Burrowing mayflies as indicators of ecosystem health: Status of populations in western Lake Erie, Saginaw Bay and Green Bay

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The U.S. Environmental Protection Agency and Environment Canada are supporting the development of indicators of ecosystem health that can be used to report on progress in restoring and maintaining the Great Lakes ecosystem, as called for in the Great Lakes Water Quality Agreement between the United States and Canada. One indicator under development is based on burrowing mayflies (Hexagenia: Ephemeroptera: Ephemeridae). We sampled in western Lake Erie, Saginaw Bay (Lake Huron), and Green Bay (Lake Michigan) in spring 2001 at 117 stations covering about 1,870 km^2 of lake bed, to determine the status of nymphal populations of Hexagenia, and to provide information that would further the technical development of an indicator of ecosystem health based on Hexagenia. In western Lake Erie, density and biomass of nymphs were generally highest on fine-grained substrate in offshore waters and were lower on coarser substrates in near shore waters. Nymphs were virtually absent from Saginaw Bay, where only one nymph was collected at 28 stations. Nymphs were collected at only 6 of 48 stations in Green Bay, and density and biomass were highest at the northern end of the bay. Polluted sediments are likely responsible for the absence or low density and biomass of nymphs observed on fine-grained substrates in western Lake Erie, Saginaw Bay, and Green Bay, all of which historically supported abundant populations.

Keywords: Hexagenia, Great Lakes, monitoring

Introduction

State of the Lakes Ecosystem Conferences (SOLEC) were hosted by the U.S. Environmental Protection Agency and Environment Canada in 1996, 1998, 2000, and 2002 to encourage the development of Great Lakes indicators of ecosystem health. These indicators are to be used for reporting to the governments of the United States and Canada and to the public on progress in restoring and maintaining the Great Lakes ecosystem, as called for in the Great Lakes Water Quality Agreement (GLWQA, 1989). Descriptions of some of the SOLEC indicators proposed for development are available in EC and EPA (1999, 2001, 2003) and a SOLEC indicator based on burrowing mayflies of the genus *Hexagenia* (Ephemeroptera: Ephemeridae) is described in Edsall (2001). *Hexagenia* was selected for development as an indicator of ecosystem health primarily because it was historically abundant in unpolluted Great Lakes mesotrophic habitats, is sensitive to and was exterminated by pollution in many of those habitats, and has demonstrated the ability to recover following pollution abatement.

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In major Great Lakes mesotrophic habitats, *Hexagenia* was abundant until the 1940s to1950s, after which populations declined sharply or were extirpated (Schneider et al., 1969; Howmiller, 1971; Cook and Johnson, 1974; Mozley and LaDronka, 1988; Edsall et al., 1991, 1999; Schloesser et al., 1991). These declines were directly linked in some areas to eutrophication and low dissolved oxygen in bottom waters (Britt, 1955; Beeton, 1961, 1969; Verduin, 1964; Carr and Hiltunen, 1965; Krieger et al., 1996), and pollution of sediments by metals and petroleum products (Edsall et al., 1991, 2001; Schloesser et al., 1991). Improvements in water and sediment quality in some of these historical *Hexagenia* habitats resulting from sharp decreases in oil loadings between the mid-to-late 1940s and 1961 (USDHEW, 1962), and decreased phosphorus loadings beginning in the late 1960s and early 1970s (Manny et al., 1988), were not immediately followed by population recovery. However, there is evidence of the beginnings of recovery in the lower Fox River, the major tributary to Green Bay, Lake Michigan (Cochran, 1992; Cochran and Kinziger, 1997), and recovery may be nearly complete in western Lake Erie (Madenjian et al., 1998; Edsall et al., 1999) and the Bay of Quinte, Lake Ontario (John Casselman, Ontario Ministry of Natural Resources, July 14, 2000, personal comm.).

The major objective of this study was to document the status of *Hexagenia* in western Lake Erie, Saginaw Bay, and Green Bay and establish a baseline for long-term monitoring of those populations using the published protocol for indicator development (Edsall, 2001).

Methods

We superimposed sampling grids on NOAA lake charts of western Lake Erie, Saginaw Bay, and Green Bay to distribute sampling effort evenly across the study area (Figures 1–3). The grid for each water body was centered normally on the lake chart at a prominent latitude-longitude intersection near the center of the water body. Each grid cell was about 8 km square. Station locations were determined by DGPS to the nearest 0.1 second of latitude and longitude. One station was located in each grid cell whose surface area was more than 50% water. Because *Hexagenia* nymphs are virtually absent in the hypolimnion (Mozley and LaDronka, 1988; Dermott, 1995), stations were not located in water deeper than 20 m. We attempted to locate all stations in sediment deposition areas where the substrate was soft mud with a sticky consistency that would support burrowing by the nymphs (Hunt, 1953; Wright and Mattice, 1981).

The actual distribution of sampling effort in Green Bay was problematic. Although we initially planned to sample in all of the 55 grid cells shown in Figure 3, published information on the bathymetry and substrate type distribution (Hall, 1970; Howmiller, 1971) suggested some grid cells might not have suitable sites for sampling and, indeed, 31 were found to be unsuitable when we visited them. Thus, we did not attempt to sample in 11 grid cells (13, 15–17,19–21 24, 27, 28, and 34), because the water was deeper than 20 m. In 20 other cells with water depths of 20 m or less, sampling revealed unsuitably coarse substrate; in these cells we collected either two or four Ponar grab samples. In practice, when two grab samples at a site yielded only coarse substrate we searched for another site in the proper depth range in the grid cell and collected two additional grab samples. If a second site in the proper depth range could not be found, or if sampling at the second site showed it also had coarse substrate we discontinued sampling and moved to the next grid cell. To partly compensate for the reduced sampling effort, we added four stations in grid cells 54 and 55 in southern Green Bay, near the mouth of the Fox River, where the beginnings of a recovery were documented by Cochran (1992), and Cochran and Kinziger (1997).

