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Mayfly Metric of the Lake Erie Quality Index: Design of an Efficient Censusing Program, Data Collection, and Development of the Metric

Final Report

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Executive Summary

The Lake Erie Quality Index (LEQI) published by the Ohio Lake Erie Commission in 1998 consists of ten "indicators" which are rated with descriptive scores of "Excellent", "Good", "Fair", or "Poor". Each descriptive score is determined on the basis of weighted numerical scores assigned to one or more (up to five) metrics (28 total). The "Biological Indicator" is scored on the basis of two metrics: "Key Indicator Species" and "Index of Biotic Integrity". The Key Indicator Species metric ranks population or reproduction trends of three species: bald eagles, walleyes, and *Hexagenia* mayflies. Recent investigations of *Hexagenia* ecology in Lake Erie indicated that the scoring system for the *Hexagenia* metric should be modified.

Three objectives were addressed in this project: (1) recommend a subset of reference stations for sampling mayflies in the western and central basins based on the analysis of accumulated information from ongoing data collections; (2) census mayfly nymph densities in May and June 2002 at over 30 central basin stations and at seven reference stations in the western basin; (3) apply new and previous data to modify the methodology for the mayfly metric in a revised Lake Erie Quality Index.

Selection of Reference Stations. The purpose of annual basin-wide sampling in the western basin is to provide a measure of the environmental condition of the basin. This is accomplished by (1) estimating the average density (number per square meter) of nymphs in soft sediments of the entire basin, and (2) observing differences in density among specific stations. The purpose of sampling in the central basin is similar except that because of the breadth of the basin, sampling has been limited mostly to the shallower sediments that lie above the summer thermocline and within about six miles (10 km) of the south shore. Resources might be conserved if the information could be obtained by sampling only a subgroup of the 30 or so stations in each basin.

Annual sampling in the western basin at 22 stations that have been sampled every year since 1995 should be continued as long as funding permits. If it becomes necessary to reduce the sampling effort, a subset of 11 stations is recommended for annual sampling (7M, 1P, 5P, 5B, 6B, 6K, 7K, 7L, 7P, 8D, and a new station north of Pelee Island).

2002 Surveys in the Western and Central Basins. Sediment samples collected in the central basin in June of 1997 through 2000 revealed *Hexagenia* nymphs at more stations and generally in greater abundance each year, and this was especially notable in the Cleveland vicinity in 1999 and the Ashtabula-Conneaut area in 2000. In 2001, however, the nymphs disappeared almost completely from sediment samples. Therefore, we

sampled the central basin again in 2002 in order to document whether the nymphs could be found throughout the sampling area or continued to be rare in our samples. It was also important to compare our central basin results with the *Hexagenia* population in the western basin in order to understand whether the observed changes in the central basin populations might be linked to lake-wide environmental conditions. For that purpose, we sampled seven stations in the western basin in May 2002 extending from Maumee Bay to the eastern edge of the basin.

Five of the seven western basin stations yielded numerous nymphs. The greatest densities were near Maumee Bay State Park and between Kelleys and Pelee islands (251 to 288 nymphs/m^2), while no nymphs were found at two stations where they have been absent or rare over the past decade. Only three nymphs (at two stations) were present in the 144 samples (36 stations) collected from the central basin. The central basin results indicate that a major change in conditions, or one or more short-term events, such as an intrusion of oxygen-depleted hypolimnion water into shallower nearshore water overlying sediments occupied by *Hexagenia*, occurred between the sampling periods in 2000 and 2001. Hypolimnion intrusion would disrupt colonization by *Hexagenia* and reset the colonization process to an earlier phase.

<u>Development of the Metric</u>. In any given year, one or a few stations with very high or very low densities of *Hexagenia* can skew the estimate of basin-wide density. Therefore, the <u>median</u> density may be a more useful estimate than the average in revealing overall trends in *Hexagenia* abundance throughout the western basin because it is not as influenced by extreme values.

A “moving” average computed from the combined data of two or more years is more likely than individual yearly averages to reflect long-term changes in water and sediment quality. On the other hand, important short-term information might be lost if annual changes in average densities are ignored and only moving averages are reported. It is important to track the <u>annual</u> basin-wide average *Hexagenia* densities in order to discern recent changes quickly. In addition, because three-year moving averages appear to reveal well the underlying long-term trend in population density, they, rather than annual averages, should be used to determine the extent to which the *Hexagenia* metric is attaining the target density. Annual <u>median</u> densities should also be presented so that the midpoint of station densities can be observed. Sampling at all 22 stations less than yearly would preclude computation of three-year moving averages, unless moving averages were computed only from the 11 reference stations that would be sampled every year.

The 1998 Lake Erie Quality Index set a target population density of 500 nymphs/m^2 in soft sediments of the western basin and established the following scores:

Descriptive Score	Mayfly Nymphs per Square Meter (Annual Average in May)	Numerical Score
Excellent	More than 450	4
Good	400-450	3
Fair	350-399	2
Poor	Fewer than 350	1

Modified scoring criteria for the western basin are suggested as follows, based on three-year moving average basin-wide densities from 1997 through 2002:

Descriptive Score	Mayfly Nymphs per Square Meter (3-Year Moving Average in May)	Numerical Score
Imperiled	More than 400	2
Good	301-400	3
Excellent	201-300	4
Good	101-200	3
Fair	30-100	2
Poor	Fewer than 30	1

High densities of mayflies indicate over-enrichment of the lake and potential dissolved oxygen depletion and should be scored as "Imperiled". In order for the western basin to support *Hexagenia* within any particular range, its food supply has to be provided at the appropriate level, i.e., rate of nutrient enrichment of the lake. That level will most likely be determined by management decisions related to the maximum sustainable catch of sport and commercial fishes while at the same time avoiding nuisance algal blooms. Managers will undoubtedly want to maintain a level of nutrient enrichment well above that which existed prior to the impacts of large-scale industrialization, urbanization, and agriculture. However, it appears that a carrying capacity of nymphs based on average densities of the early 1950s is much too high to permit maintenance of the lake quality that we now experience. Refinement of the density criteria for the scores will be required as more data on *Hexagenia* densities and related ecological factors are gathered in future years.

The Descriptive Score of "Excellent" could be shifted upward or downward to reflect management objectives. For example, if the primary objective is to maintain the highest sustainable walleye and yellow perch fishery, "Excellent" will be in the range of 201-300 nymphs/m^2. If, however, the lake is to be managed primarily to achieve maximum water clarity to grow the sport diving industry, "Excellent" might be in the range of 30-100 nymphs/m^2.

It is appropriate to apply the mayfly metric to areas of Lake Erie outside the western basin; however, different scoring scales need to be developed for each area. Research programs should be launched to determine appropriate scores. The central basin should be included in the refined *Hexagenia* metric of the LEQI because benthic conditions and the benthic biota in the western basin are not representative of those in a large part of the central basin. Therefore, the composition and abundance of the benthic communities in the central basin cannot be predicted by those in the western basin. A set of central basin stations should be monitored annually for this purpose.

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Introduction

Burrowing mayflies of the species *Hexagenia limbata* (Serville) and *H. rigida* McDunnough (Figure 1) were major items in the diets of fishes in Lake Erie, especially in the western basin, until the middle of the twentieth century. At that time they succumbed to ever-increasing levels of organic and toxic pollutants, and they disappeared from almost all of Lake Erie between 1953 and the mid-1960s (Britt 1955, Burns 1985, Krieger *et al.* 1996, Krieger 1999). During the 1990s, these mayflies rapidly recolonized the western basin of Lake Erie (Krieger *et al.* 1996, Schloesser *et al.* 2000), and they appeared to be recolonizing parts of the central basin. Their life cycle varies from one to two years, depending on several factors (Corkum *et al.* 1997). Their ecology in Lake Erie is incompletely understood; however, it is known that in the western basin *Hexagenia* has once again become important in the diets of numerous fishes, including forage and game species (Krieger 2000). They also may serve to redistribute contaminants into the food web that formerly were sequestered in the lake sediments (Corkum *et al.* 1997).

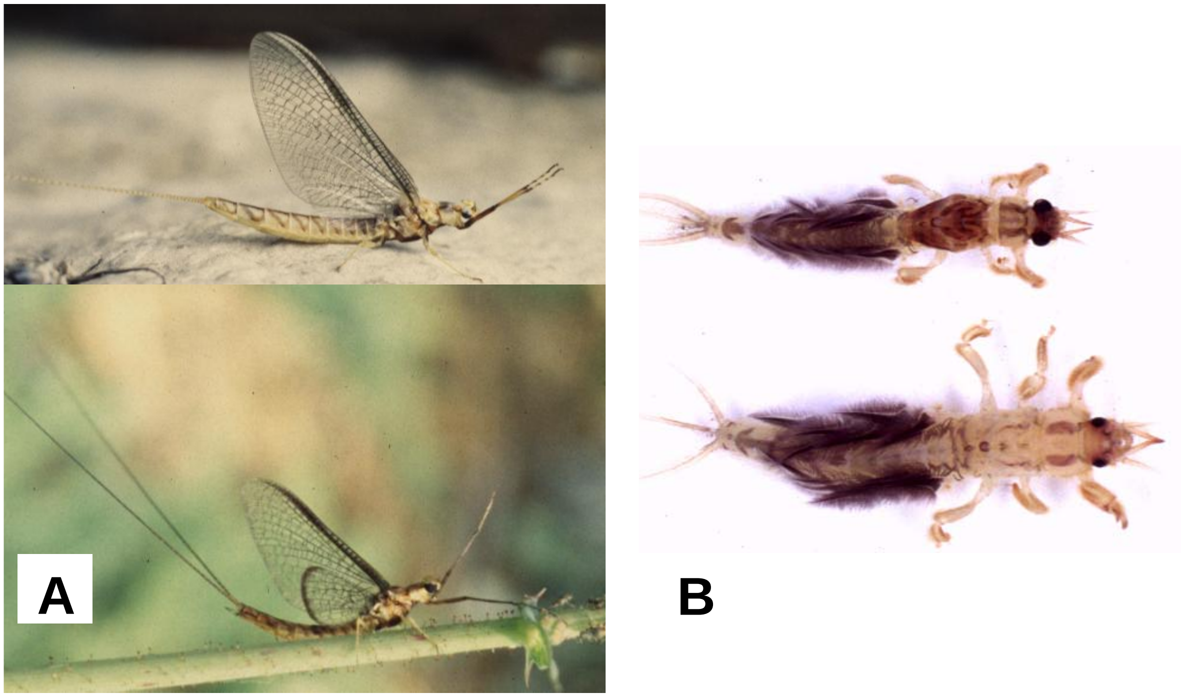


Figure 1. *Hexagenia* mayflies**.** **A.** Adult female (upper) and male (lower). **B.** Nymphs (male, upper; female, lower). Adults and nymphs shown are approximately 1.25 inches (3 cm) long, excluding the terminal filaments.

Hexagenia mayflies have long been considered to be useful as indicators of Great Lakes quality (Reynoldson *et al.* 1989). Their resurgence in the western basin of Lake Erie heightened interest in their ability to indicate lake quality at the sediment-water interface, particularly in relation to the supply of dissolved oxygen (OLEC 1998), as well as their potential role in improving components of the lake fishery. For these reasons, these mayflies were incorporated into the Lake Erie Quality Index (LEQI) published by the Ohio Lake Erie Commission in 1998 (OLEC 1998).

