J. Great Lakes Res. 32:578–595
Internat. Assoc. Great Lakes Res., 2006

Status and Trends of Benthic Populations in a Coastal Drowned River Mouth Lake of Lake Michigan

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ABSTRACT. *Muskegon Lake was designated an Area of Concern because of severe environmental impairments from direct discharge of industrial and municipal wastes. Since diversion of all municipal and industrial wastewater in 1973, few studies have assessed ecological changes associated with improved water quality. We examined distributions and long-term changes in the benthic macroinvertebrate community at 27 sites. Distributions were evaluated relative to distance from the river mouth, water depth, grain size, and known areas of sediment contamination. Temporal changes were assessed relative to wastewater diversion. Oligochaeta and Chironomidae dominated the community, and the oligochaete trophic condition index indicated that, in 1999, the lake was generally mesotrophic to eutrophic. Cluster analysis resulted in four distinct site groupings. A cluster of sites near the river mouth had the highest total density (9,375 m^{-2}) and lowest diversity (Shannon Weaver Index 1.05) suggesting an enriched habitat. A site cluster in the south central region had the lowest oligochaete density (2,782 m^{-2}), lowest oligochaete trophic condition index scores (1.00), and highest diversity (2.24), suggesting the best habitat. The chironomid community in this site cluster was dominated by predatory species, possibly resulting from high concentrations of heavy metals at some sites. Densities of all major taxonomic groups increased significantly between 1972 and 1999. Decreasing proportions of oligochaetes (0.85 to 0.68) and increasing diversity suggest improved environmental conditions over this period. Evidence suggests that changes in Muskegon Lake's benthic community were more a result of wastewater diversion than Dreissena invasion.*

INDEX WORDS: *Macroinvertebrates, multivariate statistics, historic changes, wastewater diversion, contaminants, Area of Concern.*

INTRODUCTION

Composition of the benthic macroinvertebrate community is widely considered an effective tool for evaluating environmental (trophic) conditions. Benthic macroinvertebrates are found in most habitats and are relatively easy to sample quantitatively (Canfield *et al.* 1996, Wiederholm 1980). Moreover, they form stable communities that integrate and reflect conditions of both pelagic and benthic regions over relatively long periods of time (Nalepa 1987, Wiederholm 1980). Since macroinvertebrates

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are confined to a habitat that continually receives autochthonous and allochthonous material, they integrate both autotrophic and heterotrophic processes in lakes (Wiederholm 1980).

Because benthic communities provide a "snapshot" of trophic conditions in a lake at the time samples are collected and community composition may reflect recent events, comparisons to historical data are useful in assessing long-term trends in environmental conditions and trophic state (Nalepa *et al.* 2000). Shifts in relative abundances of indicator species have been particularly effective in assessing changes in environmental conditions (Carr and Hiltunen 1965, Harman 1997, Krieger and Ross 1993, Lang 1998). For instance, prior to phosphorus abatement programs in the mid-1970s, increased densities of most benthic groups and reduced densities of pollution intolerant taxa in the Great Lakes generally reflected increased system productivity from increased nutrient loads (Carr and Hiltunen 1965, Robertson and Alley 1966). After abatement efforts were initiated, the abundance of less-tolerant species increased, and overall abundances of most benthic taxa declined in Lakes Michigan, Erie, and Ontario (Nalepa 1987, 1991; Schloesser *et al.* 1995). Given the difficulty of lake-wide experimental manipulations, comparing past and present communities may be the only practical method to assess changes resulting from human activities (Barton and Anholt 1997). In addition, these comparisons provide the only opportunity to gauge the progress of ecosystem restoration when monitoring data are limited.

In this study, we examine spatial distributions and long-term changes in the abundance and species composition of the benthic macroinvertebrate community in Muskegon Lake, a drowned river mouth lake along the southeastern coast of Lake Michigan. Prior to 1973, domestic and industrial wastes were discharged directly into the lake from various facilities located along the southern shoreline and near the mouth of the Muskegon River. The International Joint Commission (IJC) designated Muskegon Lake as an Area of Concern (AOC) because of severe environmental impairments related to these discharges. Studies of benthic communities and associated sediments in the 1950s, 1960s, and early 1970s indicated a severely degraded benthic fauna along with high levels of sediment contaminants including heavy metals and aromatic hydrocarbons (Peterson 1951, Surber 1954, Evans 1976). A tertiary wastewater treatment facility was constructed in 1973, and the discharge was diverted to a location 25 km upstream on the Muskegon River. Persistent contaminants, however, remain in sediments from some areas of the lake (Evans 1992). The response of the benthic community to the waste diversion has not been well studied. Only a few, limited surveys have been conducted since the diversion, with the last occurring in the early 1980s (Evans 1992). The objectives of our study were to evaluate benthic distributions relative to river inputs and to known areas of persistent sediment contaminants, and to assess overall changes in the benthic community since waste diversion in 1973. Since the Muskegon Lake AOC has Beneficial Use Impairments (BUIs) associated with degraded benthos and associated fisheries habitat, improvements in the benthic macroinvertebrate community can be used to assess the progress of the Remedial Action Plan (RAP) and play a critical role in future delisting assessments.

Study Area

Muskegon Lake is a large drowned river mouth lake (1,680 ha) along the southeastern shoreline of Lake Michigan. A drowned river mouth lake is formed by erosion of tributary river channels during extreme low lake levels. As water levels in the Great Lakes rose, the mouths of tributary rivers were "drowned." The formation of sand dunes at river mouths along the eastern shoreline resulted in inland lakes connected to Lake Michigan by outlet channels (Jude *et al.* 2005). Mean depth of Muskegon Lake is 7.1 m (maximum is 21 m), water volume is about 119 million m^3, and mean hydraulic retention time is about 23 days. Much of the lake's shoreline has been modified by urban and industrial development and receives 95% of its tributary inputs from the Muskegon River, which enters on the lake's east side (Fig. 1). This river is the second longest in the state (352 km) and drains a watershed of 6,819 km^2. Mean annual flow into Muskegon Lake is 55.5 $m^3 \cdot s^{-1}$. Outflow to Lake Michigan is through a navigation channel on the west side of the lake (Fig. 1).

Anthropogenic activity has affected Muskegon Lake since the early 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 constructed on the shoreline, and much of the littoral zone was filled with sawdust, wood chips, timber wastes, and bark. This was followed in the 1900s by an era of industrial

