

## **2005 Status of the Lake Ontario Ecosystem: A Biomonitoring Approach**

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### **Introduction**

The Great Lakes and Lake Ontario ecosystems have been subject to accelerated ecological change since the 1950s. These ecosystems experienced (in the 1950s and 1960s) numerous stresses including overfishing, cultural eutrophication, and contaminant discharge yielding degradation of water quality, loss of habitat, and the depreciation of fish communities. Such stresses raised public concern about the condition of the Great Lakes and led to a new period of environmental awareness and restoration in the 1970s, 1980s, and 1990s. The historic Great Lakes Water Quality Agreement (GLWQA) between the United States and Canada in 1972, later revised in 1978 and 1987 (IJC 1988), marked a new era of ecosystem management and initiated a process we term oligotrophication (reverse of eutrophication). In Lake Ontario, for example, phosphorus levels have declined over the past 20 years, but this event has come at a time when demands for a salmonid sport fishery have increased, non-native species such as the alewife have exhibited highly variable population dynamics, pelagic zooplankton production has declined, oligotrophic fish stocks are recovering,

and exotics such as the zebra mussel, quagga mussel and currently the predatory cladoceran *Cercopagis pengoi* have proliferated (Christie *et al.* 1987, EPA 1993, Mills *et al.* 2003, Mills *et al.* 2005). Clearly, Lake Ontario is an ecosystem in transition, and the public’s interest in and awareness of the Lake Ontario environment continues to increase. It is incumbent upon the scientific and management communities to understand these ecosystem changes and their implications for the life support system of this important freshwater resource.

One approach toward assessing a lake ecosystem in transition like Lake Ontario is to develop a database of key indicators that reflect ecosystem change. From 1995-2005, we have conducted a biomonitoring program in Lake Ontario that has indexed some of the primary indicators of ecosystem health as identified by the Lake Ontario Pelagic Community Health Committee (EPA 1993). The primary objective of the research was to evaluate the indexing variables of total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll *a* (Chl *a*), Secchi depth, and crustacean zooplankton (density, biomass, size structure) (1) spatially and

temporally, and (2) in critical habitats including embayments, the nearshore, and the offshore pelagia. The biomonitoring approach we describe has been successfully accomplished through interagency support of the New York State Department of Environmental Conservation (NYSDEC) including the Cape Vincent Fisheries Station and regional staffs at Watertown, Cortland, and Avon, the U.S. Fish & Wildlife Service, the Ontario Ministry of Natural Resources (OMNR), the U.S. Geological Survey – Great Lakes Science Center, and Cornell University. The program has also allowed us to (1) provide a benchmark for comparison to evaluate changes in the lower food web of Lake Ontario, and (2) link with closely allied programs such as current Sea Grant projects assessing changes in Lake Ontario's mysid population, and the benthification of Great Lakes ecosystems. The biomonitoring variables we have chosen to examine contribute to research on Lake Ontario's coastal areas and embayments which are crucial to understanding the coupling between ontogenetic patterns of habitat utilization and whole-lake predator-prey interactions, and for understanding the role of inshore habitats in food web dynamics.

### **Report Objectives**

We measured total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll *a* (Chl *a*), water temperature, Secchi depth, zooplankton density, zooplankton size, and zooplankton biomass. With these data, we addressed the following questions:

- (1) *Embayment - Nearshore - Offshore Comparisons*: Do biomonitoring variables vary between embayment, nearshore, and offshore habitats?
- (2) *East-West Comparisons*: Do biomonitoring variables vary from east to west in nearshore and offshore habitats?
- (3) *Seasonal and Year-to-Year Variability in Embayment and Nearshore Habitats*: Do biomonitoring variables in embayment and nearshore habitats differ significantly throughout the season? Do trends vary between embayments and nearshore habitats from year-to-year?
- (4) *Relationships of Variables*: Are any biomonitoring parameters related to each other?

(5) *Zooplankton Community Dynamics*: Does the biomass of major zooplankton groups differ between embayment, nearshore, and offshore habitats? Do trends vary seasonally between embayments and nearshore habitats? Does zooplankton community structure suggest a healthy balance between predatory and prey fish? Do trends in the zooplankton community reflect changes in the fish community?

(6) *Cercopagis pengoi*: How was *C. pengoi* distributed lakewide during mid-summer to fall? Are there any trends in spatial distribution? Has *C. pengoi* had any major effects on the zooplankton community? What are the implications of *C. pengoi* presence or absence on alewife populations?

(7) *Bythotrephes longimanus*: How was *B. longimanus* distributed lakewide during mid-summer to fall? Are there any trends in spatial distribution? Has *B. longimanus* had any major effects on the zooplankton community? What are the implications of *B. longimanus* presence or absence on alewife populations?

(8) *Erie/Ontario Nearshore Comparisons*: How do biomonitoring variables differ between nearshore habitats in easternmost Lake Erie and Lake Ontario?

### **Methods**

#### Sampling

The R/V's Kaho and Seth Green collected offshore water and zooplankton samples during April through October 2005. All samples collected in water equal to or deeper than 20m were considered offshore for habitat comparisons. Offshore sampling totaled 38 samples taken on 25 dates. During the month of July, 11 offshore samples were collected on 6 dates.

Water and zooplankton samples, as well as water temperature and Secchi depth data, were collected from seven nearshore and three embayment sites during the May to October sampling season. The eastern nearshore sampling locations (Galloo Island Lake, Chaumont Bay Lake, Sandy Pond Lake, and Sodus Bay Lake), and western nearshore locations (Niagara River East Lake, Niagara River West Lake, and Oak Orchard Lake), along with the three eastern embayment sampling sites

(Chaumont Bay, Sandy Pond Bay, and Sodus Bay) were sampled biweekly (Figure 1).

#### Water Chemistry

Water samples were collected for analysis of Chl *a*, TP, and SRP. Each sample was obtained by using an integrated water sampler (1.9cm inside diameter Nalgene tubing) lowered to a depth of 10m. The tube was then closed off at the surface end and the column of water transferred to 2L Nalgene containers. From each sample a 100mL unfiltered aliquot sample was frozen for later analysis of TP (Menzel and Corwin 1965). We also filtered 1-2L of water through a Whatman 934-AH glass fiber filter that was frozen for later analysis of Chl *a* using the standard acetone extraction method (Strickland and Parsons 1972). A 100mL sample of filtered water was also frozen for later analysis of SRP (Strickland and Parsons 1972).

#### Quality Assurance - Quality Control

In 2005, Quality Assurance and Quality Control (QAQC) analyses were conducted for TP and SRP. Water samples were collected from embayment and nearshore habitats using the standard sampling methods.

In July 10 aliquots of raw water were taken from one sample for TP analysis. An additional 10 aliquots of filtered water were taken from the same sample for SRP analysis. One subset of these samples was analyzed at CBFS; another subset was analyzed at the Upstate Freshwater Institute (UFI), an EPA certified laboratory located in Syracuse, NY, for comparison with CBFS results. In the event that significant differences ( $p < 0.05$ ) arose between CBFS and UFI laboratory results, an adjustment equation would have been generated and applied to CBFS results (TP and/or SRP) in order to account for those discrepancies. The adjustment equation is a regression equation that adjusts the CBFS data in relation to the UFI data. In 2005 CBFS and UFI results exhibited no significant difference in TP analysis. High sample-to-sample variability among both labs precluded the use of UFI data for SRP adjustment. As a result, there was no adjustment of the regression equation in either set of data.