The LEQI consists of ten "indicators" which are rated with descriptive scores of "Excellent", "Good", "Fair", or "Poor". Each descriptive score is determined on the basis of weighted numerical scores assigned to one or more (up to five) "metrics" (28 total). The "Biological Indicator" is scored on the basis of two metrics: "Key Indicator Species" and "Index of Biotic Integrity". The Key Indicator Species metric ranks population or reproduction trends of three species: bald eagles, walleyes, and *Hexagenia* mayflies.

The LEQI initially established scores for mayflies derived from the density of nymphs per square meter of soft sediment on the lake bottom, a greater abundance of nymphs indicating better water and sediment quality (OLEC 1998, pp. 44-46). Mayfly densities observed since 1995 and new experimental evidence indicated that the scoring system needed to be modified (Krieger 1999). A point may be reached at which a further increase in mayfly abundance reflects declining rather than improving water quality. As long as the sediments are not too toxic and dissolved oxygen levels remain above minimal concentrations throughout their nymph stage, *Hexagenia* mayflies respond to increasing food supplies (nutrient enrichment) by growing more rapidly, and the lake sediments support increasing numbers of nymphs per square meter. High food input rates, however, often lead to severe oxygen depletion over and in the lake sediments, placing continued survival of the mayflies and other bottom organisms in jeopardy. Thus, we suggested that the mayfly metric be modified to reflect over-enrichment with nutrients.

In parallel with the inclusion of *Hexagenia* in the LEQI, Version 4 of the SOLEC report “Selection of Indicators for Great Lakes Basin Ecosystem Health” (Bertram and Stadler-Salt 2000) included walleye and *Hexagenia* (Indicator #9) among metrics proposed as open and nearshore waters indicators. The report states (p. 11): “This indicator will assess the quality and amount of aquatic habitat in the Great Lakes ecosystem, and it will be used to infer progress in rehabilitating degraded habitat and associated aquatic communities.”

Objectives

The Ohio Lake Erie Office issued a “Special Request for Grant Proposals” in December 2000 “for the purpose of collecting data and developing methodologies that will be incorporated into the *2003 Lake Erie Quality Index*.” The funding priorities included: “Conduct a census of mayfly nymph densities at specific sites in the western and central basins of Lake Erie.” Thus, this project had three primary objectives: (1) to recommend a subset of “master” or “reference” sampling sites in the western and central basins based on the analysis of accumulated information from ongoing data collections; (2) To census mayfly nymph densities in May and June 2002 at over 30 central basin sites and at seven master sampling sites in the western basin; (3) To apply new and previously existing data to further develop the methodology for the mayfly indicator of the *2003 Lake Erie Quality Index*. The rationale, specific objectives, methods, results, and recommendations are presented below separately for each objective.

Selection of Reference Stations

Rationale

Substantial investments in personnel, boats, and field equipment will be required if *Hexagenia* distribution and density are to be monitored indefinitely into the future. This will especially be true if monitoring is to include the central basin as well as the western basin. At the present intensity of sampling effort, approximately 30 stations are sampled every May or June in each basin (figures 2 and 3), requiring approximately 12 days for a two- or three-person crew (including the boat operator) to cover both basins.

Basin-wide sampling in the western basin (Figure 2) is performed to accomplish two objectives: (1) to estimate the average density (number per square meter) of nymphs in soft sediments of the entire basin, and (2) to observe differences in their density among specific sites. The objectives for sampling in the central basin are similar except that because of the size of the basin, sampling has been limited mostly to the shallower sediments that lie above the summer thermocline and within about 10 km of the south shore (Figure 3). Resources might be conserved if a way could be found to obtain that information, particularly Objective (1), by sampling only a subgroup of the 30 or so stations in each basin. In order that a subgroup of “index” or “reference” stations would adequately represent the entire basin, their average value must closely approximate the basin-wide average, not only in one year, but in every year. Alternatively, it would be acceptable if the subgroup were considerably different from the basin-wide average as long as the difference was consistent from year to year, that is, highly correlated with the basin-wide average. In that case, application of a multiplication factor would permit the calculation of the basin-wide value.

With the above criteria in mind, we attempted to select an appropriate subgroup of stations from the western basin data sets. An alternative approach suggested at a mayfly workshop in February 2002 (Appendix A) sponsored by this grant would consist of selecting each station in the subgroup to represent a zone, or region, within the basin. For example, Dr. Jan Ciborowski at the University of Windsor has divided the basin into five zones (see Appendix A, pp. 7, 11). The stations selected would be those that have consistently best approximated the overall mean values of the basin or a particular region over multiple years. Further, we expected to recommend that the complete suite of stations be sampled at intervals of around three to five years. Sampling the complete set would confirm that the reference stations remain representative of the regions for which they were selected and would detect important changes in density in relatively small areas that might otherwise go unnoticed. (Other discussion of reference stations appears in Appendix A, pp. 10-12.)

Methods

Investigation of potential reference stations was restricted to the western basin because few stations in the central basin have yielded nymphs since June 2000. We inspected the western basin data sets, covering the years 1995 through 2002, in three

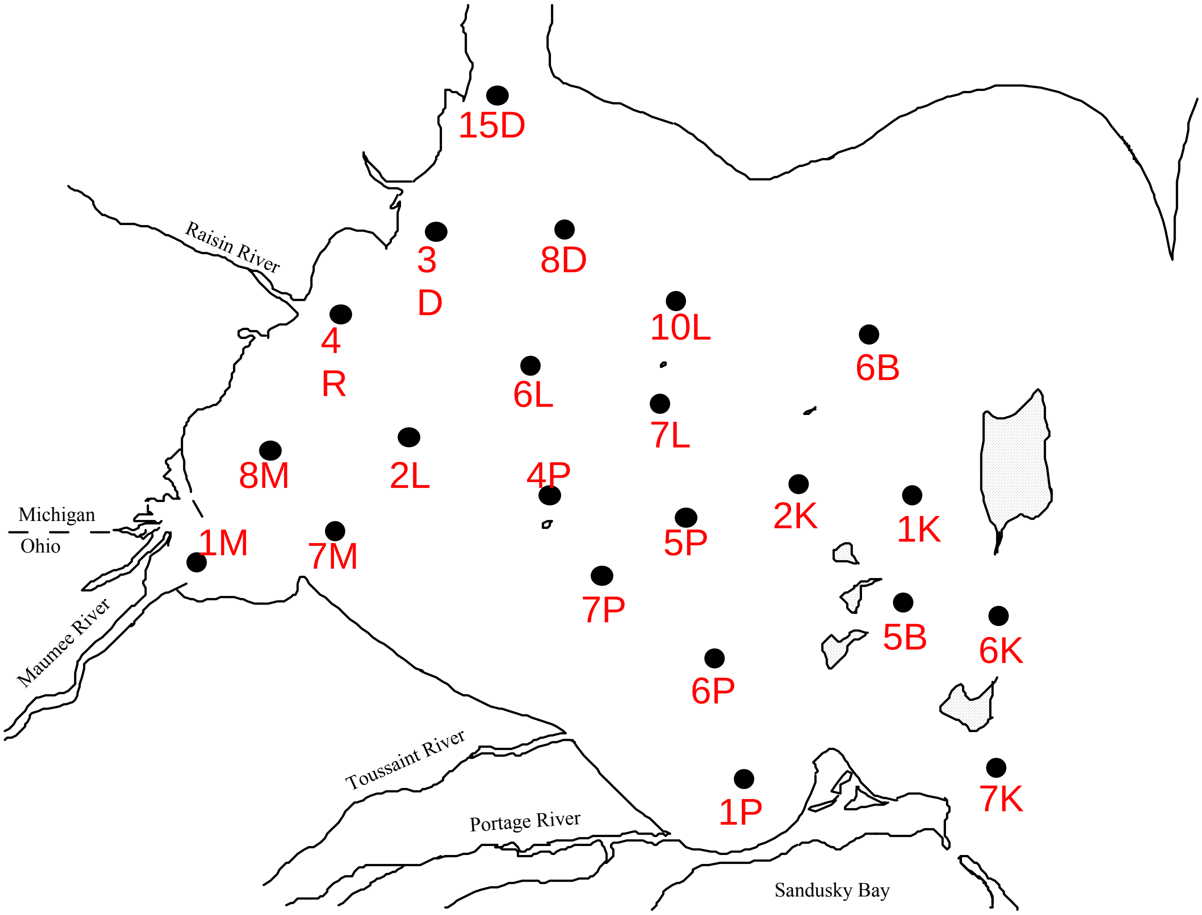


Figure 2. Western basin stations sampled from 1995 through 2003 included in this analysis.

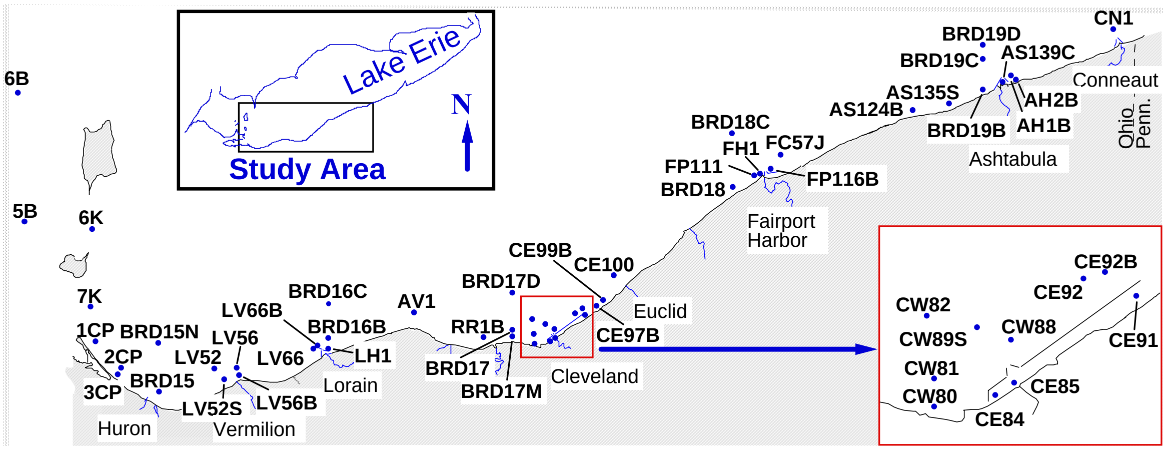


Figure 3. Central basin stations sampled for *Hexagenia* nymphs one or more years from 1997 through 2003.

ways. First, we mapped the individual station densities for each year to visualize spatial patterns – that is, to see whether densities in certain regions of the basin were always high or low relative to other regions. If so, reference stations could be selected to represent the population density in different geographical regions of the basin. For example, station 7M near Maumee Bay State Park might represent the region that has the highest density most years.

Second, we applied cluster analysis to the set of 22 stations that were sampled every May from 1995 through 2002 (data for 1999 through 2002 courtesy of Don Schloesser, USGS, Ann Arbor, MI). If clusters of two or more stations showed a close similarity based on their densities from year to year, one station in each cluster could be selected, thereby reducing the resources needed for sampling. The eight data points (one for each year) for each station consisted of the average density of four replicate Ekman grab samples (1995-1998) or three replicate Ponar grab samples (1999-2002). Ponar grabs collect nymphs more efficiently than Ekman grabs in some circumstances because Ponars penetrate deeper into certain sediments than Ekmans. In this report, Ekman densities were not converted to Ponar-equivalent densities (see Schloesser *et al.* 2000) because the conversion factor is not the same among widespread stations and our data have shown that at any station on any date, Ekman samples may yield an equivalent or higher density estimate than Ponar samples. Several cluster algorithms (Minitab 1999) were applied separately to standardized data and to log(x+1)-transformed data. Ward's and complete linkage methods based on Euclidean distance yielded almost identical results; only the results for Euclidean distance are presented here.