Sampling was conducted in 2001 from April 30 to June 4 in western Lake Erie, May 20 to 30 in Saginaw Bay, and May 9 to June 7 in Green Bay, as vessel availability and weather permitted. Thus, all sampling was completed before the annual *Hexagenia* emergence, which typically occurs in late June or early July. Each station was visited once and five samples were taken with a standard Ponar grab (0.0538 m^2 opening) during the visit. Each sample was washed gently with lake water on a coarse (3.2-mm mesh) screen (Edsall, 2001) to remove the sediment and detritus. *Hexagenia* nymphs were manually extracted from the screen, preserved in weak (about 10% v/v) formalin in a capped vial labeled with the station and sample number, and taken to the laboratory for study.

In the laboratory, nymphs from each sample were measured (total length to the nearest 0.5 mm under 7 × magnification) to provide a length-frequency distribution that would permit us to separate the nymphs of the cohort that was about to emerge from those in the younger cohort that would emerge next year. We obtained dry weights by holding each sample in a drying oven at 105°C for 12 h and then weighing the sample on an electronic balance to the nearest 0.001 g.

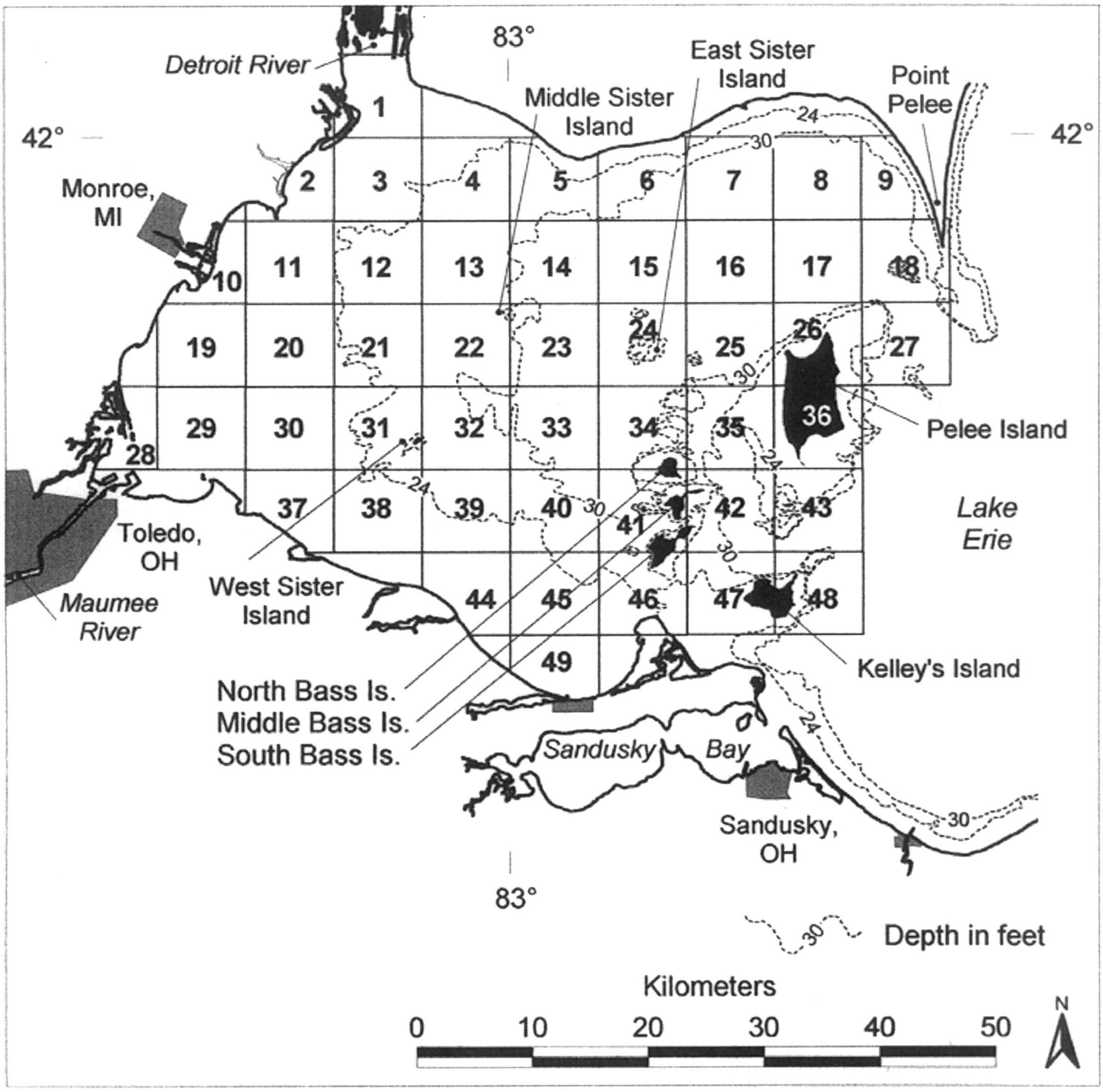

Figure 1. Sampling grid for western Lake Erie. Depths are in feet: 24 ft = 7.3 m, 30 ft = 9.1 m.

Station data (coordinates, substrate type, and water depth) and catch (density and biomass) and effort data for each station are available from the Librarian, U.S. Geological Survey, Great Lakes Science Center.