In 2005, we also conducted replicate sampling for analyses of TP, SRP, and Chl *a*. Three different samples (triplicates) were collected at each nearshore and embayment location twice in August. From each of the three samples, one aliquot was taken for TP, one for SRP, and one for Chl *a* analysis. The samples were analyzed at CBFS to determine the amount of variability between samples.

#### Zooplankton

We measured several zooplankton parameters: total density (#/L), size (mm), and biomass ( $\mu\text{g/L}$ ), as well as *C. pengoi* biomass and total biomass (expressed as proportion of total) of five subgroups of zooplankton. Zooplankton samples were collected with a standard 0.5m diameter, 153 $\mu\text{m}$  mesh nylon net. At most embayment and nearshore sites, we strained a 10m water column. At offshore sites, we sampled a 6-40m water column. The samples were anesthetized using antacid tablets, then preserved in the field with 95% ethyl alcohol. Single samples were collected on a biweekly basis at embayment and nearshore sites from May to October, except for July and August when two replicate samples were collected per site on each date.

In the CBFS laboratory, each sample was strained through a 1.02mm mesh cup to separate *C. pengoi*, *B. longimanus*, and other larger organisms (>1mm in length) from smaller zooplankton (<1mm). This was done because *C. pengoi* form clumps in the sample, making the usual random subsampling of 1mL samples inappropriate. For each sample that contained clumps of *C. pengoi*, two analyses were performed, one on the smaller zooplankton and one on the larger zooplankton (including *C. pengoi*) that were caught in the 1mm mesh strainer. The larger zooplankton were measured and enumerated by subsampling at least 100 organisms from a gridded, numbered petri dish in which the sample had been homogeneously separated and mixed.

The subsample was examined through a compound microscope at 10-40X magnification. Images from the sample were projected onto a digitizing tablet that was interfaced with a computer. The zooplankton were measured

using the digitizing tablet and identified to species, excluding nauplii and copepodites (Pennak 1978, Balcer *et al.* 1984). To calculate the total number of large crustaceans and *C. pengoi* in the clumped part of the sample, we used a ratio of wet weights of the subsample to wet weights of the total sample. Wet weights were determined using a Sartorius balance. For the smaller sized zooplankton samples, we counted and measured at least 100 organisms from one or more 1mL random subsamples using the same microscope and digitizer technique. [In earlier years of this project an electronic touch screen (1995-1997) and a 20X microprojector (1998-2000) were used for measuring the zooplankton (Hambright and Friedman 1994).]

We used length:dry-weight regression equations (CBFS unpublished data) to estimate zooplankton biomass. Biomass of *C. pengoi* was estimated using two different regression equations. Nearshore samples were analyzed using the regression  $\ln W = 1.7164 + 2.3703 \ln L$ , where  $W$  represents biomass ( $\mu\text{g}$ ) and  $L$  represents length (mm). Offshore samples were analyzed using the regression  $\ln W = 1.3690 + 2.7686 \ln L$ . Each of these regressions is based on the original length:dry weight regressions (determined using unpreserved specimens) used in 1998 but increase the estimated weight by 42% to compensate for biomass loss due to preservation (Giguere *et al.* 1989).

#### Data Analyses

We employed the following analyses to address the above objectives:

##### *(1) Spatial Variability:*

For each of the eight embayment and nearshore study parameters (TP, SRP, Chl *a*, water temperature, Secchi depth, and zooplankton density, size, and biomass), we compared the biweekly averages between the two habitats using a paired t-test for means. For the comparisons between offshore, nearshore, and embayment habitats, we examined each of seven study parameters (TP, SRP, Chl *a*, water temperature, and zooplankton density, size, and biomass) with paired two-sample t-tests assuming unequal variances. These

comparisons were made with data that was collected during the same sampling week. Zooplankton density and biomass were log transformed, and each zooplankton relationship was considered significant following the Bonferroni adjusted  $\alpha=0.0167$  ( $p<0.0167$ ). Differences in each chemical / physical relationship were considered significant at  $p<0.05$ .

##### *(2) East-West Comparisons:*

Nearshore east-west comparisons were made for the eight study parameters (TP, SRP, Chl *a*, Secchi depth, water temperature, and zooplankton density, size, and biomass). Comparisons were made between eastern sites (Galloo Island Lake, Chaumont Bay Lake, Sodus Lake, Sandy Pond Lake) and western sites (Niagara East Lake, Niagara West Lake, Oak Orchard Lake) using the biweekly data from May - October. We employed paired t-tests with untransformed (TP, SRP, Chl *a*, Secchi depth, water temperature, zooplankton size) and log ( $x+1$ ) transformed (zooplankton density and biomass) mean biweekly values to test for east-west differences. We considered each relationship significant for two-tailed tests at  $p<0.05$ .

East-west differences between offshore sites were examined for seven study parameters (TP, SRP, Chl *a*, water temperature, and zooplankton density, size, and biomass). Offshore sites included all samples taken from sites with water depths of at least 20m. The east-west dividing line was 77.8° W longitude (Figure 1). T-tests, assuming unequal variance, were used to determine the degree of difference of log-transformed (zooplankton density and biomass) and untransformed TP, SRP, Chl *a*, water temperature and zooplankton size data. Water chemistry and zooplankton comparisons were made with July data. Each relationship was considered significant for two-tailed tests at  $p<0.05$ .

##### *(3) Seasonal and Year-to-Year Variability in Embayment and Nearshore Habitats:*

We examined eight study parameters (TP, SRP, Chl *a*, Secchi depth, water temperature, and zooplankton density, size, and biomass) for

differences throughout the sampling season in both embayment and nearshore habitats. Year-to-year differences for TP, SRP, Chl *a*, Secchi depth, and water temperature were tested using a paired two sample t-test comparing 2004 and 2005 biweekly average data. We considered each relationship significant for two-tailed t-tests at  $p < 0.05$ .

*(4) Relationships of Variables:*

We investigated several nearshore and embayment biomonitoring parameters for potential relationships. We examined the influence of TP, SRP, and water temperature on Chl *a* using linear regression analysis (Zar 1984) with untransformed data.

*(5) Zooplankton Community Dynamics:*

We divided zooplankton into the following six groups: daphnids (*Daphnia mendotae*, *D. pulicaria*, *D. retrocurva*); bosminids (*Bosmina longirostris*, *Eubosmina coregoni*); calanoid copepods (*Diaptomus minutus*, *D. oregonensis*, *D. sicilis*, *D. ashlandi*, *Epischura lacustris*, *Eurytemora affinis*, *Limnocalanus macrurus*); cyclopoid copepods (*Acanthocyclops vernalis*, *Diacyclops thomasi*, *Mesocyclops edax*, *Tropocyclops prasinus*); "other" cladocera (*Ceriodaphnia quadrilangula*, *Chydorus sphaericus*, *Leptodora kindtii*, *Diaphanosoma sp.*, *Alona sp.*, *Holopedium gibberum*, *Polyphemus pediculus*, *Bythotrephes longimanus* [formerly *cederstroemi*], *Camptocercus sp.*); and *Cercopagis pengoi*. We compared average biweekly biomass proportions of each group between embayment and nearshore habitats using a paired t-test to determine differences in community composition between these areas. In addition, we compared the biomass of each group in July using t-tests assuming unequal variance on log (x+1) transformed data for embayment, nearshore, and offshore (water depth of 20m or more) areas.