Third, the mean and median densities of nymphs in the western basin were computed for each of the eight years and the results were displayed as box-and-whisker plots (Minitab 1999). Individual station average densities were next compared with the average and median western basin densities by means of Pearson correlation coefficients (Zar 1999) to determine whether any stations consistently followed the long-term pattern of density variation within the basin and/or were close to the basin-wide average or median every year.

Results

The spatial plots (Figure 4) show the dramatic increase in the density of nymphs in western Lake Erie from 1995 through 1997, a decrease in 1998, a return to higher numbers in 1999 through 2001, and another decrease in 2002. The decrease in 1998 was attributed to failure of the new year-class to hatch in the summer and fall of 1997, leaving only second-year nymphs (those that hatched in 1996) to mature (Schloesser and Nalepa 2002).

Of particular importance in considering the selection of reference stations is the change in the regions of greatest nymph density from year to year (Figure 4). From 1995 through 1998 and again in 2000 and 2002, the greatest densities were in the western part of the basin. In 1999, the greatest density was found at Station 6K, between Pelee and Kellys islands, although high densities were also present near the western end of the basin. In 2001 that station and 6P, west of South Bass Island, shared high densities with two western stations (1M and 8D). Although densities at all stations were variable from year to year, Station 5P, near the middle of the basin, yielded no nymphs any of the eight years except in 2000, when the density was only 6.9 nymphs/m^2. Station 2K, northwest of North Bass Island, also yielded no nymphs in 1995 through 1997 and again in 2001, and it always had fewer than 50 nymphs/m^2 (Figure 4). Thus, the spatial plots indicate that few, if any, stations represent particular densities relative to the basin average because the locations of relatively high and moderate densities shift from year to year. The plots also indicate, however, that one or more stations *can* be selected to monitor the region near the middle of the basin that consistently has very low densities or an absence of nymphs.

For the period from 1995 through 2002, cluster analysis grouped the stations into six major clusters, five of which contained only two stations each (Figure 5A). The sixth cluster consisted of two subclusters. One subcluster contained seven stations that spanned much of the mid-lake area from east of the Bass islands toward the western shore (Figure 5B). They were intermingled with stations in other clusters. The other subcluster contained five stations occupying the region in and near Maumee Bay and an area south of the Detroit River (Figure 5B). The five remaining clusters consisted of station pairs: adjacent stations 6B and 10L near the Canadian shore; 2K and 7K, separated by the Bass and Kelleys islands; and the pairs 15D and 5P, 6K and 1P, and 4P and 4R, each of which had widely separated members. Thus, cluster analysis over the span of 1995 through 2002 did not reveal strong geographic relationships among most stations in terms of annual mean nymph densities, but several pairs of adjacent stations (7M and 8M, 5B and 1K, 3D and 8D, 6L and 7L, 6B and 10L) showed strong similarities.

Cluster analysis was also performed for the shorter period from 1998 through 2002 in order to eliminate the earlier years of colonization. The later five years might represent more-characteristic population densities at each station than the earlier years. For this later period, a pattern similar to the eight-year pattern was found (Figures 6A and 6B). A rather distinct group of stations spanned an area from the eastern islands and southern part of the basin toward the Detroit River. This group was divided in two parts geographically as it was in the longer eight-year period by an area of low density represented by stations 2K, 4P, and 5P (Figure 5B). As before, several stations (especially 1M) were only weakly associated with other stations (Figure 6A).

Box-and-whisker plots of mean station densities for each of the years 1995 through 2002 (Figure 7) show that the range and mean number of nymphs/m^2 were very low at all stations in 1995 and were only slightly higher in 1996 except in the southwestern corner of the basin at stations 7M and 8M. The greatest spread in mean station densities occurred in 1997, when densities at two stations (7M and 8D) attained the highest values recorded in the basin since recolonization began. The range of densities again was small in 1998, accompanied by a low mean basin density. As the mean basin density increased over each of the next three years, the range of densities also increased, but never to the extreme values seen in 1997. May 2002 was similar to May 1998 in marking a sudden

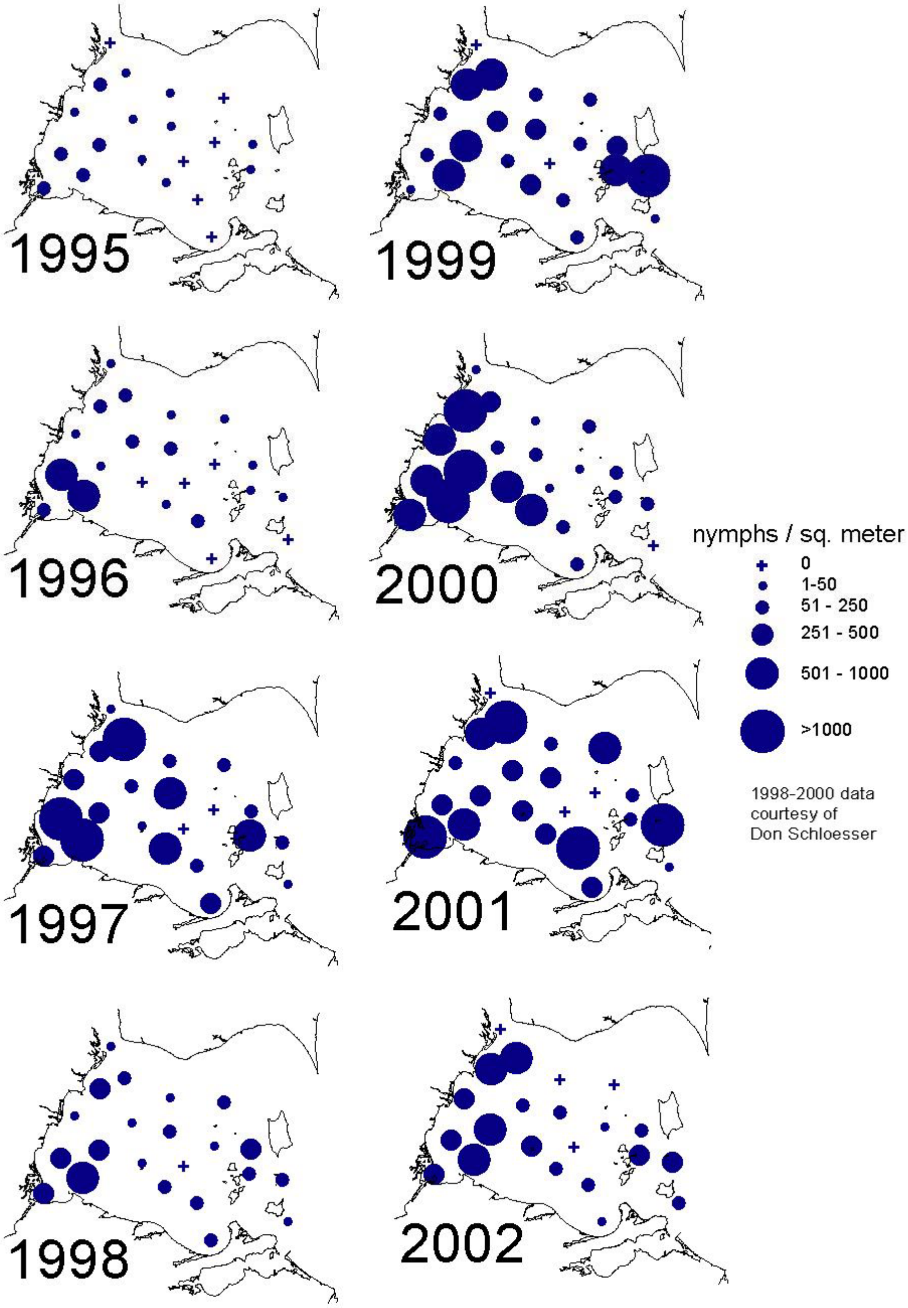
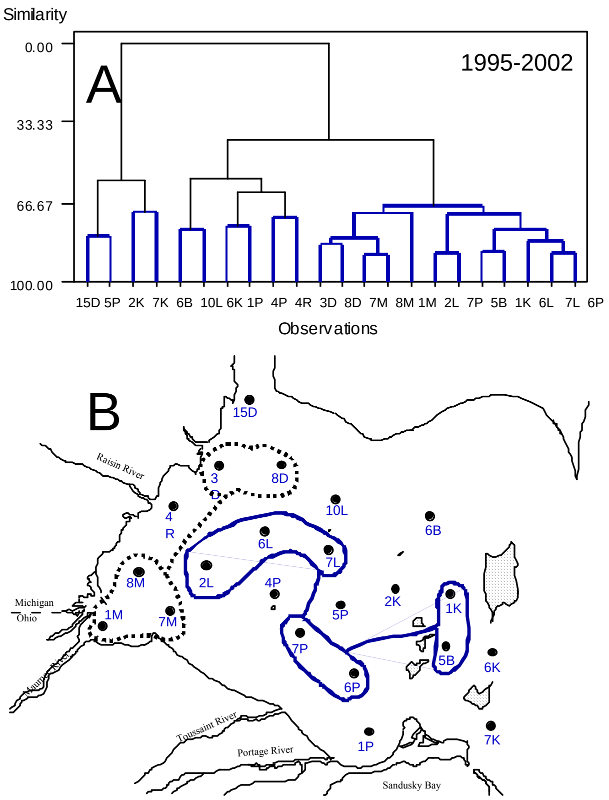


Figure 4. Average density of *Hexagenia* nymphs at each western basin station from 1995 through 2002. Stations not sampled every year are not shown.



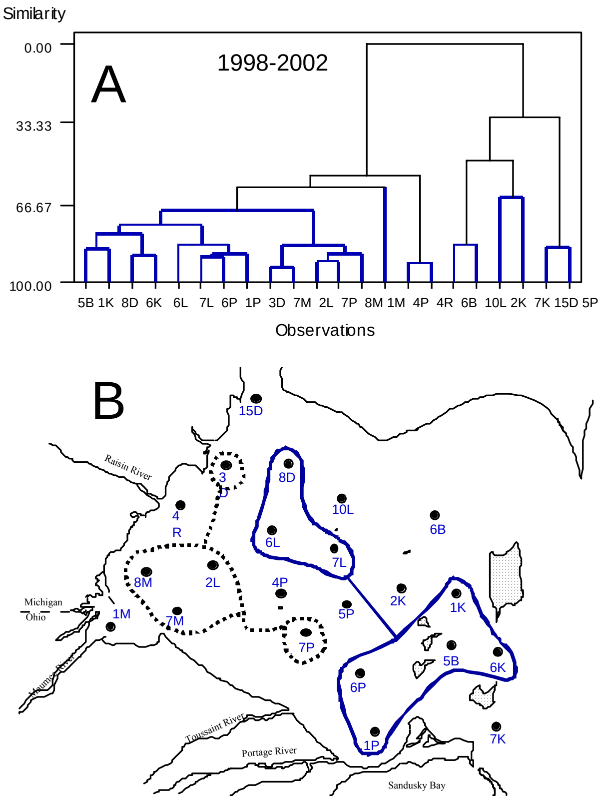


Figure 5. Results of cluster analysis of nymph densities at all stations for the period 1995-2002. **A.** Dendrogram. **B.** Spatial association of clusters. Stations grouped by a solid line or dashed line fell within two subclusters of a major cluster.