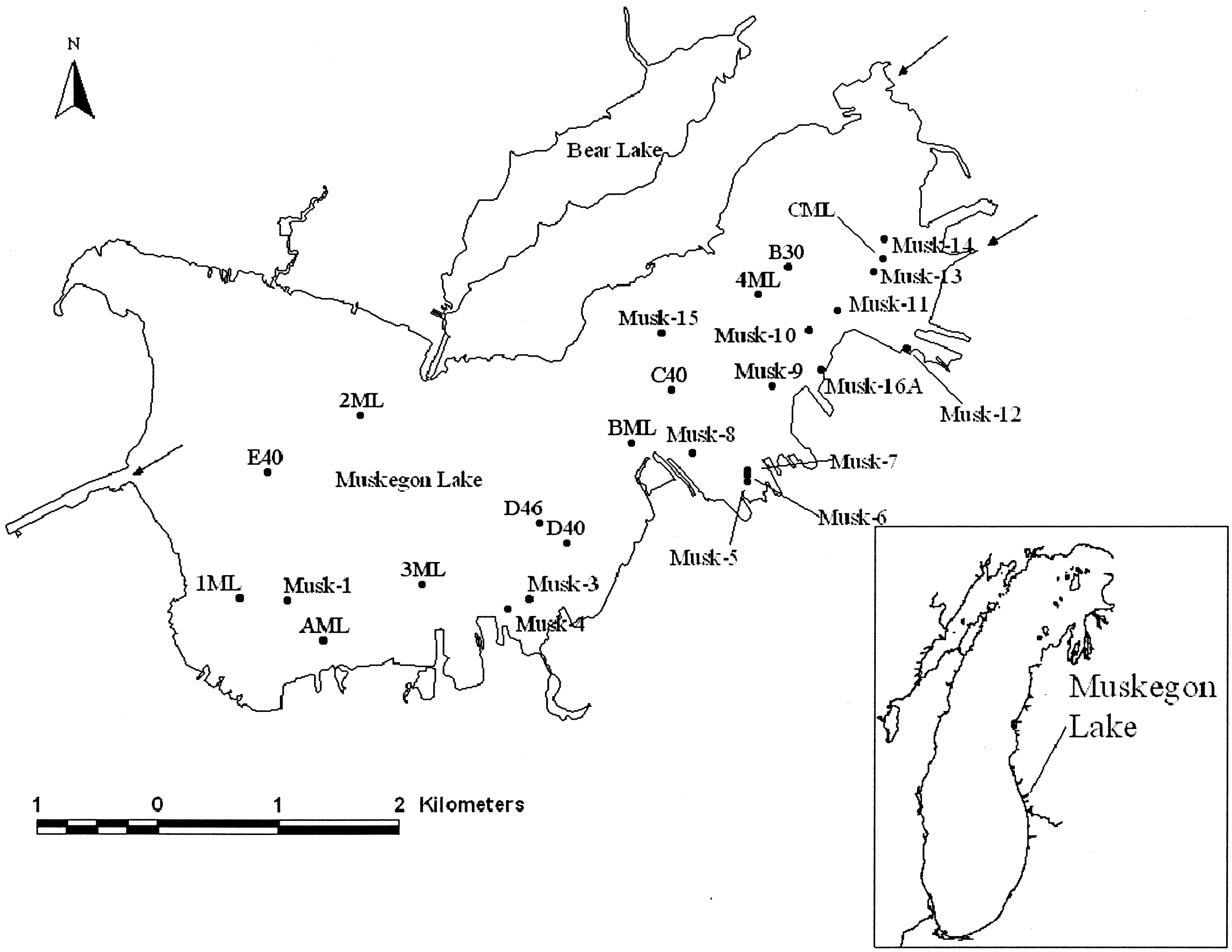

FIG. 1. Sites sampled in Muskegon Lake in fall 1999. Arrows indicate river inflows (east end of lake) and lake outflow to Lake Michigan (west end of lake). Inset indicates location of Muskegon Lake on Lake Michigan's east coast. See Table 1 for site coordinates and depths.

expansion related to heavy industry and shipping. In the 1960s and early 1970s, the lake received over 100,000 $m^3 \cdot day^{-1}$ of wastewater discharged from industrial and municipal sources (Great Lakes Commission 2000, Evans 1992). These discharges included effluents from pulp and paper, petrochemical, organic chemical, metal finishing, and manufactured gas facilities. Wuycheck (1987) and Evans (1992) provided detailed reviews of studies that described extensive water quality problems related to nutrient enrichment, nuisance algal blooms, fish tainting, excessive macrophyte growth, contaminated sediments from the discharge of heavy metals and organic chemicals, winter fish kills, thermal pollution, oil slicks, and anoxia.

MATERIALS AND METHODS

Sediment samples for analysis of the benthic community were collected on 28 and 29 October and 9 November 1999 at 27 sites located throughout the lake (Fig. 1, Table 1). Water depths at the sites ranged from 4 to 20 m. Triplicate samples were taken at each site with a petite Ponar grab (15.24 cm × 15.24 cm). Samples were washed into a large tub and then into an elutriation device with a 0.5-mm, nitex-mesh sleeve to remove silt and other fine particles. Retained material was preserved in 10% buffered formaldehyde containing rose bengal stain. An additional grab was taken at 15 of the sites (those with Musk designation; see Fig. 1) for

TABLE 1. Location (decimal degree coordinates), depth, and sediment phi of selected sites (15) sampled in Muskegon Lake, fall 1999. See text for description of phi.

Station	Lat	Long	Depth (m)	Phi
Musk-6	43.23310	86.26537	4.1	3.6[a]
Musk-12	43.24270	86.24935	4.2	1.6
Musk-16A	43.24095	86.25798	5.4	2.0[a]
Musk-5	43.23255	86.26537	6.4	3.7[a]
Musk-10	43.24385	86.25935	7.4	3.8[a]
Musk-9	43.23968	86.26302	7.5	2.2
Musk-7	43.23345	86.26542	7.9	3.6
Musk-8	43.23470	86.27102	8.2	3.8
Musk-14	43.25067	86.25187	8.6	3.7
B30	43.24850	86.26167	8.7	
Musk-11	43.24538	86.25652	8.8	3.9
CML	43.24933	86.25200	9.4	
Musk-13	43.24828	86.25303	9.6	3.7[a]
Musk-15	43.24340	86.27435	9.6	3.6
4ML	43.24650	86.26467	10.2	
BML	43.23533	86.27717	11	
C40	43.23917	86.27333	11.4	
1ML	43.22317	86.31633	11.5	
Musk-1	43.22312	86.31150	12	3.8[a]
Musk-3	43.22363	86.28698	12.2	3.7
E40	43.23250	86.31383	12.2	
D40	43.22783	86.28333	12.5	
Musk-4	43.22275	86.28908	12.8	2.1
D46	43.22917	86.28617	14.1	
2ML	43.23683	86.30450	16	
AML	43.22017	86.30783	16.6	
3ML	43.22450	86.29783	20.4	

[a]indicates the presence of an oily sheen, hydrocarbon odor, and/or tar flecks.

sediment analysis of heavy metals, total organic carbon, and grain size.

In the laboratory, retained material was transferred to a white enamel pan, and all organisms were removed and sorted into major taxonomic groups (Amphipoda, Oligochaeta, Sphaeriidae, Chironomidae, *Dreissena*, Gastropoda, and other) using a 1.75× magnifier lamp. Samples with large numbers of *Dreissena* were split (one quarter to one half) by placing the sample in a pan divided into four equal sections and counting all individuals in a given section. All organisms were identified to the lowest practical taxonomic level. When oligochaete numbers exceeded 200 in a sample, the sample was proportionately split with a Folsom plankton splitter so that at least 100 were available for identification. Chironomids and oligochaetes were cleared by placing individuals in lactic acid and warmed for 20 min at 60°C. Specimens were then mounted on slides in 100% glycerol prior to identification. The keys used for identifying species within the various taxonomic groups were: Oligochaetes (Kathman and Brinkhurst 1998); Chironomidae (Epler 1995); Hirudinea (Klemm 1972); Trichoptera (Wiggins 1977); and Ephemeroptera (Burks 1953). Gastropods were identified by Dr. John Burch (The University of Michigan Museum of Zoology, Mollusk Division, Ann Arbor, MI).

Sediment samples were analyzed for the following parameters using SW-846 methods (USEPA 1994): total organic carbon (Method 9060A; combustion/IR), semivolatile organics (Methods 3540C and 8270C; soxhlet extraction and gas chromatography/mass spectrometry), and total extractable metals (Method 3052; microwave digestion) for arsenic and selenium by graphite furnace atomic absorption spectroscopy (Method 7000), barium, cadmium, chromium, copper, nickel, lead, and zinc by inductively coupled plasma-atomic emission spectrometry (Method 6010B), and mercury by cold-vapor atomic absorption spectroscopy (Method 7471A). Total polyaromatic hydrocarbon (PAH) concentrations were expressed as the sum of the following semivolatile compounds: acenaphthene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene ,benzo(b)fluoranthene, benzo(e)pyrene, benzo(ghi)perylene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, fluoranthene, fluorine, indeno(123cd)pyrene, naphthalene, phenanthrene, and pyrene. Particle size distributions were measured by wet sieving (USEPA 2003) and reported as phi units (Holmes and McIntyre 1971). The following mesh sizes were used: 2 mm (granule), 1 mm (very coarse sand), 0.5 mm (coarse sand), 0.25 mm (medium sand), 0.125 mm (fine sand), 0.063 mm (very fine sand), and 0.031 mm (coarse silt). Details of analytical methods are given in (Rediske *et al*. 2002). Larger phi units indicate finer substrate.

Sites with similar benthic communities (all taxa) were determined using cluster analysis methods as described in Schloesser *et al* (1995). All data were ln(n+1) transformed prior to multivariate analysis. One-way ANOVA was used to determine significant differences between clusters.

Impacts of river inputs on the benthic community were determined by examining the relationship (Pearson Correlation) between distance from the river mouth and benthic abundance and composition. The nine sites used in the analysis (Musk-14, B-30, 4ML, C-40, BML, D-46, 3ML, Musk-1, and

1ML) extended along a distance gradient from near the river mouth (east end) toward the navigation channel (west end) and were located within the submerged river channel. Thus, these sites best reflect the river's influence on community composition. Depths varied from 8 to 16 m. All 27 sites were used to evaluate distribution patterns relative to water depth and grain size. Statistical relationships were examined using Pearson correlation. Non-linear variables for water depth, river distance, and grain size relationships were ln(n+1) transformed prior to analysis.