*(6) Cercopagis pengoi:*

The offshore samples collected in July by the R/Vs Kaho and Seth Green provided a comprehensive view of spatial distributions of *C. pengoi* in 2005. For this time period, offshore (water depth of 20m or more) data were analyzed using t-tests assuming unequal

variance on log (x+1) transformed *C. pengoi* density and biomass to assess east-west differences in spatial distribution. In addition, log (x+1) transformed mean biweekly values of *C. pengoi* density and biomass were analyzed using paired t-tests to look for an east-west difference among nearshore sites. Comparisons of *C. pengoi* density, average size, and biomass in offshore, nearshore, and embayment habitats were performed using t-tests assuming unequal variance for the following pairs of sampling periods: August 1998 and August 1999, August 1999 and late July 2000, late July 2000 and August 2001, August 2001 and 2002, August 2002 and July 2003, July 2003 and mid-July to mid-August 2004, and mid-July to mid-August 2004 and July 2005. Finally, we compared average densities of bosminids in the summer sampling period over the nine years of this biomonitoring project (1995-2004) to further assess changes in community structure.

*(7) Bythotrephes longimanus:*

The offshore samples collected in September and October by the R/Vs Kaho and Seth Green provide a view of spatial distributions of *B. longimanus* in 2005. Because data collected during this time period was limited to the eastern half of Lake Ontario, July offshore (water depth of 20m or more) data were analyzed using t-tests assuming unequal variance on log (x+1) transformed *B. longimanus* density and biomass to assess east-west differences in spatial distribution. In addition, log (x+1) transformed mean biweekly *B. longimanus* density and biomass were analyzed using paired t-tests to look for an east-west difference among nearshore sites. We summarized *B. longimanus* density, average size, and biomass in embayments, nearshore, and offshore habitats over the years 1998-2005 to put data from this year in a historical context.

*(8) Erie/Ontario Nearshore Comparisons:*

In 2005 a site near Buffalo (in Lake Erie) was sampled nine times (May-October) to assess potential Lake Erie contributions to Lake Ontario via the Niagara River. Paired t-tests were performed on data collected from the Buffalo site and average nearshore data from Lake Ontario for the corresponding time period to assess potential differences. This analysis

was performed on six study parameters: Chl *a*, TP, SRP, and total zooplankton density, size, and biomass. Zooplankton density and biomass were log (x+1) transformed.

## **Results**

### QAQC

In 2005, QAQC analyses were conducted for July TP and SRP samples. A comparison of samples analyzed at CBFS with those analyzed at UFI, reported TP values were not found to be significantly different ( $p>0.7$ ). SRP samples did show a significant difference ( $p<0.004$ ). However, different analysis protocols and high sample variability among both labs prevented the use of this data for adjusting the regression equation.

The analysis of August embayment and nearshore TP, SRP, and Chl *a* triplicate samples yielded slightly more than half of the samples as having a coefficient of variation (CV) less than the predetermined acceptance level of 10%. Approximately 65% of the Chl *a* triplicate samples were found to have a CV greater than 10%. The triplicate samples which were found to have a CV greater than 10% were deemed acceptable due to: (1) the low levels of TP, SRP, and Chl *a* detected in Lake Ontario, and (2) the minimal range of resulting values and corresponding standard errors within a given set of triplicate samples. Consequently, we pooled triplicate samples for each August replicate sampling effort and reported an average value for each TP, SRP, and Chl *a*, concluding that a single sample adequately reflects the conditions at the time of sampling throughout the entire field season.

### Embayment-Nearshore-Offshore Comparisons:

In 2005 we observed several significant spatial differences between embayment, nearshore, and offshore habitats.

### *Embayment-Nearshore Comparisons of Secchi depth, Chl *a*, TP, SRP, and water temperature:*

In 2005, water clarity measured using a Secchi disc was consistently greater in nearshore areas than in embayment sites, as was the case in 2004 (Figure 2). The May through October biweekly average Secchi depth for embayments (3.4m)

was significantly shallower ( $p<0.0001$ ) than the nearshore habitat average of 6.7m (Figure 2). Mean biweekly SRP concentrations were not significantly higher ( $p>0.07$ ) in embayments than in nearshore habitats. However, the May through October embayment average (5.7 $\mu\text{g/L}$ ) was still slightly higher than the corresponding nearshore habitat average SRP (4.1 $\mu\text{g/L}$ ) (Figure 4A). TP values were found to be significantly higher ( $p<0.0004$ ) in embayments than in the nearshore habitats, with average May through October concentrations of 18.0 $\mu\text{g/L}$  and 7.9 $\mu\text{g/L}$  respectively (Figure 3B). Average embayment Chl *a* concentrations (8.6 $\mu\text{g/L}$ ) were approximately six times greater than in the nearshore habitats (1.4 $\mu\text{g/L}$ ) (Figure 3A). Water temperatures averaged 20.3°C in embayments and 17.7°C in nearshore habitats (Figure 4B).

### *Embayment-Nearshore-Offshore Comparisons of July Chl *a*, TP, SRP and water temperature:*

The average Chl *a*, TP, SRP, and water temperature of the embayment, nearshore, and offshore (collected by R/V Kaho) sites for July are noted in Table 1. The average Chl *a* concentration for both offshore and nearshore samples was 1.6 $\mu\text{g/L}$ , compared to 6.5 $\mu\text{g/L}$  in embayments. Average TP concentrations were 6.6 $\mu\text{g/L}$  (offshore), 6.8 $\mu\text{g/L}$  (nearshore), and 14.1 $\mu\text{g/L}$  (embayment). Offshore SRP averaged 3.1 $\mu\text{g/L}$ , compared to 3.2 $\mu\text{g/L}$  in the nearshore habitats, and 3.7 $\mu\text{g/L}$  in embayments. Water temperature for the offshore averaged 17.6°C while the nearshore average water temperature was 20.6°C, and the embayments averaged 24.3°C.

### *Zooplankton Embayment – Nearshore - Offshore Comparisons:*

In 2005, May through October zooplankton density ( $p<0.001$ ) and biomass ( $p<0.001$ ) were significantly greater in embayments (135.4/L and 159.9 $\mu\text{g/L}$ , respectively) than in nearshore sites (8.8/L and 17.6 $\mu\text{g/L}$  respectively) (Table 2, Figure 5A&C). Average size of zooplankton was significantly ( $p<0.02$ ) smaller in embayment sites (0.47mm) than in nearshore sites (0.58mm) (Table 2, Figure 5B).