Figure 6. Results of cluster analysis of nymph densities at all stations for the period 1998-2002. **A.** Dendrogram. **B.** Spatial association of clusters. Stations grouped by a solid line or dashed line fell within two subclusters of a major cluster.

decrease in the mean density of nymphs across the western basin (Figure 7). The pattern may indicate the operation of a three- to four-year cycle of gradually increasing density followed by sudden decline. Preliminary data from May 2003 show that some mean station densities were again above 1,200 nymphs/m^2.

The median may be a more useful measure of basin-wide nymph density than the mean because it is not influenced by the size of extreme densities (especially outliers) and represents the midpoint of the values of all station densities. In the western basin, the median was always smaller than the mean, ranging from 24% of the mean in 1996 to 88% in 2002, and from 14.7 nymphs/m^2 in 1995 to 309.9 nymphs/m^2 in 2001. The mean, on the other hand, ranged from 34.6 nymphs/m^2 in 1995 to 469.2 nymphs/m^2 in 2001. The median showed the same pattern of rise and fall in nymph density as the mean. Box-and-whisker plots show whether the same stations tend to be outliers (have extreme values) from year to year. For example, Station 7M was an outlier in both 1996 and 1997; later years had no outliers (Figure 7).

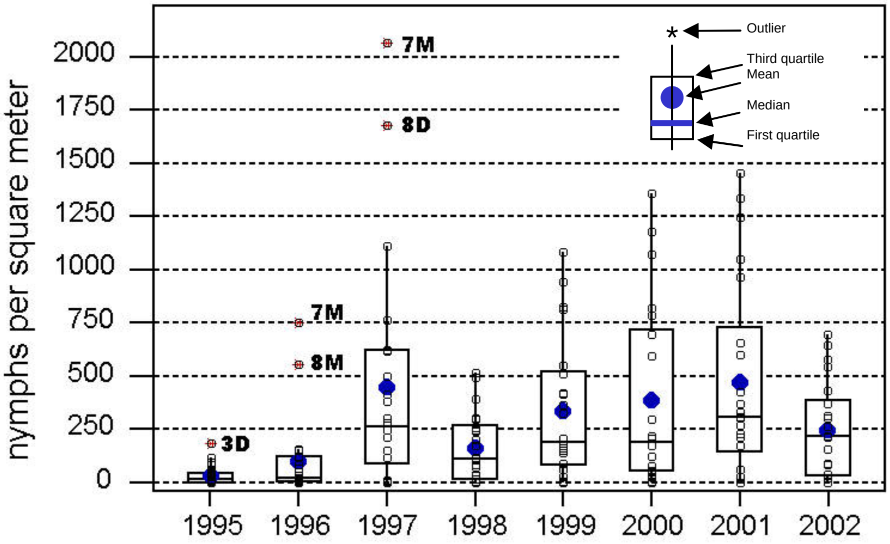


Figure 7. Box plots of basin-wide densities in the western basin of Lake Erie from 1995 through 2002.

Several stations were significantly correlated ($p \leq 0.05$) with each other over the eight-year period (Table 1). Station 7M was significantly correlated with seven other stations, 10L with six other stations, and 1P, 7P, and 4R with five other stations. All of these stations are in the western two-thirds of the basin. Several of those stations that were significantly correlated with each other were not strongly associated with each other in the cluster dendrogram (Figure 5A). This is probably accounted for by the fact that correlation analysis considers only the extent to which the density of each member of paired stations increases or decreases synchronously with the other, whereas cluster analysis using the Euclidean distance algorithm takes account of absolute densities as well as direction of change. The correlation analysis shows how closely the relative change in density at one particular station reflects relative change in density at another station. For example, density changes at Station 8D reflect very closely ($r=0.983$, $p<0.001$) the density changes at Station 7L (Table 1). A particularly strong correspondence was also present between stations 8D and 1P, 7L and 1P, 3D and 2L, 7M and 8M, 6B and 6P, 2L and 4P, and 15D and 8M. Of those, only 7M and 8M, 2L and 4P, and 2L and 3D were adjacent to each other in the basin.

Those stations that were significantly correlated with at least six (for example) other stations might be viable candidates as reference stations from the standpoint that they would show the direction and relative degree of change in densities at the other stations. (Twelve, or 55%, of the 22 stations showed significant correlations with four or more other stations; no stations showed significant negative correlations.) The candidate reference stations with six or more significant correlations are 7M and 10L.

Table 1. Pearson correlation coefficients (r) between stations and between stations and the mean and median of all 22 stations from 1995 through 2002. Only those correlations that were statistically significant ($p \leq 0.050$) are shown.

Number of Significant Correlations of Each Station with Other Stations

5B	4	7K	0	1P	5
6B	3	2L	4	4P	4
3D	4	6L	2	5P	4
8D	4	7L	4	6P	3
15D	2	10L	6	7P	5
1K	1	1M	2	4R	5
2K	2	7M	7		
6K	3	8M	2		

Correlation Coefficients (r) and Probabilities (p)

		1K	2K	10L	7P	Mean	Median
5B	r	0.734	0.764	0.738	0.819	0.899	0.829
	p	0.038	0.027	0.037	0.013	0.002	0.011

		7L	10L	7M	1P	Mean	Median
8D	r	0.983	0.726	0.739	0.904	0.841	0.875
	p	<0.001	0.042	0.036	0.002	0.009	0.004

		10L	7M	1P	Mean	Median
7L	r	0.821	0.798	0.904	0.829	0.836
	p	0.013	0.018	0.002	0.011	0.010

		2L	4P	5P	4R
3D	r	0.911	0.847	0.743	0.758
	p	0.002	0.008	0.035	0.029

		8M	1P	7P	Mean
7M	r	0.925	0.804	0.797	0.723
	p	0.001	0.016	0.018	0.043

		6K	1M	6P
6B	r	0.859	0.787	0.955
	p	0.006	0.020	<0.001

		6L	6P
6K	r	0.726	0.747
	p	0.041	0.033

		4P	5P	4R
2L	r	0.906	0.894	0.890
	p	0.002	0.003	0.003

		5P	4R
4P	r	0.892	0.840
	p	0.003	0.009

		7M	1P	7P
10L	r	0.706	0.776	0.713
	p	0.050	0.024	0.047

		6L
2K	r	0.710
	p	0.048

		7P	Mean	Median
1P	r	0.819	0.899	0.829
	p	0.013	0.002	0.011

		6P
1M	r	0.836
	p	0.010

Table 1, Continued.

		4R	Mean	Median			4R
7P	r	0.806	0.862	0.723	5P	r	0.805
	p	0.016	0.006	0.043		p	0.016
		7M	8M				Median
15D	r	0.745	0.901		Mean	r	0.943
	p	0.034	0.002			p	<0.001

Another criterion for selecting reference stations could be their significant correlation with the basin-wide mean and median. Over the eight-year period, the mean was significantly ($p \leq 0.05$) correlated with only six of the 22 stations, and the median with only five (Table 1). Stations significantly correlated with both the mean and median were 5B, 8D, 7L, 1P, and 7P. Station 7M was significantly correlated with the mean but not the median. Those six stations could serve as reference stations that would reflect the relative changes in the annual basin-wide mean but not the absolute value of the mean.

Perhaps the best reference stations would be those that are significantly correlated both with several other stations and with the basin-wide mean and/or median. The stations that fit that criterion are 5B, 8D, and 7L, each significantly correlated with four stations, and 7M, 1P, and 7P, each significantly correlated with five or more stations.

Recommendation

Annual sampling at the 22 stations should be continued as long as funding and personnel are available. Presently, this is being done by Mr. Don Schloesser (USGS, Ann Arbor, MI), who has shared his results with us. If it becomes necessary to curtail the sampling effort, and in the absence of another rationale, a subset of stations should be sampled.

The above exercises reveal a rationale for selecting a small number of sampling stations that could represent the dynamics of the entire western basin or zones within the basin. The stations should be selected because of their correlation with the basin-wide mean or median or because of their special historic, geographic, or ecological value. The following eleven candidate stations (Figure 2) are proposed:

- 7M – near Maumee Bay State Park in an area with the highest nymph densities in the western basin most years (Figure 4); first sampled in 1930 (Schloesser *et al.* 2000); significantly correlated with the basin-wide mean.
- 1P – between Port Clinton and Catawba Point in an area of sub-optimal (sand-silt) habitat but of interest to businesses and residents of the area; sampled since 1993; significantly correlated with the basin-wide mean and median.
- 5P – mid-basin area west of North Bass Island mostly devoid of nymphs in the 1990s and early 2000s; sampled since 1993.

- 5B – east end of Middle Bass Island; sampled since 1953 (Britt *et al.* 1973); significantly correlated with the basin-wide mean and median.
- 6B – northwest of Pelee Island, west of Pelee Passage where short-term intrusions of hypolimnionic water from the central basin may occur; sampled since 1953 (Britt *et al.* 1973).
- 6K – between Pelee and Kelleys islands at margin of western and central basins, probably subject to ephemeral intrusions of hypolimnionic water from the central basin; sampled since 1996.
- 7K – between Kelleys Island and Marblehead Point at margin of western and central basins, probably subject to ephemeral intrusions of hypolimnionic water from the central basin; sampled since 1996.
- 7L – significantly correlated with the basin-wide mean and median; first sampled in 1961 (Schloesser *et al.* 2000).
- 7P – significantly correlated with the basin-wide mean and median; sampled since 1993.
- 8D – significantly correlated with the basin-wide mean and median; first sampled in 1930 (Schloesser *et al.* 2000).
- A new station, or one of those presently sampled by Dr. Jan Ciborowski, representative of the large region in the northeastern part of the basin where *Hexagenia* are generally absent (J. Ciborowski, pers. comm.).

The central basin should be included in the refined *Hexagenia* metric of the LEQI because benthic conditions and the benthic biota in the western basin are not representative of those in a large part of the central basin. Therefore, the composition and abundance of the benthic communities in the central basin cannot be predicted by those in the western basin. Changes in the benthic communities of the central basin may lag the changes in the communities of the western basin by years or decades, may not resemble those changes, or may not occur at all. Unlike in the western basin, extensive sampling of the central basin did not begin until the late 1970s, after *Hexagenia* had disappeared from most of the western basin; and even then, sampling was largely restricted to nearshore areas (Krieger and Ross 1993). Therefore, data showing that *Hexagenia* was ever present in the central basin are very sparse (Reynoldson and Hamilton 1993).

Limited success in finding nymphs in central basin sediments from 1997 through 2003 indicates that a different sampling approach than previously employed may be in order. Rather than sampling along the entire Ohio shoreline with low intensity (30 stations along ~120 miles), it may be more productive to abandon stations along the more-rural shoreline and concentrate the same number of stations in the vicinity of harbors and cities. Candidate areas, with several stations in each, include the harbors and vicinities of the Areas of Concern in Ohio (Lorain, Cleveland, and Ashtabula), and of Huron, Fairport Harbor (Painesville), and Conneaut.

2002 Surveys in the Western and Central Basins

Rationale

Staff of our laboratory, in cooperation with staff of the USGS in Ann Arbor and Sandusky, have surveyed *Hexagenia* nymph distribution and densities in the western basin since 1995 and in the nearshore region of the central basin within Ohio since 1997 (Krieger 2000, 2001, 2002). During the first four years of sampling in the central basin (June of 1997 through 2000), we observed *Hexagenia* nymphs at more stations each year, and this was especially notable in the Cleveland vicinity in 1999 and the Ashtabula-Conneaut area in 2000 (Figure 8). Sampling in June 2001 revealed a very different picture, however. Rather than a further expansion of the distribution of nymphs, we observed an almost complete disappearance of nymphs from our sediment samples (Figure 8). It was important, therefore, to sample the central basin again in 2002 in order to document whether the nymphs could be found throughout the sampling area or continued to be rare in our samples.

