Hydrobiologia **219**: 63–81, 1991.
M. Munawar & T. Edsall (eds),
Environmental Assessment and Habitat Evaluation of the Upper Great Lakes Connecting Channels.

Effects of pollution on benthic invertebrate communities of the St. Marys River, 1985

A. J. Burt, P. M. McKee, D. R. Hart & P. B. Kauss[1]
Beak Consultants Limited, 14 Abacus Road, Brampton, Ontario, L6T 5B7 Canada; [1]Ontario Ministry of the Environment, 1 St. Clair Avenue West, Toronto, Ontario, M4V 1K6, Canada

Key words: St. Marys River, sediment quality, benthic communities, pollution

Abstract

A survey was undertaken in 1985 to assess spatial and temporal trends in the benthic community structure in relation to sediment contamination and wastewater sources at 70 stations between Whitefish Bay and lower Lake George in the St. Marys River. Cluster analysis identified seven benthic communities. Three were identified as pollution impacted, based on a preponderance of tubificids and nematodes, usually at high densities (up to 259000 m^{-2}), but sometimes at low densities (< 100 m^{-2}) at individual stations. Impacted communities occurred downstream of industrial and municipal sources and in depositional areas, and were confined mainly to Canadian waters. Unimpacted communities had greater numbers of taxa, and occurred upstream of point sources, along the U.S. shoreline, and in most areas of downstream lakes. Impacted and unimpacted communities were separated along particle size and contaminant gradients in river sediments. Despite recent reductions in pollutant loadings and improvements in sediment quality, no major changes were apparent in the status of the benthic community from earlier surveys.

1. Introduction

The St. Marys River, which flows from Lake Superior to Lake Huron, has been known to be polluted by steel and paper mill discharges since the 1940's, as evidenced by impairment of water quality, sediments, and the zoobenthos. Surveys of the impacted benthic communities in 1967 (Veal, 1968) and 1973 (Hamdy *et al.*, 1978) indicated zones of severe impairment downstream of discharges from Algoma Steel, Abitibi-Price Paper and the Sault Ste. Marie Sewage Treatment Plant (STP). On the basis of the latter survey, further reductions in waste loading from the contributing industries were recommended by the Ontario Ministry of the Environment (OME) and International Joint Commission.

A follow-up survey was conducted in 1983 (McKee *et al.*, 1984) to examine benthos and sediment quality relationships in light of ongoing pollution abatement programs at Algoma Steel and changing hydrological conditions brought about by the Great Lakes Power Corporation generating station. This survey indicated that the benthic communities of the St. Marys River were similar to those found in 1967 (Veal, 1968) and 1973 (Hamdy *et al.*, 1978), with zones of severe or moderate impact adjacent to and downstream of the industrial and municipal discharges. A severely impacted community characterized earlier by high densities of *Limnodrilus*/*Tubifex* was less pronounced in 1983, and was confined to a region downstream of St. Marys Falls. This has been identified as a region of heavy metal and

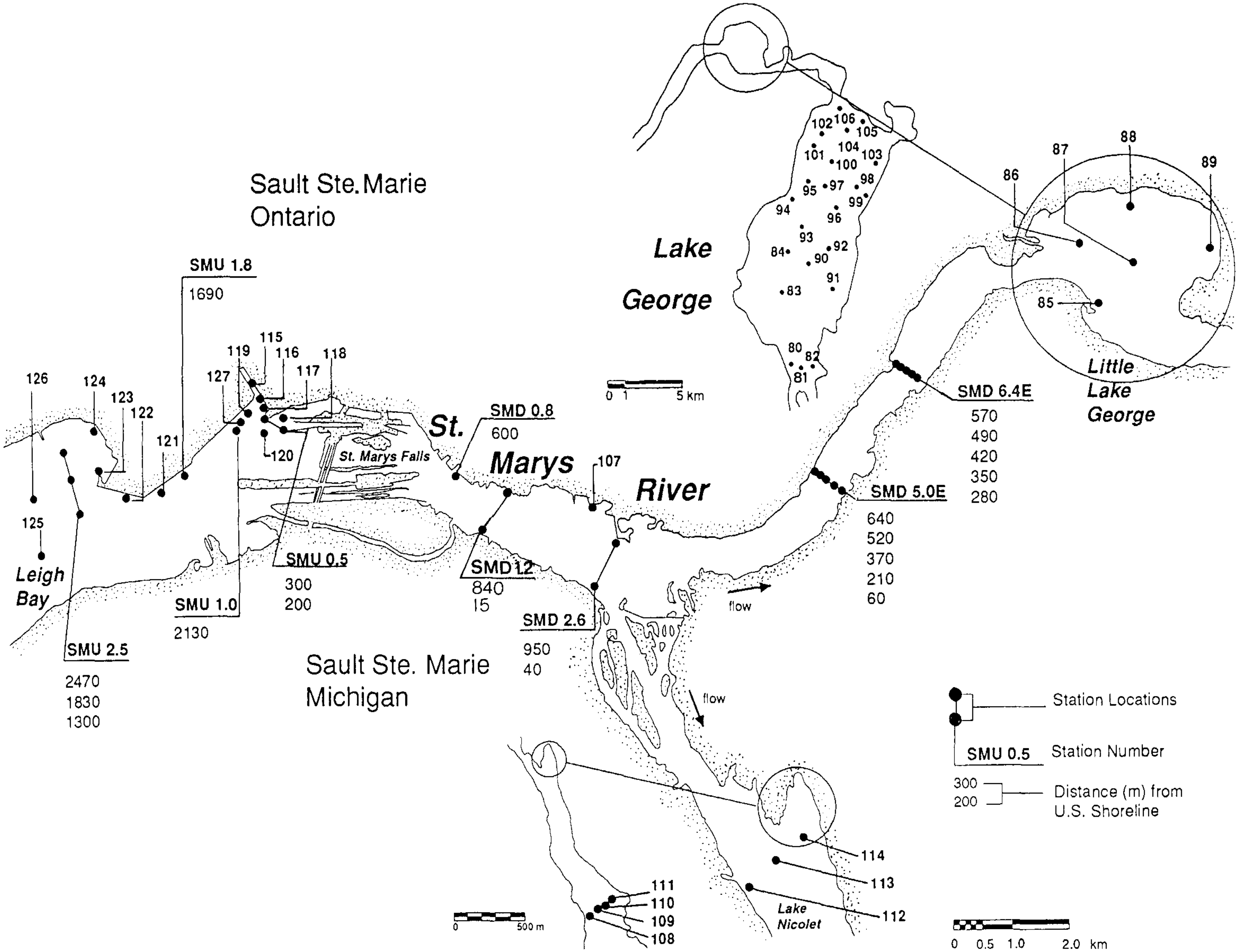

Fig. 1. Sediment and benthic fauna sampling station locations in 1985.

oil and grease contamination. Reductions in pollutant loadings by industry prior to 1983 appeared to have contributed to the minor community changes.

The 1983 survey was less extensive than those in earlier years, with little or no sampling downstream of the industrial region in Lake George, Little Lake George or Lake Nicolet, or upstream of Algoma Steel to Whitefish Bay (Fig. 1). Since benthic community effects were still apparent throughout the industrial region in 1983, additional sampling further upstream and downstream was identified as necessary to define their full extent. On the basis of a survey by Hiltunen & Schloesser (1983) in 1974–75, the benthic community was believed to be impacted to a point at least 30 km downstream of Sault Ste. Marie. The present survey was undertaken to augment the 1983 results by McKee *et al.* (1984) and verify Hiltunen & Schloesser (1983). Emphasis was placed on the lower and upper river areas not sampled in 1983. This paper documents the results of the 1985 benthic survey, compares the 1985 data with those from earlier studies, and evaluates relationships between benthic community structure and sediment quality.

2. Methods

2.1. *Field survey*

The 1985 survey was carried out in September–October. A total of 70 stations were sampled (Fig. 1), with 11 stations corresponding to 1983 locations. Station transects were denoted as either upstream (SMU) or downstream (SMD) distances from the St. Marys Falls and from the U.S. shore. For example, Station SMD 6.4E–490 indicates a location of 6.4 miles downstream of the falls in the eastern channel and 490 m from the U.S. shore.

Benthic samples were collected primarily by Ponar grab, but two Stations (SMU 0.5–200 and SMD 0.8–600) required airlift sampling (described by Barton & Hynes, 1978) due to substrate characteristics. The Ponar grab sampled a bottom area of 0.052 m^2. The diver-operated airlift sampler was equipped with 200 μm mesh Nitex collecting bags, and was used to sample 0.075 m^2 quadrats on the river bed. All benthic samples were washed through 200 μm mesh and were preserved in 5 to 10 percent formalin.

A survey completed in 1983 (McKee *et al.*, 1984) indicated that three replicate samples at each sampling station were sufficient for estimation of log-transformed total organism density with a standard error = 20 percent of the mean density. On this basis, three replicate samples were collected at each 1985 sampling station.