Results and discussion

Western Lake Erie

We intended to use the cohort-based approach given in Edsall (2001) to estimate the mean annual biomass and annual production of the populations sampled in the present study. We collected sufficient numbers of nymphs in western Lake Erie to estimate the mean annual biomass and annual production, but the length-frequency distribution of the nymphs in our samples was essentially unimodal (Figure 4), which prevented us from distinguishing the cohorts and using the cohort-based method. As a result, we reported the density and biomass of all of the nymphs of both cohorts in each sample.

We found *Hexagenia* nymphs at 44 of 49 stations. The substrate in the study area was mud (32 stations), mixtures of mud and fine or coarse sand (5 stations),

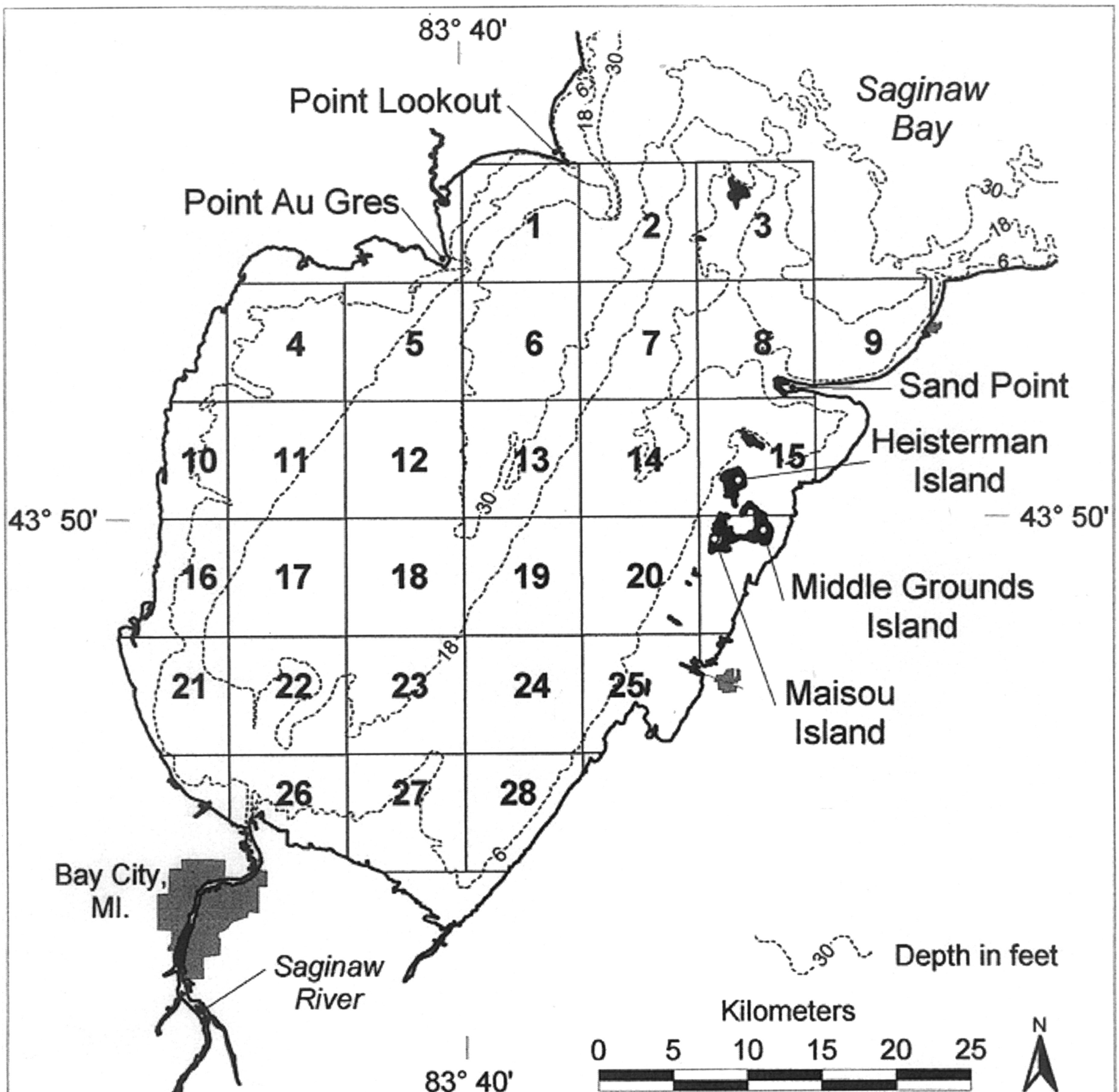

Figure 2. Sampling grid for Saginaw Bay, Lake Huron. Depths are in feet: 6 ft = 1.8 m, 18 ft = 5.5 m, 30 ft = 9.1 m.

fine and coarse sand (11 stations), and hard clay (1 station). Nymphs were absent at one station with mud substrate (station 33), three with fine sand (stations 19, 36, and 44), and one with coarse sand (station 1). Mean density and biomass were highest on mud substrates (136 nymphs m^{-2} and 2.8 g m^{-2}) and much lower on the other substrates (9.4 nymphs m^{-2} and 0.3 g m^{-2}).

There was no obvious zonation of substrates that would fully explain the observed pattern of density and biomass values across the basin. Density and biomass (0–364.3 nymphs m^{-2}; mean, 98.5) and biomass (0–6.2 g m^{-2}; mean, 2.1) were highest offshore in the western half of the basin, along the northern side of the basin, and in the southeastern corner of the basin (Figures 5 and 6), and the two metrics were closely related (Figure 7; R = 0.81).

