 ± 99	230 ± 57	459 ± 150	144 ± 76	445 ± 251	474 ± 155	388 ± 124
Sphaerium sp.	402 ± 137	158 ± 63	230 ± 76	100 ± 63	431 ± 217	72 ± 72	57 ± 14
Musculium sp.	0	0	0	14 ± 14	0	0	0
Dreissena polymorpha	129 ± 75	14 ± 14	40860 ± 13976	0	14 ± 14	14 ± 14	5626 ± 1730
Isopoda							
Caecidotea	0	0	0	0	29 ± 29	0	0

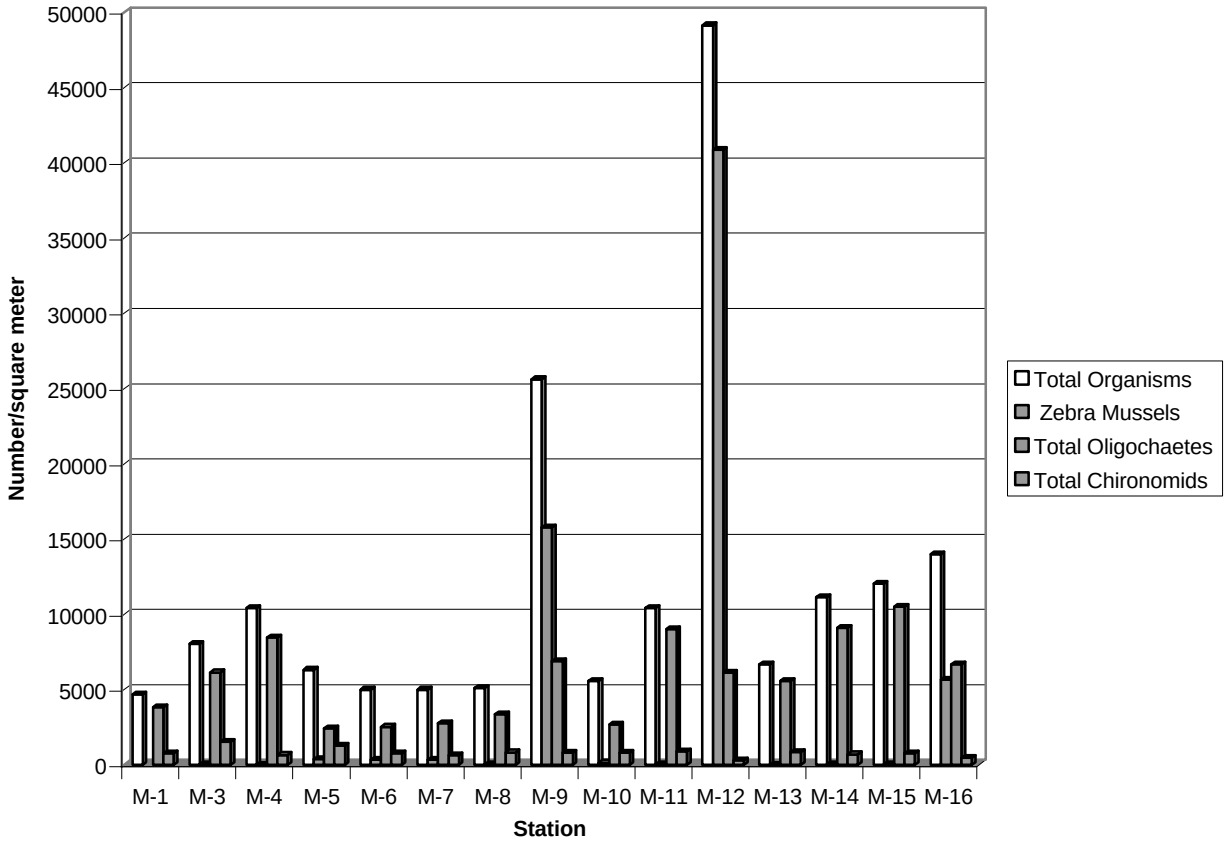
TABLE 4.4.1.1 (CONTINUED) BENTHIC MACROINVERTEBRATE DISTRIBUTION IN MUSKEGON LAKE (#/M^2), OCTOBER 1999. MEAN NUMBER OF ORGANISMS (± STANDARD ERROR) REPORTED FOR EACH STATION.

Station	Musk-10	Musk-11	Musk-12	Musk-13	Musk-14	Musk-15	Musk-16
Taxa							
Amphipoda							
Gammarus sp.	43 ± 25	43 ± 25	502 ± 152	0	57 ± 38	172 ± 25	0
Hyalella sp.	0	0	14 ± 14	0	29 ± 29	0	14 ± 14
Echinogammarus sp.	0	0	100 ± 14	0	0	0	0
Diptera							
Ceratopogonidae*	0	0	0	29 ± 29	43 ± 43	0	0
Probezzia sp.	14 ± 14	0	0	14 ± 14	14 ± 14	0	0
Chaoboridae							
Chaoborus sp.	215 ± 90	57 ± 14	0	187 ± 100	43 ± 25	100 ± 52	57 ± 38
Chironomidae							
Chironominae							
Chironomus sp.	14 ± 14	258 ± 43	43 ± 25	244 ± 52	100 ± 38	431 ± 132	287 ± 87
Cladopelma sp.	0	0	0	0	0	0	0
Cryptochironomus sp.	14 ± 14	144 ± 29	29 ± 14	43 ± 25	144 ± 14	72 ± 38	43 ± 0
Cryptochironomus digitatus	0	0	0	0	0	14 ± 14	0
Dicrotendipes sp.	0	0	0	0	0	0	0
Paratanytarsus sp.	0	0	0	0	0	14 ± 14	0
Polypedilum spp.	0	0	29 ± 29	0	0	0	0
Tanytarsus sp.	0	0	0	0	0	0	0
Orthocladiinae							
Heterotrissocladius oliveri	0	0	0	0	0	0	14 ± 14
Tanypodinae							
Ablabesmyia annulata	14 ± 14	0	0	29 ± 14	57 ± 14	0	0
Coelotanypus concinnus	474 ± 217	187 ± 57	0	43 ± 25	86 ± 25	43 ± 43	0
Conchapelopia sp.	0	0	0	0	0	0	0
Procladius sp.	43 ± 43	244 ± 57	172 ± 114	273 ± 100	244 ± 115	86 ± 66	57 ± 29
Ephemeroptera							
Caenis sp.	0	0	29 ± 29	0	0	0	0
Tricoptera							
Ocetis sp.	0	0	14 ± 14	0	0	0	43 ± 25
Neureclipsis sp.	0	0	0	0	0	0	0

TABLE 4.4.1.2 MEAN ABUNDANCE (#/M^2) AND RELATIVE DENSITIES (%) OF MAJOR TAXONOMIC GROUPS IN MUSKEGON LAKE, OCTOBER 1999.

Station	Oligochaetes	Chironomids	Sphaeriids	Amphipods	*Dreissena*	Other	Total
M-1	3802(81.8)	646(13.9)	0(0)	43(0.9)	0(0)	158(3.4)	4649
M-3	6132(76.5)	1392(17.4)	115(1.4)	144(1.8)	29(0.4)	200(2.5)	8012
M-4	8461(81.4)	646(6.2)	0(0)	1249(12.0)	0(0)	43(0.4)	10399
M-5	2395(38.0)	1249(19.8)	1607(25.5)	287(4.6)	359(5.7)	402(6.4)	6299
M-6	2511(50.4)	690(13.9)	646(13.0)	359(7.2)	316(6.3)	458(9.2)	4980
M-7	2740(55.0)	559(11.2)	904(18.2)	29(0.6)	316(6.3)	430(8.6)	4978
M-8	3458(66.7)	647(12.5)	632(12.2)	57(1.1)	14(0.3)	373(7.2)	5181
M-9	6898(26.9)	703(2.7)	329(1.3)	200(0.8)	15758(61.5)	1723(6.7)	25611
M-10	2669(48.2)	559(10.1)	1521(27.5)	43(0.8)	129(2.3)	616(11.1)	5537
M-11	8986(86.5)	833(8.0)	388(3.7)	43(0.4)	14(0.1)	129(1.2)	10393
M-12	6111(12.4)	273(0.6)	689(1.4)	616(1.3)	40860(83.2)	575(1.2)	49124
M-13	5554(83.0)	632(9.4)	258(3.9)	0(0)	0(0)	244(3.6)	6688
M-14	9094(81.5)	631(5.7)	876(7.8)	86(0.8)	14(0.1)	459(4.1)	11160
M-15	10489(87.2)	660(5.5)	546(4.5)	172(1.4)	14(0.1)	143(1.2)	12024
M-16	6674(47.8)	401(4.1)	445(3.2)	14(0.1)	5626(40.3)	804(5.8)	13964

FIGURE 4.4.1.1 GENERAL DISTRIBUTION OF BENTHIC MACROINVERTEBRATES IN MUSKEGON LAKE, OCTOBER 1999.



station near Ruddiman Creek (M-1) was historically influenced by the discharge of paper mill effluent and would also have organically enriched sediments. Sites with the highest levels of contaminants (M-5, M-6, and M-16) had lower oligochaete densities (≈ 50%). While the sandy substrate and lower levels of organic carbon at M-16 would tend to reduce oligochaete densities, the sediments near the Division Street Outfall (M-5 and M-6) had higher levels of organic carbon (4.1 mg/kg and 5.3 mg/kg) the stations with the highest oligochaete populations (M-14, 2.3 mg/kg and M-15, 2.5 mg/kg).