Surficial sediments (top 3 cm) were collected at each station for physical/chemical analysis using a Shipek sampler. Substrate characteristics, water depth, and perceived current strength were also recorded. Sediments from at least 3 grabs at each station were homogenized in a clean, solvent-rinsed stainless steel tray using stainless steel utensils. Sediments were then partitioned into subsamples for analysis of trace organic and inorganic constituents by the OME laboratories, using documented procedures (OME, 1983). Results of these analyses were used to evaluate sediment quality-benthic community relationships.

2.2. *Benthic analyses*

Benthic organisms were sorted from sediment and debris using a dissecting microscope (10 × power) and grouped by major taxa. After sorting, a subsample of the tubificids (all of sample up to 100 individuals) and chironomids (> = 10 percent subsample of each major chironomid group sorted) in each sample was cleared and mounted in 'CMCP-10' mounting medium on microscope slides. Chironomids were generally decapitated to facilitate clearing of the head capsule. Benthic organisms were identified using various taxonomic keys – Klemm (1985) for Oligochaeta; Oliver & Roussel (1983) for Chironomidae; Mackie *et al.*, (1980) and Clarke (1973) for Mollusca; Wiggins (1977) for Trichoptera; and Pennak (1978) for other groups.

2.3. *Statistical analyses*

The 1985 benthic communities were described on the basis of species compositional similarities between stations. Squared Euclidean distance was used as an inverse similarity measure for this purpose. Biologically similar stations are characterized by a small interstation distance. The distance formula for Stations *j* and *k* (Norusis, 1986) is as follows:

$$D^2(j, k) = \sum_{h=1}^{n} (X_{hj} - X_{hk})^2$$

where:

X_{hj} = log transformed density of species *h* at Station *j*.

The distance matrix contains an interstation distance for each pair of sampling stations. This information can be used to group the stations into clusters of biologically similar stations. The grouping procedure, or Q-mode cluster analysis, used in this study was a hierarchical agglomerative technique (Ward's method; Norusis, 1986). At each stage, one station is combined either with another station or with an existing cluster of stations, according to its affinities, and the affinities of the newly formed cluster are recalculated. The process continues until all stations are accounted for. Each cluster so defined can be interpreted as a distinct benthic community.

Characterization of station clusters was based on comparison of total organism density, species richness, tubificid dominance, and species composition between clusters. This information was used to identify station clusters, and from the spatial distribution of these clusters to delimit impacted zones. Spatial patterns and impacted zones in 1985 were related to known past and present pollution inputs, and compared to spatial patterns and impacted zones during previous surveys.

Several independent methods were used to examine the sediment quality characteristics of the St. Marys River benthic communities. First, discriminant analysis was performed on the sediment quality data in order to identify environmental gradients in sediment quality which tend to distinguish between the stations in different benthic faunal clusters. This method has been described by Green (1979), and other authors (e.g., Hutchinson, 1978), as a means of representing the ecological niche space occupied by different communities.

A second method of examining sediment quality-benthic faunal relationships is by derivation of a quantitative benthic community index, with a value at each station, to be used as a dependent variable in regression analysis of the sediment data. Thus, the sediment characteristics which are the best predictors of the community index can be identified. This approach differs from discriminant analysis primarily in the nature of the dependent variable. In discriminant analysis, the dependent variable reflects cluster membership, based on overall species composition, while a community index can reflect more specific attributes of species composition in a quantitative manner.

The community index used in this approach was a measure of dominance by a particular group of taxa (or guild). Guilds were defined by R-mode cluster analysis, which groups species based on similar spatial distributions (i.e., similar densities at each station). Densities were log transformed, as in the Q-mode cluster analysis. An index of dominance by each guild was calculated at each station as follows:

$$I_g = \frac{\sum_{i=1}^{S_g} \log(X_i + 1)}{\sum_{i=1}^{S} \log(X_i + 1)}$$

where:

S_g = number of taxa in the guild,
S = total number of taxa present, and
X_i = density of species i.

The dominance index ranges from zero to one in magnitude.

Some guilds consisted of recognized pollution tolerant taxa. Their index values were plotted on study area maps to illustrate association with known point sources. Bivariate correlations with sediment variables were determined, and stepwise multiple regression analysis was performed to find the best set of sediment variables for prediction of the community index.

Some sediment variables were transformed prior to use in discriminant, correlation or multiple regression analysis, in order to improve their statistical distributions. Trace metals, pesticides, oil and grease, total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and phosphorus were log-transformed. An angular transformation was used for particle size variables, and a square root transformation for loss on ignition (LOI). The pH and Eh distributions were not transformed. Water depth was included as a predictor variable, with log transformation.

3. Results and discussion

3.1. Indicator species in the St. Marys River

In the following discussion, reference is frequently made to the relative tolerance or intolerance of benthic species found in the St. Marys River (Table 1) to polluted conditions. Clean-water indicators are reported as more prevalent at locations well removed from effluent discharges, while tolerant forms prevail in the apparently impacted areas found downstream of the major point sources. It would be expected that station locations remote from pollution sources in the St. Marys River would reflect a healthy benthic community structure. The source of the St. Marys River is Lake Superior (Whitefish Bay, Fig. 1) and therefore, the water quality is very good. The pollution tolerance of benthic invertebrates, as outlined below, typically refers to tolerance of organic pollution and associated low dissolved oxygen conditions, rather than to tolerance of toxic metals and organic compounds.

Invertebrate forms found in the study area which are generally considered to be intolerant included mayflies such as *Hexagenia, Ephemera, Baetis* and *Caenis* (Roback, 1974). *Hexagenia* has been reported as rare or absent in sediments contaminated by oily substances in the St. Marys River (Hiltunen & Schloesser, 1983). The lumbriculid *Stylodrilus heringianus* may also be considered a clean-water indicator. This species prefers sandy to gravelly substrates such as found in much of the study area (i.e. near SMD 6.4E, SMD 1.2), but is typically absent or reduced in numbers in disturbed areas such as near urban centres (Nalepa & Thomas, 1976).

Other species such as the tubificids *Aulodrilus* spp., *Potamothrix moldaviensis* and *Spirosperma ferox* are mesotrophic indicators, and *Rhyacodrilus* spp. is usually found in oligotrophic waters (Cook & Johnson, 1974); thus, these species are probably intolerant of heavy organic pollution. Nematodes apparently reach their highest densities in mesotrophic regions, with a low tolerance for highly polluted habitats (Golini, 1979). The polychaete *Manayunkia speciosa* is also considered indicative of moderate organic pollution (Poe & Stefan, 1975), but intolerant of severe organic pollution (Mackie & Qadri, 1971). Other mesotrophic indicators include the chironomids *Polypedilum, Nanocladius, Psectrocladius, Rheotanytarsus, Dicrotendipes* and *Microtendipes*. Gill-breathing gastropods such as *Valvata* and *Amnicola* also appear to be relatively intolerant to heavy organic pollution (Freitag *et al.*, 1973).

Among the pollution-tolerant forms, tubificids and chironomids are most noteworthy. High densities of the tubificids *Limnodrilus* spp. (including immatures without capilliform chaetae), *Tubifex tubifex, Quistadrilus multisetosus* and *Ilyodrilus templetoni* (both including immatures with capilliform chaetae) are characteristic of areas showing organic enrichment throughout the Great Lakes (Cook & Johnson, 1974; Brinkhurst & Cook, 1974). Similarly, the chironomids *Procladius, Chironomus* and *Cryptochironomus* are common in polluted conditions in the Great Lakes (Cook & Johnson, 1974).

3.2. Cluster analysis of spatial patterns in 1985

Seven clusters were defined in 1985 using Q-mode (station) clustering (Fig. 2, Table 2) with three

Table 1. Benthic invertebrates collected from the St. Marys River in October 1989 and their frequency of occurrence