During July, the average embayment zooplankton density (97.2/L), average size

(0.51mm), and biomass (130.5µg/L) were not significantly different than the density (4.0/L), average size (0.56mm) and biomass (7.8µg/L) of nearshore samples (Table 3). The average size of zooplankton in offshore samples (0.89mm) was significantly greater than the average size in nearshore samples ( $p<0.005$ ) and embayment samples ( $p<0.003$ ). Zooplankton density and biomass in offshore samples (6.4/L and 14.6µg/L, respectively) were significantly greater than density and biomass in nearshore samples (Table 3), but not significantly different than density and biomass in embayment samples (Table 3).

#### East - West Comparisons

In addition to examining spatial differences between habitats (embayment, nearshore, and offshore), we examined regional differences between the east and west sites of Lake Ontario.

*East-West Nearshore Comparisons of Secchi depth, Chl a, TP, SRP and water temperature:* East-West nearshore comparisons were made using biweekly data from May through October. Mean Secchi depth was found to differ significantly ( $p<0.003$ ) between eastern and western sampling sites in 2005 (Figure 6D). Western nearshore Secchi depths averaged 5.6m, while eastern nearshore Secchi depths averaged 7.6m (Figure 6D). No significant difference ( $p>0.5$ ) was found between eastern and western nearshore temperatures in 2005 with average values of 18.3 °C in the eastern nearshore, and 17.3 °C in the western nearshore. There were also no significant differences observed in Chl a, TP, SRP between eastern and western sites (Figures 6A-6C). This pattern is similar to that seen in 2004 (Table 4). The average Chl a concentration was 1.4 µg/L in both the eastern and western nearshore sites. Average TP concentrations were 8.0µg/L in the east and 7.8µg/L in the west. Eastern nearshore SRP concentrations averaged 4.5µg/L and western sites averaged 3.7 µg/L.

*East-West, North-South Offshore Comparisons of Chl a, TP, SRP, and water temperature:*

The comparisons of the offshore biomonitoring study parameters from north to south and east to west yielded no significant differences.

*East-West Nearshore Zooplankton Comparisons:* No significant differences were found between eastern and western Lake Ontario for average size, density, and biomass of zooplankton, or for the density and biomass of *Cercopagis pengoi* or *Bythotrephes longimanus* (Table 5, Figures 6E and 6F).

*East-West Offshore Zooplankton Comparisons:*

In the July east-west comparison for offshore sampling stations, there was no significant difference in zooplankton density, average size, or biomass between east and west (Table 6). Mean density was generally greater in the west than the east, and average size and zooplankton biomass were generally greater in the east, although these differences were statistically insignificant (Table 6). *Cercopagis pengoi* density was significantly greater at eastern sites ( $p<0.04$ ) (Table 6, Figure 8A). *C. pengoi* biomass and density showed a trend toward greater values in the east, but this difference was not significant (Table 6, Figures 7A, 8A and 9A). There was no significant difference in *B. longimanus* density or biomass between eastern and western samples in July (Table 6, Figures 7B, 8B and 9B).

#### Seasonal and Year-to-Year Variability in Embayment, Nearshore and Offshore Habitats

In 2005, we observed seasonal differences in Secchi depth, Chl a, TP, SRP, water temperature, and all three zooplankton parameters in embayment, nearshore and offshore habitats.

*Secchi depth, Chl a, TP, SRP, and water temperature:* Water clarity of nearshore habitats in 2005 was generally consistent from May through October, but we did see a decreased average (5.7m) in July (Figure 2). The sharpest decrease in clarity came in Sandy Pond Lake, which went from a maximum depth of 7.6m in late June to a minimum of 1.5m by early July. Lakewide nearshore Secchi depths ranged from a maximum of 14.1m (late May, Oak Orchard Lake) to a minimum of 1.2m (mid-October, Oak Orchard Lake). Embayment Secchi depths were shallowest in September and deepest in July (Figure 2). Embayment Secchi depths ranged from 0.8m (Sandy Pond Bay, mid-August thru

mid September) to 5.5m (Chaumont Bay, late May, mid-June thru early August).

Chl *a* concentrations were higher in embayments than in nearshore areas, exhibiting an increasing trend from May to September, then decreasing slightly in October (Figure 3A). Nearshore concentrations increased slightly through May and June and then remained constant throughout the remaining sampling season (Figure 3A). Both embayment and nearshore mean Chl *a* concentrations peaked in September at 16.9µg/L, and 1.9µg/L respectively. Embayment Chl *a* concentrations varied from 0.4µg/L in Chaumont Bay (mid-May) to 51.3µg/L in Sandy Pond Bay (mid-August). Nearshore Chl *a* ranged from less than 0.2µg/L (Sodus Bay Lake, early May) to more than 3.1µg/L (Chaumont Bay Lake, early July). Offshore Chl *a* averaged 1.5µg/L (Figure 3A), ranging from 0.6µg/L to 3.2µg/L.

TP concentrations were higher in embayments than nearshore habitats, similar to 2004 (Figure 3B). Monthly average embayment TP concentrations increased from May to September, while nearshore TP concentrations remained relatively constant during the same period. In October, embayment TP concentrations decreased substantially from the September peak, but the nearshore values remained relatively unchanged. Average embayment TP values peaked in September at 28.5µg/L and nearshore concentrations reached 9.6µg/L in October. Embayment TP ranged from 4.4µg/L at Chaumont Bay Lake (late May) to 39.9µg/L at Sandy Pond Bay (mid-September). Nearshore TP ranged from 5.9µg/L at Oak Orchard Lake and Niagara River East (late May and mid-July respectively) to 15.3µg/L at Sodus Bay Lake (mid-October). The average offshore TP concentration was 6.9µg/L (Figure 3B), ranging from 5.3µg/L to 9.0µg/L.

Mean monthly embayment and nearshore SRP concentrations exhibited a relatively similar monthly pattern throughout 2005 (Figure 4A). Nearshore SRP concentrations had a minimum of 2.1µg/L at Niagara River West (early June) and a maximum of 13.2µg/L at Sodus Bay Lake

(mid-October). Embayment SRP ranged from 2.4µg/L at Sandy Pond Bay (early June) to 16.5µg/L (mid-October) at Sodus Bay. In embayment sites monthly SRP concentrations peaked mid-season, with the embayment maximum reaching 8.0µg/L in August. Both nearshore and offshore sites reached maximum average concentrations in October (8.2µg/L and 4.4µg/L, respectively) (Figure 4A).

Water temperatures for both embayment and nearshore habitats exhibited a similar seasonal pattern: warming into August, and cooling into fall (Figure 4B). Monthly average temperatures peaked during August at 24.3°C (embayments) and 23.5°C (nearshore). Embayment temperatures ranged from a minimum of 12.0°C in early May at Sodus Bay to a maximum of 25.3°C in late July in Chaumont Bay. Nearshore temperatures ranged from 6.2°C in late May at Oak Orchard Lake to 24.6°C at Sodus Bay Lake during early August. Offshore temperatures exhibited a similar seasonal trend as that seen in the embayments and offshore, but continued to warm later in the year, reaching a peak monthly average in September of 20.0°C (October offshore data unavailable) (Figure 4B).