Factors other than substrate type that presently influence the density and biomass of *Hexagenia* in western Lake Erie are incompletely known. A review of the status of *Hexagenia* in western Lake Erie (Edsall et al., 1999) presented evidence that low dissolved oxygen levels near the lake bed caused by vertical thermal

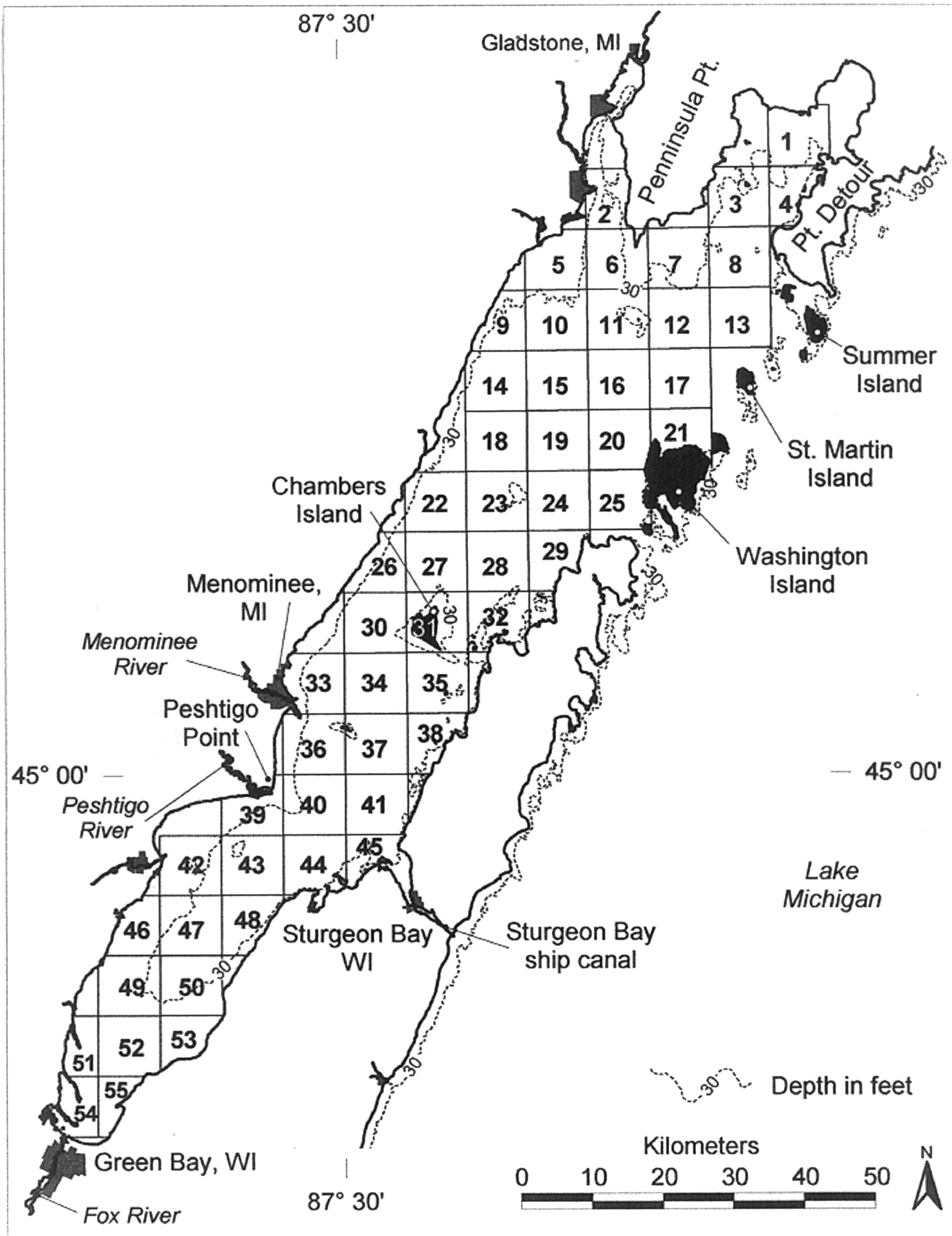

Figure 3. Sampling grid for Green Bay, Lake Michigan. Depths are in feet: 30 ft = 9.1 m.

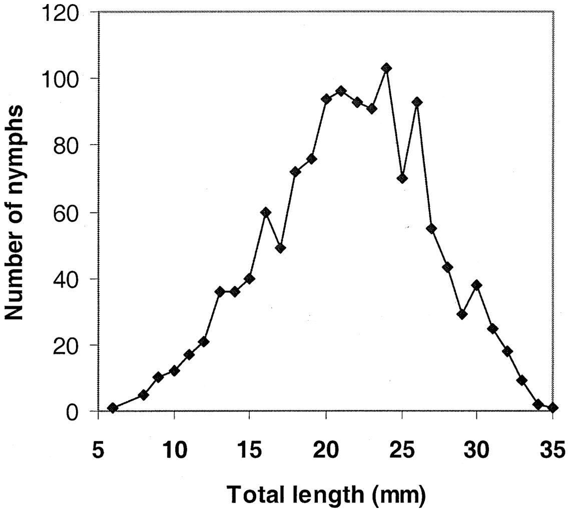

Figure 4. Length-frequency distribution of *Hexagenia* nymphs collected in western Lake Erie, spring 2001.

stratification or intrusions of central basin hypolimnionic water could have been a contributing factor. The review also presented evidence that areas in western Lake Erie where nymphs were absent or in low abundance were still impacted by toxic pollutants and