Taxa	Status	Taxa	Status	Taxa	Status
COELENTERATA		*Immature with hair setae*	C	*Microtendipes sp.*	R
Hydra sp.	L(R)	*Immature without hair setae*	L(C)	*Pagastiella sp.*	L(R)
PLATYHELMINTHES		*Dina sp.*	R	*Parachironomus sp.*	R
Planaria sp.	R	*Glossiphonia complanata*	R	*Paralauterborniella sp.*	R
NEMERTEA		*Helobdella sp.*	R	*Paratendipes sp.*	R
Prostoma rubrum	R	*Helobdella stagnalis*	R	*Phaenopsectra sp.*	R
NEMATODA	A	*Piscicola punctata*	R	*Polypedilum sp.*	C
ANNELIDA		*ANTHROPODA*		*Pseudochironomus sp.*	R
Manayunkia speciosa	L(C)	*Asellus sp.*	R	*Rheotanytarsus sp.*	L(R)
Branchiobdellidae	R	*Lirceus sp.*	L(R)	*Stempellina sp.*	R
Enchytraeidae	L	*Crangonyx sp.*	R	*Stictochironomus sp.*	R
Glossoscolecidae	R	*Gammarus sp.*	R	*Tanytarsus sp.*	R
Lumbriculus variegatus	R	*Hyallela azteca*	R	*Xenochironomus sp.*	R
Stylodrilus heringianus	R	*Orconectes sp.*	R	*Diamesa sp.*	R
Amphichaeta americana	R	*Hydracarina*	C	*Monodiamesa sp.*	R
Chaetogaster diaphanus	R	*Collembola*	R	*Odontomesa sp.*	R
C. diastrophus	R	*Chloroperlidae*	R	*Potthastia sp.*	R
C. setosus	R	*Baetis sp.*	R	*Corynoneura sp.*	R
Nais barbata	R	*Ephemera sp.*	R	*Cricotopus sp.*	R
N. bretscheri	R	*Hexagenia sp.*	C	*Epiococladius sp.*	R
N. communis	R	*Ephemerella sp.*	R	*Heterotrissocladius sp.*	R
N. pardalis	R	*Paraleptophlebia sp.*	R	*Nanocladius sp.*	R
N. simplex	R	*Brachycerus sp.*	R	*Orthocladius sp.*	R
N. variabilis	R	*Caenis sp.*	R	*Paracladius sp.*	R
Ophidonais serpentina	R	*Stenonema sp.*	R	*Psectrocladius sp.*	R
Piquetiella michigansis	R	*Tetragoneura sp.*	R	*Pseudosmittia sp.*	R
Pristina foreli	R	*Notonecta sp.*	R	*Synorthocladius sp.*	R
P. osborni	R	*Sialis sp.*	R	*Thienemanniella sp.*	R
Ripistes parasita	R	*Hydropsche sp.*	R	*Ablabesmyia sp.*	R
Slavina appendiculata	R	*Agraylea sp.*	R	*Clinotanypus sp.*	R
Specaria josinae	R	*Hydroptrila sp.*	R	*Larsia sp.*	R
Stylaria fossularis	R	*Oxyethira sp.*	R	*Nilotanypus sp.*	R
S. lacustris	R	*Lepidostoma sp.*	R	*Procladius sp.*	C
Uncinais uncinata	R	*Ceraclea sp.*	R	*Tanypus sp.*	R
Vejdovskyella comata	R	*Mystacides sp.*	R	*Thienemannimyia sp.*	L(C)
V. intermedia	R	*Nectopsyche sp.*	R	*Bezzia complex*	C
Aulodrilus americana	C	*Oecetis sp.*	R	*Hemerodromia sp.*	R
A. limnobius	R	*Triaenodes sp.*	R	*MOLLUSCA*	
A. piqueti	R	*Molanna sp.*	R	*Elliptio sp.*	R
A. pluriseta	C	*Phryganea sp.*	R	*Sphaerium sp.*	R
Ilyodrilus templetoni	R	*Ptilostoma sp.*	R	*S. simile*	R
Isochaetides curvisetosus	R	*Phylocentropus sp.*	R	*S. striatium*	R
I. freyi	R	*Polycentropus sp.*	R	*Pisidium sp.*	C
Limnodrilus claparedianus	R	*Chironomus sp.*	R	*Ferrissia sp.*	R
L. hoffmeisteri	R	*Cladopelma sp.*	R	*Amnicola limosa*	C
L.udekemianus	R	*Cladotanytarsus sp.*	R	*Lymnaea sp.*	R
Potamothrix moldaviensis	R	*Cryptochironomus sp.*	C	*Helisoma sp.*	R
P. vejdovskyi	R	*Cryptotendipes sp.*	C	*Gyraulus parvus*	R
Quistadrilus multisetosus	R	*Demicryptochironomus sp.*	R	*Physa gyrina*	R
Rhyacodrilus coccineus	R	*Dicrotendipes sp.*	R	*Valvata sincera*	L(C)
Spirosperma ferox	C	*Glyptotendipes sp.*	R	*V. tricarinata*	R
Tubifex tubifex	R	*Harnischia sp.*	R	*Campeloma decisum*	R

Presence codes:
A – Abundant (> = 20% community at > = 50% of the stations)
L – Locally abundant (> = 20% community at any station)
C – Common (<20% of the community at >30 of the stations)
R – Rare (<20% of the community at < = 30 of the stations)

Table 2. Characteristics of benthic community clusters in the St. Marys River – 1985

Parameter	Cluster number						
	1	2	3	4	5	6	7
Number of stations	16	7	9	11	8	14	5
Dominant groups (Abundant)	Nematoda (33%) Manayunkia sp. (23%) Chironomidae (18%) Tubificidae[1] (14%)	Manayunkia sp. (43%)* Nematoda (25%) Tubificidae[1,2] (16%)	Nematoda (45%) Tubificidae[1] (39%) Chironomidae (6%)	Nematoda (37%) Tubificidae[1] (33%) Limnodrilus hoffmeisteri (26%) Chironomidae (16%)	Chironomidae (54%) Nematoda (23%)	Chironomidae (32%) Nematoda (20%) Isopoda (19%) Tubificidae[1] (11%)	Chironomidae (38%) Nematoda (28%) Tubificidae[1] (10%)
Common taxa (Present at all Stations)	*Procladius* sp. *Bezzia complex* *Spirosperma ferox*	Nemertea *Stylodrilus heringianus* *Spirosperma ferox* *Pisidium* sp.	*Nais variabilis*		Tubificidae[1] *Procladius* sp. *Cricotopus* sp. *Bezzia complex*	*Manayunkia* sp. *Pisidium* sp. *Amnicola* sp. *Valvata sincera* *Procladius* sp. *Polypedilum* sp.	*Helisoma* sp. *Procladius* sp. *Chironomus* sp. *Polypedilum* sp. *Hyallela* sp. Hydracarina
Mean no. taxa	27	23	15	12	39	40	32
Mean total density (No/m^2)	128,000	192,000	259,000	71,000	56,000	165,000	201,000
Substrate	Brown silt over sand/clay	Coarse sand variable silt	Organic silt	Silt	Variable silty-coarse sand	Silt over sand	Brown silt over sand/clay
Water depth (m)	2-4	3-14	1-16	2-9	1-6	2-11	3-12
Visible oil	Absent to slight (10)[3]	Absent to abundant (5)[3]	Slight to abundant (9)[3]	Absent to abundant (10)[3]	Absent to slight (2)[3]	Absent to slight (1)[3]	Absent to abundant (4)[3]
Current	None to slight	Slight to moderate	None	None to strong	None to moderate	None to slight	None to slight

*( ) Mean percent composition of major taxonomic groups within a cluster.

1 Immature Tubificidae without hair chaetae – i.e., *Limnodrilus* spp.

2 Immature Tubificidae with hair chaetae – i.e., *Tubifex tubifex.*

3 Number of stations where visible oil present.

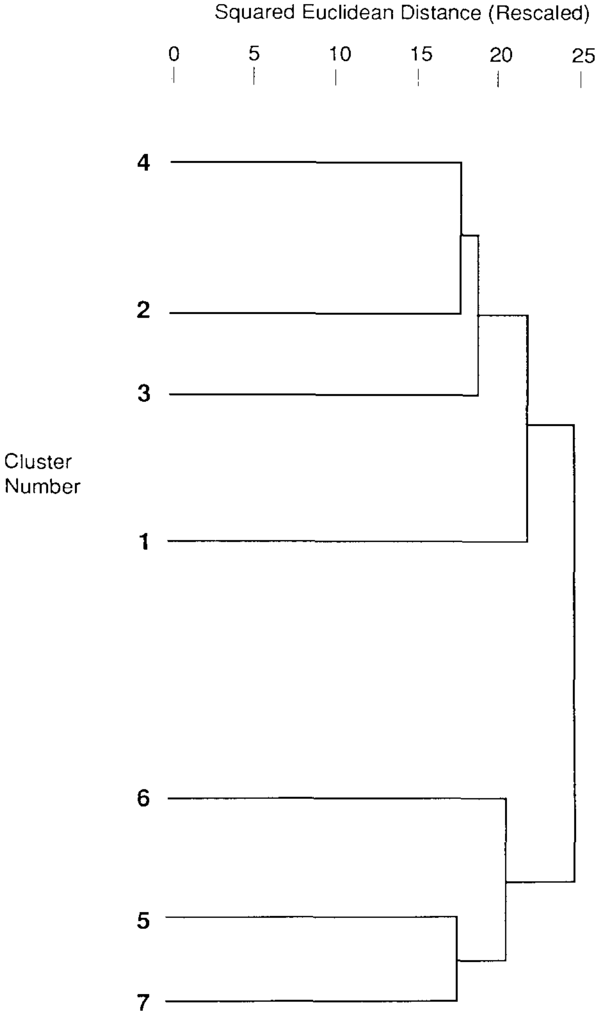

Fig. 2. Relationships between 1985 benthic station clusters derived by Ward's method.

clusters (2 to 4) identified as including pollution-impacted stations. The stations in these three clusters were dominated by facultative (including mesotrophic) to severe pollution-tolerant taxa. As the degree of organic enrichment increased, total community density also increased, together with a decline in the total number of taxa present. In situations where toxicity was apparent, very low densities and number of taxa were reported. These groups were associated with known industrial outfalls or downstream depositional areas. The remaining four clusters (1, 5, 6, and 7) generally describe stations that were upstream of effluent discharges, near the U.S. shoreline or well downstream of discharges.