We also compared 2004 and 2005 annual means derived from biweekly data (secchi depth, Chl *a*, TP, SRP, and water temperature) in both embayment and nearshore habitats (Figure 2, 3&4). Secchi depth did not differ significantly in either embayment or nearshore comparisons. Embayment biweekly Secchi values averaged 3.9m in 2004 compared to 3.4m in 2005 ( $p>0.22$ ). Nearshore Secchi values averaged 6.4m in 2004 and 6.7m in 2005 ( $p>0.59$ ).

Chl *a* concentrations were also not found to be significantly different between 2004 and 2005 for either embayment or nearshore sites ( $p>0.5$ ,  $p>0.17$  respectively). Average embayment Chl *a* in 2005 was 8.6µg/L, compared to its 2004 value of 7.9µg/L. Nearshore biweekly Chl *a* concentrations were 1.9µg/L in 2004 and 1.4µg/L in 2005.

Total phosphorous concentrations in embayments in 2005 were slightly lower (18.0µg/L) than in 2004 (18.5µg/L) (Figure 3B).

The nearshore TP values were also lower in 2005 (7.9µg/L) than in 2004 (9.1µg/L). These annual TP differences, both in embayment and nearshore comparisons, were insignificant ( $p>0.7$  and  $p>0.19$ , respectively).

Embayment and nearshore SRP concentrations were both found to be significantly higher in 2005 compared to 2004 (Figure 4A). The embayment SRP mean in 2005 was 5.7µg/L compared to 3.8µg/L in 2004 ( $p<0.04$ ). The nearshore SRP mean was 4.1µg/L in 2005, compared to a 2004 mean of 2.7µg/L ( $p>0.03$ ).

Water temperatures were found to differ significantly between 2004 and 2005 in the nearshore habitats ( $p<0.002$ ), but not in the embayments ( $p>0.13$ ) (Figure 4B). The biweekly embayment temperature average was insignificantly lower in 2005 (17.7°C) than in 2004 (19.2 °C). The biweekly nearshore average temperature in 2005 (20.3°C) was significantly higher than in 2004 (17.1 °C).

*Zooplankton:* Zooplankton densities were highest in embayments during the entire 2005 sampling season, peaking in early September (Figure 5A). The lowest zooplankton densities occurred at offshore sites in May. For individual dates and habitats, the lowest nearshore zooplankton density was 0.29/L at the Oak Orchard (OOL) site in early May and the lowest embayment density was 0.94/L at Chaumont Bay (CBB) in early July. The highest densities were 57.8/L at Sodus Lake (SOL) in mid-June and 722.3/L at Sandy Pond Bay in early September. At offshore sites, the lowest density was seen in mid-October (0.57/L) and the highest was observed in early September (41.6/L).

Zooplankton average size at embayment sites was highest in late May (0.59mm) and lowest in mid-October (0.36mm) (Figure 5B). At nearshore sites, average size was highest in mid-May (0.77mm) and lowest in early June (0.45mm). Offshore mean zooplankton size was highest in late July (0.99mm) and lowest in late September (0.57mm) (Figure 5B). Figure 10 shows mean monthly zooplankton size for each habitat in 2004 and 2005. Offshore average size

was greater than both embayment and nearshore average size for each time period data were available, with the exception of nearshore habitats in September 2005. Whereas offshore average size declined rather steadily over the 2004 sampling season, in 2005 it remained high through August before rapidly dropping near 0.6mm in September and October. Embayment and nearshore seasonal trends in zooplankton lengths in 2005 were generally similar to the trends in 2004. (Figure 10).

Mean zooplankton biomass from May through October was highest at the embayment sites in late May (376.0µg/L) (Figure 5C). The lowest mean biomass occurred at the nearshore sites in late May (0.9µg/L). Mean biomass of the zooplankton community in embayment areas remained greater than in nearshore and offshore habitats during the entire sampling season. The maximum zooplankton biomass at a single site on a sampling date in embayment and nearshore habitats was 708.6µg/L in late May at Sandy Pond Bay, and 100.1µg/L in mid-September at Niagara River West Lake. The minimum biomass at an individual site on a single date for embayments was 2.8µg/L at Chaumont Bay in early July, while it was 0.6µg/L for nearshore sites at Sodus Lake in late May. Offshore mean biomass values were generally similar to nearshore values, with nearshore values slightly larger in early July and mid-September (Figure 5C).

#### Relationships Among Variables

We examined the relationships of TP, water temperature, and SRP with Chl *a* using a linear regression analysis of biweekly data for embayment and nearshore sites (Figure 11). The 2005 biweekly water temperature-Chl *a* relationship, TP-Chl *a* relationship, and SRP-Chl *a* relationship were all found to be positively correlated in both embayment and nearshore habitats. When Chl *a* was regressed against water temperature, temperature explained 21% of the variability in embayment Chl *a* (insignificant at  $p>0.13$ ), and 38% of the variability in nearshore habitats (significant at  $p<0.04$ ) (Figure 11A). When Chl *a* was regressed against TP, we found that TP significantly explained ( $p<0.002$ ) 67% of the

Chl *a* variability in embayments, and insignificantly ( $p>0.28$ ) explained 11% of Chl *a* variability in nearshore areas (Figure 11B). The regression of SRP against Chl *a* insignificantly explained 13% of the variability in embayment Chl *a* ( $p>0.25$ ). The regression of nearshore Chl *a* against SRP insignificantly explained 13% of the variability of Chl *a* ( $p>0.24$ ) (Figure 11C).

#### Zooplankton Community Dynamics

*Embayment - Nearshore:* In 2005, two zooplankton taxa significantly differed in proportion of their total biomass between embayments and nearshore sites (Table 2). Bosminids had a significantly greater proportion of biomass in embayments ( $p<0.05$ ), while calanoid copepods had a significantly greater proportion in nearshore habitats ( $p<0.02$ ). The proportion of *C. pengoi* biomass was on average greater in the nearshore sites (0.06) than embayment sites (0.012), but the difference was not statistically significant (Table 2). The proportion of *B. longimanus* biomass was on average greater in the nearshore sites (0.019) than embayment sites (0.001), but the difference was not statistically significant (Table 2).

The bosminid proportion of total biomass in nearshore habitats peaked in mid-July (Figure 12A). Bosminid proportion of biomass in embayments fluctuated between 0.06 and 0.18 during the first half of the sampling season, then increased beginning in August, reaching a high of 0.63 in late September. Daphnids peaked in percent biomass in mid-August in the nearshore and in mid-June for embayment sites, with a secondary peak in late August (Figure 12B). Calanoid copepod contribution to total zooplankton biomass dropped from a high of 0.59 in mid-May to a low of 0.11 in late July, then increased to approximately one third of total zooplankton biomass for September and October (Figure 12C). Cyclopoid copepod proportions were greatest in nearshore habitats during late May of 2005, and in embayments during mid-May, composing 51 and 83 percent of total zooplankton biomass during those periods, respectively. Cyclopoid proportion of biomass reached a low for nearshore sites in early August, and a low for embayments in late August (Figure 12D). *Cercopagis pengoi* was rare in the first three and last four sampling

weeks, but peaked in nearshore sites in early July, reaching 43 percent of total zooplankton biomass. *C. pengoi* percentage of total biomass peaked in late July in embayments, reaching 0.24 (Figure 12E). Nearshore *Bythotrephes longimanus* were detected at very low levels through the summer before peaking twice in the fall at proportions of total zooplankton biomass of 0.14 in early September and 0.23 in early October. *B. longimanus* did not contribute a proportion of zooplankton biomass of over 0.03 in embayments during 2005 (Figure 12F). “Other” cladocera were small contributors to total zooplankton biomass during the first three sampling weeks of the season. Other cladocera proportion of total biomass then peaked in nearshore sites at 0.27 in late August, while embayment proportion peaked at 0.23 in early July (Figure 12G).