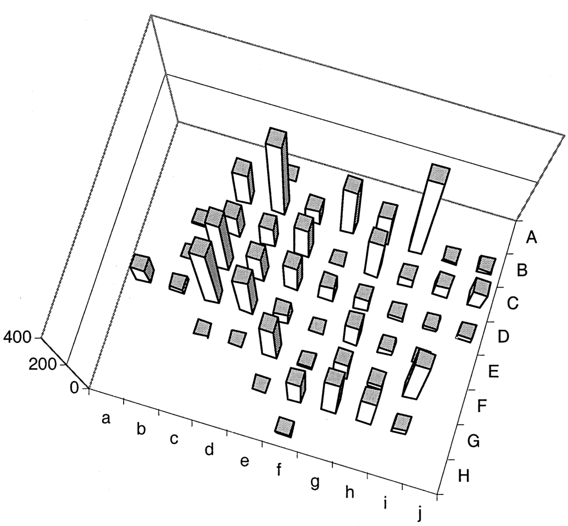

Figure 5. *Hexagenia* density (number m^{-2}) at 49 stations in western Lake Erie, spring 2001. Station orientation follows that in Figure 1. Row "A" bounds the north side of the study area and includes only station 1 at the mouth of the Detroit River (density = 0); row "H" bounds the south side of the study area and includes only station 49 (density = 29.7); row "a" bounds the west side of the study area and includes only station 28 near Toledo, Ohio (density = 74.3); and row "j" bounds the east side of the study area and includes stations 9, 18, and 23 near Point, Pelee, Ontario (density = 14.9, 85.5, and 78.1, respectively).

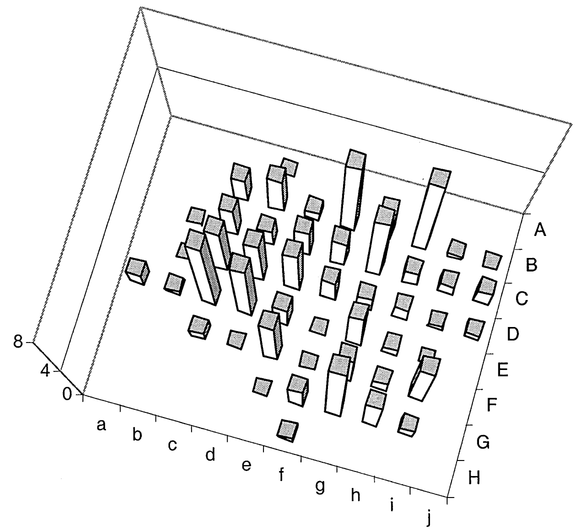

Figure 6. *Hexagenia* biomass (g m^{-2}) at 49 stations in western Lake Erie, spring 2001. Station orientation follows that in Figure 5.

eutrophication. A subsequent review (Schloesser et al., 2000) reached essentially the same conclusions.

Saginaw Bay, Lake Huron

Hexagenia was represented at the 28 stations sampled in inner Saginaw Bay by a single nymph collected at station 14. The substrate at station 14 and at six other stations in the study area was mud. The other substrates in the study area were fine sand (12 stations), fine sand mixed with mud, clay, or rock rubble (5 stations), coarse sand and coarse sand mixed with gravel or rock rubble (3 stations), and bedrock (1 station).

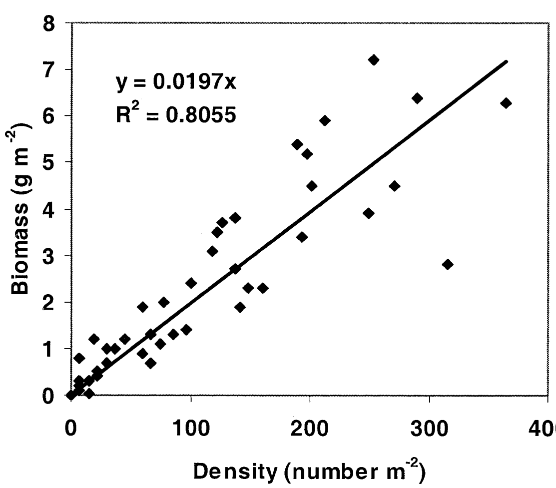

Figure 7. Relation between *Hexagenia* density and biomass at 49 stations in western Lake Erie, spring 2001.

The virtual absence of *Hexagenia* in our samples from Saginaw Bay limits discussion. However, data for 1955, 1956, and 1965 (Surber, 1955; Schneider et al., 1969; Schuttema and Powers, 1966) provide an historical context for our results. These earlier studies showed that the mean density of mayflies (mostly *Hexagenia*) declined from 63 m^{-2} in 1955, to 9 m^{-2} in 1956, to 1 m^{-2} in 1965, and Schneider et al. (1969) hypothesized that the decline was due to an unspecified catastrophic event in 1955 or 1956. It is not known precisely when *Hexagenia* disappeared completely from Saginaw Bay, but no mating swarms were reported after the 1950s (Reynoldson et al., 1989). Diet studies of yellow perch *(Perca flavescens*; Tharratt, 1959) and rainbow smelt (*Osmerus mordax*; Gordon, 1961) in the bay show *Hexagenia* was still being eaten in substantial numbers by those fishes in October 1956, but no nymphs were found in stomachs of about 50,000 yellow perch examined in 1986 to 1988 (Haas and Schaeffer, 1992). In 1988 to 1991, the Michigan Department of Natural Resources introduced nearly one billion *Hexagenia* eggs and larvae into the bay in an attempt to restore this resource (Bryant, 1992) and in July 1993, two *Hexagenia* nymphs were found in yellow perch stomachs in the inner bay near Au Gres, the site of heaviest plantings (Haas, 1995). No nymphs were collected during extensive benthic sampling in 1986 to 1988 (Schaeffer et al., 2000), and only five nymphs were collected in extensive benthic sampling in 1987 to 1988 and 1990 to 1996 (Nalepa et al., 2003).