Densities of Chironomidae ranged between 1,392/m^2 and 273/m^2 and this taxa group was the second most abundant group at 7 of the 15 of the stations sampled (Table 4.4.2). A total of 14 taxa were identified (Table 4.4.1.1). *Chironomus* spp. and *Procladius* spp. were found at all sites except M-6. Abundance of *Chironomus* spp. ranged 0/m^2 to 1163/m^2) and was generally the most common chironomid encountered. *Procladius* spp. abundance was low and did not exceed 273/m^2. With the exception of *Coelotanypus concinnus* and *Cryptochironomus* spp., the remaining species were found infrequently and were generally

low in abundance. *Cryptochironomus* spp. was present at all sites except M-1 and generally in lower abundance than *Chironomus* spp. Organisms from this genus are predatory in nature and do not exclusively feed on organic detritus like *Chironomus* spp. (Berg 1995). Sites with the highest levels of heavy metals (M-5, M-6, and M-7) had chironomid populations dominated by this organism, which may suggest an impact from contaminated sediments. *Chironomus* spp. was the most abundant midge genera in the enriched stations with the highest oligochaete densities.

4.4.2 Analysis of Macroinvertebrate Results Using Trophic Indices and Diversity Metrics

The benthic macroinvertebrate data were analyzed by a variety of trophic status indices and diversity metrics. The following indices and metrics were utilized:

- Shannon Weaver Diversity (Krebs 1989)
- Margalef's Richness (Krebs 1989)
- Evenness (Krebs 1989)
- Pielou's J (Krebs 1989)
- Oligochaete Index (Howmiller and Scott 1977 and Hilsenhoff 1987)
- Chironomid Index (Hilsenhoff 1987)
- Oligochaete + Chironomid Index (*)
- Trophic Index (Hilsenhoff 1987)

* Modified from Howmiller and Scott (1977)

Tolerance values used to calculate the Trophic Index and the individual indices for Chironomids and Oligochaetes were taken from Winnell and White (1985), Lauritsen et al. (1985), Hilsenhoff (1987), Schloesser et al. (1995), and Barbour et al. (1999). The results of the population metrics are summarized in Table 4.4.2.1. Trophic Indices for the benthic populations are shown in Figure 4.4.2.1. Lower scores for total organisms, oligochaetes, and

TABLE 4.4.2.1 SUMMARY OF DIVERSITY AND TROPHIC STATUS METRICS FOR THE BENTHIC MACROINVERTEBRATES IN MUSKEGON LAKE, OCTOBER 1999.

Metric	M-1	M-3	M-4	M-5	M-6	M-7	M-8	M-9	M-10	M-11	M-12	M-13	M-14	M-15	M-16
Hilsenhoff	8.3865	8.8546	6.0045	6.8754	6.7584	6.4994	8.3561	7.0702	7.4549	9.1667	7.1698	8.9730	8.5295	8.3145	7.4694
Oligochaete	8.2854	8.9614	6.2585	6.9419	6.9170	5.5842	8.9156	7.7809	8.3180	9.3893	8.8738	9.1560	8.9780	8.4430	8.0726
Chironomid	9.3378	9.4052	9.3067	7.8069	7.6896	7.9128	8.5689	8.1020	7.7385	8.5500	8.5684	8.7841	8.0182	8.9804	9.0607
Shannon- Weaver	1.9464	1.8849	1.5637	2.1258	2.1697	2.2149	1.9476	1.5125	2.2021	1.7772	0.7375	1.6583	1.8104	1.5016	1.6967
Margalef's richness	1.8947	1.8912	1.5136	2.5148	1.9969	2.5842	2.1094	2.6600	2.3203	1.8380	2.1292	1.8176	1.9321	1.9159	2.0955
Evenness	0.4120	0.3659	0.3184	0.3643	0.4864	0.3983	0.3691	0.1621	0.4307	0.3285	0.0871	0.3088	0.3217	0.2363	0.2598
J	0.6870	0.6521	0.5774	0.6780	0.7507	0.7064	0.6615	0.4539	0.7233	0.6149	0.2320	0.5853	0.6149	0.5100	0.5573
Total Organisms	4650	8013	10399	6300	4980	4980	5081	25605	5540	10395	49125	6652	11118	12027	13966
Zebra Mussels	0	29	0	359	316	316	14	15758	129	14	40860	0	14	14	5626
Total oligochaetes	3803	6133	8461	2397	2512	2741	3358	6890	2669	8988	6112	5547	9094	10492	6675
Total Chironomids	761	1521	646	1277	746	631	818	789	789	890	273	832	689	761	459
Taxa richness	17	18	15	23	18	23	19	28	21	18	24	17	19	19	21
Chiro/Oligo Ratio	0.1698	0.2270	0.0763	0.5210	0.2743	0.2042	0.1923	0.1021	0.2097	0.0926	0.0446	0.1138	0.0694	0.0629	0.0602
Chironomid Detritivores	445	1163	560	14	0	72	244	129	29	258	43	258	115	431	287
Chironomid Predators	201	230	86	1234	689	502	416	574	545	574	230	388	531	230	115

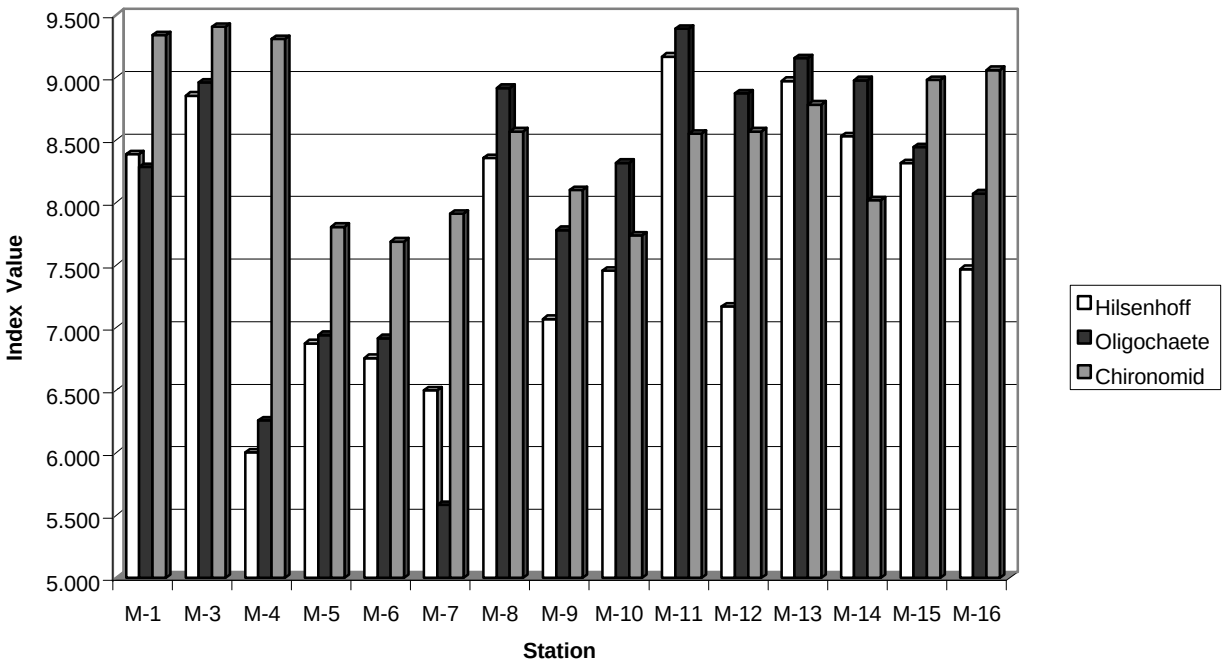


FIGURE 4.4.2.1 SUMMARY OF TROPHIC INDICES FOR THE BENTHIC MACROINVERTEBRATES IN MUSKEGON LAKE, OCTOBER 1999.

chironomids were noted at M-5, M-6, and M-7 than most of the other locations in Muskegon Lake. This indicates that organisms less tolerant of organic enrichment were present in this area. A further analysis of the chironomid populations is shown in Figure 4.4.2.2. When the chironomids are split into detritivores and predators, sediment feeding organisms in the Chironominae group are reduced in the area of the Division Street Outfall. When the chironomids are split into detritivores and predators, sediment feeding organisms in the Chironominae group are reduced in the area of the Division Street Outfall. In contrast, predatory chironomids in the Tanypodinae group are abundant at this location. This pattern is reversed at the other locations, as sediment feeding genera are greater in number. The presence of more predatory chironomids may indicate toxicity in the sediments as sediment feeding organisms are reduced. A similar shift in benthic populations was noted in a highly contaminated area of White Lake (Rediske et al. 1998) that was impacted by elevated concentrations of chromium, arsenic, and mercury.