*Offshore:* Calanoid and cyclopoid copepods dominated the offshore community during May and June 2005. In early July, *Cercopagis pengoi* was the largest single contributor to zooplankton biomass, with a proportion of total biomass of 0.41, while calanoid copepods had a proportion of total biomass of 0.32. “Other” cladocerans had the largest proportions of total zooplankton biomass in late July and October (0.43 and 0.45, respectively). Calanoid copepods contributed the largest proportion (0.38) of zooplankton biomass in early August, while daphnids contributed the most to biomass in late August and September (0.35 and 0.31, respectively). Other important contributors to offshore biomass were bosminids during early and mid-September, with proportions of total biomass of 0.30 and 0.28, respectively. Of these species, all except *B. longirostris* contributed to an overall large offshore zooplankton average size. In offshore habitats, the dominant cyclopoid copepod *D. thomasi* annual average size was 0.72mm, *D. retrocurva* annual average size was 0.69mm, *H. gibberum* annual average size was 0.55mm, and calanoid copepod annual average size was 0.94mm. Other less frequently detected species that contributed to large zooplankton average size when present in offshore habitats were *C. pengoi*, *B. longimanus*, and *L. kindti*.

*Embayment - Nearshore - Offshore:* In July there were two notable differences between

components of the zooplankton community in the three different habitats (Table 3). Calanoid copepod biomass values at offshore sites (8.9µg/L) were significantly higher than calanoid nearshore biomass (1.6µg/L) ( $p<0.0167$ ) (Table 3, Figure 13). “Other” cladocera biomass was also significantly higher at offshore sites (7.2µg/L) than nearshore sites (0.7µg/L) ( $p<0.0167$ ) (Table 3). *B. longimanus* was present in offshore habitats, but not detected in the nearshore or embayments during July (Table 3).

#### *Cercopagis pengoi*

Offshore and nearshore biomass and density of *C. pengoi* in July are presented in Figures 7A and 8A, respectively. During July 2005, average densities of *C. pengoi* at offshore, nearshore, and embayment sites were 0.26/L, 0.18/L, and 0.20/L, respectively (Figure 14A). There were no statistically detectable differences in east-west nearshore data during the entire sampling season for *C. pengoi* density or biomass (Table 5). No statistically detectable differences in the offshore east-west comparisons of *C. pengoi* average size or biomass were found. Offshore *C. pengoi* density, however, was significantly greater ( $p<0.04$ ) in the east (0.36/L) than the west (0.09/L) during July 2005 (Table 6).

Longitude did not explain an appreciable amount of the variation in *C. pengoi* distribution in Lake Ontario during July 2005 (Figure 9A).

Statistical differences were detected in *C. pengoi* density, average size, and biomass when offshore samples from July 1999 and August, 2000 were compared (Table 7). *C. pengoi* density, average size, and biomass in offshore habitats during late July 2000 were all significantly lower ( $p<0.005$ , 0.005 and 0.00005, respectively) than in offshore habitats in August 1999 (Table 7). However, *C. pengoi* density, average size, and biomass significantly increased again in offshore habitats in August 2001 (all  $p<0.05$ ) (Table 7). In July 2003 offshore *Cercopagis* samples, significant decreases were found in density ( $p<0.02$ ), average size ( $p<0.001$ ), and biomass ( $p<0.02$ ) when compared to August 2002 data (Table 7). Statistical differences were detected in all three

offshore *C. pengoi* parameters between July 2003 and mid-July to mid-August 2004. Mean density, average size, and biomass each increased ( $p<0.002$ ,  $p<0.0002$ , and  $p<0.0006$ , respectively) (Table 7). No significant changes occurred in *C. pengoi* density, average size, or biomass between any pair of consecutive years sampled at either nearshore or embayment habitats between 1999 and 2004. When mid-July to mid-August 2004 and July 2005 nearshore samples were compared, *C. pengoi* density was significantly greater in 2004 ( $p<0.04$ ), whereas average size was significantly greater in 2005 ( $p<0.02$ ). No significant changes occurred in offshore *C. pengoi* density, average size, or biomass between mid-July to mid-August 2004 and July 2005 (Table 7).

Trends in the mean densities of bosminids during the July/August offshore sampling efforts over the past eleven years of this biomonitoring project were examined to determine if the arrival of *C. pengoi* in Lake Ontario was associated with a change in zooplankton community structure. After more than a 20-fold increase in bosminid density from 1995 to 1996 and 1997, values plummeted in 1998 when *C. pengoi* first arrived (Figure 15). Even though the density remained low in 1999, it increased to almost 19 bosminids per liter in 2000 as *C. pengoi* densities simultaneously decreased. However, in 2001 bosminid density once again declined dramatically to six bosminids per liter, and appeared to be associated with an increase of offshore *C. pengoi* density. *C. pengoi* offshore density increased from 0.53/L in 2001 to 0.64/L in 2002 (Table 7) and was associated with a decline in offshore bosminid density to 1.6/L, again suggesting a relationship with increased *C. pengoi* density (Figure 15). July of 2003 saw offshore bosminid densities increase to 6.7/L while *C. pengoi* offshore density (0.05/L) was considerably lower than in August 2002 (0.64/L). During mid-July to mid-August 2004, offshore bosminid density decreased to 3.2/L and *C. pengoi* densities increased to 0.37/L. In July 2005, bosminid density again decreased to 0.62/L while *C. pengoi* density also decreased to 0.26/L (Table 7, Figure 15).

*Bythotrephes longimanus*

*B. longimanus* was detected in 34 out of 145 samples throughout the 2005 season. In offshore habitats, *B. longimanus* was detected in 11 samples between June and October. The average size of *B. longimanus* in offshore samples was 2.10mm (Table 8). The maximum biomass of *B. longimanus* from a single offshore sample was 7.8µg/L at Smokey Point on October 20. In nearshore habitats, *B. longimanus* was detected in 18 samples from May through October. The average size of *B. longimanus* in nearshore samples was 2.06mm (Table 8). The maximum biomass of *B. longimanus* from a single nearshore sample was 4.7µg/L at Sandy Pond on September 6. In embayments, *B. longimanus* was detected in five samples in September and October. The average size of *B. longimanus* in embayment samples was 2.22mm (Table 8). The maximum biomass of *B. longimanus* from a single embayment sample was 2.9µg/L at Chaumont Bay on September 1.

Offshore and nearshore biomass and density of *B. longimanus* in July are presented in Figures 7B and 8B, respectively. During September-October 2005, average densities of *B. longimanus* at offshore, nearshore, and embayment sites were 0.023/L, 0.006/L, and 0.008/L, respectively (Figure 14B). There were no statistically detectable differences in east-west nearshore data during the entire sampling season for *B. longimanus* density or biomass (Table 5). No statistically detectable differences in the offshore east-west comparisons of *B. longimanus* average size and biomass were found during July 2005 (Table 6).