Changes in the benthic community after waste diversion were determined by comparing data collected in the present study to data collected in June 1972, which was the year just before diversion began (Evans 1976). In the 1972 study, sites were sampled with a petite Ponar and sediments were washed through a 0.60-mm-mesh screen. Of the sites sampled in 1972, 5 were re-sampled and another 10 were matched to 1999 sites based on geographic proximity and comparable water depth. The 15 pairs of sites (Musk-1 and E-40-S, Musk-5 and C-20-S, Musk-6 and C-10-S, Musk-7 and C-30-S, Musk-10 and B-20-S, Musk-11 and B-30-S, Musk-12 and Sta-9, Musk-15 and C-30-N, Musk-16A and Sta-8, 3ML and E-65-M, B-30 and B-30-N, C-40 and C-40-M, D-40 and D-40-S, D-46 and D-50-M, and E-40 and E-40-N, from 1999 and 1972, respectively) were mostly located along the southern shoreline and ranged between 4.1 and 14.1 m in water depth. Some differences in abundance and composition may be observed based on different sampling seasons. To minimize this, comparison of densities were limited to broader taxonomic groups. The following metrics were calculated for each year: Shannon-Weaver diversity ($\log_2$, hereafter referred to as diversity), oligochaete-chironomid ratio (oligochaete density/(oligochaete density + chironomid density)), taxa richness (number of individual taxa), proportion of oligochaetes in total benthos (not including *Dreissena*), and a chironomid Trophic Condition Index (C-TCI).

The C-TCI is determined by placing each species into one of three ecological categories based on its tolerance to organic enrichment. Group 0 includes species characteristic of oligotrophic conditions, Group 1 contains species typically found in mesotrophic or slightly enriched conditions, and Group 2 comprises species known to be tolerant of eutrophic or considerably enriched conditions. The trophic tolerance of species follows that of Winnell and White (1985). When a species was encountered that was not classified in Winnell and White (1985), the biotic index by Hilsenhoff (1987) and regional tolerance values from Barbour *et al.* (1999) were used to make classifications. Classification schemes of both Hilsenhoff (1987) and Barbour *et al.* (1999) were on a ten-point scale and were partitioned among the ecological groups within the TCI. To obtain an index value for the TCI, the number of individuals in each category is multiplied by the category values (species in category 0 are assigned a value of 0.5). The products are then summed and divided by the total number of individuals. The oligochaete-chironomid ratio (O:C ratio) generally reflects the tendency for tolerant oligochaete species to increase their abundance relative to sedentary chironomids in conditions of nutrient enrichment (Wiederholm 1980). As a result, higher ratios indicate increased abundance of oligochaetes and reduced water quality (Evans 1992).

An additional metric calculated for the 1999 data only, was the oligochaete TCI (O-TCI) (Milbrink 1983). Calculation of this metric for 1972 data was not possible because oligochaetes were not identified to species. The index is similar to the chironomid TCI except that a fourth category is included. This category contains only *Limnodrilus hoffmeisteri* and *Tubifex tubifex* because these species can tolerate gross organic pollution. Also, the index is weighted based on total oligochaete densities, with higher densities leading to higher index values (Milbrink 1983). Index values range from 0 to 3 with higher values indicating greater nutrient enrichment. Values < 0.6 suggest oligotrophic conditions, values 0.6–1.0 suggest mesotrophic conditions, and values > 1.0 suggest eutrophic conditions; values close to 3 indicate gross organic pollution (Milbrink 1983).

Differences in sediment metal concentrations in 1972 and 1999 were determined by comparing concentrations at three sites. Stations Musk-1, Musk-10, and Musk-15 sampled in 1999 were similar in location and water depth to Stations E-40-S, B-20-S, and C-30-N sampled in 1972. Musk-1 and Musk-15 were located in the western and central basins of the lake (Fig. 1) and Musk-10 was located near the southeastern shore, adjacent to a former industrial area. Thus, these sites were spatially representative of lake conditions and likely reflected broad scale as well as local trends. In 1972, sediment samples were collected by removing the top 2 cm from sediments taken with an Eckman grab, whereas in 1999 samples were collected with a petite Ponar grab and a well-mixed subsample removed for analysis. The

TABLE 2. Concentrations of heavy metals (mg·kg^{-1}, dry weight), PAH compounds (mg·kg^{-1}, dry weight), and total organic carbon (TOC,% dry weight) in sediments at 15 sites in Muskegon Lake, 1999. Probable effect concentrations (PECs) were from MacDonald* et al. *(2000) (see text for explanation). Concentrations in bold exceed PEC guidelines.

Site	TOC	PAH	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	Se
Musk-1	4.5	U[a]	10	3.9	**250**	63	24	120	260	0.38	0.72
Musk-3	5.5	U[a]	6.1	2	71	52	19	83	190	0.2	0.44
Musk-4	< 0.5	U[a]	5.2	0.13	4.8	4	2	5.8	13	U[a]	U[a]
Musk-5	4.1	2.7	11	**12**	**210**	**260**	38	**270**	**600**	**1.7**	0.49
Musk-6	5.3	4.8	9.5	**7.9**	**160**	**260**	38	**280**	**640**	**1.7**	0.53
Musk-7	8	U[a]	11	4.2	**120**	100	29	**140**	290	0.56	0.48
Musk-8	4.9	U[a]	6.7	4.4	107	83	25	125	255	0.52	0.68
Musk-9	< 0.5	1.0	5.6	0.38	9.6	6.8	3.4	12	30	U[a]	U[a]
Musk-10	1.1	U[a]	6.2	2.9	77	58	22	89	200	0.34	0.58
Musk-11	4.3	U[a]	6.8	2.3	61	49	20	67	160	0.26	0.59
Musk-12	< 0.5	U[a]	5.2	0.078	2.8	3.4	2.6	6.2	14	U[a]	U[a]
Musk-13	4.2	U[a]	10	3.1	80	39	19	63	160	0.25	0.38
Musk-14	2.3	U[a]	5.2	1.1	30	33	14	31	100	0.14	0.38
Musk-15	2.5	U[a]	5.8	2.5	68	46	19	64	160	0.26	0.42
Musk-16A	1.4	**143**	3.7	1.3	20	16	6.8	31	67	0.14	U[a]
Mean(S.E.)	3.30(0.58)	37.8(35)	7.2(0.62)	3.21(0.82)	84.7(19.2)	71.5(21.0)	18.8(3.0)	92.5(22.1)	209(49)	0.54(0.16)	0.52(0.03)
PEC		22.9	33	4.98	111	149	48.6	128	459	1.06	N/A

[a]"U" Indicates undetectable levels.

petite Ponar has a penetration depth of ≈ 12 cm. Thus, based on an estimated sedimentation rate of 1 cm·yr^{-1} for Muskegon Lake (Rediske *et al.* 2002), the 1999 samples were representative of the mean concentration of metals in sediments deposited from 1987 to 1999. Differences in benthic densities, metrics, and metal concentrations at paired sites between the two years (1972 vs. 1999) were tested using the Mann-Whitney U-test.

RESULTS

Sediment Variables

Grain size (phi) ranged from 1.6 (medium to fine sand) to 3.9 (very fine sand to coarse silt) (Table 1) and was not significantly correlated with depth ($r = 0.28$, $P > 0.05$), or distance from the river ($r = 0.09$, $P > 0.05$). Total organic carbon (TOC) was variable and ranged from < 0.5 to 8.0% (Table 2). Relationships between TOC and distance from the river mouth or water depth were not significant ($r = 0.22$ and 0.11, $P > 0.05$). Concentrations of individual metals ranged from undetectable to 640 mg·kg^{-1} (dry weight) (Table 2). Zinc, chromium, and lead had the highest mean concentrations, and mercury and selenium had the lowest. Overall, highest concentrations of heavy metals were found at sites Musk-5, 6, 7, and 8, all in the southeastern region of the lake. Concentrations of cadmium, chromium, copper, lead, mercury, and zinc at Musk-5 and 6 were the highest of all sites (Table 2) and exceeded consensus-based Probable Effect Concentrations (PECs) (MacDonald *et al.,* 2000). These locations were in an area influenced by an industrial stormwater outfall. Lowest concentrations of heavy metals were consistently found at Musk-4, 12, and 16A. Stations Musk-4 and 12 had TOC concentrations of < 0.5%. Station Musk 16A, located adjacent to a former foundry and manufactured gas facility, contained sands and gravels with coal tar flecks (Table 1). The highest concentration of PAH compounds, 143 mg·kg^{-1} (dry weight), was found at this station. This concentration also exceeded PEC guidelines.