It was also important to be able to compare our central basin results with the condition of the *Hexagenia* population in the western basin. By doing so, we could understand whether the observed changes in the central basin populations were possibly linked to lake-wide environmental conditions. For that purpose, we sampled seven stations in the western basin extending from Maumee Bay to the eastern edge of the basin (Figure 9). Our rationale for initially choosing those seven stations and our recommendation of four additional stations for inclusion in future surveys are explained in the previous section of this report.

Methods

We sampled sediments at the seven western basin stations 20-29 May 2002, and at 36 stations in the nearshore region of the central basin from Cedar Point to Conneaut, Ohio, 4-13 June 2002 (figures 8 and 9). Table 2 lists the coordinates and depth of each station sampled in 2002. The central basin stations incorporated several stations new to this series of annual surveys but along transects established decades ago by the USGS Sandusky office. These were stations BRD15N, BRD16C, BRD17, BRD17M, BRD17D, BRD18C, BRD19C, and BRD19D, and they were several kilometers further offshore than other stations (Figure 3). Together with a few of our previously established stations, most of them were sufficiently deep [up to 64 feet (19.3 m)] that the lake sediments most years would be in the metalimnion or hypolimnion, i.e., near or below the thermocline. Sediments in the hypolimnion are particularly subject to oxygen depletion in summer. Because we had found few nymphs in our samples the previous year and yet winged *Hexagenia* were seen onshore, we had hypothesized that some nymphs may be residing in deeper waters than we had sampled before.

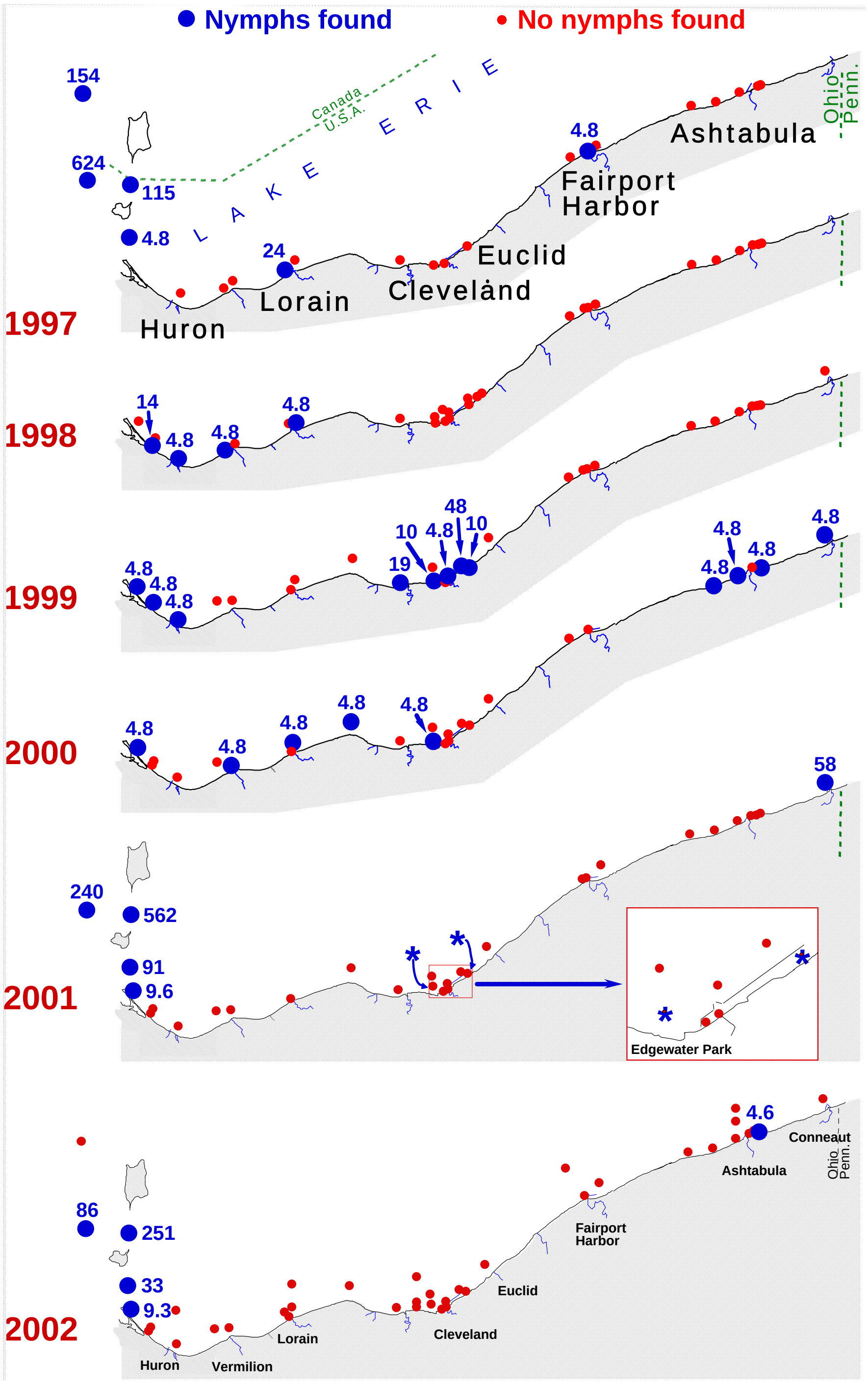


Figure 8. Mean densities (number/m^2) of *Hexagenia* nymphs in May to early June in Ohio nearshore sediments of the central basin (1997 through 2002) and easternmost western basin (1997, 2001, 2002). Asterisks in 2001 indicate sightings of vacant burrow holes. Low densities in 2000 probably resulted from sampling after emergence began.

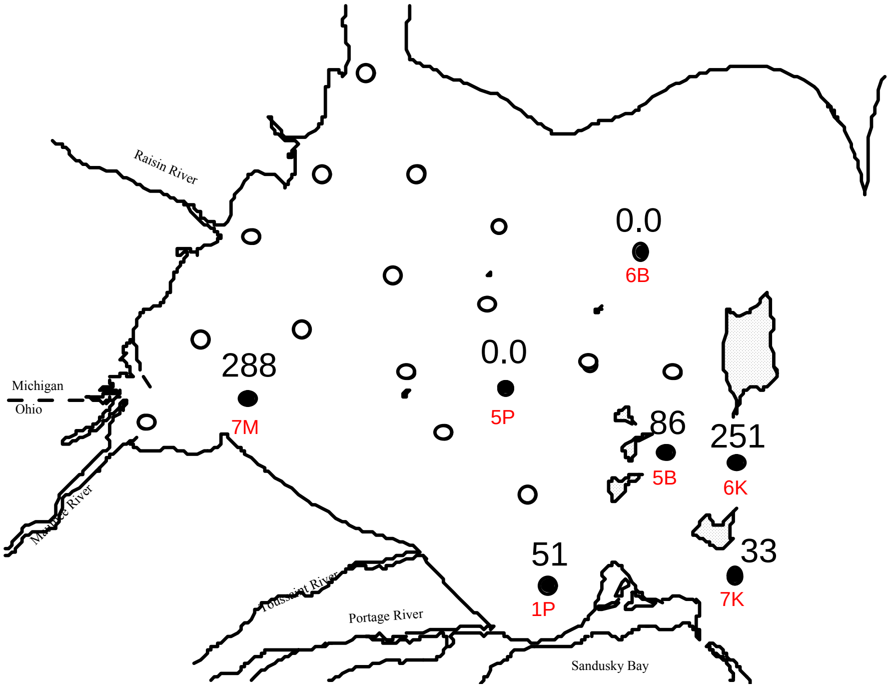


Figure 9. Mean densities (number/m^2) of *Hexagenia* nymphs in May 2002 at the seven western basin stations sampled as part of this project (solid circles).

Field methods were identical to those detailed in earlier reports (Krieger 1999, 2000) with the exceptions mentioned below. Basically, four replicate samples were collected with a Ponar grab at each station aboard the *R/V Pike* operated by Mr. Drew Jones or Mr. Mike Bur of the USGS Sandusky research station. The sediments were rinsed through a 0.60 mm-mesh sieve on board with a stream of lake water. The sample residues were preserved with formaldehyde and were stained in the laboratory with Phloxine B dye. *Hexagenia* nymphs were removed from the residues and counted.

At stations where several nymphs were observed while sieving the Ponar samples, four replicate Ekman grab samples were also collected so that the relative efficiencies of the two samplers at collecting the nymphs could be determined. This additional sampling effort was necessary to permit quantitative comparison of Ponar samples collected in 2002 and later against the Ekman samples collected in 2001 and earlier. We changed samplers for three reasons: (1) the Ponar has become the sampler of choice throughout most of the Great Lakes because of its ability to sample a wider variety of sediments than most other commonly used samplers; (2) preliminary studies in the western basin have shown that the Ponar grab is somewhat more effective in sampling all the mayflies in the sediment in the spring than are the Ekman, Petite Ponar, and Petersen samplers

Table 2. Coordinates and depths of Lake Erie stations sampled for this project in 2002.

Western Basin				**Central Basin**				**Years Successfully Sampled (√)**				
Station	**N Latitude**	**W Longitude**	**Depth, 2002 ft (m)**	**Station**	**N Latitude**	**W Longitude**	**Depth latest yr, ft (m)**	**98**	**99**	**00**	**01**	**02**
5B	41°41.50'	82°46.00'	29 (9.0)*	BRD15	41°24.37'	82°29.52'	34 (10.4)	√	√	√	√	√
				BRD15N	41° 29.25'	82°29.52'	46 (14.1)					√
6B	41°52.00'	82°49.00'	38 (11.5)	CP1	41°30.01'	82°38.07'	36 (11.0)	√	√	√	√	√
				CP2	41°26.60'	82°.35.00'	35 (10.7)	√	√	√	√	√
6K	41°40.00'	82°40.00'	38 (11.6)	CP3	41°25.71'	82°35.04	29 (8.8)	√	√	√	√	√
7K	41°34.00'	82°40.00'	39 (12.0)	LV52	41°27.30'	82°24.00'	43 (13.1)		√	√	√	√
7M	41°44.00'	83°17.83'	20 (6.1)	LV56	41°27.30'	82°21.10'	42 (12.8)		√	√	√	√
				LV66	41°28.75'	82°11.17'	32 (9.8)	√	√	√	a	√
1P	41°32.92'	82°55.00'	19 (5.9)	LH1	41°28.50'	82°11.10'	32 (9.8)			√	√	√
5P	41°44.00'	82°58.25'	32 (9.9)									
				BRD16B	41°29.57'	82°09.46'	37 (11.3)	√	√	√	a	√
				BRD16C	41°31.64'	82°09.46'	51 (15.5)					√
				AV1	41°32.50'	82°01.00'	53 (16.0)		√	√	√	√
				RR1B	41°29.83'	81°51.72'	38 (11.6)	√	√	√	√	√
				BRD17S	41°30.44'	81°48.00'	40 (12.2)					√
				BRD17I	41°31.25'	81°48.00'	49 (14.9)					√
				BRD17D	41°35.78'	81°48.00'	61 (18.6)					√
				CW81	41°30.80'	81°45.33'	43 (13.1)	√	√	√	√	√
				CW82	41°32.88'	81°45.84'	53 (16.2)		√	√	√	√
				CE84	41°29.83'	81°43.50'	30 (9.2)	√	√	√	√	√
				CE85	41°30.30'	81°42.75'	35 (10.7)	√	√	√	√	√
				CW88	41°31.50'	81°42.70'	40 (12.2)	√	√	√	√	√
				CE91	41°32.25'	81°39.33'	27 (8.1)	√	√	√	√	√
				CE92	41°32.70'	81°40.50'	43 (13.1)		√	√		√
				CE100	41°36.20'	81°35.83'	45 (13.6)	√	√	√	√	√
				BRD18	41°45.47'	81°19.22'	31 (9.5)	√	√	√	a	a
				BRD18B	41°47.79'	81°19.22'	50 (15.2)					a
				BRD18C	41°49.22'	81°19.22'	60 (18.4)					√
				FP111	41°46.10'	81°18.40'	36 (11.0)	√	√		√	a
				FH1	41°45.95'	81°16.91'	15 (4.5)	√	√	√	√	√
				FP116B	41°46.92'	81°16.87'	51 (15.5)	√	√		a	a
				FH3	41°48.30'	81°15.15'	51 (15.5)				√	√
				AS124B	41°52.35'	80°59.25	38 (11.5)	√	√		√	√
				BRD19	41°54.38'	80°49.42'	30 (9.2)					a
				BRD19B	41°54.55'	80°49.49'	42 (12.8)	√	√	√	√	√
				BRD19C	41°55.86'	80°49.49'	50 (15.3)					√
				BRD19D	41°57.24'	80°49.49'	59 (18.3)					√
				AS135S	41°52.95'	80°55.60'	42 (12.8)	√	√	√	√	√
				AS139C	41°54.89'	80°48.31'	30 (9.2)	√	√	√	√	√
				AH1B	41°55.15'	80°47.70'	23.6 (7.2)	√	√	√	√	√
				AH2B	41°54.92'	80°47.36'	30 (9.1)	√		√	√	√
				CN1	41°59.90'	80°34.00'	49 (14.8)		√	√	√	√