The finding of *Hexagenia* nymphs in yellow perch stomachs in 1993, and the few nymphs collected in benthic studies since 1987 suggest that some areas in the inner bay may be able to support *Hexagenia* and that recovery in those areas is possible. However, the Saginaw River and Saginaw Bay are still listed as one of the 42 Areas of Concern in the Great Lakes (IJC, 1985), and pollution studies indicate the lower river and offshore sediment deposition areas in the bay where sediments from the river would tend to accumulate may still be unsuitable for *Hexagenia*. The river suffers multiple inputs of chemicals from agriculture, industry, and municipalities and its waters and sediments are the major source of pollution to the bay (Moll et al., 1995; Rossman, 1995). Toxic organic compounds were a problem in the early 1980s (Rice, 1983), and concentrations of metals in river sediments were high enough in 1989 to 1990 to cause them to be classified as moderately polluted with nickel and heavily polluted with copper and zinc (USEPA, 1993), according to USEPA guidelines for dredged sediments (USEPA, 1977). Sampling in the lower river and inner bay in 1988 (Rossman, 1995) and in the lower river in 1990 to 1991 (Moll et al., 1995) showed that chromium, copper, lead, zinc, and nickel exceeded USEPA guidelines for dredged sediments. A study of *Hexagenia* in the upper Great Lakes connecting channels (Edsall et al., 1991) showed that annual production of nymphs was low or that nymphs were absent in sediments polluted by metals and oil at levels that exceeded USEPA guidelines for dredged sediments. Thus, the virtual absence of *Hexagenia* in most of the inner bay, as shown by the present study, is consistent with the observed effects of polluted sediments on *Hexagenia* in the Great Lakes (Edsall et al., 1991) and the literature describing the pollution status of the bay.

Green Bay, Lake Michigan

Hexagenia nymphs were present at 6 of 48 stations sampled in Green Bay. At the mouth of Big Bay De Noc in northern Green Bay, 52 nymphs were collected at station 1, 1 at station 3, and 17 at station 4. One nymph was also collected at each of stations 29, 32, and 38 along the eastern shore of the middle reach of Green Bay. All of the nymphs were collected at six of eight stations where the substrate was a mixture of mud and fine sand. Substrates at the other stations were mud (18 stations), fine sand (3), coarse sand and mud (1), coarse sand (14), and rock (2). Although the substrates at eight of the nine stations in grid cells 50 to 55 in southern Green Bay were mud or mud and fine sand, no *Hexagenia* were collected in those cells.

There are no published accounts of the historical abundance of *Hexagenia* in northern Green Bay, but fish diet studies showed *Hexagenia* was the organism found most frequently in yellow perch stomachs in Big Bay De Noc in 1956 (Toth, 1959) and it made up 60% of the diet by weight in yellow perch in Little Bay De Noc in 1966 (Dodge, 1968).

The virtual absence of *Hexagenia* in samples we collected in middle and lower Green Bay is consistent with the status of *Hexagenia* there as described by Howmiller (1971). He cited an anecdotal account that *Hexagenia* was once quite abundant in the bay, piling up 'by the bushel under electric lights in the city of Green Bay on many summer evenings'. However, by 1939, only 37% of samples taken north of Long Tail Point (grid cell 54 in Figure 3) in the southern end of the bay contained *Hexagenia*, and density in those samples was low (Anon., 1939). In 1952 and 1955, *Hexagenia* was essentially absent in the southern end of the bay

(Surber and Cooley, 1952), and no nymphs were found at any of 113 stations sampled in the middle and lower bay in 1966–1969 (Howmiller, 1971).

The Fox River is the largest tributary to the bay, its inflow nearly equaling that of all other tributaries combined (Howmiller, 1971). The river was heavily polluted in the 1960s, and in 1967 the river water caused low dissolved oxygen concentrations (0–1.7 mg l^{-1}) in the bay as far as 27 km from the river mouth (Schraufnagel et al., 1968). These low dissolved oxygen levels in lower Green Bay were similar to concentrations reported by Britt (1955) and others and linked causally to the massive die-off and virtual extinction of *Hexagenia* in western Lake Erie in the mid-to-late 1950s. The continued absence of *Hexagenia* in lower Green Bay suggests that area may still be too polluted to support *Hexagenia*. However, the reports of *Hexagenia* in the lower Fox River (Cochran, 1992; Cochran and Kinziger, 1997) indicate that water and sediment quality in the river are improving and that recovery in lower Green Bay can be expected. The recovery of *Hexagenia* in western Lake Erie was preceded by reports of the reestablishment of small, source populations in or near the mouths of tributaries where water and sediment quality had first improved following pollution clean-up efforts (Edsall et al., 1999), and a similar recovery process may be underway in Green Bay.

An unexpected positive result was that density and biomass values of *Hexagenia* in the samples were highly correlated, indicating that either a simple count of nymphs on the wash screen in the field, or the dry weight biomass data collected in the laboratory, could be used to provide reliable status information on the population. Thus, the protocol used here seems suitable for long-term monitoring studies using *Hexagenia* as an indicator of ecosystem health. If additional sampling and study reveals that the two cohorts in a grab sample can be reliably separated, then the cohort-based method can be applied to the data to estimate mean annual biomass and annual production.

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References

Anon., 1939. Investigations of the pollution of the Fox and East Rivers and of Green Bay in the vicinity of the City of Green Bay. Rept. Wisconsin State Comm. Water Poll. and State Board of Health in collaboration with the Green Bay Metropolitan Sewerage Comm, Green Bay, WI.