Abundances and Composition

Mean total macroinvertebrate densities ranged from 2,585 to 49,124 m^{-2} at individual sites. A total of 55 taxa were collected (Table 3), and the mean number per site was 20 (range 14–29). Oligochaetes were the most abundant group at all but two of the sites sampled, and densities ranged from 1,767 to 10,489 m^{-2}. This group accounted for 12–91% of all organisms collected at a given site and exceeded 50% at 20 of 27 sites. Eighteen oligochaete species were identified, with *Aulodrilus pigueti*, *Quis-*

TABLE 3. Taxa collected at 27 sites in Muskegon Lake, Michigan, 1999. Given for each taxon is the overall mean density (m^{-2} ± SE) and the number of stations where it was found (n). The density of each taxa at each site is given in Carter (2002).

Taxon	Abundance, No. m^{-2} (n)	Taxon	Abundance No. m^{-2} (n)
Turbellaria	152 ± 58 (23)	**Bivalvia**	
Oligochaeta		*Pisidium* sp. Pfeiffer	367 ± 73 (25)
Lumbriculidae		*Sphaerium* sp. Scopoli	89 ± 23 (20)
Stylodrilus heringianus Claparede	1 ± 0.53 (1)	*Musculium* sp. Link	2 ± 1 (4)
Naididae		*Dreissena polymorpha* Pallas	2372 ± 1600 (20)
Arcteonais lomondi Martin	3 ± 1 (4)	**Isopoda**	
Dero digitata Muller	42 ± 13 (17)	*Caecidotea* sp. Packard	10 ± 10 (8)
Dero flabelliger Stephenson	1 ± 0.53 (1)	**Amphipoda**	
Piguetiella michiganensis Hiltunen	4 ± 4 (1)	*Gammarus* sp. Fabricus	172 ± 53 (23)
Slavina appendiculata d'Udekem	5 ± 4 (3)	*Hyalella azteca* Saussure	15 ± 4 (13)
Tubificidae		*Echinogammarus ischnus* Stebbing	14 ± 9 (3)
Aulodrilus americanus Brinkhurst and Cook	13 ± 9 (3)	**Diptera**	
Aulodrilus limnobius Bretscher	46 ± 10 (19)	**Ceratopogonidae**	3 ± 2 (2)
Aulodrilus pigueti Kowlewski	596 ± 109 (26)	*Probezzia* sp. Kieffer	5 ± 2 (8)
Aulodrilus pluriseta Piguet	253 ± 170 (15)	**Chaoboridae**	
Ilyodrilus templetoni Southern	22 ± 7 (12)	*Chaoborus* sp. Lichtenstein	104 ± 16 (25)
Isochaetides freyi Brinkhurst	23 ± 8 (11)	**Chironomidae**	
Limnodrilus cervix var. Brinkhurst	7 ± 2 (9)	**Chironominae**	
Limnodrilus hoffmeisteri Claparede	76 ± 16 (23)	*Chironomus* sp. Meigen	370 ± 66 (26)
Limnodrilus maumeensis Brinkhurst and Cook	11 ± 4 (9)	*Cladopelma* sp. Kieffer	3 ± 3 (1)
Limnodrilus udekemianus Claparede	11 ± 4 (9)	*Cryptochironomus* sp. Kieffer	64 ± 10 (24)
Potamothrix moldaviensis Vejdovsky and Mrazek	1 ± 0.53 (1)	*Cryptochironomus digitatus* Malloch	1 ± 0.53 (1)
Quistadrilus multisetosus Smith	224 ± 52 (26)	*Dicrotendipes* sp. Kieffer	1 ± 0.53 (1)
Immature Oligochaeta	3510 ± 441 (27)	*Paratanytarsus* sp. Thieneman and Bause	1 ± 0.53 (1)
Polychaeta		*Polypedilum* sp. Kieffer	2 ± 1 (2)
Manayunkia speciosa Leidy	1 ± 0.74 (2)	*Tanytarsus* sp. Wulp	1 ± 1 (1)
Hirudinea		*Tribelos jucundum* Walker	2 ± 2 (1)
Glossiphoniidae		**Orthocladiinae**	
Alboglossiphonia heteroclita Linnaeus	2 ± 2 (1)	*Heterotrissocladius oliveri* Saether	1 ± 0.53 (1)
Helobdella stagnalis Linnaeus	1 ± 1 (1)	**Tanypodinae**	
Helobdella elongata Castle	2 ± 2 (1)	*Ablabesmyia annulata* Say	6 ± 3 (6)
Mollusca		*Coelotanypus concinnus* Coquillet	141 ± 47 (17)
Gastropoda		*Conchapelopia* sp. Fittkau	3± 3 (2)
Amnicola sp. Gould and Haldeman	2 ± 2 (1)	*Procladius* sp. Skuse	124 ± 14 (26)
Bithynia sp. Leach	5 ± 2 (6)	**Ephemeroptera**	
Valvata tricarinata Say	30 ± 10 (12)	*Caenis* sp. Stephens	2 ± 1 (2)
Valvata sincera Say	5 ± 2 (6)	**Tricoptera**	
		Oecetis sp. McLachlan	4 ± 2 (5)
		Neureclipsis sp. McLachlan	1 ± 0.53 (1)

tadrilus multisetosus, and *Limnodrilus hoffmeisteri* being the most common. *A. pigueti* and *Q. multisetosus* were both found at 26 sites, and mean densities (± standard error) were 596 ± 109 and 224 ± 52 m^{-2}, respectively, whereas, *L. hoffmeisteri* was found at 23 sites, and mean density was 76 ± 16 m^{-2}. Chironomids were the second most taxa-rich group with 14 taxa collected (Table 3). Of these, *Chironomus* sp., *Cryptochironomus* sp., and *Procladius* sp. were the most widely distributed and found at 26, 24, and 26 of 27 sites, respectively. *Chironomus* sp. was the most abundant with a mean density of 370 ± 65 m^{-2} (range 14–1,206 m^{-2}), whereas *Cryptochironomus* sp. did not exceed 144 m^{-2}.

Sphaeriids were found at 25 of 27 sites, and *Pisidium* was the predominant genus. Mean density was 367 ± 73 m^{-2} (Table 3). Amphipods were found at 24 sites and included three taxa (*Gammarus* sp., *Hyalella azteca*, and *Echinogammarus ischnus*). Total amphipod densities were generally low (≤ 359 m^{-2}) except at three sites (Musk-4, Musk-12, and E-40) where densities were 660-1,200 m^{-2}. The invasive amphipod *Echinogammarus ischnus* was found at three sites (Musk-9, Musk-12, and E-40), but maximum density was only 57 m^{-2}. *Dreissena polymorpha* (hereafter referred to as *Dreissena*) was widely distributed, occurring at 20 of 27 sites, and mean density was 2,372 ± 1,600 m^{-2}. Greatest mean densities of *Dreissena* occurred at Musk-16A (5,562 m^{-2}), Musk-9 (15,758 m^{-2}), and Musk-12 (40,860 individuals m^{-2}); mean densities at the other 17 sites did not exceed 400 m^{-2}. The remaining groups, i.e. Turbellaria, Polychaeta, Hirudinea, Gastropoda, Isopoda, Ceratopogonidae, Chaoboridae, Ephemeroptera, and Trichoptera (collectively referred to as others) were generally found in low abundance and/or occurred infrequently. Densities of each taxa at each site are given in Carter (2002).

TABLE 4. Relationship of taxa density and community metrics to distance from river mouth, water depth, and sediment grain size (phi). Values given are Pearson Correlation coefficients. Significant correlations (P ≤ 0.05) are denoted with an asterisk.

	Distance (m)	Depth (m)	Phi
Number of sites (n)	9	27	15
Density			
Sphaeriidae	–0.39	–0.58*	0.26
Dreissena	0.12	–0.64*	–0.73*
Oligochaeta	–0.63	–0.07	–0.29
Chironomidae	0.31	0.17	0.61*
Predatory Chironomidae	–0.43	–0.04*	0.40
Amphipoda	–0.14	0.05	–0.56*
Others	0.53	–0.49*	–0.47
Total	–0.69*	–0.46*	–0.81*
Metrics			
Taxa Richness	–0.40	–0.32	–0.33
Diversity	0.12	0.14	0.62*
Chironomid-TCI	0.61	–0.15	0.33
Oligochaete-TCI	–0.39	0.66*	0.04
Oligochaete/Chironomid	–0.47	–0.49*	–0.27
Proportion of Oligochaetes	–0.18	0.56*	0.60*

Community Indices

Based on the O-TCI at all 27 sites, the oligochaete community was indicative of mesotrophic to eutrophic conditions. The mean O-TCI score was 1.43 ± 0.07 (range 0.78-1.94). There were no sites with an index value indicative of oligotrophic conditions or conditions of gross organic pollution. Twelve sites had O-TCI scores ≥ 1.5 (tending toward eutrophic conditions), with the majority (8) being at depths ≥ 10 m. The 15 other sites had O-TCI scores that ranged from 0.78 to 1.48, more indicative of mesotrophic to meso-eutrophic conditions. Ten of the sites with these scores were at depths < 10 m. The C-TCI indicated that all sites in the lake tended to be eutrophic, and no scores were below 1.8.