Cluster 2 consisted of five stations downstream of the Sault Ste. Marie STP, a station at the north end of Lake Nicolet, and one near the Algoma slip (Fig. 3). The mean number of taxa per station was relatively low (23), while the mean total density was relatively high (192000 m^{-2}) in comparison with the unimpacted group of station clusters (1, 5, 6, and 7) (Table 2). Most of the common species among Cluster 2 stations were indicative of mesotrophic conditions, with more sensitive groups such as gastropods, isopods, ephemeropterans, and trichopterans either substantially reduced in density or absent. Consequently, stations included in Cluster 2 were considered to be slightly impaired.

Stations included in Cluster 3 were situated near the Canadian shore of the river, downstream of the main industrial outfalls; downstream of the Sault Ste. Marie STP; in Little Lake George; and in upper Lake George (Fig. 3). These stations are in depositional areas characterized by a silt substrate, a weak current, and oil accumulation in the sediment. Characteristic organisms at stations within Cluster 3 consisted of nematodes, unidentified immature tubificids without capilliform chaetae (likely *Limnodrilus* spp.), and the naidid oligochaete *Nais variabilis*, as well as other organisms that tend to be pollution-tolerant (Table 2). The relative abundance of the tubificid fraction was substantially greater than that observed at Cluster 2 stations (39% vs 16%, respectively). Of particular note was the low density or absence of the polychaete *M. speciosa* at Cluster 3 stations, in contrast to its abundance at stations in the closely related Cluster 2 (Fig. 2), suggesting greater impairment of water and sediment quality than occurred at stations in Cluster 2. This greater degree of impairment is reflected in a much lower mean number of taxa (15) and a much greater mean total density (259000 m^{-2}) relative to Cluster 2 (Table 2). Both of these features are typical of organic enrichment. On this basis, as well as the species assemblage, Cluster 3 stations were considered moderately impaired.

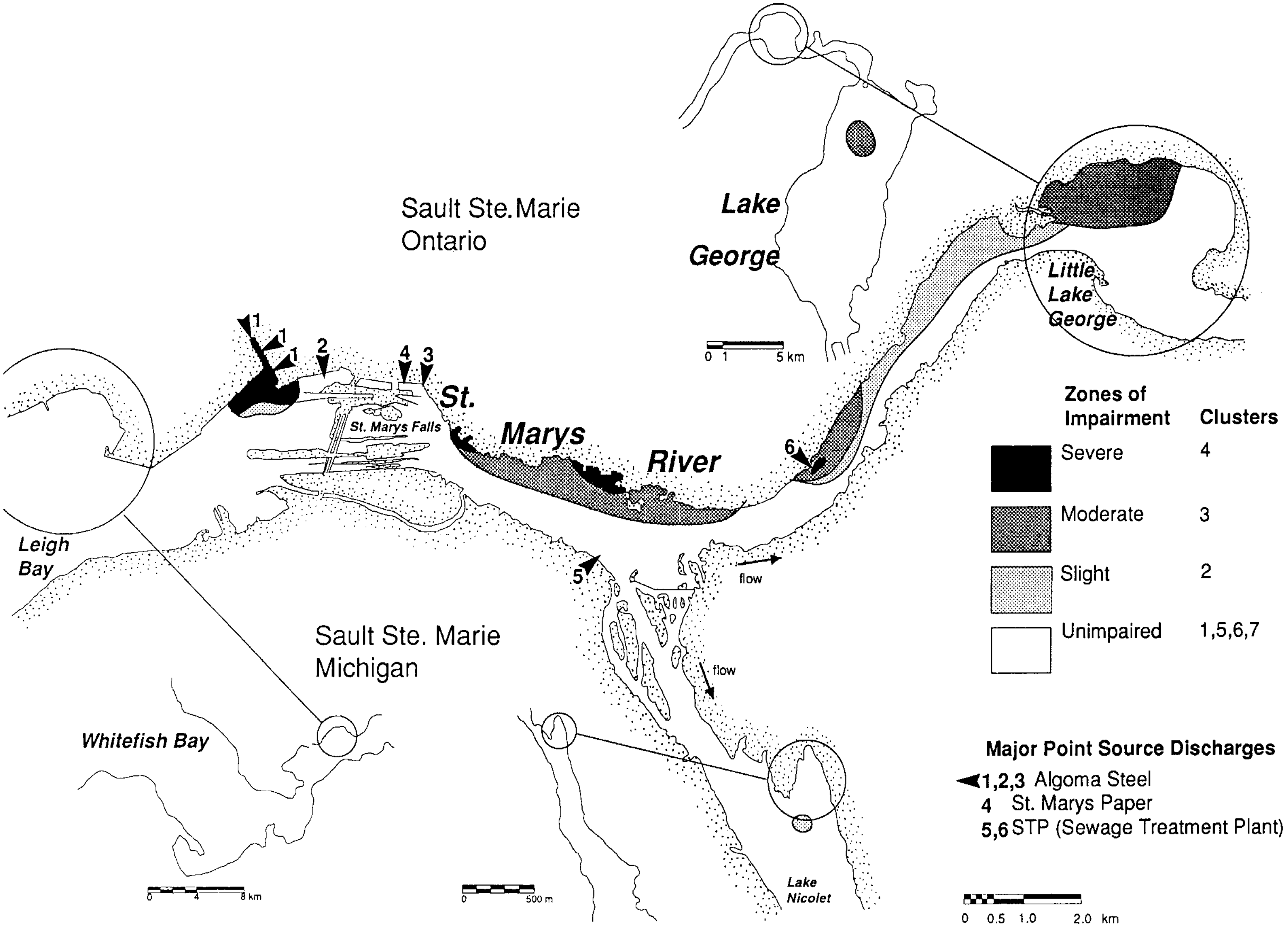

Fig. 3. Distribution and zones of impairment of benthic fauna in 1985.

Cluster 4 included eight stations in the immediate vicinity of the Algoma Steel slip, two stations near the Canadian shore below the St. Marys rapids, and one station immediately downstream of the STP (Fig. 3). Physical environmental conditions described at stations within this cluster group were variable and the substrate was frequently heavily contaminated by oily residue (Table 2). Cluster 4 was defined biologically by the presence of unidentified immature tubificids without capilliform chaetae (likely *Limnodrilus* spp.) and nematodes were also present at a majority of stations. Other common species included the tubificid *Q. multisetosus* and the chironomids *Procladius* and *Cryptochironomus*. All of these species are tolerant of organic pollution. A few other pollution-tolerant taxa were also common (Table 2). The mean number of taxa per station (12) in Cluster 4 was the lowest of all clusters (Table 2). The variation in total densities at stations within Cluster 4 was very large, with very high densities occurring at organically enriched areas, and very low densities at some locations where effluent discharges may be exerting a toxic effect. For example, the mean total density of organisms at Station 116 in the Algoma slip was only 88 m^{-2}, suggesting a toxic inhibition of benthic community development by steel mill effluents, perhaps in combination with poor physical habitat conditions. At Station SMD 5.0E–520 near the STP, severe organic enrichment is implied by the extremely high mean total density of 345 000 m^{-2}. Biologically unusual stations within Cluster 4 included Station 127 where nematode densities reached 220 000 organisms m^{-2} (70% of the population) and SMD 0.8–600 where coelenterates (*Hydra* sp.) accounted for 51 percent of the community. The very low number of taxa and preponderance of pollution-tolerant forms in Cluster 4 are indicative of severe environmental impairment.

3.3. Unimpacted areas

The remaining four clusters (1, 5, 6 and 7) included stations which were either upstream of the discharges, near the U.S. shore or too far downstream to be substantially affected (Fig. 3). As such, they were characterized by benthic associations which were low in tubificid oligochaetes, high in average numbers of taxa (27 to 40 per station), and are considered to be relatively unimpaired.

Cluster 1, the largest cluster in terms of numbers of member stations (16), occurred primarily in Lake George on silty substrate. Other environmental factors were variable, although oil tended to be either visibly absent or present only as slight traces (Table 2). Cluster 1 was biologically characterized by nematodes, polychaetes, the chironomid *Procladius*, immature tubificids without capilliform chaetae (likely *Limnodrilus* spp.), and the ceratopogonid *Bezzia* (Table 2). Several other species were also common to the majority of the stations in this cluster. The presence of non-tolerant organisms at most of the stations and relatively high mean numbers of taxa suggest that Cluster 1 stations were unimpaired overall, with some degree of organic enrichment.

Stations in Cluster 5 were generally situated upstream of pollution sources in the St. Marys River. Environmental characteristics were variable for all recorded parameters (Table 2). Characteristic taxa were Nematoda, immature Tubificidae, *Bezzia, Procladius*, and *Cricotopus*. Other frequently occurring taxa included non-tolerant forms such as ephemeropterans and trichopterans. Tubificids tended to be a minor portion of this community, with chironomids forming the majority of the assemblage. The high mean number of taxa (39), the low mean total density (56 000 m^{-2}), and the location of these stations either upstream or well downstream of pollution sources suggest that this cluster represents a relatively unimpaired community.