Beeton, A. M., 1961. Environmental changes in Lake Erie. Trans. Am. Fish. Soc. 90, 153–159.

Beeton, A. M., 1969. Changes in the environment and biota of the Great Lakes. In: *Eutrophication: Causes, Consequences, Correctives*, pp. 150–187, National Academy of Science, Washington, D.C.

Britt, N. W., 1955. Stratification in western Lake Erie in summer of 1953: Effects on the *Hexagenia* Ephemeroptera population. Ecology 36, 239–244.

Bryant, W. C., 1992. Accelerating the return of burrowing mayfly nymphs to Saginaw Bay. Michigan. Dingell-Johnson completion Rept., 1992, Study 456, Ann Arbor, Michigan.

Carr, J. F., Hiltunen, J. K., 1965. Changes in the bottom fauna of western Lake Erie from 1950 to 1961. Limnol. Oceanogr. 10, 551–569.

Cochran, P A., 1992. The return of *Hexagenia* (Ephemeroptera: Ephemeridae) to the lower Fox River, Wisconsin. Great Lakes Entomol. 25, 79–81.

Cochran, P. A., Kinziger, A. P., 1997. *Hexagenia bilineata* (Ephemeroptera: Ephemeridae) persists at low levels of abundance in the lower Fox River, Wisconsin. Great Lakes Entomol. 30, 89–92.

Cook, D. G., Johnson, M. G., 1974. Benthic macroinvertebrates of the St. Lawrence Great Lakes. J. Fish. Res. Board Can. 31, 763–782.

Dermott, R., 1995. Production and growth efficiency of two burrowing invertebrates, *Hexagenia limbata,* and *Diporeia hoyi,* in Batchawana Bay, Lake Superior. Can. Tech. Rept. Fish. Aquat. Sci. 2034.

Dodge, K. E., 1968. Food habits of the yellow perch, *Perca flavescens* (Mitchill), in Little Bay De Noc. Lake Michigan. M. S. Thesis, Michigan State University, East Lansing.

EC and EPA (Environment Canada and U.S. Environmental Protection Agency), 1999. State of Great Lakes 1999. ISBN 0-662-28115-2; EPA 905-R-99-008. Cat. No. EN40-11/35-1999E. Toronto and Chicago.

EC and EPA, 2001. State of Great Lakes 2001. ISBN 0-662-30488-8, EPA 905-R-01-004. Cat. No. EN40-11/35-2001E. Toronto and Chicago.

EC and EPA, 2003. State of Great Lakes 2002. ISBN 0-662-34798-6, EPA 905-R-03-003. Cat. No. EN40-11/35-2003. Toronto and Chicago.

Edsall, T. A., 2001. Burrowing mayflies (*Heaxagenia*) as indicators of ecosystem health. Aquat. Ecosyst. Health Manage. 4, 283–292.

Edsall, T. A., Haas, R., Adams, J. V., 2001. Annual production of *Hexagenia* nymphs in U.S. waters of Lake St. Clair. J. Great Lakes Res. 27, 449–456.

Edsall, T. A., Madenjian, C. P., Manny, B. A., 1999. Burrowing mayflies in Lake Erie–a review. In: M. Munawar, T. Edsall and

I. F. Munawar (Eds.), *The State of Lake Erie: Past, Present, and Future*, pp. 219–231. The Netherlands, Ecovision World Monograph Series, Backhuys Publishers.

Edsall, T. A., Manny, B. A., Schloesser, D. W., Nichols, S. J., Frank, A. M., 1991. Production of *Hexagenia limbata* nymphs in contaminated sediments in the upper Great Lakes connecting channels. Hydrobiologia 219, 353–361.

GLWQA (Great Lakes Water Quality Agreement), 1989. Revised Great Lakes Water Quality Agreement of 1978 with annexes and terms of reference between the United States and Canada, signed at Ottawa November 22, 1978, and phosphorus load reduction supplement, signed October 16, 1983, as amended by protocol, signed November 18, 1987. International Joint Commission, United States and Canada, Washington, D.C. and Ottawa.

Gordon, W. C., 1961. Food of the American smelt in Saginaw Bay, Lake Huron. Trans. Am. Fish. Soc. 90, 439–443.

Haas, R., 1995. History and status of fisheries in Saginaw Bay, Lake Huron. In: M. Munawar, T. Edsall and J. Leach (Eds.), *The Lake Huron ecosystem: ecology, fisheries, and management*, pp. 291–311. The Netherlands: Ecovision World Monograph Series, Backhuys Publishers.

Haas, R., Schaeffer, J., 1992. Predatory-prey and competitive interactions among walleye, yellow perch, and other forage fishes in Saginaw Bay, Lake Huron. Fisheries Division Research Rept. No. 1984. Michigan Department of Natural Resources, Lansing.

Hall, C. A., 1970. Survey of surficial bottom sediments and the distribution of manganese nodules in Green Bay, Wisconsin, M.S. Thesis, University of Wisconsin, Madison.

Howmiller, R. P., 1971. The benthic macrofauna of Green Bay, Lake Michigan, M. S. Thesis, University of Wisconsin, Madison.

Hunt, B. P, 1953. The life history and economic importance of a burrowing mayfly, *Hexagenia limbata*, in southern Michigan lakes. Michigan Department of Conservation, Bulletin of the Institute for Fisheries Research, No. 4, Ann Arbor.

IJC (International Joint Commission), 1985. 1985 report on Great Lakes water quality. Great Lakes Water Quality Board Report to the IJC. Windsor, Ontario.