Mean diversity was 2.71 ± 0.11 and ranged from 1.09 to 3.5. Twenty of the sites sampled had diversity scores ≥ 2.3, and only two sites (Musk-12 and CML) had values < 2.0. The oligochaete-chironomid ratio (O/C) ranged from 0.67 to 0.99. Twenty-four of the sites had an O/C ≥ 0.80.

Spatial Distributions

There was a significant negative correlation between total density and distance from the river mouth (P ≤ 0.05, r = –0.69, Table 4). This spatial relationship generally reflected density patterns of oligochaetes relative to the river, even though total oligochaete density was not significantly related to distance from the river mouth. Of the oligochaete species, only *Quistadrilus multisetosus* showed a significant relation to river mouth distance (P ≤ 0.05, r = –0.87). While total chironomid density was not correlated, densities of *Chironomus* sp. increased significantly with increased distance from the river mouth (P ≤ 0.05, r = 0.75).

Densities generally decreased as water depth increased (Table 4). Total density and densities of Sphaeriidae, *Dreissena*, and "others" were negatively correlated with water depth (Pearson correlation, P ≤ 0.05). Of the six community metrics, three were significantly related to depth. The O-TCI index and the proportion of oligochaetes increased with depth, but the O/C ratio declined.

There was a significant negative correlation (P ≤ 0.05) in total density, amphipoda, and *Dreissena* density with grain size (reduced density with finer particle size), whereas there was a significant positive correlation (P ≤ 0.05) for chironomids, diversity, and proportion of oligochaetes (Table 4).

The densities of Oligochaeta and predatory chironomids (*Coelotanypus concinnus* and *Procladius*

TABLE 5. Relationship of taxa density and community metrics to heavy metal concentrations from 15 sites in Muskegon Lake. Values given are Pearson Correlation coefficients. Significant correlations (P ≤ 0.05) are denoted with an asterisk. See Table 2 for heavy metal concentrations.

	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	Se
Density									
Sphaeriidae	0.22	0.54*	0.21	0.5	0.46	0.46	0.46	0.5	0.24
Dreissena	–0.33	–0.37	–0.42	–0.32	–0.54*	–0.38	–0.39	–0.3	–0.6*
Oligochaeta	–0.65*	–0.66*	–0.66*	–0.63*	–0.64*	–0.71*	–0.67*	–0.63*	–0.43
Chironomidae	0.27	0.47	0.35	0.43	0.43	0.42	0.43	0.38	0.34
Predatory Chironomidae	0.56*	0.82*	0.51	0.77*	0.66*	0.72*	0.73*	0.77*	0.37
Amphipoda	–0.24	–0.18	–0.31	–0.08	–0.39	–0.17	–0.18	–0.06	–0.54*
Others	–0.26	–0.18	–0.32	–0.14	–0.33	–0.19	–0.2	–0.12	–0.48
Total	–0.47	–0.48	–0.55*	–0.42	–0.65*	–0.51	–0.51	–0.41	–0.68*
Metrics									
Taxa Richness	–0.11	–0.48	–0.55*	–0.42	–0.65*	–0.51	–0.08	–0.03	–0.31
Diversity	0.52*	0.63*	0.67*	0.62*	0.73*	0.7*	0.68*	0.61*	0.6*
Chironomid-TCI	0.45	0.48	0.47	0.47	0.52*	0.54*	0.51	0.45	0.42
Oligochaete-TCI	–0.29	–0.55*	–0.34	–0.6*	–0.44	–0.58*	–0.57*	–0.61*	–0.03
Oligochaete/Chironomid	–0.19	–0.05	–0.32	–0.03	–0.18	–0.14	–0.11	0.01	–0.28
Proportion of Oligochaetes	0.06	–0.12	0.13	–0.17	0.12	–0.1	–0.08	–0.19	0.44

sp.) were significantly correlated with concentrations of most of the heavy metals (Table 5), but the nature of the relationships differed. Oligochaetes were negatively correlated (r range 0.63 to 0.71, P ≤ 0.05) with eight of the nine metals, whereas predatory chironomids were positively correlated (r range 0.56 to 0.82, P ≤ 0.05) with seven of the nine metals. Neither group was significantly related to selenium and predatory chironomidae were not significantly related to chromium. The remaining groups of organisms, except total Chironomidae, were significantly correlated with only one or two metals (Table 5). Diversity was the only community metric significantly correlated with all concentrations of heavy metals (Table 5) (r range 0.52 to 0.73, P ≤ 0.05). The oligochaete-chironomid ratio and proportion of oligochaetes were not correlated with any metal concentrations.

Four groupings resulted from the cluster analysis, and these groupings included 18 of the 27 sites (Fig. 2). The site clusters occurred in distinct regions of the lake. The southeast (SE) cluster included sites located along the eastern shore near the mouth of the Muskegon River (CML, Musk-11, Musk-13, Musk-14), and metrics suggested these sites were the most enriched. Total density (9,375 m^{-2}), oligochaete density (7,932 m^{-2}), O-TCI (1.81), and O/C (0.97) were the highest of the four groupings, while diversity (1.05) was the lowest (Table 6). This grouping had the highest densities of *Quistadrilus multisetosus* (279 ± 123 m^{-2}) and the chironomid *Procladius* sp. (226 ± 28 m^{-2}), although they were not significantly different (ANOVA, df 3, F = 1.80, 2.54 respectively, P > 0.05) from the other groups. *Limnodrilus hoffmeisteri* (154 ± 51 m^{-2}) was significantly higher at this grouping than the others (ANOVA, df 3, F = 5.84, P ≤ 0.05). Also, this grouping had the lowest density of the tubificid oligochaete *Aulodrilus pigueti* (326 ± 169m^{-2}), although differences were not significant (ANOVA, df 3, F = 1.34, P > 0.05). Sites in the South Central (SC) grouping (Musk-5, Musk-6, Musk-7, Musk-8, Musk-10, and B-30) were in relatively shallow water (7.2 m) near a stormwater outfall. Sites in this grouping had the lowest oligochaete density (2,782 m^{-2}) and O-TCI scores (1.00), and the highest diversity (2.24) (Table 6). Moreover this grouping had the highest mean density of *A. pigueti* (651 ± 170 m^{-2}), the lowest density of *L. hoffmeisteri* (17 ± 4 m^{-2}) and relatively low density of *Q. multisetosus* (139 ± 57 m^{-2}). These values indicated the best habitat quality of the site groupings. Inconsistent with this premise however, was the finding that predatory chironomids, which tend to be pollution tolerant, were most abundant in this community. *Coelotanypus concinnus*, was significantly more abundant at the SC sites (mean 503 ± 126 m^{-2}) (ANOVA, df 3, F = 8.41, P ≤ 0.05) than at SE, WC, and SW sites (104 ± 30, 14 ± 8, and 0 m^{-2}, respectively). Conversely,