Cluster 6 was the second largest cluster (16 stations), with stations located in Leigh Bay, near the U.S. shore below the St. Marys Falls, in Lake Nicolette, and in Lake George. Essentially all locations were either upstream or across the river from point sources, or were well removed downstream (Lake George) in depositional areas. Characteristics of these locations included a substrate of silty sand and a local macrophyte community (Table 2). Characteristic taxa included the ubiquitous nematodes and immature tubificids (without capilliform chaetae), chironomids, polychaetes, pea clams, and snails (Table 2). Other commonly occurring taxa included the isopods *Asellus* and *Lirceus*, the amphipod *Hyalella azteca*, and the intolerant groups such as ephemeropterans. This assemblage is a mixture of facultative and non-tolerant organisms. The mean number of taxa at each station in this cluster (40) was the highest of all seven (Table 2). As in Cluster 5, chironomids were dominant (32% of the community). This cluster is classified as relatively unimpaired, based on the high number of taxa, the presence of intolerant forms, and remote location of these stations from sources of pollution.

Cluster 7 is the smallest of all the clusters (5 stations), and included only stations located upstream of the St. Marys Falls, downstream of the STP, and in Little Lake George. Stations in this cluster were characterized by a brown silty substrate and a general presence of aquatic macrophytes. Taxa common to all stations in Cluster 7 included primarily chironomids and nematodes with immature tubificids, Hydracarina, amphipods and snails also present (Table 2). Most of these taxa are facultative or tolerant forms. In general, stations within this cluster may be classified as unimpaired by virtue of the relatively high mean number of taxa (32), notwithstanding the fact that some stations (SMD 6.4E–280 and Station 89) have a high visible oil content in the sediments.

3.4. *Sediment quality relationships*

Discriminant analysis revealed a possible sediment quality basis for separation of the seven station groups defined by cluster analysis. Stations in the same cluster (with the same numeric label in Fig. 2) have similar overall species compositions. Clusters 2, 3, and 4 were considered to represent impacted groups, based on the recognized pollution tolerance of their characteristic species.

Clusters 3 and 4 were distinguished by high sediment concentrations of iron and zinc in relation to particle size (DF1 in Fig. 4). Cluster 2 sediments were distinguished on the same discriminant function by a greater fraction of Particle Size 2 (45 to 1 000 μm) but lower concentrations of these metals. Relationships between bulk sediment chemistry as examined here, and benthic community response, are poorly understood, and may be strongly influenced by the fractions of sediment contaminants that are loosely associated with the sediment and therefore are more bioavailable. Nonetheless, geometric mean iron concentrations of 3.1 percent and 6.3 percent and zinc concentrations of 174 $\mu g\, g^{-1}$ and 257 $\mu g\, g^{-1}$ at stations defined by Clusters 3 and 4 (Table 3), respectively, are considerably higher than the OME dredge disposal guidelines of 1 percent for iron and 100 $\mu g\, g^{-1}$ for zinc (Persaud & Wilkens, 1976), indicating that these key elements in DF1 could adversely affect benthic organisms and influence benthic community structure. Cluster 3 sediments were distinguished from those of Cluster 4 by higher concentrations of PCBs and a reduced fraction of finer particulate material (DF2) (Table 3). The first three discriminant functions were statistically significant ($p < 0.05$), with the first two collectively accounting for 72 percent of the variance in cluster membership.

Station Clusters 1, 5, 6, and 7 were not readily distinguishable from each other on the basis of the first two discriminant functions, but were reasonably well distinguished as a group from each of the three impacted station clusters. With the other functions, primarily DF3 (a particle size gradient), some discrimination within this group was achieved. Cluster 1 had the most fine material ($<45\ \mu$m), while Cluster 5 had the least. Three stations within this four-cluster group were misclassified by the full set of discriminant functions (i.e., predicted on the basis of sediment characteristics to be in the wrong cluster). The overall percentage of stations correctly classified was 95.7 percent.

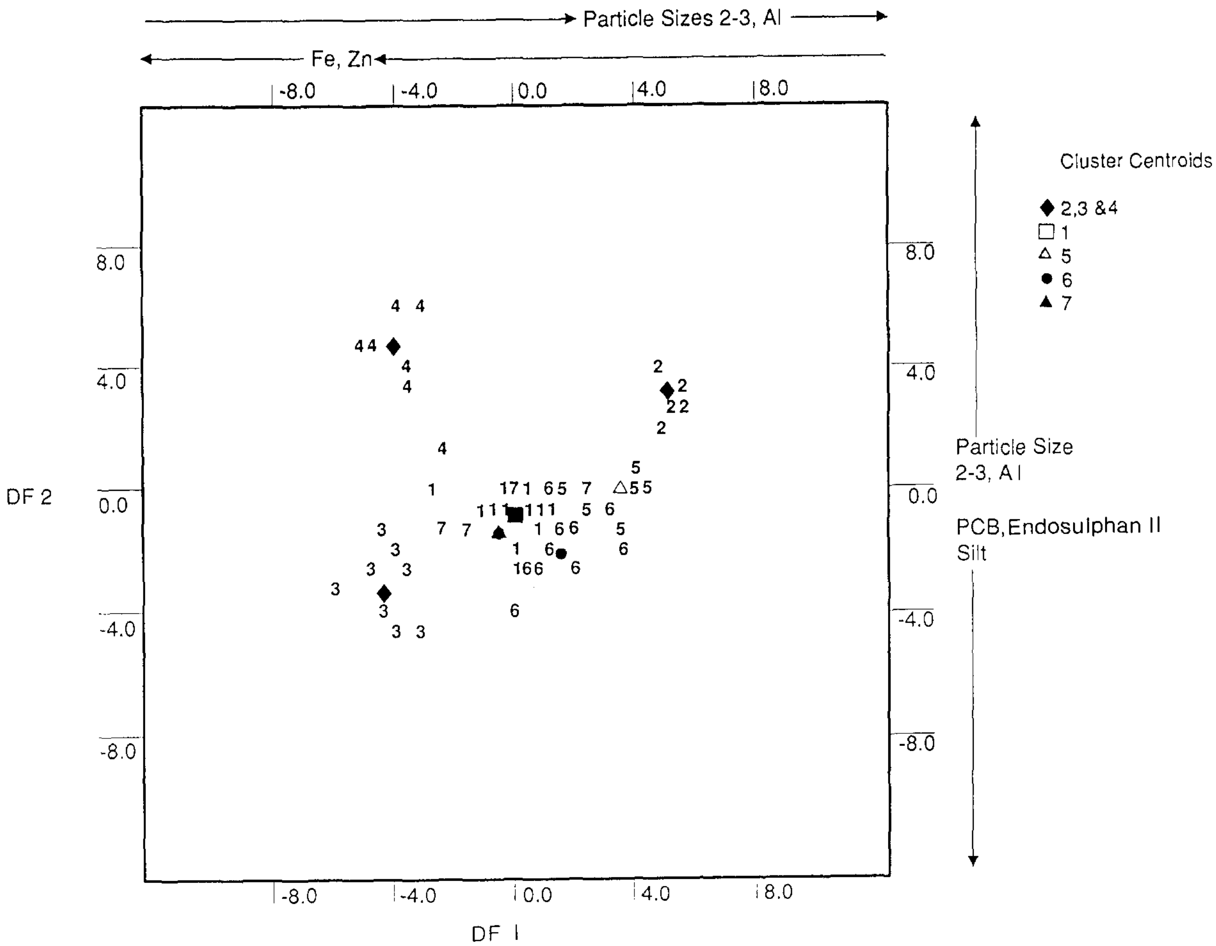

Fig. 4. Station clusters plotted on first two discriminant functions.

Table 3. Station cluster means of selected sediment characteristics

Sediment Variable[1]	Station cluster mean						
	1	2	3	4	5	6	7
Iron ($\mu g\ g^{-1}$)	24,000	7,940	30,900	63,100	9,120	8,130	22,390
Zinc ($\mu g\ g^{-1}$)	123.0	30.2	173.8	257.0	22.4	29.5	97.7
Particle Size 2 (45-1000 μm) (%)	37.6	88.8	42.5	64.3	83.3	77.0	47.5
Particle Size 3 (<45 μm) (%)	62.3	8.7	56.4	31.9	12.4	22.2	51.5
Silt (%)	63.3	9.9	58.4	24.7	17.4	29.1	56.4
Aluminium ($\mu g\ g^{-1}$)	11,500	3,020	9,120	7,760	3,720	4,370	8,710
PCBs ($ng\ g^{-1}$)	21.4	20.0	37.2	25.1	20.0	24.0	22.9
Endosulphan II ($ng\ g^{-1}$)	4.1	4.0	4.5	5.9	4.0	4.0	4.0

[1] Sediment variables shown are the main contributors to discriminant functions 1 and 2, with standardized coefficients exceeding 1.9 in absolute value.