* 2003 depth

a = attempted but no useful samples obtained

(Schloesser and Nalepa 2002); and (3) other agencies presently censusing *Hexagenia* in the western basin, especially the USGS Great Lakes Science Center with whom we continue to collaborate, are using a Ponar sampler.

Results

Few nymphs were present in the 144 samples collected from the central basin in 2002 (Appendix B). One nymph (equivalent to 4.6 nymphs/m^2) was found in Ashtabula Harbor (Station AH2B) and two nymphs (9.3 nymphs/m^2) were found offshore of Cedar Point (Station 1CP) (Figure 8). The population was more abundant along the edge of the western basin between Marblehead Peninsula and Kelleys Island (33 nymphs/m^2) and much more abundant between Kelleys Island and Pelee Island (251 nymphs/m^2) (Figure 9).

Mean *Hexagenia* densities ranged widely, from 0 to 288 nymphs/m^2, at the seven stations we sampled in the western basin (Figure 9). No nymphs were found at the two stations (6B and 5P) where they have generally been absent or rare over the past decade. The greatest density was at 7M, which has had one of the greatest densities among all stations most years (Figure 4). The density at Station 6K was only slightly lower than that at 7M, and stations 5B, 7K, and 1P had relatively low densities (Figure 9).

Discussion and Recommendation

The finding of only three nymphs at two stations in our central basin sampling area in 2002 indicates that the similar results in 2001 were valid. The mean population density in the western basin in 2001 and 2002 bracketed that in 2000 (Figure 10), when the nymphs were becoming more widespread in the central basin; yet the sparse population in the central basin seems largely to have disappeared between June 2000 and June 2001. These results indicate that a major change in conditions or one or more short-term events, such as an intrusion of oxygen-depleted hypolimnionic water into shallower nearshore water overlying sediments occupied by *Hexagenia*, occurred between our sampling periods in 2000 and 2001. Hypolimnionic intrusion would disrupt colonization by *Hexagenia* and reset the colonization process to an earlier phase.

The same stations in the western and central basins were sampled again in May and June 2003 as part of a small grant (LEPF SG202-03) to this investigator. Those results, presented at the June 2003 meeting of the International Association for Great Lakes Research, again showed a near-absence of nymphs in the central basin study area while a relatively dense population persisted in most of the western basin.

Development of the Metric

A. Median and Moving Average for Reporting *Hexagenia* Densities

Rationale

As has been shown (Figure 4), *Hexagenia* density at individual stations varies widely from year to year. That large variability is reflected in large annual changes in the basin-wide average (mean) density (Figure 10). Furthermore, in any given year, one or a

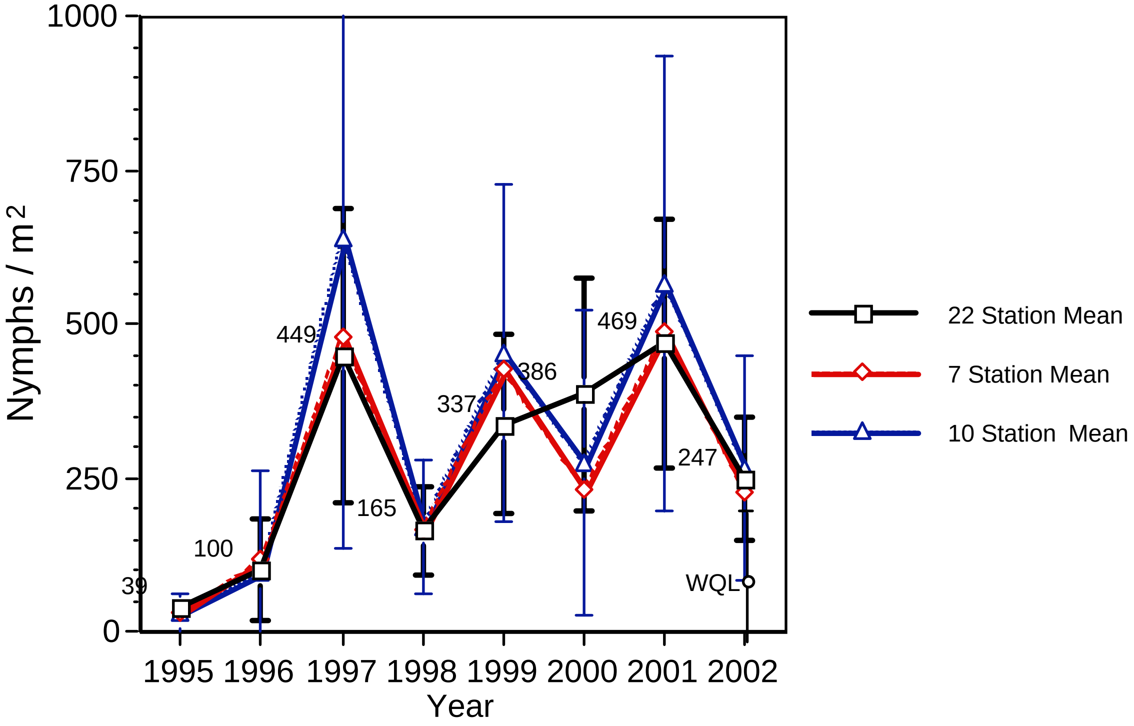


Figure 10. Comparison of mean nymph densities (± 95% confidence intervals) in the western basin of Lake Erie as determined by sampling at 22 stations (see Figure 2), at a subset of 7 stations sampled as part of this project in 2002, and at a subset of 10 stations that incorporate the 7 stations. The 10 stations (plus another in the northeastern corner of the basin not yet sampled) are those recommended in this report. Values of the means of the 22 stations are also shown. (Data for 1999 through 2002 courtesy of Don Schloesser, USGS, Ann Arbor, MI)

few stations with very high or very low densities skew the basin-wide average density. Therefore, the median density may provide a more useful estimate than the average of overall trends in *Hexagenia* abundance throughout the basin because it is not as influenced by extreme values (Zar 1999, p. 25).

When change over time is being investigated, that change often can be observed more accurately by computing an average from the combined data of two or more years. The resulting statistic is a “moving” average, so named because with each year of new data, the data from the oldest year are removed and the data for the newest year are incorporated. The more-extreme changes seen in annual data thereby appear smaller because moving averages show a more gradual change over time. Nicholls *et al.* (2001) provided an example of such an application to Lake Erie in which they presented widely varying monthly average total-phosphorus concentrations on the same graphs as the 12-month moving median (rather than moving average) values.

When thinking of *Hexagenia* as an environmental indicator in Lake Erie, an important consideration is that year-to-year changes in population density probably do not indicate rapid fluctuations in the quality of Lake Erie but most likely are an integrated response to numerous naturally variable environmental factors and sampling "error" (Krebs 1999, p. 11). Therefore, a moving average is more likely than individual yearly averages to reflect long-term changes in water and sediment quality (see Appendix A, p. 6).

On the other hand, important short-term information might be lost if annual changes in average densities are ignored and only moving averages are reported. For example, the sudden decrease in average density from 1997 to 1998 probably represented an important change in the condition of the *Hexagenia* population and demonstrated that the population had not approached a steady-state condition. A moving average would obscure the severity of the change and might even delay its detection. Furthermore, a moving average that incorporates too many years – perhaps four or five – might be too slow to reveal an important trend in increasing or decreasing population density.

Methods

The average western basin density and 95% confidence interval (N=22 stations) for each year from 1995 through 2002 were calculated. The data were next combined into two-year data sets (N=44) that included the mean density at each station for each year. For example, for the 1995-1996 data set, station 4R was represented by 9.6 nymphs/m^2 (1995) and 24.0 nymphs/m^2 (1996). The moving average density and 95% confidence interval was calculated for each of the seven pairs of years (1995-1996, . . . , 2001-2002). Likewise, the data were combined into three-year sets (N=66), and the statistics were calculated for each of the six resulting sets.

Results

The annual basin-wide averages (Figure 11A) revealed the wide fluctuation in *Hexagenia* density from year to year mentioned above. By contrast, the two-year moving averages (Figure 11B) greatly dampened the annual fluctuations, and the three-year moving averages (Figure 11C) dampened them even more. However, because the data from each year influence the average for as long as they are included in the data set (two or three years), the large decrease in population density that occurred in 1998 did not appear as a decrease in the two-year data until 1999, and not in the three-year data until 2000. Yet, by 2000 the population density had already increased again for two successive years.

Recommendation

It appears important to track the annual basin-wide average *Hexagenia* densities in order to discern recent changes quickly. In addition, because the three-year moving averages appear to reveal well the underlying long-term trend in population density, they should be used to determine the extent to which the *Hexagenia* metric is attaining the target density. Annual median densities should also be presented so that the midpoint of station densities can be observed.