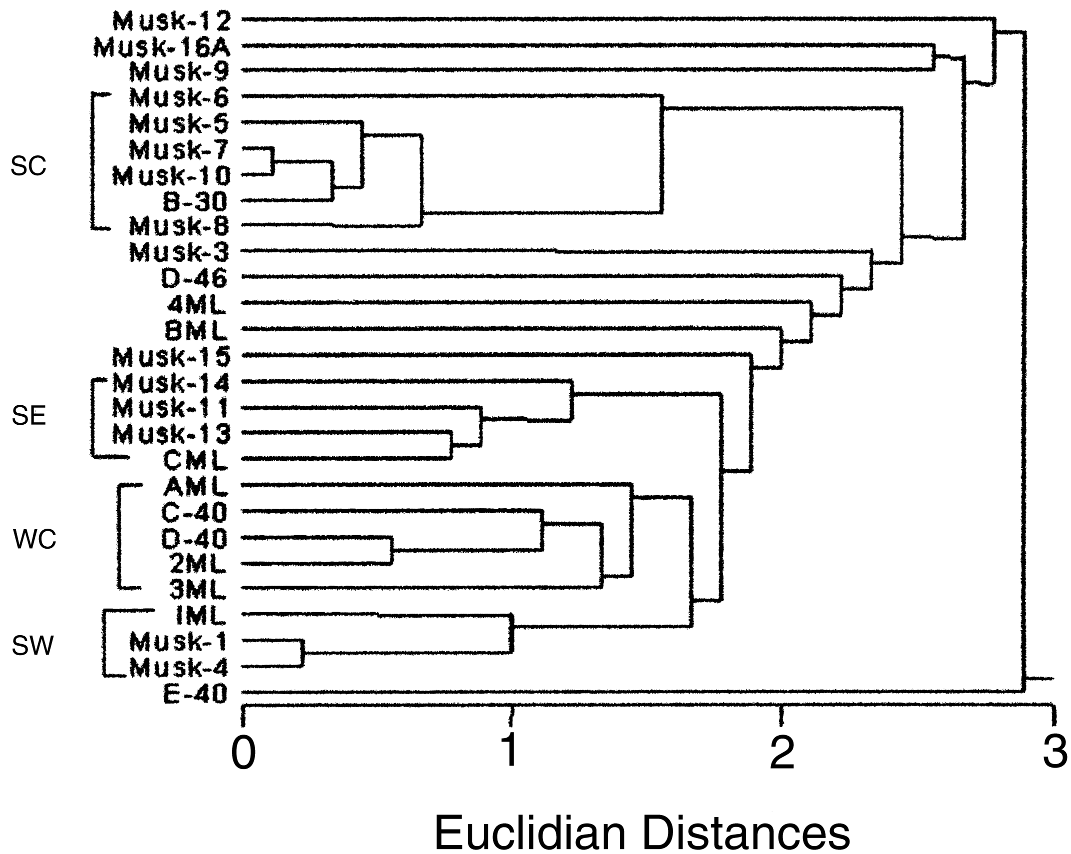

*FIG. 2. Cluster tree resulting from centroid analysis of densities of select benthic taxa (***Aulodrilus americanus, A. pigueti, A. pluriseta, Ilyodrilus templetoni, Limnodrilus cervix** *var., immature tubificids without hair chaetae,* **Amnicola** *sp.,* **Bithynia** *sp.,* **Valvata tricarinata, Dreissena, Chironomus** *sp., and* **Ceolotanypus concinnus***) from Muskegon Lake, 1999. Clusters are indicated on left: SE is the South East group, SC is the south Central group, WC is the West Central group, and SW is the South West group.*

densities of *Chironomus* sp. at the SC sites (mean 65 ± 42 m^{-2}) were significantly lower (ANOVA, df 3, F= 5.84, P ≤ 0.05) than at the other site groups: (168 ± 48 m^{-2}), WC (544 ± 138 m^{-2}), and SW (708 ± 249 m^{-2}). Sites in the West Central (WC) grouping (AML, 2ML, 3ML, C-40, and D-40) were mostly located in offshore areas in the northern, central, and western portions of the lake. Lastly, sites in the South West (SW) grouping (Musk-1, Musk-4, and 1ML) were located in the southwestern portion of the lake. Densities of *Chironomus* sp. in the WC and SW groupings were significantly higher (ANOVA, df 3, F= 6.91, P ≤ 0.05) than the other groupings, 544 ± 138 m^{-2} and 708 ± 249 m^{-2}, respectively. The SW grouping had the highest density of *Aulodrilus pluriseta* (1954 ± 1,324 m^{-2}).

Historical Comparison: 1972 and 1999

Total non-*Dreissena* density increased significantly from 2,858· to 6,452·m^{-2} between 1972 and 1999 (Mann-Whitney U-test; P ≤ 0.05, Table 7). Densities of all major groups increased (range 1.8 to 4.3-fold). Increases in densities of amphipods and sphaeriids were the greatest, 13 and 57-fold, respectively (Table 7). Community metrics also changed between 1972 and 1999. The proportion of oligochaetes and the O/C ratio were significantly lower, and diversity and taxa richness were significantly higher in 1999 compared to 1972 (Mann-Whitney U-tests; P ≤ 0.05) (Table 7). The only metric that was not significantly different between the two years was the chironomid-TCI (Mann Whitney U-test; P > 0.05). The numerically dominant

TABLE 6. Mean (± standard error) densities (m^{-2}) and community index values at the four site-groupings resulting from cluster analysis of all sites in Muskegon Lake, 1999. An asterisk indicates a significant difference between site groupings (one-way ANOVA $P \leq 0.05$). Significant differences between site groups were determined using LSD. Groups with the same letters are not significantly different ($P \leq 0.05$).

	South Central (SC)	West Central (WC)	South West (SW)	South East (SE)
Number of sites (n)	6	5	3	4
Depth (m)*	7.2(0.72)^{a}	15.3(1.62)^{b}	12.1(0.38)^{bc}	9.3(0.32)^{ac}
Density				
Sphaeriidae*	1,086(174)^{a}	132(30)^{b}	72(72)^{c}	448(145)^{ab}
*Dreissena**	198(61)^{a}	87(29)^{a}	5(5)^{b}	7(4)^{b}
Oligochaeta*	2,782(154)^{a}	3,343(781)^{a}	4,897(1826)^{ab}	7,932(824)^{b}
Chironomidae	648(107)	675(163)	909(263)	632(82)
Predatory Chironomidae*	593(124)^{a}	96(23)^{b}	148(53)^{bc}	330(48)^{ac}
Amphipoda	129(62)	182(93)	440(404)	39(18)
Others*	1,775(304)^{a}	633(118)^{b}	612(342)^{b}	731(237)^{b}
Total*	6,879(221)^{ac}	4,650(791)^{b}	6,418(1995)^{abc}	9,295(984)^{ac}
Metrics				
Taxa Richness*	21(0.77)^{a}	22(0.93)^{a}	16(1.20)^{b}	20(0.91)^{a}
Diversity*	2.24(0.11)^{a}	1.51(0.21)^{b}	1.23(0.22)^{bc}	1.05(0.07)^{c}
Chironomid TCI*	2.00(0.005)^{a}	1.99(0.006)^{b}	1.99(0.007)^{b}	1.92(0.03)^{b}
Oligochaete TCI*	1.00(0.09)^{a}	1.52(0.09)^{a}	1.49(0.22)^{a}	1.81(0.09)^{b}
Oligochaete/Chironomid*	0.95(0.01)^{a}	0.83(0.04)^{b}	0.83(0.08)^{b}	0.97(0.006)^{ac}
Proportion of Oligochaetes*	0.69(0.05)^{a}	0.82(0.02)^{b}	0.74(0.08)^{b}	0.42(0.05)^{b}

TABLE 7. Mean (± standard error) density (m^{-2}) and community index values for 15 pairs of sites in Muskegon Lake, Michigan in 1972 and 1999. See text for sites used for comparison and explanation of the various indices. Proportion of oligochaetes excludes* Dreissena. *Diversity for 1999 was calculated with Oligochaeta lumped into a single group. An asterisk indicates a significant difference between years (Mann-Whitney U-test, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$).

	Year	
	1972	1999
Density		
Sphaeriidae	40(14)	582(133)***
Dreissena	0	3,200 (2714)
Oligochaeta	2,558(717)	4,562(664)**
Chironomidae	158(45)	677(75)***
Predatory Chironomidae	38(10)	303(78)***
Amphipoda	13(7)	179(56)***
Others	238(48)	28(86)*
Total (excl. *Dreissena*)	2,858(710)	6,452(598)***
Metrics		
Taxa Richness	3(0.27)	13(0.36)***
Diversity	0.68(0.11)	1.66(0.17)***
Chironomid-TCI	1.85(0.13)	1.97(0.01)
Oligochaete/Chironomid	0.92(0.02)	0.84(0.02)**
Proportion of Oligochaetes	0.85(0.03)	0.68(0.04)**

chironomid species at matched sites in both years were *Chironomus* sp., *Cryptochironomus* sp., *Coelotanypus concinnus*, and *Procladius* sp., despite collection in different seasons.

A comparison of sediment concentrations of eight heavy metals in 1972 and 1999 at three sites indicated that concentrations declined by 41 to 69% over this time period (Table 8). Declines were significant for all metals except for chromium and mercury (Mann Whitney U-test; $P \leq 0.05$). In 1999, chromium was the only element above the PEC.