Data for the Shannon-Weaver Diversity and Pielou's J Indices are shown in Figure 4.4.2.3. Stations M-5, M-6, M-7, and M-10 had Shannon-Weaver Diversity values in excess of 2.0. Benthic macroinvertebrate populations from these locations were characterized by lower numbers of oligochaetes and more predatory chironomids. All stations with the exception of

FIGURE 4.4.2.2 SUMMARY OF CHIRONOMID DETRITIVORES AND PREDATORS FOR THE BENTHIC MACROINVERTEBRATES IN MUSKEGON LAKE, OCTOBER 1999.

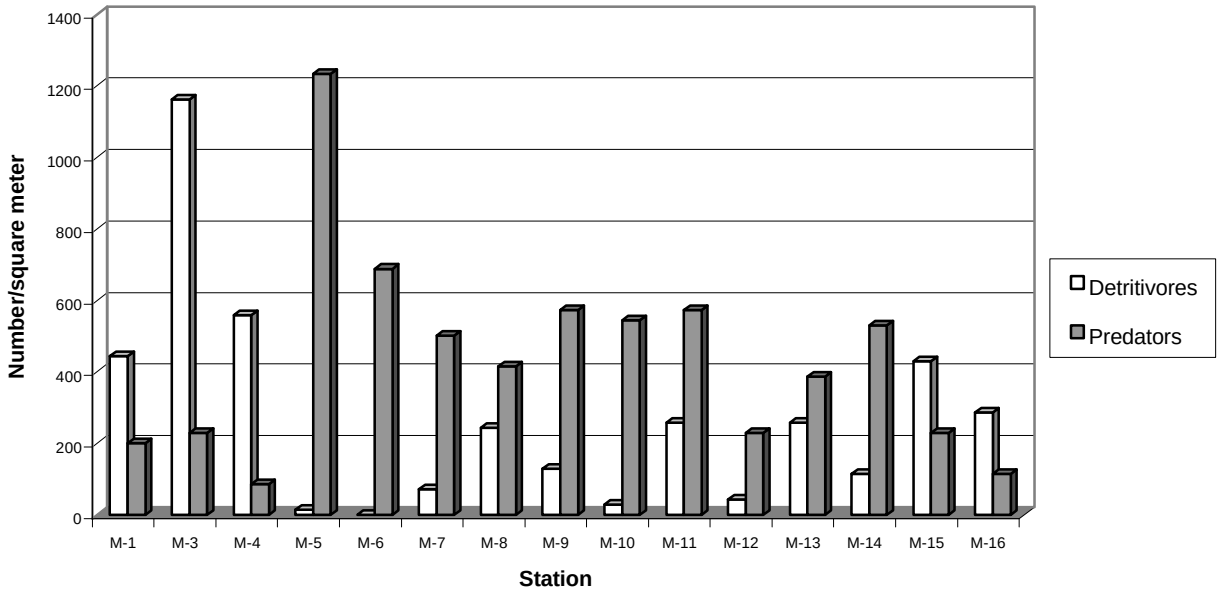
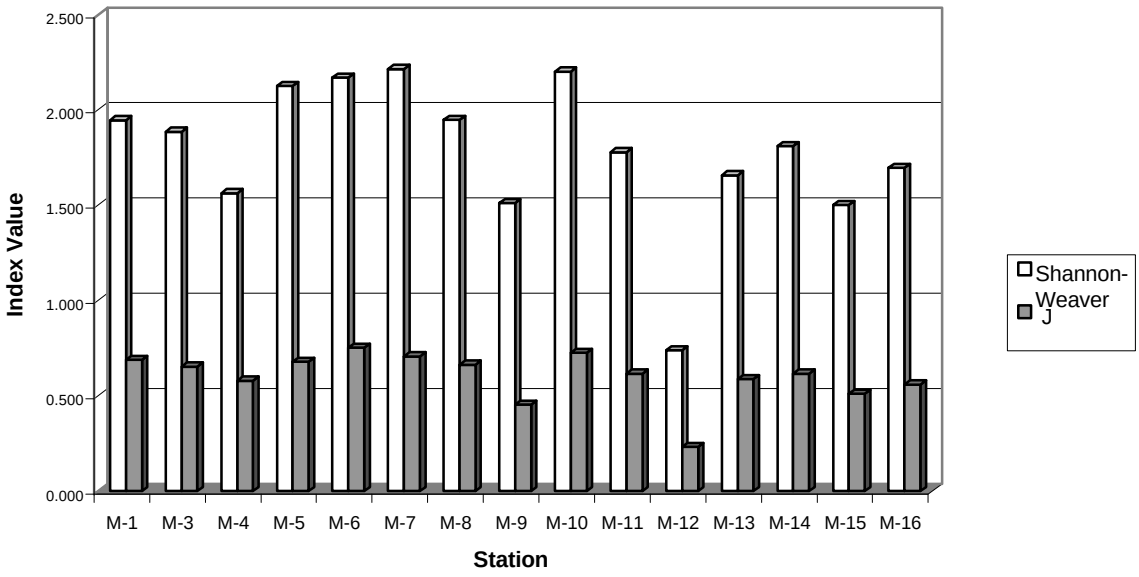


FIGURE 4.4.2.3 SUMMARY OF DIVERSITY AND THE J INDEX VALUES FOR THE BENTHIC MACROINVERTEBRATES IN MUSKEGON LAKE, OCTOBER 1999.



M-12, which was highly impacted by zebra mussels, had diversity values ranging from 1.5 – 2.0. Very little variation was noted in the J value with the exception of M-12 that was influenced by excessive numbers of zebra mussels.

4.4.3 Benthic Macroinvertebrate Analyses Based On Location Groups

The benthic macroinvertebrate data were further analyzed to determine if statistically significant differences existed between locations potentially impacted by the Division Street Outfall (M-5 through M-7) and stations potentially influenced by the Lakey/Teledyne Foundry complex (M-10 and M-11). The same metrics in Table 4.4.2.1 were utilized except that the values were calculated based on the individual replicates.

For the purpose of statistical analysis, the following groups were examined:

- Control (M-13, M-14, and M-15)
- Group 1 – Division Street Outfall (M-5, M-6, and M-7)
- Group 2 – Foundry (M-10 and M-11)

Group 1 locations were in the Division Street Outfall area and had the highest reported values for heavy metals; Group 2 locations were in the vicinity of the Lakey/Teledyne foundry complex. Station M-12 was not included in the analysis due to the sandy substrate and the presence of a large zebra mussel population. The calculated data for the above metrics are summarized in Table 4.4.3.1. Box plots of the data for the Oligochaete Index, N, the Oligochaete/Chironomid ratio, and total Oligochaetes are shown in Figures 4.3.1-4.3.4, respectively. Stations in the Division Street Outfall area have fewer total organisms, a smaller oligochaete population, and a higher proportion of chironomids to oligochaetes compared to the control or foundry locations. The box plot of the Oligochaete Index (Fig 4.4.3.1) suggests that more pollution intolerant species are present (lower index value); however the data are skewed by the larger populations present at the control and foundry sites.

A separate Analysis of Variance (ANOVA) for each of the metrics was used to investigate differences between the three groups of sites. The null hypothesis is that the mean diversity measures for each group are equal. The null hypothesis was rejected if statistically significant p values ($p < 0.05$) were obtained. Post hoc comparisons on the means of the above groups were then performed using the Student-Newman-Keuls (SNK) test. The results of the ANOVA and SNK ranks are summarized in Table 4.4.3.2. All analyses were performed using SAS and SPSS.