3.5. Temporal comparisons of spatial patterns

Results of the 1985 cluster analysis can be summarized in terms of the following pollution impairment zones:

1. severe:
   a) extreme tubificid dominance (i.e., *L. hoffmeisteri* and immatures without capilliform chaetae), tolerant chironomids, low numbers of taxa but high total densities (Cluster 4), or
   b) communities with either very low total densities and low numbers of taxa, and/or high densities of nematodes with few other taxa (Cluster 4);
2. moderate: tubificid dominance with high densities of nematodes and the presence of various facultative chironomids, absence of polychaete worms, reduced numbers of taxa, and high total densities (Cluster 3);
3. slight: nematode and polychaete dominance with moderate densities of tubificids and some non-tolerant groups present (Cluster 2); and
4. unimpaired: communities tending towards chironomid dominance, with several non-tolerant groups (e.g., ephemeropterans and trichopterans) present, low tubificid densities, and high numbers of taxa (Clusters 1, 5, 6 and 7).

The spatial distribution of these four zones, based on assignment of each cluster of stations to one of the zones (Fig. 3), was used to infer any major changes in benthic community status between years.

In comparisons among surveys, methodological differences must be considered. Increased sorting efficiency (due in part to smaller mesh size in 1983–85 than in 1968–73, and the use of a microscope in 1985 but not in previous years) contributed to higher total densities in 1985 than in earlier surveys. Total organism densities in 1985 ranged from 88 to 591 000 organisms m^{-2}, compared to a range of 104 to 40 000 m^{-2} in 1983, a difference of up to one order of magnitude (Burt *et al.*, 1988).

In addition, numerous faunal shifts between 1983 and 1985 were indicated (Burt *et al.*, 1988). Two particularly notable shifts involved nematodes and polychaetes which were rare or absent in all previous OME surveys, and abundant and often dominant in 1985. These organisms are small enough that their enumeration is influenced by mesh size or sorting efficiency (Golini, 1979). Other small organisms, which occurred in higher densities in 1985, included naidid oligochaetes and early instar chironomids. However, other shifts in abundances such as the increased densities in 1985 of *Hexagenia*, a comparatively large mayfly nymph, were probably not related to mesh size or sorting technique.

Total organism densities reported at some locations in 1985 are very high ($> 100\,000$ m^{-2}) and comparable to the maximum densities reported in the most heavily polluted harbours of the Great Lakes (Cook & Johnson, 1974). These high densities can, to some extent, be accounted for by the large numbers of very small organisms retained by a 200 μm mesh. In contrast, most benthic surveys of the Great Lakes have been carried out using a U.S. #30 (about 500 μm) mesh, which would retain fewer organisms.

In spite of the differences between surveys, the inferred zones of impairment in 1985 were similar to those reported in 1983. Both surveys indicated a zone of severe impairment below the St. Marys Falls near the Canadian shore at SMD 0.8. In 1985, however, this zone did not include SMD 1.2–840 (Fig. 1 and 3), suggesting some improvement since 1983. This change was primarily due to the presence in 1985 of large numbers of the nemertean, *Prostoma rubrum*, which is typically found in well-oxygenated, littoral standing water and cannot tolerate low oxygen conditions (Pennak, 1978).

The 1985 survey indicated severe impairment, possible resulting from toxicity, in the vicinity of the Algoma slip. In 1983, this area was identified as moderately impaired, based on 4 stations located outside the slip. The extra stations in closer proximity to the slip accounts for the change in status of this area in 1985 relative to 1983.

Both the 1983 and 1985 surveys suggested a zone of moderate impairment which extends downstream from St. Marys Falls, close to the Canadian shore. Another zone of moderate impairment was associated with the Sault Ste. Marie STP, extending to within 370 m of the U.S. shore. Differences from the 1983 pattern included the identification of SMD 5.0E–520 and Station 107 as severely impaired in 1985. Analysis of the detailed species lists from both years substantiates the differentiation of SMD 5.0E–520 from adjacent stations on the basis of a more complete tubificid dominance (primarily *L. hoffmeisteri*) and the occurrence of only three other taxa. In 1985, the differentiation of Station 107 from nearby stations was related to a lower total density and fewer taxa.

In 1983, a zone of slight impairment was evident within the Lake George Channel discharging into Little Lake George. In 1985, this zone extended from SMD 5.0E–210 downstream of the STP outfall past transect SMD 6.4E (except SMD 6.4E–210 near the U.S. shore), into Little Lake George (Fig. 3). In the earlier OME surveys (1968 and 1973), this section was designated as moderately impacted. The improvement here is based on the presence of taxa such as *S. heringianus* and *P. rubrum*, as well as a slight increase in taxa and reduction in densities relative to the moderate impact zones.

A zone of moderate impairment at Stations 86, 87, and 88 (in Little Lake George) was identified in 1985, not sampled in 1983 but species assemblages were similar to those reported in 1973 and were characterized by high tubificid densities (primarily *L. hoffmeisteri*) and low numbers of taxa. The extent of this zone is similar to that indicated in 1973 (Hamdy *et al.*, 1978). A zone of moderate impairment was also identified in Lake George in 1985, at the two deep water stations.

Hiltunen & Schloesser (1983) and others (Edsall *et al.*, 1990; Schloesser *et al.*, 1990) have related the distribution of the Ephemeroptera *Hexagenia* to the presence or absence of visible oily residues in sediments of the St. Marys River system. Substrates collected from Lake George in 1985 were contaminated by oily substances at most stations between the STP and upper Lake George (Fig. 5), similar to the pattern indicated by Hiltunen & Schloesser (1983). The 1985 results suggest that the extent of sediment contamination by oil in the Lake George Channel has not changed from that observed in 1975. Oil was very limited in distribution in the more extensive study of the Lake Nicolet Channel in 1975 but was absent in stations sampled in this area in 1985 (Fig. 5). The distribution of *Hexagenia* in 1985 has also remained similar to that observed in 1975. In 1985, *Hexagenia* was absent from sediments in 27 of 32 stations analyzed in the St. Marys River, Lake Nicolet, Lake George Channel, Little Lake George, and Lake George where even slight amounts of visible oil were present (Fig. 5). In the remaining 19 stations where visible oil was absent, 16 had *Hexagenia* populations present. At two of the three remaining stations where *Hexagenia* was absent, the bottom substrate was primarily sand which deters *Hexagenia* inhabitation (Edmunds *et al.*, 1976).

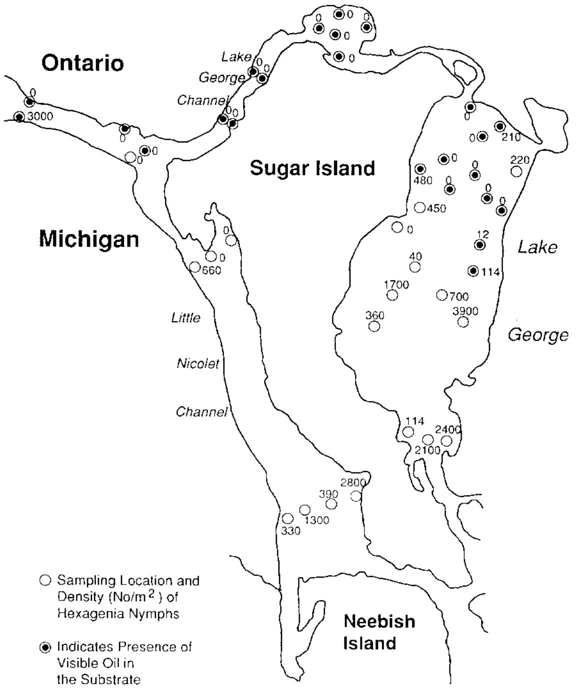

Fig. 5. Distribution of hexagenia nymphs and visible oil in the St. Marys River sediments in 1985.

In general, reductions in pollutant loadings from the Algoma Steel terminal basin and St. Marys Paper operations since 1973 have contributed to minor community changes (Burt *et al.*, 1988). However, these changes have not been reflected in major improvements in pollution status of the benthic community from 1968 or 1973.

3.6. Community index analysis

R-mode cluster analysis (species grouping) separated the benthic species into five clusters or guilds (Fig. 6). Similarities between guilds with respect to their spatial distributions are indicated by the rescaled distance values at which they combine. Distance is an inverse measure of similarity. Five guilds, labelled A to E on the dendrogram, are evident at an interpretation level of 13.5 on the distance scale.