DISCUSSION

Indices derived from the benthic macroinvertebrate community showed that Muskegon Lake in 1999 was mainly meso-eutrophic to eutrophic. In particular, the oligochaete trophic condition index (O-TCI) supports this conclusion. The community was largely dominated by *Aulodrilus pigueti* (a mesotrophic indicator) and *Quistradrilus multisetosus* (a eutrophic indicator). The former was the most abundant species at most of the sites sampled. *Limnodrilus hoffmeisteri* (generally indicative of gross organic pollution) was present at many sites, but abundances were low, suggesting that organic enrichment was not severe. Values of the C-TCI in-

TABLE 8. Mean (± standard error) heavy metal concentrations (mg/kg, dry weight sediment) and percent decline at three comparable sites in Muskegon Lake, Michigan between 1972 and 1999. An asterisk indicates a significant difference between metal concentrations (Mann-Whitney U-test, *P ≤ 0.05). Concentrations in bold exceed PEC guidelines.

	Year		
Metal	1972	1999	% Decline
Arsenic	18(1.8)	7.3(1.3)*	59.4%
Cadmium	**10**(1.5)	3.1(0.42)*	69.0%
Chromium	**274**(47.6)	**132**(59.2)	51.8%
Copper	94(12.2)	55.7(5.0)*	40.7%
Nickel	39(3.7)	21.7(1.45)*	44.4%
Lead	**165**(11.8)	91.0(16.2)*	44.8%
Zinc	**475**(16.8)	207(29.1)*	56.4%
Mercury	0.6(0.1)	0.33(0.04)	45.0%

dicated that the lake was mainly eutrophic and, therefore, generally more enriched than indicated by the O-TCI. While interpretable differences between these two indices are rather minimal, the O-TCI probably offers a more accurate depiction of current lake status. Oligochaetes tend to form more stable communities than chironomids. Seasonal variation in chironomid community composition can be substantial because of emergence; this in turn affects index values (Mozley and Winnell 1975).

Given the number of significant correlations between depth and various measures of the benthic community, there is no doubt that depth influenced the composition of the fauna (see Brinkhurst 1974). However, we also observed clear effects of riverine inputs. The Muskegon River has one of the largest drainage basins in Michigan and passes through an 8 km^2 drowned river mouth wetland. Given the high discharge rates into the lake, considerable impacts on the benthic community might be expected. Significant correlations between distance from the river mouth and total benthic abundance and the eutrophic oligochaete *Quistadrilus multisetosus* suggest that the river is, indeed, contributing substantial amounts of organic matter to the lake. Nutrient budgets developed by Freedman *et al.* (1979) indicated the Muskegon River was the major source of nutrients to the lake even before wastewater diversion; total phosphorus loading from the Muskegon River averaged 290 $kg{\cdot}d^{-1}$, while the load removed from diversion averaged 132 $kg{\cdot}d^{-1}$. Wastewater diversion had the greatest effect on the discharge of oxygen demanding materials from municipal sewage and paper mill effluent as BOD loading was decreased by 8,000 $kg{\cdot}d^{-1}$. Decreasing benthic densities suggest that impacts of organic inputs from the river are focused mainly near the river mouth and have little impact on densities on the west end of the lake. The influence of organic loading from the Muskegon River also has implications related to delisting the AOC. Current guidance (U.S. Policy Committee 2001) recommends that AOCs can be delisted when pollutant sources within the boundary are mitigated and any current impacts are related to natural or external sources. In the case of Muskegon Lake, nutrient loading from the Muskegon River has replaced the historical influence of anthropogenic sources as the predominant factor controlling the diversity and trophic status of the benthic macroinvertebrate community.

Cluster analysis of the sites resulted in four distinct groupings among 18 of the 27 sites. Of these, the most notable differences in community composition occurred at sites in the Southeast (SE) and South Central (SC) groupings. The SE site group was located nearest the mouth of the Muskegon River, and benthic community composition likely reflected river inputs. Values of most indices and high total densities suggest that organic enrichment at sites in this grouping was substantial. On the other hand, the abundances of the mesotrophic indicator species, *Aulodrilus pigueti*, and the relatively large numbers of taxa would also suggest that conditions at these sites were not as degraded as found in some areas within the Great Lakes (see Canfield *et al.* 1996, Schloesser *et al.* 1995).

Densities and index values indicated that habitat quality with respect to organic pollution was better at sites within the SC grouping than at sites in the other groupings. The O-TCI for this group was the lowest, and diversity was the highest, of the four site groups. In addition, low densities of oligochaetes indicate less organic enrichment. However, some aspects of community composition suggested that perturbations besides organic enrichment were impacting the community. While community composition and densities among the other site groups (SW, WC, and SE) generally reflected responses to depth or distance from the river mouth, composition and density at sites in the SC group did not fit these trends (e.g., sites had lowest density of oligochaetes but were not located farthest from river mouth). A factor that may have impacted community composition in the SC grouping was the relatively high concentrations of heavy metals found at these sites which were located near past discharges of foundry and metal finishing plants. Concentrations of metals including arsenic, barium, cadmium, chromium, copper, nickel, lead, zinc, and mercury at some SC sites were the highest of any sites sampled in the lake (Table 2). Further, these concentrations exceeded the Probable Effects Concentrations (PECs) established by MacDonald *et al.* (2000) for freshwater ecosystems. A PEC can be defined as pollutant concentrations above which adverse effects on sediment-dwelling detritivores such as oligochaetes and some chironomids are likely to be observed (Ingersoll *et al.* 2001, MacDonald *et al.* 2000). Sediment bioassay tests at two SC sites (Musk-5 and 6) produced statistically significant mortality to the amphipod Hyalella azteca after 10 days as compared to controls (Rediske *et al.* 2002).

Correlation analysis suggests that metal concentrations rather than substrate type were a main factor influencing faunal composition in this area of the lake. Grain size (phi) was not significantly correlated with either oligochaete or predatory chironomid densities. However, oligochaete, predatory chironomid densities, and diversity were significantly correlated with most heavy metals. Reduced oligochaete densities and the dominance of predatory chironomids at the SC sites may have been a result of metal toxicity. Although oligochaetes are generally not sensitive to many specific metals (Chapman *et al.* 1980), elevated levels of all measured metals may have produced sublethal effects. Predatory chironomids (*C. concinnus* was most abundant at these sites) are epibenthic, tend to be more tolerant of pollution, and are generally less affected by heavy metal toxicity since direct sediment ingestion would be reduced compared to burrowing or grazing chironomids (Berg 1995). Alternatively, *C. concinnus* may thrive in this area because of less competition for food or space. In a similar Michigan drowned river mouth lake, White Lake, a shift in the benthic composition favoring predatory chironomids was also observed in an area with high concentrations of heavy metals (Rediske *et al.* 1998). Shifts in the benthic community favoring orthoclad chironomids in response to heavy metal contamination was previously noted in stream environments (Clements *et al.* 1988, Clements 1999, Hickey and Clements 1998). While this group is not predatory, orthoclad chironomids generally feed on periphytic algae as scrapers and gatherers (Merritt and Cummins 1996), and this would also minimize their direct exposure to contaminated sediments. Positive correlation between diversity and metals reflects these compositional shifts. While densities generally decreased relative to metals, some species (i.e., predatory chironomids) were prevalent at sites with high metal concentrations.

Reduced densities of *Chironomus* sp. at the SC sites suggests that sediment contamination may have inhibited larval development or perhaps triggered an avoidance reaction (Wentsel *et al.* 1977a, Wentsel *et al.* 1977b). Wentsel (1977b) found that *Chironomus tentans* larvae exhibited an avoidance reaction to sediments contaminated with heavy metals in laboratory experiments and were absent from highly contaminated areas in Palestine Lake, Indiana. Moreover, other factors imply that high heavy metal concentrations at SC sites may have affected benthic abundances and composition. The relatively low levels of organic matter and larger grain size (sand) found at SC sites may serve to enhance availability of contaminants to the benthos (Gossiaux *et al.* 1993, Rediske *et al.* 2002). Thus, while low benthic densities (especially oligochaetes and total benthos) and trophic indices indicated relatively low levels of organic enrichment at SC sites, the community may have been more influenced by elevated levels of heavy metals. The findings of this study confirm that interpretation of community metrics based on community response to organic enrichment can be problematic when heavy metal contamination is present. Many species that are tolerant of organic enrichment are intolerant of heavy metals (Clements 1994, Hickey and Clements 1998, Winner *et al.* 1980). Further, this also indicates that community measures such as diversity and taxa richness can be coarse indicators of environmental conditions. Generally, these are most effective when used in conjunction with other community metrics, species compositions and densities or in comparison with historic data.