TABLE 4.4.3.1 SUMMARY STATISTICS FOR THE ANALYSIS OF INDIVIDUAL BENTHIC MACROINVERTEBRATE SAMPLES FROM MUSKEGON LAKE, OCTOBER 1999.

	Division Street Outfall								
	M-5 A	M-5B	M-5C	M-6 A	M-6B	M-6C	M-7 A	M-7B	M-7C
Total Oligochaetes	3230	1808	2153	775	3014	3832	2196	474	560
Total Chironomids	1636	1851	258	301	603	1163	474	517	689
Total Chironomid Predators	1636	1851	215	301	603	1163	344	517	646
Total Chironomid Detritivores	0	0	43	0	0	0	129	0	43
Hilsenhoff index	7.342	6.790	7.121	6.832	6.471	6.954	8.076	7.793	7.543
Oligochaete index	8.597	6.040	8.095	8.526	6.463	6.961	8.483	8.908	8.403
Chironomid index	7.726	7.821	8.217	7.600	7.550	7.785	8.145	7.900	7.763
Shannon- Weaver	2.060	1.780	1.817	1.872	1.890	2.024	1.850	2.115	2.116
Margalef's richness	1.851	1.280	1.754	1.164	1.518	1.482	1.700	1.820	1.722
Evenness	0.461	0.494	0.385	0.650	0.473	0.541	0.398	0.518	0.553
J	0.727	0.716	0.655	0.813	0.716	0.767	0.667	0.763	0.781
N	5683	5382	5167	2282	5253	6458	6803	3789	3401
Taxa richness	16	11	15	9	13	13	15	15	14
Chiro/Oligo	0.507	1.024	0.120	0.389	0.200	0.303	0.216	1.091	1.231

	Foundry Area					
	M-10 A	M-10B	M-10C	M-11 A	M-11B	M-11C
Total Oligochaetes	2971	1508	3532	10027	8220	8772
Total Chironomids	215	947	517	818	990	689
Total Chironomid Predators	215	904	517	603	775	344
Total Chironomid Detritivores	0	43	0	215	215	344
Hilsenhoff index	7.463	7.279	7.676	9.161	9.029	9.471
Oligochaete index	8.330	8.285	8.422	9.425	9.234	9.672
Chironomid index	7.700	7.786	7.667	8.532	8.387	8.806
Shannon- Weaver	2.003	2.131	1.895	1.308	1.414	1.468
Margalef's richness	1.510	1.416	1.725	1.389	1.309	1.303
Evenness	0.530	0.648	0.416	0.264	0.316	0.334
J	0.759	0.831	0.683	0.496	0.551	0.572
N	5468	4780	5986	11577	9597	10020
Taxa richness	13	12	16	13	13	13
Chiro/Oligo	0.072	0.628	0.146	0.082	0.120	0.079

	Control								
	M-13 A	M-13B	M-13C	M-14 A	M-14B	M-14C	M-15 A	M-15B	M-15C
Total Oligochaetes	3186	6503	6890	12487	8909	5900	8568	8389	33511
Total Chironomids	818	431	646	947	517	431	1033	474	474
Total Chironomid Predators	474	215	474	775	431	388	344	215	129
Total Chironomid Detritivores	344	215	172	172	86	43	689	258	344
Hilsenhoff index	9.050	8.789	8.891	8.238	8.881	8.734	7.646	8.434	7.370
Oligochaete index	9.758	8.839	9.026	8.739	9.191	9.258	7.596	8.643	7.384
Chironomid index	8.753	8.410	9.073	8.436	7.808	7.350	8.904	9.327	8.800
Shannon- Weaver	1.742	1.150	1.521	1.694	1.285	1.879	1.226	1.678	1.634
Margalef's richness	1.531	1.016	0.999	1.445	1.193	1.688	0.868	1.412	1.242
Evenness	0.408	0.316	0.458	0.363	0.301	0.409	0.378	0.383	0.366
J	0.660	0.499	0.661	0.626	0.517	0.678	0.558	0.636	0.619
N	4865	7020	8182	16146	10071	7234	10032	9982	35018
Taxa richness	14	10	10	15	12	16	9	13	14
Chiro/Oligo	0.257	0.066	0.094	0.076	0.058	0.073	0.121	0.056	0.014

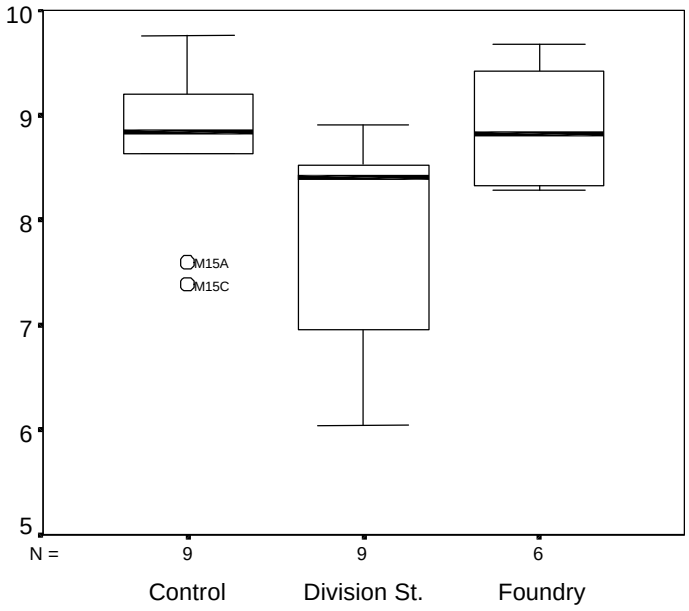


FIGURE 4.4.3.1 BOX PLOT OF THE OLIGOCHAETE INDEX DATA FOR MUSKEGON LAKE BENTHIC MACROINVERTEBRATE STATIONS (BOX = 25%-75% DATA DISTRIBUTION), OCTOBER 1999.

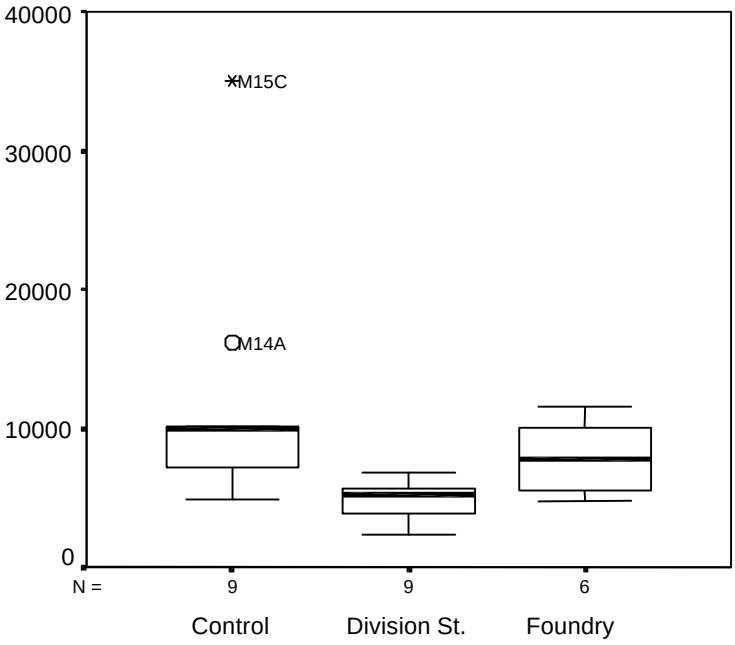


FIGURE 4.4.3.2 BOX PLOT OF THE TOTAL NUMBER OF ORGANISMS FOR MUSKEGON LAKE BENTHIC MACROINVERTEBRATE STATIONS (BOX = 25%-75% DATA DISTRIBUTION), OCTOBER 1999.