Longitude did not explain an appreciable amount of the variation in *B. longimanus* distribution in Lake Ontario during September-October 2005 (Figure 9B).

Erie - Ontario Nearshore Comparisons

The comparison of Lake Erie (at Buffalo) and Lake Ontario nearshore data yielded no significant differences in Chl *a*, TP, SRP, zooplankton density or average size. Zooplankton biomass at the Buffalo site was

found to be significantly greater ( $p<0.05$ ) than nearshore Lake Ontario biomass.

**Significant Research Findings**

Embayment-Nearshore-Offshore Comparisons

In 2005, embayments continued to be very productive habitats in comparison to nearshore and offshore areas of Lake Ontario. In embayments, TP concentrations from May to October were slightly more than 2.0 times higher than those in nearshore habitats, and almost 2.5 times higher than concentrations at the offshore sites (Figure 3B). No TP concentrations at offshore sites in 2005 were found to exceed the target value (10µg/L) set for the offshore pelagia by the Great Lakes Water Quality Agreement (GLWQA).

Chl *a* concentrations (May through October, 2005) for embayments were 5.9 times greater than for nearshore habitats (Figure 3A). Embayment Chl *a* was also 5.4 times greater than the offshore Chl *a* during the same time period.

May through October 2005 SRP concentrations for embayments were almost 1.2 times higher than for nearshore habitats. Embayment SRP concentrations were also 1.5 times higher than offshore SRP (Figure 4A).

Annual Secchi depths were found to be 1.8 times deeper at nearshore sites than embayments, corresponding with the elevated Chl *a* concentrations of embayment habitats.

In 2005, embayment sites had over 15 times the zooplankton density and nine times the biomass of nearshore sites, and only a moderately lower average zooplankton size than nearshore sites (Table 2). For July 2005, embayment density was over 24 times greater than nearshore density and over 15 times greater than offshore density. Embayment biomass was over 16 times greater than nearshore biomass, and over five times the offshore biomass. Embayment average size was similar to nearshore average size, but was significantly smaller than offshore average size (Table 3).

### East-West / North-South Comparisons

The east-west comparisons of bi-weekly study variables for nearshore sites yielded a significantly greater ( $p < 0.006$ ) Secchi depth (1.4 times greater) in the eastern half of Lake Ontario. This is attributed to the seasonal means of 8.6m for Galoo Island Lake and 7.9m Sodus Lake in the east, which were both at least 1.5 times greater than any of the western nearshore stations (Figure 6D).

For the east-west comparison of nearshore data including total zooplankton density, average size, biomass, and *C. pengoi* and *B. longimanus* density and biomass, no significant differences were found (Table 5). In the comparison of east-west offshore samples, the only difference found was significantly greater *C. pengoi* density in eastern samples (Table 6).

### Sodus Bay – Sandy Pond Bay

As in 2004, Sodus Bay and Sandy Pond Bay were found to be the most productive sites in 2005 (Figure 6A-C, 6E-F). Seasonal Chl *a* averages of 6.0µg/L (Sodus Bay) and 20.1µg/L (Sandy Pond) and zooplankton biomasses of 190.7µg/L (Sodus Bay) and 237.9µg/L (Sandy Pond) exceeded all other sites. The seasonal mean Secchi depths found at Sodus Bay (3.1m) and Sandy Pond Bay (2.0m) were the shallowest of all sampled habitats (Figure 6D) and corresponded with the elevated Chl *a* values.

### Seasonal Variability in Embayment and Nearshore Habitats

Several water quality parameters exhibited seasonal trends. Mean monthly Chl *a* and TP concentrations in embayments steadily increased through the sampling season, peaking in late August - early September, and then decreasing sharply by mid-October (Figure 3A & B). Nearshore Chl *a* and TP remained fairly constant throughout the 2005 season. Embayment SRP peaked in late August and decreased slightly through October. Nearshore SRP concentrations steadily increased through the year and reached their peak in October (Figure 4A).

For zooplankton, embayments had the highest biomass and density for the entire May through October season, with biomass peaking in late

May and density peaking in early September. For nearshore sites, density peaked in early June and biomass peaked in mid-September. Offshore density and biomass peaked in late August (Figure 5A & C). Zooplankton average size was smallest in embayments throughout the season except for in late May and early June, when nearshore average size was slightly smaller (Figure 5B). Offshore average size was greater than both nearshore and embayment habitats whenever it was available (mid-May, early June, July, early August, mid-September, and mid-October), except for mid-September, when nearshore average size was slightly larger (Figure 5B). The average size of crustacean zooplankton peaked in mid-July for offshore habitats, in mid-May for nearshore habitats, and in late May for embayment sites (Figure 5B).

### Zooplankton Community Dynamics

In 2005, daphnids were the largest contributors to biomass in nearshore habitats, with calanoid copepods and cyclopoid copepods contributing nearly equal biomasses. In embayments, bosminids and cyclopoid copepods each comprised one third of total biomass. The only significant difference in community composition between nearshore habitats and embayments in 2005 was greater calanoid copepod biomass in the nearshore (Table 2). Cyclopoid copepods were prominent at both embayment and nearshore habitats, especially in the early season (Figure 12D). Although July 2004 offshore cyclopoid copepod biomass was higher than the biomass of any other offshore taxa, calanoid copepods and “other” cladocerans were the largest contributors to offshore biomass in July 2005 (Table 3).

Zooplankton average size in embayment habitats was low (0.3-0.6mm) from spring through fall due to high densities of Bosminids and other small cladocerans, such as *Chydorus sphaericus* and *Ceriodaphnia quadrangula*. Cyclopoid copepods were an important contributor to embayment biomass, but cyclopoid average size in embayments was 0.52mm, as compared to 0.69mm in offshore habitats. Similar conditions existed in nearshore habitats, with cyclopoid copepods averaging 0.53mm in length. Offshore habitats had consistently large zooplankton average sizes due to an abundance of large

calanoid copepods, cyclopoid copepods, and daphnids from the spring through fall, as well as large seasonal biomass contributions from *H. gibberum*. *C. pengoi*, *B. longimanus*, and *L. kindti* were detected less frequently, but also increased offshore zooplankton average size when present.

#### *Cercopagis pengoi*

In 2005, *C. pengoi* was first observed in mid-May in nearshore samples, in early June in offshore samples, and in mid-June in embayment samples. *C. pengoi* proportion of biomass peaked in early July in nearshore sites, and in mid-July in embayments (Figure 12E). The highest biomass observed in Lake Ontario was 8.2 µg/L at the Sandy Pond nearshore site in early August. No spatial differences in biomass or density were found between east-west nearshore comparisons (Table 5). *C. pengoi* density was significantly higher in eastern offshore samples (0.36/L) than western offshore samples (0.09/L) (Table 6). *C. pengoi* densities in the eastern and western basins of Lake Ontario were similar; longitude did not account for any east-west difference in density. Figures 13 and 14 reflect comparisons of *C. pengoi* biomass and density for the month of July. *C. pengoi* was greatest in biomass and density at offshore sites, similar to the pattern seen prior to 2004 (Figures 13 and 14).