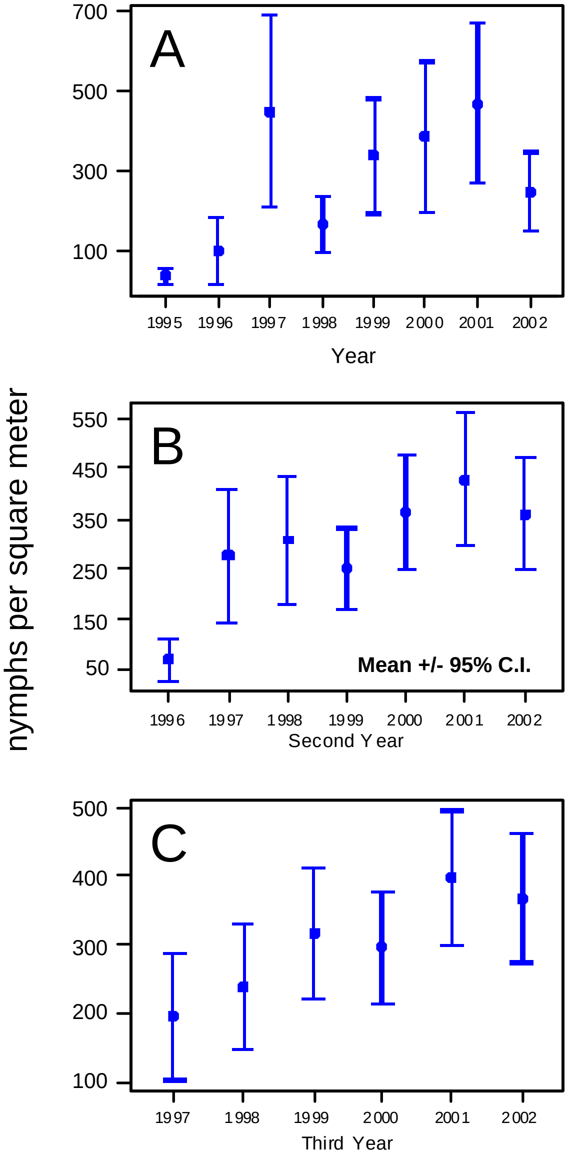


Figure 11. Number of *Hexagenia* nymphs/m^2 in the western basin of Lake Erie: (A) annual average, (B) two-year moving average, (C) three-year moving average.

B. Frequency of Estimation of Average Density in Western Basin

Rationale

At the onset of this project, it seemed that it might be practical to reduce sampling frequency in the western basin from yearly to every two years, or even less often. However, the annual data gathered since 1995 have shown that the *Hexagenia* densities at individual stations and the basin-wide average densities are highly variable from year to year (figures 4 and 10). Important information on year-class success would be lost if sampling frequency were reduced to every two or three years. However, as discussed previously, the proposed subset of 11 stations could be sampled every year to provide year-class information for various regions within the western basin and the remaining stations could be sampled less frequently. Sampling at all 22 stations less than yearly would also preclude computation of three-year moving averages, unless the decision were made to compute the moving averages only from the 11 stations that would be sampled every year.

Recommendation

The recommendation at this time is to sample all 22 stations every year. A twenty-third station (the eleventh station in the proposed subset) should be added in the deep northeast corner of the western basin.

C. Target Density for Achieving a Score of “Excellent”

Rationale

In any aquatic ecosystem, the biomass of the animals at all trophic levels (herbivores, carnivores, detritivores) changes according to the amount and quality of food available to them, assuming all other variables (including predation) are constant. The “bottom-up” concept (Kalff 2002, p. 444) leads to the expectation that the quantity of plant nutrients entering Lake Erie controls the productivity of all plant and animal life in the lake. That is, the amount of algal growth in the lake increases as the quantity of phosphorus entering the lake increases. (Phosphorus is considered to be the limiting nutrient for most algal growth in Lake Erie.) As the abundance of planktonic algae (phytoplankton) increases, the abundance of the planktonic animals (zooplankton) that graze on the algae increases. In a cascading effect, the abundance of fishes that feed on zooplankton increases, as does the abundance of fishes that feed on other fishes, such as adult walleye and yellow perch. Likewise, as the quantity of phosphorus declines, the abundance of algae, zooplankton, and fishes is expected to decline in turn. In fact, the inputs of phosphorus declined over the past three decades (Makarewicz and Bertram 1991, Nicholls et al. 2001, Baker and Richards 2002), and by the early 2000s the abundance of walleye had declined to approximately half of what it was in the late 1980s (Figure 12) (Ryan *et al.* 2003).

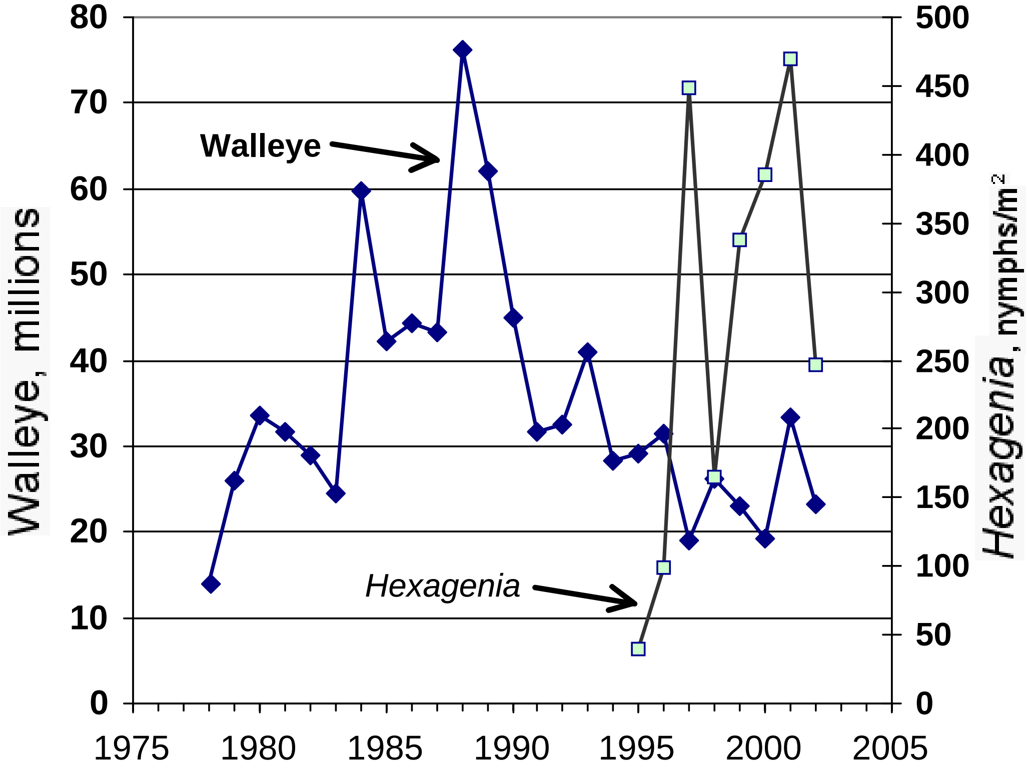


Figure 12. Millions of walleye in Lake Erie (Ryan *et al*. 2003) and average density of *Hexagenia* nymphs in the western basin.

The abundance of animals such as *Hexagenia* that live in the bottom sediments is also expected to be controlled indirectly by nutrient inputs because they obtain nourishment from the decaying remains of the algae, zooplankton, and fish as well as the bacteria and fungi that carry out the decay process. The expected response seems to have occurred in the first half of the twentieth century as the inputs of phosphorus in untreated sewage, industrial outfalls, and agricultural runoff increased (Reynoldson and Hamilton 1993) until consequent low dissolved oxygen concentrations (hypoxia) resulted in the sudden die-off of the mayflies (Britt 1955). Had the mayflies still been present during the quarter century leading to the 1990s, one might expect that as the quantity of phosphorus in the water of Lake Erie declined during that period, fewer *Hexagenia* would be found as well. Instead, the mayflies began to recolonize the western basin in the early 1990s and underwent a logarithmic increase in abundance in the western basin from 1992 until 1997 (Madenjian *et al.* 1998). Since that time, their abundance has fluctuated considerably (Figure 10).

The abundance of *Hexagenia* did not adhere to the bottom-up concept during the 1990s because at least one environmental factor other than phosphorus concentration – probably dissolved oxygen – exerted an overriding influence on the success of this benthic invertebrate between the early 1950s and early 1990s. It is possible, though evidence is lacking, that persistent organic contaminants in the sediments, including insecticides such as DDT and industrial compounds such as PCBs and PAHs (Burns 1985, Great Lakes Water Quality Board 1987) prevented the return of *Hexagenia* until the contaminated sediments became buried deeply enough by newly deposited, cleaner sediments. However, independent experiments over the years (Burns 1985; J.J.H. Ciborowski, Univ. of Windsor, pers. comm. May 1999) showed that *Hexagenia* eggs can hatch and the nymphs can grow and mature in western basin sediments where nymphs continue to be absent, as long as sufficient oxygen is provided.

It is apparent that recent low dissolved oxygen concentrations (hypoxia) during summer stratification have excluded *Hexagenia* from much, if not most, of the deeper areas of the central basin (Reynoldson and Hamilton 1993), but the role of hypoxia in controlling the success of *Hexagenia* in the western basin and shallower nearshore sediments of the central basin is much less understood. Evidence (Bridgeman and Schloesser 2003) indicates that hypoxia presently impacts the abundance of the nymphs in parts of the western basin by reducing the hatching success of year classes. If hatching success and resulting abundance in a given year are based on the random occurrence of weather events that bring about hypoxia, then the long-term trend in *Hexagenia* abundance is likely to reflect the abundance of its food resources. Ultimately, then, the abundance of *Hexagenia* in the western basin is probably linked to phosphorus inputs because in Lake Erie phosphorus is usually the nutrient in shortest supply relative to the nutritional needs of algae (Makarewicz and Bertram 1991).

If the abundances of both walleye and mayflies are ultimately controlled by phosphorus inputs, the sizes of the populations of both animals might be expected to show the same trend over time. However, an increased abundance of walleyes, but more likely of bottom-feeding forage fishes, might exert “top-down” controls (Kalff 2002, p. 444), thereby reducing the size of the *Hexagenia* population. In Figure 12, annual walleye abundance in Lake Erie (Ryan *et al.* 2003) and annual *Hexagenia* abundance in the western basin from 1995 through 2002 are plotted together. There is little correspondence in the population changes from year to year between the two organisms. This may indicate that the hatching success and survivorship after hatching of walleye and *Hexagenia* in any given year are controlled by different combinations of environmental factors. The general target for walleye abundance in Lake Erie has been set at 30 million to 50 million fish (Roger Knight, ODNR, 26 August 2003, personal communication), which is higher than the estimated abundance most years since 1995 (Figure 12).

Nicholls *et al.* (2001) reported an increase in total phosphorus concentrations in Canadian nearshore waters of western Lake Erie in the late 1990s, which generally corresponds to the increase in *Hexagenia* density during that period. However, the lack of evidence showing a definite linkage between phosphorus inputs and *Hexagenia* abundance leaves little basis upon which to establish a target density of *Hexagenia* nymphs in the sediments.

The Lake Erie Quality Index (OLEC 1998, pp. 44-46) initially set a target population density of 500 nymphs/m^2 and established the following scores for mayflies, based on the density of nymphs per square meter of soft sediment on the lake bottom:

Descriptive Score	Mayfly Nymphs per Square Meter (Annual Average in May)	Numerical Score
Excellent	More than 450	4
Good	400-450	3
Fair	350-399	2
Poor	Fewer than 350	1

In our final report to the Ohio Lake Erie Office for Project LEPF-08-94 (Krieger 1999), we suggested that the scoring method be revised based on the mayfly densities observed since 1995 and on new experimental evidence. There were several reasons for this recommendation. First, a higher density of mayflies is not necessarily a positive condition, either for people on shore in the summer or for the ecology of Lake Erie. The State of Lake Erie report (OLEC 1998, p. 46) states, "The best available data, from 1930 to the early 1950s, indicate average densities of up to 500 nymphs per square meter. *The Lake Erie Commission has set a goal of re-establishing mayfly nymphs in the western basin of Lake Erie to this average density of 500 nymphs per square meter*" (OLEC's italics). It should be noted that the data collected from 1929 to the 1950s (Britt 1955, Wright *et al.* 1955, Britt *et al.* 1973) were collected during a period of massive nutrient enrichment of the lake, and the 1929-1930 study of Wright *et al.* (1955) was initiated because large-scale impacts of nutrients and toxic organics in the western basin were already suspected. As long as sediment toxicity permits reproduction and dissolved oxygen concentrations remain above a lethal threshold throughout their nymph stage, *Hexagenia* mayflies respond to increasing food supplies (nutrient enrichment) by growing more rapidly, and the lake sediments support increasing numbers of nymphs per square meter. Hanes and Ciborowski (1992) showed that larvae reared from eggs at a low density (159 nymphs/m^2) and high food supply grew larger than larvae reared under other conditions, but that larval mortality increased at high density (7,950 nymphs/m^2) and (or) low food supply.