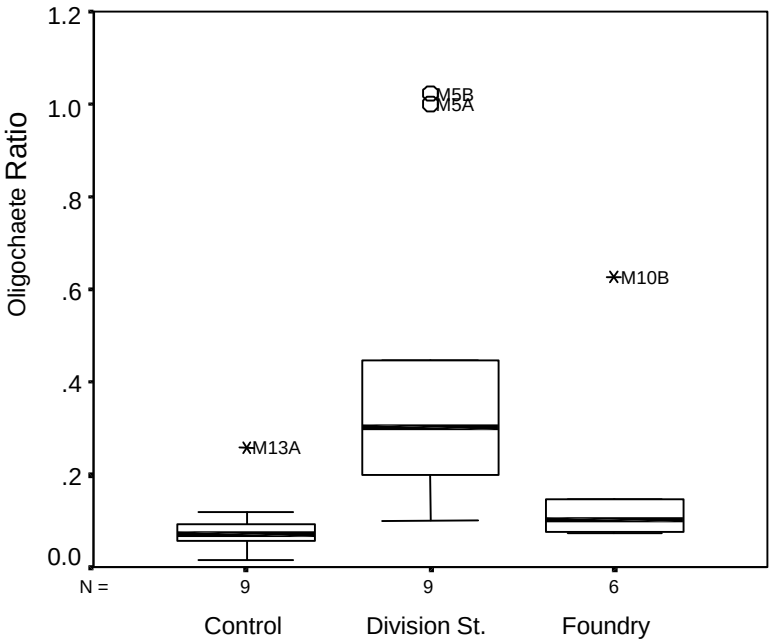


FIGURE 4.4.3.3 BOX PLOT OF THE OLIGOCHAETE/CHIRONOMID RATIO FOR MUSKEGON LAKE BENTHIC MACROINVERTEBRATE STATIONS (BOX = 25%-75% DATA DISTRIBUTION), OCTOBER 1999.

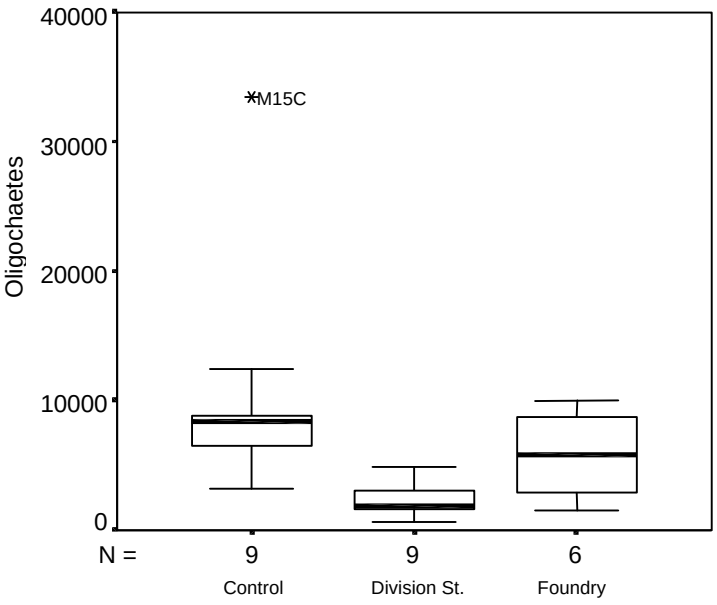


FIGURE 4.4.3.4 BOX PLOT OF THE TOTAL OLIGOCHAETE NUMBERS FOR MUSKEGON LAKE BENTHIC MACROINVERTEBRATE STATIONS (BOX = 25%-75% DATA DISTRIBUTION), OCTOBER 1999.

TABLE 4.4.3.2 RESULTS OF ANOVA AND SNK EVALUATIONS OF BENTHIC MACROINVERTEBRATE DATA FOR MUSKEGON LAKE, OCTOBER 1999.

Diversity Measure	ANOVA p-value*	SNK post-hoc results**
Shannon-Weaver	.0035	SNK Grouping Mean N group A 1.9471 9 Division Street B 1.7032 6 Foundry B 1.5343 9 Control
Evenness	.0054	SNK Grouping Mean N group A 0.49700 9 Division Street B 0.41800 6 Foundry B 0.37578 9 Control
J	.0023	SNK Grouping Mean N group A 0.73389 9 Division Street B 0.64867 6 Foundry B 0.60600 9 Control
Margalef's Richness	.0570	
Oligochaete Index	.0124	SNK Grouping Mean N group A 8.8947 6 Foundry A 8.7149 9 Control B 7.8307 9 Division Street
Chironomid Index	<.0001	SNK Grouping Mean N group A 8.5401 9 Control B 8.1463 6 Foundry C 7.8341 9 Division Street
Hilsenhof	<.0001	SNK Grouping Mean N group A 8.4481 9 Control A 8.3465 6 Foundry B 7.2136 9 Division Street
Total Chironomids	.5050	
Total Predators	.1866	
Taxa Richness***	.3715	
Chironomid to Oligochaete Ratio***	.0328	SNK Grouping Mean N group A 18.278 9 Division Street B 11.917 6 Foundry B 7.111 9 Control
Total Number of Organisms***	.0011	SNK Grouping Mean N group A 17.333 9 Control A 13.667 6 Foundry B 6.889 9 Division Street
Total Oligochaetes***	.0441	SNK Grouping Mean N group A 10483 9 Control B A 5838 6 Foundry B 2373 9 Division Street
Total Detritivores***	.0004	SNK Grouping Mean N group A 258.33 9 Control B 136.34 6 Foundry C 23.92 9 Division Street

* Reject the null hypothesis and conclude that at least one group has a different mean and $p < 0.05$. If you reject Ho then run the post-hoc SNK procedure.

** Different letters indicate a statistically significant difference in the means of the groups.

*** Nonparametric ANOVA done on the ranks of the data.

Based on the ANOVAs and SNK groupings, the following conclusions can be drawn:

- The Division Street Outfall group had a significantly higher mean than either the Foundry or the Control groups for Shannon-Weaver, Evenness, J, and Chironomid to Oligochaete Ratio. The Foundry and Control groups were not significantly different.
- The Division Street Outfall group had a significantly lower mean than either the Foundry or the Control groups for the Oligochaete Index, Hilsenhof Index, and Total Number of Organisms. The Foundry and Control groups were not significantly different.
- The Control group had a significantly higher mean than the Foundry group, which had a significantly higher mean than the Division Street group for the Chironomid Index and Total Detritivores.
- For Total Oligochaetes the Control group had a significantly higher mean than the Division Street Outfall group. The Control group and the Foundry group were not significantly different. The Foundry group and the Division Street Outfall group were also not significantly different.

4.4.4. Benthic Macroinvertebrate Data Summary

The benthic macroinvertebrate community of Muskegon Lake is characterized by organisms that are tolerant of organic (nutrient) enrichment. The presence of organic deposition from the Muskegon River, the eutrophic conditions in the lake, and the historical anthropogenic enrichment from the paper mill and the wastewater treatment plant all act to increase the densities pollution tolerant organisms. To this extent, detritivores such as tuberficids and chironomids from the genus *Chironomus* should dominate the benthic populations (Winnell and White 1985). While these conditions would indicate habitat degradation in a more pristine system, organic enrichment forms the basis for structuring the benthic community in Muskegon Lake. The only sites that do not fit this characterization were from the Division Street Outfall, the lakeshore industrial area, and one site near the abandoned foundry complex. These locations had fewer total organisms and consequently, better scores for most diversity metrics. The most notable difference with respect to this group of stations was a change in chironomid species from detritivores to predators. A shift to more opportunistic organisms has previously been attributed to contaminant impact (Dauer 1991). A more detailed evaluation of the nutrient and organic composition would need to be performed to determine if this shift was related to food quality or a response to sediment contamination. These stations had similar TOC and grain size distributions when compared to the control group so response to contamination is the most likely explanation.

4.5 Sediment Quality Triad Assessment

Sediment Quality Triads for the areas of sediment contamination in Muskegon Lake were calculated using chemistry, toxicity, and diversity metrics (Canfield et al. 1998, Del Valles and Chapman 2000). For the chemistry metric of the triad, concentrations of chromium, lead, cadmium, copper, and mercury were summed. PAH compounds were not included since they were present at very high levels in only one location and would bias the chemistry assessment. As a result, a triad diagram was not prepared for location M-16. Sediments at this location were toxic to amphipods and midges and PAH levels were in excess of 5X the PEC guidelines. For the toxicity component, amphipod and midge mortality were used. The diversity metric included the following metrics: Shannon-Weaver, oligochaete trophic index, chironomids trophic index, Hilsenhof trophic index, J, Margalef's Richness, evenness, N, taxa richness, Chironomid/Oligochaete ratio, total chironomids, total oligochaetes, total predatory chironomids, and total chironomid detritivores. The actual diversity measures used were the absolute deviation from the average of the reference sites M-13, M-14, and M-15. These reference sites have benthic macroinvertebrate assemblages that were characteristic of organic enrichment in the sediments. The Sediment Quality Triad diagrams for the Ruddiman Creek area, the Division Street Outfall, and the former foundry complex are shown in Figures 4.5.1, 4.5.2, and 4.5.3, respectively. Triad diagrams for the Division Street Outfall (Fig 4.5.2) show the greatest deviation from the reference locations for chemistry, toxicity, and diversity. At these locations, heavy metals exceeded PEC guidelines, statistically significant toxicity to amphipods was observed at two of the three sites, and benthic macroinvertebrate populations were reduced in total organisms and found to contain more predatory genera. The area downstream of Ruddiman Creek (Fig 4.5.1) showed moderate differences in chemistry, toxicity, and diversity when compared to the reference locations. Stations near the former foundry complex (Fig 4.5.3) showed the least amount of difference from the reference conditions for chemistry and toxicity. The deviation in diversity at M-10 from the reference sites was 71% of the maximum observed deviation indicating that the benthic community structure was impacted. This location was also characterized by a reduction in total numbers and a shift to more predatory genera. There is insufficient information available to determine an environmental reason for diversity differences at this site.