*C. pengoi* was detected in 57.1% of all the samples in May through October in 2005, an increase from the detection rates of 45.3% in 2004, 31.8% in 2003, 31.6% in 2002, and 50.0% in 2001, yet lower than the rate of 62.3% of the samples in 2000. Since its appearance in 1998, *C. pengoi* density has appeared to be inversely related to bosminid density, although 2005 data did not support the relationship (Table 7, Figure 15). One possible explanation why 2005 had such low bosminid density at the same time as relatively low *C. pengoi* density is the large population of *Bythotrephes longimanus* detected in 2005. *B. longimanus* likely fed on *C. pengoi* as well as *B. longirostris*, suppressing populations of both species.

#### *Bythotrephes longimanus*

In 2005, *B. longimanus* was detected in all three habitats, in samples ranging from May through October. *B. longimanus* was first observed in mid-May in nearshore samples, in early June in offshore samples, and in early September in embayments. *B. longimanus* proportion of biomass peaked in early October in nearshore habitats, accounting for a maximum of 22.6% of total zooplankton biomass. In embayments, *B. longimanus* contributed a maximum of 2.4% of total zooplankton biomass in late September (Figure 12F). The highest biomass observed in Lake Ontario was 7.84 µg/L at the Smokey Point offshore site in mid-October. No spatial differences in biomass or density were found between east-west nearshore or offshore comparisons (Table 5, Table 6). *B. longimanus* biomass (July) and density (September and October) were highest at offshore sites (Figure 13, Figure 14).

*B. longimanus* was observed in 2005 at the highest May-October density and biomass since it was first detected by this study in 1998 (Table 8). *B. longimanus* was detected in 34 out of 145 (23.4%) samples in 2005 after being detected in only three samples in 2004 and no samples in 2003. *B. longimanus* appears to be present in densities sufficient to suppress *Cercopagis pengoi* populations in Lake Ontario.

#### Linkages between Lake Ontario Zooplankton and Alewife Populations.

Lake managers recognize the importance of ecological indicators, especially their utility in assessing management and restoration efforts. Zooplankton are positioned in the food chain of freshwater lakes to reflect ecological balance between algae and fish. In fact, mean zooplankton length can be used as an indicator of the balance between plankton eating fish and fish predators (Mills and Schiavone 1982). A common symptom of degraded ecosystems is distortion of the expected relationship between the biomass of organisms and body size. The virtual absence of large-bodied zooplankton like *Daphnia* in freshwater lakes in response to intense planktivory by fish, for example, is a deviation from an expected size distribution. In lakes with a diverse population of quality-sized

piscivores that are sufficient in number to control populations of small plankton-eating fish, larger-bodied zooplankton are usually abundant. In lakes where plankton eating fish exhibit slow growth and larger planktivores are scarce, the density of predators is most likely low. Under conditions where predation is successfully controlling planktivore density, mean body lengths of crustacean zooplankton are greater than 0.8-1.0 mm. The dominance of small crustacean zooplankton, on the other hand, points to the absence of sufficient number of predators to suppress planktivore density.

Alewife (*Alosa pseudoharengus*) is the dominant planktivore in Lake Ontario. Intense planktivory by these fish has historically structured the zooplankton community toward small species like *Bosmina*. Zooplankton are the principal food of juvenile and adult alewife and these fish can account for more than 96% of predation on zooplankton (Rand et al. 1995). Alewife abundance declined 42% from the early 1980s to the early 1990s (O’Gorman et al. 2000), and changes in the zooplankton community were observed in response to this decline. Among the more significant changes during this period were a shift to larger zooplankton species and increased abundance of summer cyclopoid copepods.

In Lake Ontario, the impact of planktivory by alewife may be greater at one time of the year than another. For instance, adult alewife in this large lake migrate inshore in the springtime and return to the offshore through July. Consequently, one would expect that the impact on offshore zooplankton by adult alewife would be highest in epilimnetic waters sometime mid-summer through early fall. For the period mid-July through mid-September 2005, we found that offshore mean zooplankton size was 0.82mm, suggesting that piscivores are either in balance with their alewife prey or are greatly suppressing populations of adult alewife. This represents an increase from an average size of 0.74mm in 2004. In 2005, populations of adult and juvenile alewife were not sufficiently abundant to suppress larger sized zooplankton species like *Cercopagis pengoi*, *B. longimanus*, *D. retrocurva*, *D. thomasi*, *H. gibberum*, *L. macrurus*, and *E. lacustris*. Like the period from

the early 1980s to the early 1990s when alewife densities were declining, offshore cyclopoid copepod biomass in Lake Ontario in 2005 was higher than any other offshore taxa. Finally, lakes with large populations of alewife typically have zooplankton that are very small (0.3 to 0.4 mm, CBFS unpublished data), whereas offshore crustacean zooplankton in Lake Ontario during mid summer to early fall were considerably larger, averaging 0.82mm in length.

The relationship between zooplankton average size and alewife abundance is complicated by the presence of the predatory exotic zooplankters, *Cercopagis pengoi* and *Bythotrephes longimanus*. *C. pengoi* possesses a tail spine several times its body length, preventing young-of-the-year planktivores from preying upon it until their gape is large enough to accommodate the spine (Bushnoe et al. 2003). In Lake Ontario, *Cercopagis* abundance is inversely related to bosminid density so declines in *Bosmina* could contribute to a shift in the mean size of zooplankton toward larger organisms. However, *C. pengoi* is a moderately large sized cladoceran and adult alewife are known to feed on this organism. *C. pengoi* was present in 57% of Lake Ontario zooplankton samples collected in 2005. Consequently, the high occurrence rate of *C. pengoi* observed in Lake Ontario samples in 2005 provides some additional evidence that adult alewife numbers were likely low and were not sufficiently abundant to suppress *Cercopagis* abundance.

The exotic predatory macrozooplankton *Bythotrephes longimanus* is a large spiny zooplankton that was observed in Lake Ontario from May through October 2005. *B. longimanus* was not detected in Lake Ontario in 2003, and was detected in only three samples in 2004. *Bythotrephes* has been shown to be a preferred food item for alewives in the Great Lakes (Pothoven 2004), so the emergence of *Bythotrephes* in 2005 provides one more line of evidence that adult alewife abundance is currently suppressed in Lake Ontario. *Bythotrephes* is likely suppressing populations of *C. pengoi* as well, so the existence of a robust *Bythotrephes* population makes an even more compelling line of evidence for reduced numbers of alewife in Lake Ontario.

Given the dependence of Lake Ontario adult alewife on microzooplankton for food, and that high mean body size of zooplankton is inversely related to alewife abundance, we conclude that current densities of adult alewife in Lake Ontario are low. The supportive evidence for this conclusion is based on the facts that 1) a high mean body size of offshore crustacean zooplankton (0.82 mm) in mid summer to early fall, 2) the observance of the large cladoceran *C. pengoi* in 57% of all samples collected in Lake Ontario in 2005 April through mid-October, and 3) the emergence of the predatory macrozooplankton *B. longimanus* throughout 2005.

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