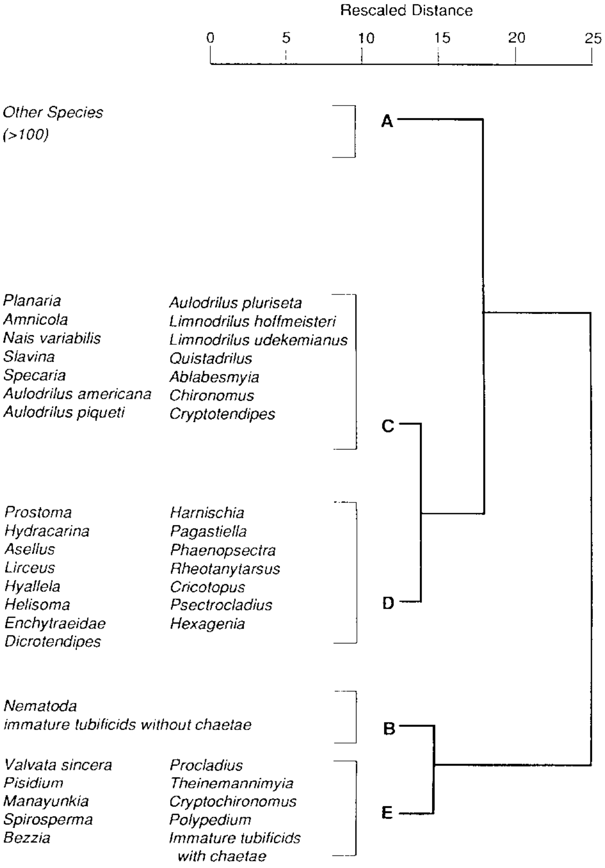

Fig. 6. Species clusters (guilds) based on concordance of spatial distributions.

Guilds B and C were comprised primarily of pollution tolerant taxa (Fig. 6). Guild B consisted of Nematoda and immature Tubificidae without capilliform chaetae. The immatures are most likely *L. hoffmeisteri* based on the relative abundance of adults. Station clusters 2, 3, and 4 were all characterized by dominance of Guild B taxa as indicated by the dominance index Ig, and were identified as pollution-impacted. Guild C included both pollution-tolerant species, such as *Limnodrilus* spp., *Q. multisetosus*, and *Chironomus*, and some species that are less tolerant of organic pollution, such as *Aulodrilus* spp., suggesting that Guild C occurs in areas that are less impaired than areas inhabited by Guild B.

Species Guilds D and E included some relatively intolerant and mesotrophic taxa, such as *Hexagenia* (Guild D) and *Polypedilum* (Guild E), with relatively few eutrophic indicators. Guild D was probably more indicative of unimpacted conditions than Guild E, based on the occurrence of the intolerant *Hexagenia* in the former, and greater representation of forms tolerant of organic enrichment in the latter (e.g., Tubificidae, *Procladius, Manayunkia*). High index values for these guilds, particularly for Guild D, tend to occur at stations assigned to Station Clusters 1, 5, 6, and 7, which are described as relatively unimpaired.

Species Guild A included a large number of species (> 100), most of which were uncommon at most locations. Because most of the dominant forms and many of the key indicator species occurred in Guild B to E, interpretation of the pollution indicator value of Guild A was not attempted.

Guild B and Guild C dominance indexes (I_g) were each positively correlated with various heavy metals, solvent extractables, and TOC ($p < 0.01$). Guild B dominance was also positively correlated with several pesticides (Table 4), while Guild C dominance was also correlated with fine particulates, phosphorus, LOI, and TKN. Guild B dominance was negatively correlated with Eh, indicating association with reducing environments.

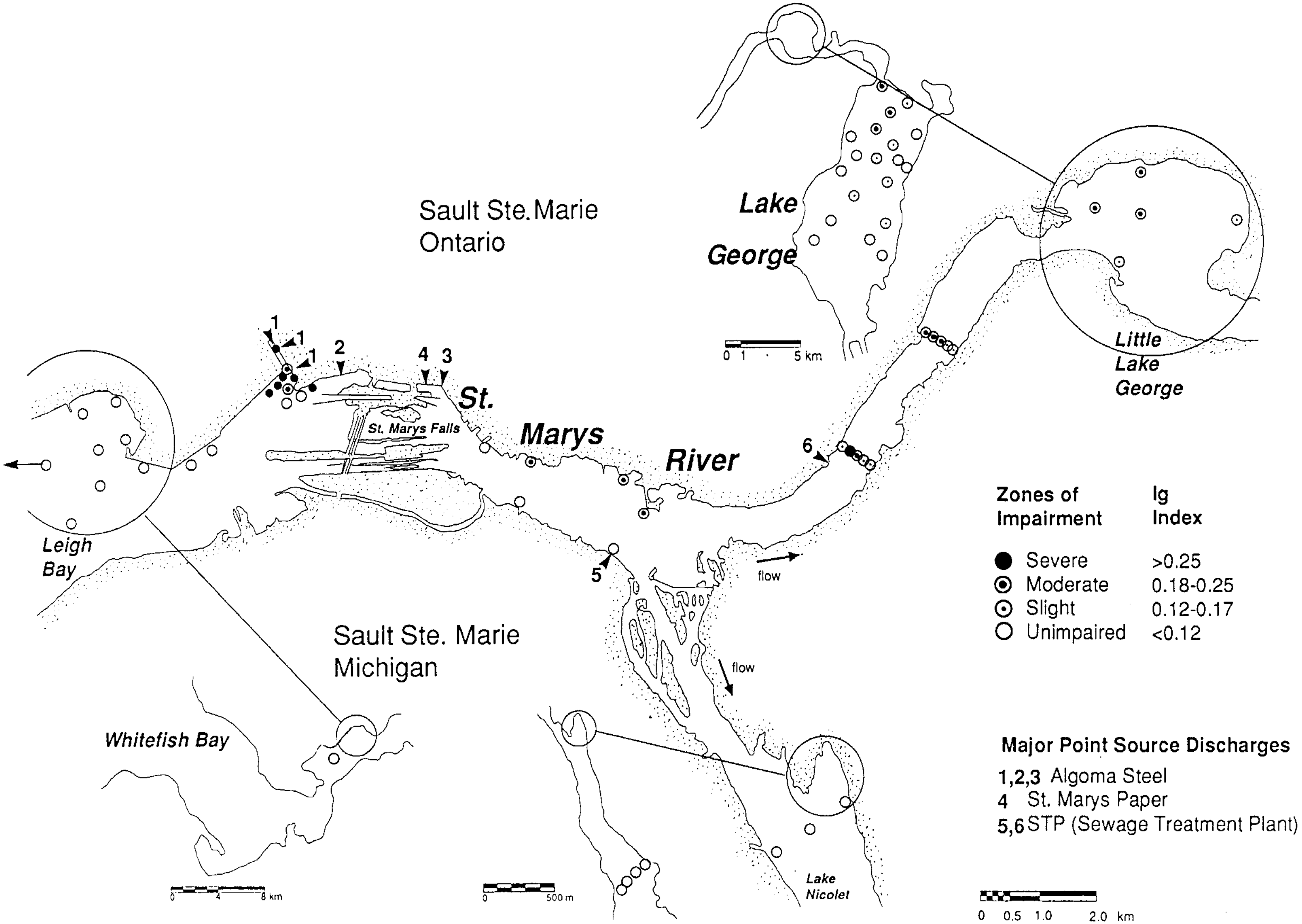

Fig. 7. Distribution of dominance index (guild *B*) in 1985.

Table 4. Sediment characteristics associated with the guild B dominance index (Ig)

Sediment Variable	Mean sediment characteristic					
	Ig Index ranges				Standard partial regression coefficient	Significance level (p)
	<0.12	0.12-0.179	0.18-0.249	≥0.25		
Phosphorus (%)	0.3	0.5	0.4	0.36	-0.177	0.411
Coarse Particulates (> 1,000 μm) (%)	0.81	0.36	1.2	1.0	0.105	0.268
Eh (meV)	478	458	407	262	-0.147	0.142
Loss on Ignition (LOI) (%)	2.1	2.5	2.6	2.9	-0.845	>0.001
Clay Fraction (%)	4.0	7.6	7.6	6.1	0.474	0.003
Total Kjeldahl Nitrogen (TKN) (%)	0.55	0.91	0.66	0.55	-0.255	0.095
Heptachlor Epoxide ($ng\ g^{-1}$)	0.00	1.1	0.00	1.9	0.254	0.008
Arsenic ($\mu g\ g^{-1}$)	3.1	5.5	6.5	17	-0.630	0.020
Mercury ($\mu g\ g^{-1}$)	0.02	0.08	0.07	0.10	0.653	>0.001
Chromium ($\mu g\ g^{-1}$)	22	31	40	41	-0.308	0.040
Zinc ($\mu g\ g^{-1}$)	40	107	126	316	-0.331	0.159
Copper ($\mu g\ g^{-1}$)	14	28	30	34	0.393	0.091
Total Organic Carbon (TOC) (%)	10	18	22	81	1.187	0.000
Aluminium ($\mu g\ g^{-1}$)	5,370	8,320	7,760	7,240	-0.410	0.097
Iron ($\mu g\ g^{-1}$)	12,000	20,900	25,700	60,300	0.570	0.071

These correlations support the contention that dominance by Guilds B and C is representative of impaired conditions.