The individual site Triads were analyzed for correlations between the three component measurements. The results are summarized below:

	Chemistry	**Toxicity**	**Diversity**
Chemistry	1.000		
Toxicity	0.869 (.0002)	1.000	
Diversity	0.793 (.0021)	0.664 (.0186)	1.000

(p value)

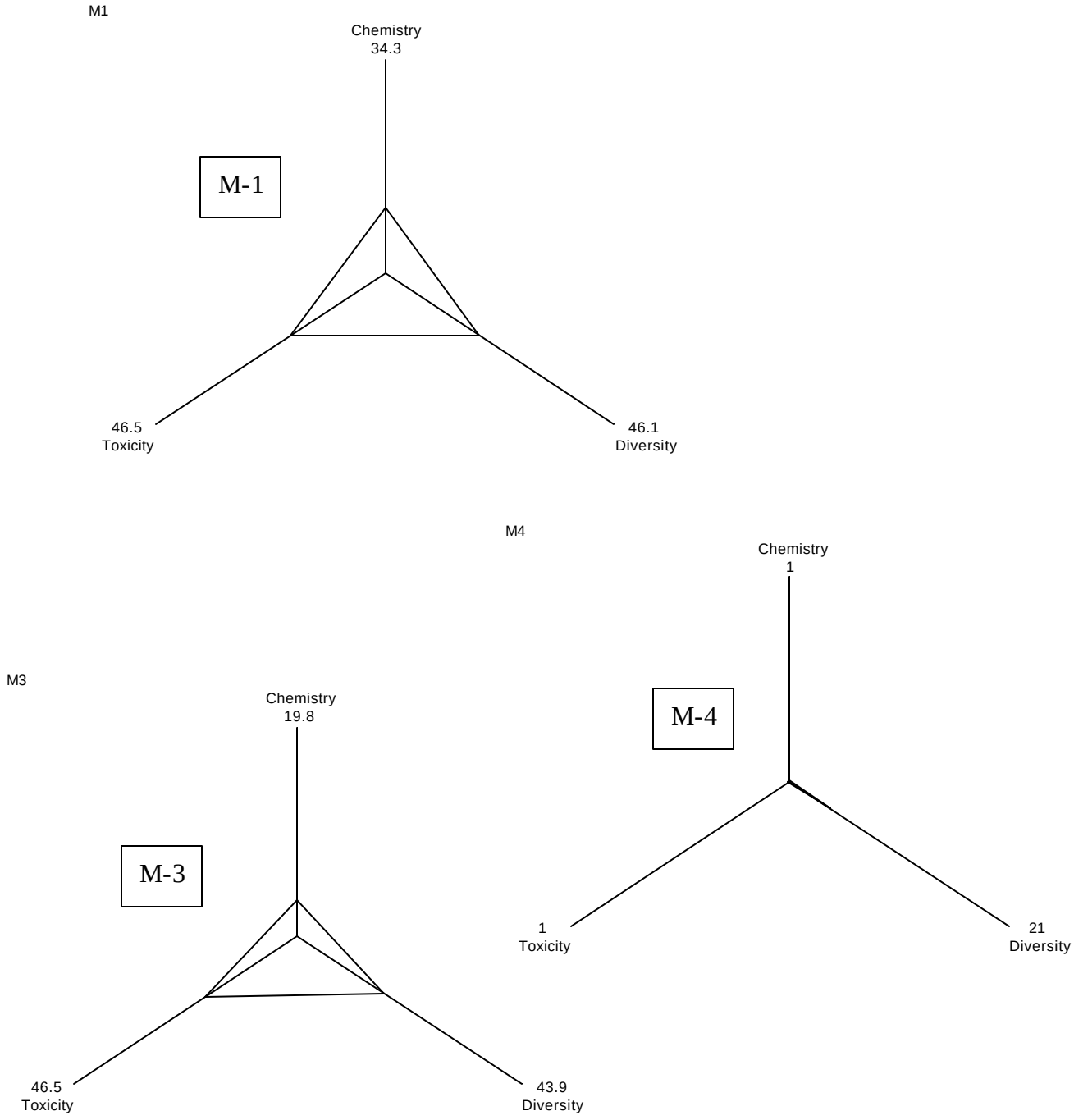


FIGURE 4.5.1. SEDIMENT QUALITY TRIAD DIAGRAMS FOR THE RUDDIMAN CREEK AREA OF MUSKEGON LAKE.

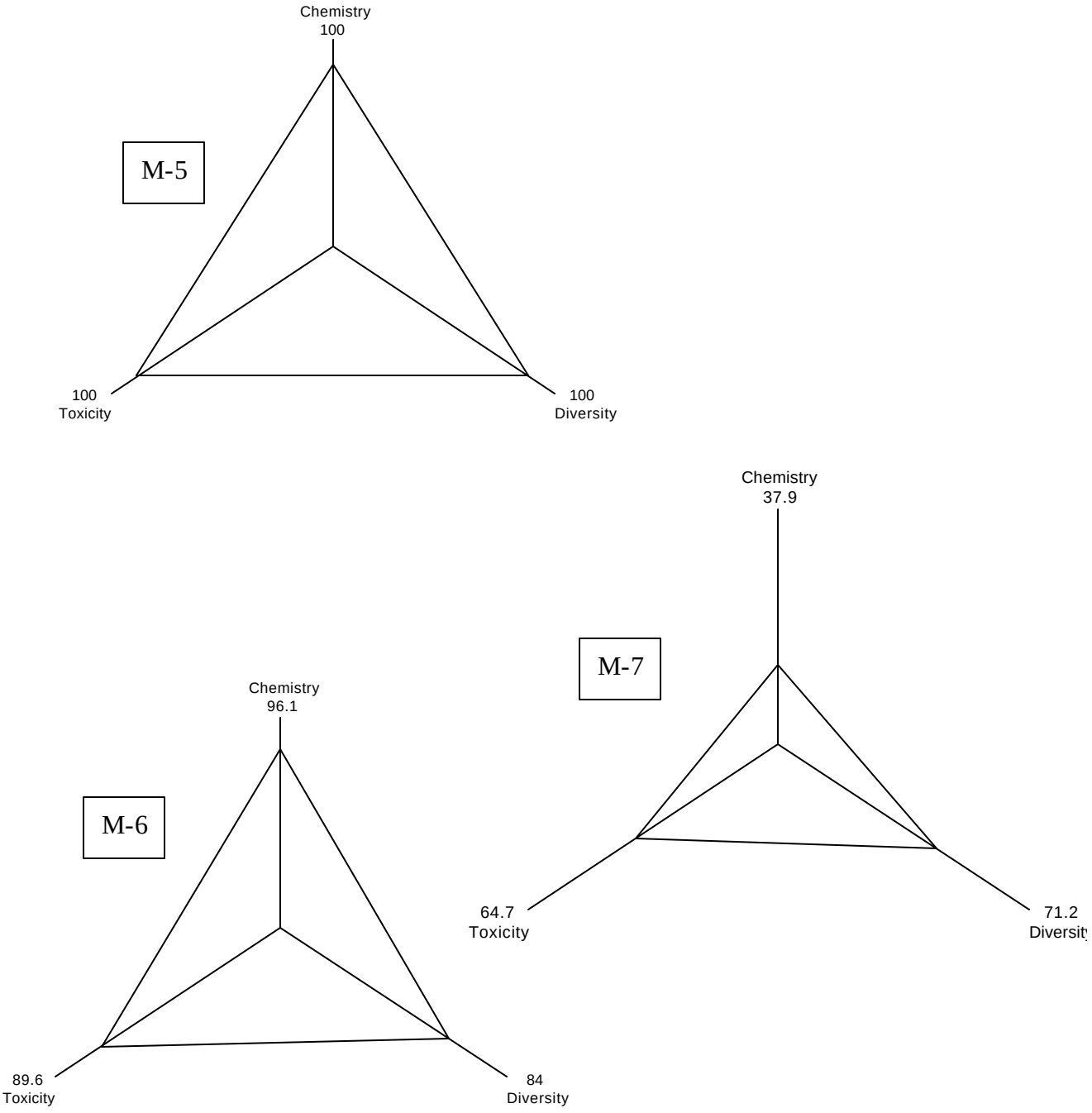
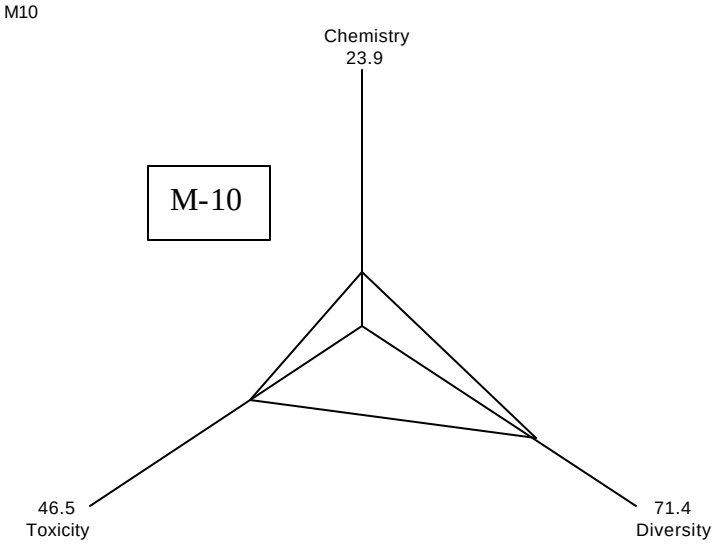