For Muskegon Lake as a whole, densities of all major taxa increased in 1999 compared to 1972. While there were some differences in the time of year collections were made (June in 1972 vs. October/November in 1999) and mesh size used (0.6 mm in 1972 vs. 0.5 mm in 1999) between the two studies, we believe these differences played a minor role in the large density increases observed in 1999. In the Great Lakes region, increased densities of certain macroinvertebrates (especially oligochaetes) have been considered indicative of degraded conditions or nutrient enrichment (Carr and Hiltunen 1965, Krieger 1984, Nalepa 1987, Winnell and White 1985). In lake systems, organic material from autochthonous and allochthonous sources settles to the bottom and serves as food for the benthos, leading to density increases. Although densities increased between 1972 and 1999 suggesting an increase in organic inputs and a degradation of habitat conditions, community indices indicated an improvement in conditions. The proportion of oligochaetes and the O/C ratio declined, while taxa richness and diversity increased. Collectively, these community changes suggest that, whereas overall productivity in Muskegon Lake remains high, environmental conditions have improved since 1972. Krieger and Ross (1993) found increases in taxa richness, increased densities of chironomids and sphaeriids, and reduced proportion of oligochaetes were particularly indicative of improved conditions in the Cleveland Harbor area of Lake Erie.

Conditions in 1972 could be considered a product of "cultural eutrophication" resulting from the discharge of approximately 135,000 m^3d^{-1} of combined municipal and industrial wastewater into the lake (Evans 1992). In 1972, mean surface concentration of total phosphorus was 67 $\mu g \cdot L^{-1}$, mean chlorophyll *a* was 25 $\mu g \cdot L^{-1}$, and Secchi depth averaged 1.5 m (Evans 1992, Freedman *et al.* 1979). Levels of all three variables exceed those indicative of eutrophic conditions (Wetzel 1983). High system productivity in addition to high loadings of BOD from municipal sewage and paper mill wastes likely led to periodic oxygen depletion and anoxic conditions observed in areas below the thermocline in 1972 (Freedman *et al.* 1979). Although duration of these anoxic events varied (Freedman *et al.* 1979), such conditions would likely favor tolerant oligochaetes, resulting in their dominance in the benthos as well as restricting many of the less-tolerant invertebrates (Krieger and Ross 1993). After wastewater diversion in 1973, concentrations of total phosphorus and chlorophyll decreased by 37% and 62% within a few years (Evans 1992, Freedman *et al.* 1979). However, chlorophyll (9.5 $\mu g \cdot L^{-1}$) and Secchi depth (approximately 1.5 m) suggested eutrophic conditions persisted, and anoxia was still observed (Freedman *et al.* 1979). In 1980, the benthic community remained dominated by oligochaetes, and total densities actually decreased (Evans 1992). By the mid-1990s, near-surface concentrations of chlorophyll (range 7–11 $\mu g \cdot L^{-1}$) and total phosphorus (range 20–26 $\mu g \cdot L^{-1}$) were lower than levels considered indicative of eutrophic conditions, and Secchi depth increased to 2–4 m (Gary Fahnenstiel, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, unpublished data). In 2003 levels of chlorophyll and total phosphorus remained similar to levels found in the mid-1990s and summer anoxia was absent (Alan Steinman, Annis Water Resources Institute, Grand Valley State University, Muskegon, Michigan, unpublished data). These improved conditions likely played a large role in observed increases in macroinvertebrate densities and improvements in community indices. Reductions in sediment concentrations of heavy metals may also have contributed to the recovery of the benthic community.

When evaluating temporal changes in the benthos, the invasion of the zebra mussel (*Dreissena polymorpha*) cannot be ignored. Impacts of *Dreissena* on the benthos and water quality parameters such as chlorophyll, and phosphorus concentrations have been well documented (Dermott and Kerec 1997, Fahnenstiel *et al.* 1995, Griffiths 1993, Haynes *et al.* 1999). Based on rates of expansion in southeastern Lake Michigan (Nalepa *et al.* 2006), *Dreissena* probably invaded Muskegon Lake in the early 1990s. Impacts of *Dreissena* on water quality and the benthos of Muskegon Lake are difficult to discern mainly because no data were collected just prior to the invasion. As noted, by the mid-1990s levels of chlorophyll and total phosphorus were greatly reduced compared to 1972, and water clarity had increased. These changes may have been a result of waste diversions, establishment of *Dreissena*, or a combination of both. *Dreissena* was widespread in Muskegon Lake, being found at 20 of 27 sites, but densities were less than 400 m^{-2} at all but three sites. The substrate at sites with higher densities (5,600 to 40,900 m^{-2}) was more favorable (wood chips, coarse sand, and gravel) than the soft substrate (silt) found at most of the other sites. While densities are a function of substrate type in a given system, the overall mean density of *Dreissena* in Muskegon Lake (2,400 m^{-2}) was generally comparable to mean densities found in other regions within the Great Lakes such as Lake St. Clair (mean density 3,200 m^{-2}, Nalepa *et al.* 1996) and inner Saginaw Bay (mean density 4,000 m^{-2}, Nalepa *et al.* 1995).

While *Dreissena* may be impacting the overall benthic community of Muskegon Lake, distribution patterns and relative densities suggest that these impacts were probably minor compared to the temporal influences of wastewater diversion or the spatial influences of depth, river inputs, and sediment concentrations of heavy metals. Sphaeriids tend to respond negatively to *Dreissena* (Dermott and Kerec 1997, Nalepa *et al.* 1998, Nalepa *et al.* 2003), but densities of sphaeriids were significantly higher in 1999 than in 1972. Further, the increase in densities of oligochaetes between 1972 and 1999 was also not likely related to *Dreissena*. In Saginaw Bay, oligochaete densities actually declined in soft-substrate areas where few mussels were found (Nalepa *et al.* 2003). It was suggested that high densities of mussels in hard substrate areas were depleting food resources for oligochaetes found in soft-substrate areas. This does not appear to have been the case in Muskegon Lake. On the other hand, some benthic changes could be related to *Dreissena*. The increase in amphipods in 1999 compared to 1972 may have been at least partly a result of the *Dreissena* invasion. In Saginaw Bay, amphipod abundances (*Gammarus* sp.) increased more than 3-fold after *Dreissena* became established (Nalepa *et al.* 2003).

Overall, it appears that spatial and temporal patterns in the benthic community of Muskegon Lake were more influenced by nutrient/organic inputs than toxic contaminants. Prior to waste diversion, nutrients and organic inputs from domestic wastes and chemical pollutants led to a severely degraded benthic community (Evans 1992, Rediske *et al.* 2002). These discharges were sources of heavy metals, PAHs, wood pulp, sulfides, fuel oil, and PCBs to the lake. Sediment toxicity in conjunction with anoxia induced by high organic loads likely suppressed all macroinvertebrate taxa. With respect to the status of Muskegon Lake as an AOC, the BUI of degraded benthos was clearly reflected in community diversity and TCI scores in the 1972 data. After diversion, indicators of water quality such as phosphorus and chlorophyll concentrations and water clarity improved. Sediment quality also improved as current concentrations of heavy metals reflect a 40%–69% reduction from previous levels. While sediment pollutants may still be impacting the benthic community in some areas (i.e., SC group of sites), overall improvements in community structure would suggest that wastewater diversion had a positive influence on benthic populations. Based on recent nutrient concentrations and the absence of summer anoxia, it is anticipated that the benthic community will continue to recover from the degraded condition of 30 years ago. It is recommended that a similar monitoring program be conducted in future years to document the progress of recovery and to determine if the BUI (degradation of benthos) has been restored. Documenting the progress of recovery and the determination of restoration endpoints for the benthic community are key steps in the delisting of AOCs. Based on the results of this investigation, benthic community diversity and TCI indices appear to be very good indicators of ecosystem recovery and should be considered for use in the delisting process. The results also suggest that the impact of heavy metals is limited to a region of the SC area. This location should be examined in greater detail for toxicity and impacts to the benthic community to determine the need for future remediation.

ACKNOWLEDGMENTS

We wish to thank the crews of the R/V *Mudpuppy* (EPA) and R/V *Cyclops* (GLERL). Michael Winnell provided assistance with oligochaete and chironomid taxonomy. Eric Andrews, Betty Doyle, Mike Sweik, and Shanna McCrumb provided assistance with the chemical analyses. This research was funded by grant #985906-01 from the Environmental Protection Agency's Great Lakes National Program Office (GLNPO) to the Annis Water Resources Institute. We also wish to thank EPA/GLNPO Project Officer Marc Tuchman for his support and contributions. David Barton and two anonymous reviewers provided helpful suggestions that improved this paper. The Gas Chromatograph/Mass Spectrometer used by GVSU was partially funded by a National Science Foundation Grant (DUE-9650183). This is GLERL contribution no. 1387

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Submitted: 29 August 2005
Accepted: 17 May 2006
Editorial handling: David R. Barton