Guild E dominance was positively correlated only with depth ($p < 0.01$), and negatively correlated only with p,p-DDE, suggesting that these taxa are not strongly indicative of pollution status. Guild D dominance was negatively associated with various heavy metals, endrin, solvent extractables, phosphorus, loss-on-ignition (LOI), total organic carbon (TOC), and total Kjeldahl nitrogen (TKN). Thus, this group represents a relatively clean-water faunal assemblage, both on the basis of biological indicators and negative correlations with sediment-associated contaminants and organic matter.

Based on correlations with sediment characteristics (Table 4), Guild B dominance appears to be the best general indicator of toxic contaminants (both metals and pesticides). This guild is also defined by two of the most abundant indicator taxa (Nematoda and *Limnodrilus* spp.), further facilitating interpretation of spatial trends in environmental quality. The highest Guild B dominance index values are in the vicinity of the Algoma slip and the Sault Ste. Marie STP (Fig. 7). Values greater than 0.25 for Guild B in these areas were considered indicative of severe impact. Zones of moderate impact (index 0.18 to 0.25) were also apparent in a depositional area downstream of St. Marys Falls on the Canadian shore, downstream of the Sault Ste. Marie STP to Little Lake George, and in a deep water depositional area of Lake George near the inlet.

Impact zones defined on the basis of Guild B dominance (Fig. 7) closely resemble the zones previously defined in terms of station clusters 2, 3, and 4 (Fig. 3). However, they suggest a slightly greater degree and extent of impact of Little Lake George and Lake George than discerned by station cluster distributions.

The best multivariate equation for prediction of Guild B dominance from sediment characteristics includes significant ($p < 0.05$) positive contributions from mercury, heptachlor epoxide, clay, and TOC (Table 3). High concentrations of these constituents tend to increase the predicted dominance index. The equation includes significant negative contributions from arsenic, chromium, and LOI. The complete equation explains 72 percent of variation in the dominance index (adjusted $R^2 = 0.72, p < 0.001$).

The sediment characteristics identified by the multiple regression analysis as the best quantitative predictors of Guild B dominance differ from those identified by discriminant analysis as the key contributors to qualitative discrimination between station clusters defined on the basis of overall species composition. This is not surprising in view of the different dependent variables involved (indicator species dominance vs. station cluster membership). Nevertheless, the concordance of impacted zones derived from the dominance index and station cluster patterns strengthens the finding of the continued existence of pollution tolerant benthic communities downstream of the Algoma Steel, St. Marys Paper and Sault Ste. Marie STP discharges, extending downstream along the Canadian shoreline as far as upper Lake George.

4. Acknowledgements

We wish to acknowledge the contributions of Mr. Y. Hamdy, Ms. Mary Kirby, and Mr. B. Bowman of the Ontario Ministry of the Environment in the experimental and statistical design of this programme. The captain and crew of the 'Monitor V' assisted with the field survey. Mr. Dennis Farara sorted and analyzed the benthic samples for the oligochaetes while Ms. Marion Brinkman analyzed the Chironomidae and remaining taxa. Mr. P. Mark Green drafted the figures.

References

Barton, D. R. & H. B. N. Hynes, 1978. Wave-zone macrobenthos of the exposed Canadian shores of the St. Lawrence Great Lakes. J. Great Lakes Res. 4: 27–45.

Brinkhurst, R. O. & D. G. Cook, 1974. Aquatic earthworms. In; C. W. Hart & S. L. H. Fuller (eds.). Pollution Ecology of Freshwater Invertebrates. pp. 143–156. Academic Press, New York.

Burt, A. J., P. M. McKee & D. R. Hart, 1988. Benthic invertebrate survey of the St. Marys River, 1985. Rep. Prep. for Ont. Min. Env., Avail. from Wat. Resources Br., Great Lakes Sect., 1 St. Clear Avenue West, Toronto, Ontario, Canada M4V 1K6.

Clarke, A. H., 1973. The freshwater molluscs of the Canadian Interior Basin. Malacologia 13: 1.

Cook, D. G. & M. G. Johnson, 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Bd Can. 3: 763–782.

Edmunds, G. F., Jr., S. L. Jensen & L. Berner, 1976. The Mayflies of North and Central America. Univ. Minnesota Press, Minneapolis. 330 pp. ISBN 0–8166–0759–1.

Edsall, T. A., B. A. Manny, D. W. Schloesser, S. J. Nichols & A. M. Frank, 1991. Production of *Hexagenia limbata* nymphs in contamined sediments in the Upper Great Lakes Connecting Channels. Hydrobiologia 219: 353–361.

Freitag, R., P. Fung, J. S. Mothersill & G. K. Prouty, 1973. Geographical distribution and spatial relationships of macroinvertebrates of Nipigon Bay, Lake Superior, Ontario. Lakehead University M.S. Rep. 1–29.

Golini, V. I., 1979. Benthic macro- and microinvertebrates of Lake Ontario, 1977: distribution and relative abundance. Env. Can., Fish. Mar. Serv., MS Rep. 1519.

Green, R. H., 1979. Sampling Design and Statistical Methods for Environmental Biologists. Wiley & Sons, New York. 257 pp. ISBN 0–471–03901–2.

Hamdy, Y., J. D. Kinkead & M. Griffiths, 1978. St. Marys River water quality investigations 1973–74. Great Lakes Surv. Unit, Wat. Res. Branch, Ont. Min. Env. Avail. from Wat. Res. Br., Great Lakes Sect., 1 St. Clair Avenue West, Toronto, Ontario, Canada M4V 1K6.

Hiltunen, J. K. & D. W. Schloesser, 1983. The occurrence of oil and the distribution of *Hexagenia* (Ephemeroptera: Ephemeridae) nymphs in the St. Marys River, Michigan and Ontario. Freshwat. Invertebr. Biol. 1983, 2 (4): 199–203.

Hutchinson, G. E., 1978. An Introduction to Population Ecology. Yale University Press, New Haven & London. 260 pp. ISBN 0–300–02155–0.

Klemm, D. J. (ed), 1985. A Guide to the Freshwater Annelida (Polychaeta, Naidid and Tubificid Oligochaeta and Hirudinea) of North America. Kendall/Hunt Publishing Co., Dubuque Iowa, 198 pp. ISBN 0–8403–3577–6.

Mackie, G. L. & S. U. Qadri, 1971. A polychaete, *Manayunkia speciosa*, from the Ottawa River and its North American distribution. Can. J. Zool. 49: 780–782.

Mackie, G. L., D. S. White & T. W. Zdeba, 1980. A guide to the freshwater molluscs of the Laurentian Great Lakes with species emphasis on the genus *Pisidium*. U.S. Env. Protect. Agency EPA–600/3–80–068.

McKee, P. M., A. J. Burt & D. R. Hart, 1984. Benthic invertebrate and sediment survey of the St. Marys River, 1983. Rep. Prep. Ont. Min. Env., Wat. Res. Br., Great Lakes Sect., 1 St. Clair Avenue West, Toronto, Ontario, Canada M4V 1K6.

Nalepa, T. F. & N. A. Thomas, 1976. Distribution of macrobenthic species in Lake Ontario in relation to sources of pollution and sediment parameters. J. Great Lakes Res. 2: 150–163.

Norusis, J. J., 1986. Advanced Statistics SPSS/PC + for the IMB PC/XT/AT. SPSS Inc., Chicago, IL.

Oliver, D. R. & M. E. Roussel, 1983. The genera of larval midges of Canada. In; The Insects and Arachnids of Canada, Part 2. Biosystematics Res. Inst., Ottawa, Canada.

OME (Ontario Ministry of the Environment), 1983. Handbook of Analytical Methods for Environmental Samples. Lab. Serv. Appl. Res. Br., Rexdale, Ontario, Canada, M9W 5L1.

Pennak, R. W., 1978. Freshwater Invertebrates of the United States, 2nd Edition. John Wiley and Sons. 803 pp. ISBN 0-471-04249-8.

Persaud, D. & W. D. Wilkens, 1976. Evaluating construction activities impacting on water resources. Ont. Min. Env., Wat. Resources Br., 1 St. Clair Avenue West, Toronto, Ontario, Canada M4V 1K6.

Poe, T. P. & D. C. Stefan, 1975. Several environmental factors influencing the distribution of the freshwater polychaete, *Manayunkia speciosa* Seidy. Chesapeake Sci. 15: 235–237.

Roback, S. S., 1974. Insects: In; C. W. Hart & S. L. H. Fuller (eds.) Pollution Ecology of Freshwater Invertebrates. Academic Press, New York: 314–376.

Schloesser, D. W., T. A. Edsall, B. A. Manny & S. J. Nichols, 1991. Distribution of *Hexagenia* nymphs and visible oil in sediments of the Upper Great Lakes Connecting Channels. Hydrobiologia 219: 345–352.

Veal, D. M., 1968. Biological survey of the St. Marys River 1968. Biol. Br., Ont. Wat. Resources Commiss.

Wiggins, G. B., 1977. Larvae of the North American Caddisfly Genera (Trichoptera). University of Toronto Press. 401 pp. ISBN 0-8020-5344-0.