FIGURE 4.5.2. SEDIMENT QUALITY TRIAD DIAGRAMS FOR THE DIVISION STREET OUTFALL AREA OF MUSKEGON LAKE.



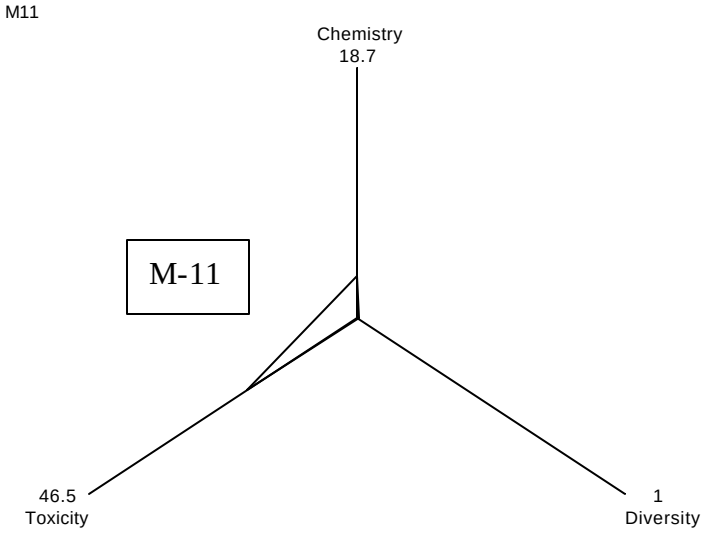


FIGURE 4.5.3. SEDIMENT QUALITY TRIAD DIAGRAMS FOR THE FORMER FOUNDRY COMPLEX AREA OF MUSKEGON LAKE.

A positive correlation was found between each pair of measures. Sites with high levels of metals were also high in toxicity. Sites with elevated levels of heavy metals also had diversity values that were unlike the reference sites. Similarly, sites with high toxicity had diversity metrics that were dissimilar to the reference sites.

The data making up the Sediment Quality Triad were also examined by Principal Component Analysis (PCA) to examine the similarity between sediment sampling sites. Standardized values were computed for each site and measurement used in the Triad by subtracting the mean and dividing the result by the standard deviation. Separate PCAs were run on the six chemistry variables, the two toxicity variables, and the 14 diversity measures. Principal component scores were then calculated for each site for the chemistry, toxicity, and diversity PCAs.

The principle component scores were then used to develop a distance matrix for each pair of sites. The distance site *i* is from site *j* equaled the sum of the absolute values of the differences in the principal component scores for chemistry, toxicity, and diversity. A cluster analysis was then performed on the distance matrix. The results of the PCA and Cluster Analysis is shown in Figure 4.5.4. Three distinct clusters were present: Cluster 1 - M5 and M6; Cluster 2 - M1, M7, M8, and M10; Cluster 3 - M3, M4, M11, M13, M14, and M15. Two of the three Division Street Outfall sites (M5 and M6) form Cluster 1. The three reference sites were all contained in Cluster 3, along with two Ruddiman Creek sites. The two sites in the area near the former Foundry Complex (M10 and M11) were not in the same cluster.

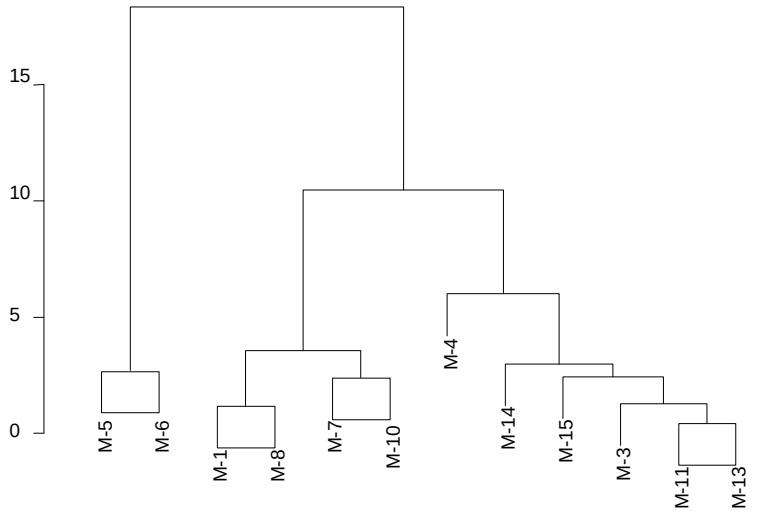


FIGURE 4.5.4 RESULTS OF A CLUSTER ANALYSIS PERFORMED ON PRINCIPAL COMPONENT SCORES FOR SEDIMENT QUALITY TRIAD MEASURES FOR MUSKEGON LAKE SEDIMENT.

These results of the Sediment Quality Triad and Cluster Analysis show that the near shore locations at the Division Street Outfall (M-5 and M-6) exhibit the greatest degree of anthropogenic perturbation with respect to sediment chemistry, toxicity and diversity. The deep basin down stream from Ruddiman Creek (M-1), the more exterior stations at the Division Street Outfall (M-7 and M-8), and the foundry site M-10 were strongly impacted by anthropogenic disturbance. Although Sediment Quality Triad diagrams were not prepared for M-16 due to the high levels of PAH compounds, this location would rank very high with respect to chemistry and toxicity.

In addition to triad diagrams, an assessment matrix (Chapman 1992) has been used to examine the relationship between sediment chemistry, toxicity, and benthic macroinvertebrate data. An assessment matrix for the Muskegon Lake data is presented in Table 4.5.1. Stations exceeding the PEC (MacDonald et al. 2000) were classified as having a potential impact from

TABLE 4.5.1 SEDIMENT QUALITY ASSESSMENT MATRIX FOR MUSKEGON LAKE DATA, OCTOBER 1999. ASSESSMENT MATRIX FROM CHAPMAN (1992).