Krieger, K. A., Schloesser, D. W., Manny, B. A., Trisler, C. E., Heady, S. E., Ciborowski, J. H., Muth, K. M., 1996. Recovery of burrowing mayflies (Ephemeroptera: Ephemeridae: *Hexagenia*) in western Lake Erie. J. Great Lakes Res. 22, 254–263.

Madenjian, C. W., Schloesser, D. W., Krieger, K. A., 1998. Population models of burrowing mayfly recolonization in western Lake Erie. Ecol. Applic. 8, 1206–1212.

Manny, B. A., Edsall, T. A., Jaworski, E., 1988. The Detroit River, Michigan: an ecological profile. U.S. Fish and Wildlife Service, Biol. Rept. 85 (7.17), Washington, D.C.

Moll, R. A., Jude, D., Rossman, R., Kantak, G. V., Barres, J., DeBoe, S., Giesey, J., Tuchman, M., 1995. Movement and loadings of inorganic contaminants through the lower Saginaw River. J. Great Lakes Res. 21, 17–34.

Nalepa, T. F., Fanslow, D. L., Lansing, M. B., Lang, G. A., 2003. Trends in the benthic macroinvertebrate community of Saginaw Bay, Lake Huron, 1987 to 1996: Responses to phosphorus abatement and the zebra mussel, *Dreissena polymorpha*. J. Great Lakes Res. 29, 14–33.

Mozley, S. C., LaDronka, R. M., 1988. *Ephemera* and *Hexagenia* (Ephemeridae, Ephemeroptera) in the Straits of Mackinac, 1955–56. J. Great Lakes Res. 14, 171–177.

Reynoldson, T. B., Schloesser, D. W., Manny, B. A., 1989. Development of a benthic invertebrate objective for mesotrophic Great Lakes waters. J. Great Lakes Res. 15, 669–686.

Rice, C. P., 1983. PCBs in Saginaw River sediments. In: C.P. Rice (Ed.), *PCB and PBB contamination in the Saginaw and Pine Rivers off east central Michigan*, pp. 10–52. Final project report to East Central Michigan and Planning Development Region, Saginaw Michigan.

Rossman, R., 1995. Trace element concentrations in 1988 Saginaw Bay sediments: comparison with historical data. In: M. Munawar, T. Edsall, and J. Leach (Eds.), *The Lake Huron Ecosystem: ecology, fisheries, and management,* pp. 313–324. The Netherlands: Ecovision World Monograph Series, Backhuys Publishers.

Schaeffer, J. S., Diana, J. S., Haas, R. C., 2000. Effects of long-term changes in the benthic community on yellow perch in Saginaw Bay, Lake Huron. J. Great Lakes Res. 26, 340–351.

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

Schloesser, D. W., Krieger, K. A., Ciborowski, J. H., Corkum, L. D., 2000. Recolonization and possible recovery of burrowing mayflies (Ephemeroptera: Ephemeridae: *Hexagenia* spp.) in Lake Erie of the Laurentian Great Lakes. J. Aquat. Ecosyst. Health Recov. 8, 125–141.

Schneider, J. S., Hooper, F. F., Beeton, A. M., 1969. The distribution and abundance of benthic fauna in Saginaw Bay, Lake Huron, pp. 80–90. Proc. 12th Conf. Great Lakes Res., University of Michigan, Ann Arbor, Michigan, 1969, May 5–7. Internat. Assoc. Great Lakes Res.

Schraufnagel, F. H., Montie, L. A., Leuschow, L. A., Lisack, J., Karl, G., McKersie, J. R., 1968. Report on an investigation of the pollution in the lower Fox River and Green Bay made during 1966 and 1977. Wisconsin Dept. Nat. Resources Int. Rept. Mimeo, Madison, WI.

Schuttema, G. S., Powers, R. E., 1966. The distribution of benthic fauna in Lake Huron. Proc. 9th Conf. Great Lakes Res., Publ. No. 15, pp. 155–163, Great Lakes Res. Div., University of Michigan, Ann Arbor.

Surber, E. W, 1955. Results of a biological survey of Saginaw Bay, June 24, 1955. Rep. to Mich. Water Resources Comm., Lansing, MI.

Surber, E. W., Cooley, H. L., 1952. Bottom fauna studies of Green Bay, Wisconsin, in relation to pollution. U.S. Public Health Serv. and Wisconsin State Comm. Water Poll.

Tharratt, R. C., 1959. Food of yellow perch, *Perca flavescens* (Mitchill) in Saginaw Bay, Lake Huron, M.S. Thesis, University of Michigan, Ann Arbor.

Toth, R. J., 1959. Studies of the life history of the yellow perch, *Perca flavescens* (Mitchill) in Big Bay De Noc, Lake Michigan, M.S. Thesis, Michigan State University, East Lansing, MI.

USDHEW (U.S. Department of Health, Education, and Welfare), 1962. Pollution of the navigable waters of the Detroit River, Lake

Erie, and their tributaries within the state of Michigan. Detroit, Michigan.

USEPA (United States Environmental Protection Agency), 1977. Guidelines for the pollution classification of Great Lakes harbor sediments. USEPA, Great Lakes National Program Office, Chicago, Illinois.

USEPA, 1993. Assessment and remediation of contaminated sediments (ARCS) program: biological and chemical assessment of contaminated Great Lakes sediments. EPA 905-R93-006. Great Lakes Program Office, Chicago, Illinois.

Verduin, J., 1964. Changes in western Lake Erie during the period 1948–1962. Verhandl. Intern. Ver. Limnol. 15, 639–644.

Wright, L. L., Mattice, J. S., 1981. Effects of temperature on adult size and emergence success of *Hexagenia bilineata* under laboratory conditions. J. Freshwat. Ecol. 1, 27–39.