As shown by Reynoldson and Hamilton (1993) from historical evidence supplied by sediment cores, *Hexagenia* appears to have undergone a large population increase in the western basin during the period from the beginning of European settlement, deforestation, and drainage of the Lake Erie basin until the time of its sudden disappearance from the western basin in the 1950s (Britt 1955). Therefore, it appears that average densities of 300 to 500 nymphs/m^2 (and individual station densities up to 9,000 nymphs/m^2) observed in the first half of the twentieth century (Britt 1955) were artificially high. Most Lake Erie benthic biologists believe the available evidence indicates that it was primarily suffocation by hypoxia over sporadic periods during summers that first caused the demise of the *Hexagenia* population and then prevented its recovery for decades. The oxygen depletion was brought about by over-enrichment (cultural eutrophication) of the lake that resulted in a high sediment oxygen demand. Thus, in the absence of severe oxygen depletion, the *Hexagenia* population probably responds favorably to increasing nutrient enrichment (accompanied by increasing oxygen demand) through increased growth rates and higher densities of nymphs.

It is probable that a maximum density would be reached above which additional increases in density would be limited by crowding (Hanes and Ciborowski 1992). Furthermore, when the oxygen demand reaches a critical point, periods of hypoxia below about 1.2 mg/L (Eriksen 1963) result in suffocation and the sudden loss of the *Hexagenia* population. Britt (1955) recorded such an event in the late-summer of 1953.

Recommendation

Modified scoring criteria for the western basin are suggested as follows, based on three-year moving average basin-wide densities from 1997 through 2002:

Descriptive Score	Mayfly Nymphs per Square Meter (3-Year Moving Average in May)	Numerical Score
Imperiled	More than 400	2
Good	301-400	3
Excellent	201-300	4
Good	101-200	3
Fair	30-100	2
Poor	Fewer than 30	1

On the basis of the above evidence, the mayfly metric should be modified to incorporate a single range of *Hexagenia* densities scored as "Excellent" as before, but bracketed above and below by two separate ranges of density scored as "Good". That is, too few mayflies will not sustain the Lake Erie fishery, but high densities of mayflies indicate over-enrichment and potential dissolved oxygen problems. Lower densities should successively be scored “Fair” and “Poor” as in the original metric. However, the highest densities should be scored as “Imperiled”. In order for the western basin to support *Hexagenia* within any particular range, its food supply has to be provided at the appropriate level. That level will most likely be determined by management decisions related to the maximum sustainable catch of walleye, yellow perch, and other sport and commercial fishes while at the same time avoiding nuisance algal blooms. It seems certain that managers (and society) will want to maintain the productivity of western Lake Erie well above the pristine productivity that existed prior to the impacts of large-scale industrialization, urbanization, and agriculture. However, it appears that a carrying capacity based on average densities of the early 1950s is much too high to permit maintenance of the lake quality that we now experience.

Basin-wide densities in May of more than 300 nymphs/m^2 probably indicate that nutrient loading to the lake is too high to sustain the mayflies without the risk of triggering hypoxia events in the western basin in summer during prolonged periods of calm weather. Therefore, densities in the range of about 301 to 400 nymphs/m^2 should receive a score of “Good” rather than “Excellent”. This recommendation is based on empirical evidence rather than a quantitative analysis of population densities in relation to environmental data.

Refinement of the density criteria for the scores will be required as more data on *Hexagenia* densities and related ecological factors are gathered in future years.

The evidence indicates that, at present, the mayfly population in much of the western basin is threatened with extinction each summer as the result of declining dissolved oxygen concentrations. Any increase in the inputs of limiting nutrients (phosphorus) to the basin will probably yield an increase in primary and secondary production (including more *Hexagenia*), which in turn could lead to catastrophic declines in dissolved oxygen concentrations in summer as the decay of the increased biomass places a greater demand on the dissolved oxygen supply. Because hypoxia has been recorded in parts of the western basin in the 1990s (Krieger *et al.* 1996) and early 2000s (Bridgeman and Schloesser 2003), even the 3-year moving averages from 1999 through 2002 ranging between around 300 to 400 nymphs/m^2 (Figure 11C), with a recommended score of "Good", appears to reflect excessive oxygen demand in the western basin. Based on the same rationale, three-year moving average densities higher than 400 nymphs/m^2 should be scored as "Imperiled".

Reduced oxygen demand that would not result in dangerously low dissolved oxygen concentrations during prolonged calm weather would indicate the presence of a smaller food supply (or lower food quality) for *Hexagenia*. The maximum population size that can be sustained without threat of extinction from hypoxia is probably below 300 nymphs/m^2. Therefore, "Excellent" conditions are indicated at *Hexagenia* densities sustained within the range of about 201 to 300 nymphs/m^2.

It must be stressed that below the productivity threshold where dissolved oxygen depletion threatens the survival of *Hexagenia* and other bottom-dwelling invertebrates and fishes, the Descriptive Score of "Excellent" could be shifted downward to relatively low densities of *Hexagenia*, depending on management objectives. If the primary objective is to maintain the highest sustainable walleye and yellow perch fishery, then "Excellent" will be in the range of 201-300 nymphs/m^2. If, at the other extreme, the lake is to be managed primarily to achieve maximum water clarity for SCUBA and snorkeling in order to grow the tourist industry, then "Excellent" might be in the range of 30-100 nymphs/m^2. Thus, this metric is based both on biology and policy.

It is appropriate to apply the mayfly metric to areas of Lake Erie outside the western basin. However, different scoring scales need to be developed for the different regions, such as the epilimnionic sediments (those above the summer thermocline) of the central basin, Presque Isle Bay, and the eastern basin. To date, data on population densities in most of those areas are nonexistent or are too sparse to permit development of the appropriate scores. Research programs should be launched to provide such data. Annual sampling should be continued in the central basin epilimnionic sediments in order to observe recovery of *Hexagenia* in that region, perhaps by using tools such as a remotely operated vehicle (ROV) to detect their presence in low numbers. Video observation via ROV at the margin of the central and western basins in 2003 and 2004 has shown promise as a survey tool (Ohio Sea Grant R/ER-66-PD and Lake Erie Protection Fund grant SG232-04 to Heidelberg College).

It should be noted that *Hexagenia* has been incorporated as Indicator #9a in the latest *State of the Great Lakes* report (Environment Canada and US EPA 2003, p. 43). That report assesses the *Hexagenia* indicator as “mixed, improving” in the Great Lakes as a whole. This rating was assigned because, according to the report, mayfly populations have largely recovered in the western basin of Lake Erie and have shown signs of recovery in Green Bay of Lake Michigan and Bay of Quinte of Lake Ontario, while recovery of mayflies has not been observed in Saginaw Bay of Lake Huron or many polluted portions of the St. Marys and Detroit rivers. The same report rates the abundance of the benthic amphipod, *Diporeia* (scud), Indicator #93a, which only occurs in Lake Erie in the eastern basin, as “mixed, deteriorating” because over the past 12 years it has decreased in abundance and large areas are now devoid of this fish food resource (p. 48). Aquatic oligochaete communities, Indicator #93, are assessed as “mixed” (p. 49).

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Appendix A. Refining and Implementing the Mayfly (*Hexagenia*) Metric of the Lake Erie Quality Index, Proceedings of a Workshop Held 8-9 February 2002 at Heidelberg College, Tiffin, Ohio

The proceedings can be downloaded at
http://www.heidelberg.edu/offices/wql/WorkshopProced.pdf

Appendix B. Abundance of *Hexagenia* Nymphs in Samples Collected May-June 2002 in the Western and Central Basins.

	Replicate -- **PONAR**						Replicate -- **EKMAN**					
Station	1	2	3	4	Mean	**#/sq.m.**	1	2	3	4	Mean	**#/sq.m.**
5B*							6	2	5	5	4.50	**86.4**
6B	0	0	0	0	0.00	**0.0**						
6K	3	15	18	18	13.50	**251.0**	6	9	5	7	6.75	**129.6**
7K	0	0	3	4	1.75	**32.5**	4	2	4	1	2.75	**52.8**
1P	2	1	3	5	2.75	**51.1**	0	0	6	0	1.50	**28.8**
5P	0	0	0	0	0.00	**0.0**	1	0	0	0	0.25	**4.8**
7M	13	13	21	15	15.50	**288.1**	30	19	20	7	19.00	**364.8**
1CP	1	0	0	1	0.50	**9.3**	0	1	0	0	0.25	**4.8**
2CP	0	0	0	0	0.00	**0.0**						
3CP	0	0	0	0	0.00	**0.0**						
BRD15	0	0	0	0	0.00	**0.0**						
BRD15N	0	0	0	0	0.00	**0.0**						
LV52	0	0	0	0	0.00	**0.0**						
LV56	0	0	0	0	0.00	**0.0**						
LV66	0	0	0	0	0.00	**0.0**						
LH1	0	0	0	0	0.00	**0.0**						
BRD16B	0	0	0	0	0.00	**0.0**						
BRD16C	0	0	0	0	0.00	**0.0**						
AV1	0	0	0	0	0.00	**0.0**						
RR1B	0	0	0	0	0.00	**0.0**						
CW81	0	0	0	0	0.00	**0.0**						
CW82	0	0	0	0	0.00	**0.0**						
CE84	0	0	0	0	0.00	**0.0**						
CE85	0	0	0	0	0.00	**0.0**						
CW88	0	0	0	0	0.00	**0.0**						
CE91	0	0	0	0	0.00	**0.0**						
CE92	0	0	0	0	0.00	**0.0**						
BRD17	0	0	0	0	0.00	**0.0**						
BRD17M	0	0	0	0	0.00	**0.0**						
BRD17 D	0	0	0	0	0.00	**0.0**						
CE100	0	0	0	0	0.00	**0.0**						
BRD18												
BRD18C	0	0	0	0	0.00	**0.0**						

Appendix B. Continued.

FH1	0	0	0	0	0.00	**0.0**						
FH3	0	0	0	0	0.00	**0.0**						
AS124B	0	0	0	0	0.00	**0.0**						
AS135S	0	0	0	0	0.00	**0.0**						
BRD19B	0	0	0	0	0.00	**0.0**						
BRD19C	0	0	0	0	0.00	**0.0**						
BRD19D	0	0	0	0	0.00	**0.0**						
AS139C	0	0	0	0	0.00	**0.0**						
AH1B	0	0	0	0	0.00	**0.0**						
AH2B	0	0	0	1	0.25	**4.6**	0	0	0	0	0.00	**0.0**
CN1	0	0	0	0	0.00	**0.0**						

* No Ponar samples collected; Stone Laboratory staff collected Ekman samples.