Station	Sediment Chemistry	Toxicity Test	Benthic Community	Possible Conclusions
M-5 M-6 M-16	**+**	**+**	**+**	Impact highly likely; contaminant induced degradation of sediment dwelling organisms evident
M-3 M-4 M-9 M-11 M-12 M-13 M-14 M-15	**-**	**-**	**-**	Impact highly unlikely; contaminant degradation of sediment dwelling organisms not likely
M-8 M-1	**+**	**-**	**-**	Impact unlikely; contaminants unavailable to sediment dwelling organisms
	-	**+**	**-**	Impacts possible; Unmeasured contaminants or conditions exist that have the potential to cause toxicity
M-10	**-**	**-**	**+**	Impacts unlikely; no degradation of sediment dwelling organisms in the field apparent relative to sediment contamination; physical factors may be influencing benthic community
	+	**+**	**-**	Impact likely; toxic chemicals probably stressing system
	-	**+**	**+**	Impact likely; unmeasured toxic chemicals contributing to the toxicity
M-7	**+**	**-**	**+**	Impact likely; sediment dwelling organisms degraded by toxic chemical, but toxicity tests not sensitive to chemicals present

+ = Indicator classified as affected; as determined based on comparison to the PEC or control site

- = Indicator not classified as affected; as determined based on comparison to the PEC or control site

sediment chemistry. Toxicity and benthic community impacts were based on observing a statistically significant difference in mortality and diversity/trophic status metrics, respectively. Using this assessment methodology, the Division Street Outfall (M-5, M-6 and M-7) and the lakeshore industrial area (M-16) were likely to be impacted by contaminated sediments. At these locations, sediment chemistry was elevated, laboratory toxicity was observed, and impacted benthic communities were noted. The remaining stations

4.6 Summary And Conclusions

A preliminary investigation of the nature and extent of sediment contamination in Muskegon Lake was performed using Sediment Quality Triad methodology. Sediment chemistry, solid-phase toxicity, and benthic macroinvertebrates were examined at 15 locations. In addition, three core samples were evaluated using radiodating and stratigraphy to assess sediment stability and contaminant deposition. High levels of cadmium, copper, chromium, lead, and mercury were found in the Division Street Outfall area. These levels exceeded the Probable Effect Concentrations (PECs) for current sediment quality guidelines. Most of the heavy metals were found in the top 80 cm of the core samples. Deeper layers of contamination were only found near the former Teledyne foundry and downstream from Ruddiman Creek. High concentrations of PAH compounds were found at a location down gradient from the former lakeshore industrial area. These levels also exceeded PEC guidelines. Sediment toxicity was observed at two stations in the Division Street Outfall area and at the lakeshore industrial area. These locations had the highest concentrations of metals and PAH compounds, respectively. Benthic macroinvertebrate communities throughout Muskegon Lake were found to be indicative of organically enriched conditions. The locations in the Division Street Outfall area were significantly different than reference sites, as indicated by fewer numbers and a smaller population of detritivores.

Sediment Quality Triad diagrams were prepared and significant correlations were obtained between chemistry and toxicity and chemistry and diversity ($p < .01$). Toxicity and diversity also were positively correlated ($p < .05$). Based on the results of this investigation, the Division Street Outfall and the location down gradient from the lakeshore industrial area are priority areas for further investigation and potential remediation due to adverse ecological effects, toxicity, and high contaminant levels.

Stratigraphy and radiodating analyses conducted on sediment cores provided important information related to depositional history. Ruddiman Creek appears to have a significant influence on the deposition of heavy metals in the southwestern part of Muskegon Lake. A peak in metals deposition was found that corresponded to the 100+ year flood that occurred in 1986. The historical deposition was considerably higher than current rates. The deep zone off the Car Ferry Dock was not found to be an area that accumulates sediments. High inventories of ^{210}Pb were found near the bottom of this 80 cm core, indicating active mixing and movement of sediments. The presence of elevated metals in the deeper strata plus the high ^{210}Pb inventories suggest that contaminated sediments are moved from the eastern part of Muskegon Lake to this location where they are mixed and made available for resuspension by the currents traveling along the old river channel. The core from the Division Street Outfall showed relatively stable sediments in the top 20 cm followed by a stable zone of heavy

accumulation after 1960. Based on these results it is apparent that the removal of contaminated sediments from Ruddiman Creek and the lagoon would reduce the loading of heavy metals to western Muskegon Lake. The areas of high sediment contamination in the eastern part of the lake also appear to be mixed and subject to transport.

4.7 References

Barbour, M.T., J. Gerritsen, B.D. Snyder, J.B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Berg, M.H. 1995. Larval food and feeding behavior. Pages 139-168 in P. Armitage, P. S. Cranston and L. C. V. Pinder, eds. The Chironomidae: The biology and ecology of non-biting midges. Chapman and Hall, London, England.

Chapman, P.M. 1992. Sediment quality triad approach. In: Sediment Classification Methods Compendium. EPA 823-R-92-006. USEPA. Washington, D.C.

Del Valls, T.A. and P.M. Chapman. 1998. Site-specific sediment quality values for the Gulf of Cadiz (Spain) and San Francisco Bay (USA), using the sediment quality triad and multivariate analysis: Cienc. Mar. 24:313–336.

EPA 1990. Macroinvertebrate Field and Laboratory Methods for Evaluating the Biological Integrity of Surface Waters. EPA/600/4-90/03.

Evans, E.D. 1992. Mona, White, and Muskegon Lakes in Muskegon County, Michigan The 1950s to the 1980s. Michigan Department of Natural Resources. MI/DNR/SWQ-92/261. 91pp.

Dauer, D.M. 1991. Biological criteria, environmental health, and estuarine macrobenthic community structure: Mar. Pollut. Bull. 26:249–257.

Hilsenhoff, W.L. 1987. An Improved Biotic Index of Organic Stream Pollution. Great Lakes Entom. 20:31-39.

Howmiller, R.P., M.A. Scott. 1977. An environmental index based on the relative abundance of oligochaete species. J. Water Pollut. Cont. Fed. 49: 809-815.

Krebs, C. J. (1989). Ecological methodology. New York: Harper & Row. 325 pgs.

Lauritsen, D.D., S.C. Mozley, D.S. White. 1985. Distribution of oligochaetes in Lake Michigan and comments on their use as indices of pollution. J. Great Lakes Res. 11:67-76.

MacDonald, D.D., C.G. Ingersoll, T.A. Berger. 2000. Development and Evaluation of Consensus-Based Sediment Quality Guidelines for Freshwater Ecosystems. Arch. Environ. Contam. Toxicol. 39(1):20-31.

Milbrink, G. 1983. An improved environmental index based on the relative abundance of oligochaete species. Hydrobiologia 102: 89-97.

Rediske, R., G. Fahnenstiel, P. Meier, T. Nalepa, and C. Schelske, 1998. Preliminary Investigation of the Extent and Effects of Sediment Contamination in White Lake, Michigan. U.S. Environmental Protection Agency. EPA-905-R-98-004.

Robbins, J.A., and L.R. Herche. 1993. Models and uncertainty in ^{210}Pb dating of sediments. Int. Ver. Theor. Angew. Limnol. Verh 25:217-222.

Schelske, C.L. and D. Hodell. 1995. Using carbon isotopes of bulk sedimentary organic matter to reconstruct the history of nutrient loading and eutrophication in Lake Erie. Limnol. Oceanogr. 40:918-929.

Schloesser, Don W., Trefor B. Reynoldson, Bruce A. Manny. 1995. Oligochaete fauna of western Lake Erie 1961 and 1982: signs of sediment quality recovery: J. Great Lakes Res. 21(3):294-306.

Winnell, M.H., D.S. White. 1985. Trophic status of southeastern Lake Michigan based on the Chironomidae(Diptera). J. Great Lakes Res. 11:540-548.

5.0 Recommendations

Three areas of significant sediment contamination were identified in this investigation. The contaminated areas and recommendations are provided below:

1. Division Street Outfall. This area has the highest concentration of heavy metals, significant sediment toxicity, and an impacted benthic invertebrate community. There is also indirect evidence that sediments from this area are being transported into the central region of Muskegon Lake. The chemical and physical composition of sediments in the Division Street Outfall should be further delineated and carefully examined for remediation. Since there are a number of abandon brownfield sites in the area and the presence of a large urban storm drain, potential sources of the sediment contamination need to be evaluated and if necessary, controlled as part of the remediation program.
2. Lakeshore Industrial Area. The presence of elevated levels of PAH compounds and high sediment toxicity at this location makes this a priority area for further investigation. The extent of sediment contamination needs to be delineated and the possibility of a venting groundwater plume or the leaching of contaminants form a submerged deposit needs to be evaluated. If an impacted groundwater plume is identified, source control will be necessary to prevent contaminants from entering the lake. Because of the environmental significance of PAH compounds and the high concentrations present at the site, this location should also be evaluated for remediation after the source is identified.
3. Ruddiman Creek. The presence of heavy metals near the confluence of Ruddiman Creek and in the downstream deposition basin suggests that this small watershed is a continuing source of sediment contamination. Investigations and remediation evaluations by the MDEQ and USACOE are in process. Preliminary results from these investigations suggest that a combination of sediment removal and source control will be necessary to complete the remediation. The findings of this investigation should assist in assessing the priority status of sediment remediation in Ruddiman Creek.