Assessment of the phytoplankton and zooplankton populations in the Niagara River (Canada) Area of Concern in 2014

R.M. Rozon, K.L. Bowen, H.A. Niblock, M.A.J. Fitzpatrick and W.J.S. Currie

Great Lakes Laboratory for Fisheries and Aquatic Sciences
Central and Arctic Region, Fisheries and Oceans Canada
867 Lakeshore Road
Burlington, ON
L7S 1A1

2016

Canadian Technical Report of
Fisheries and Aquatic Sciences 3184

Fisheries and Oceans Canada | Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3184

2016

Assessment of the phytoplankton and zooplankton populations in the Niagara River (Canada) Area of Concern in 2014

by

R.M. Rozon, K.L. Bowen, H.A. Niblock, M.A.J. Fitzpatrick and W.J.S. Currie

Great Lakes Laboratory for Fisheries and Aquatic Sciences,
Central and Arctic Region, Fisheries and Oceans Canada,
867 Lakeshore Road, Burlington, ON, L7S 1A1

Cat. No. Fs97-6/3184-PDF ISBN 978-0-660-06792-6 ISSN 1488-5379

Correct citation for this publication:

R.M. Rozon, K.L. Bowen, H.A. Niblock, M.A.J. Fitzpatrick and W.J.S. Currie. 2016. Assessment of the Phytoplankton and Zooplankton Populations in the Niagara River (Canada) Area of Concern in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3184: iv + 66p.

TABLE OF CONTENTS

ABSTRACT

R.M. Rozon, K.L. Bowen, H.A. Niblock, M.A.J. Fitzpatrick and W.J.S. Currie. 2016. Assessment of the Phytoplankton and Zooplankton Populations in the Niagara River (Canada) Area of Concern in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3184: iv + 66p.

This report collects all available plankton community data for the Niagara River Area of Concern (AOC) designated *requires further assessment* for the Beneficial Use Impairment (BUI 13): “degradation of phytoplankton and zooplankton populations”. The Niagara River connecting channel, though it joins well-studied Lake Erie and Lake Ontario is data-poor, with no active plankton sampling programs. A single season of sampling in 2014 took place monthly from June-Oct for water quality, zooplankton and phytoplankton composition and density. Oligotrophic conditions persisted throughout the season and plankton densities were extremely low, though this was expected in a high-flow system such as the Niagara River. The residence time for plankton in the Niagara River is only 11-28 hours, but could be much longer if plankton are entrained in the hydroelectric reservoirs. Given the results of this survey, no impairment of plankton populations is indicated.

RÉSUMÉ

R.M. Rozon, K.L. Bowen, H.A. Niblock, M.A.J. Fitzpatrick and W.J.S. Currie. 2016. Évaluation du phytoplancton et du zooplancton Populations secteur préoccupant de la rivière Niagara (Canada) en 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3184: iv + 66p.

Ce rapport rassemble toutes les communautés planctoniques de données disponibles pour le secteur préoccupant Niagara River (SP) désignée comme exigeant une évaluation plus approfondie d’utilisations bénéfiques altérées (UBA 13): "la dégradation des populations de phytoplancton et de zooplancton". La rivière Niagara canal de liaison, mais il rejoint le lac Érié bien étudié et le lac Ontario est pauvre en données, sans programmes d'échantillonnage de plancton actifs. Une seule saison d'échantillonnage en 2014 A eu lieu chaque mois de Juin-Oct pour la qualité de l'eau, le zooplancton et la composition du phytoplancton et la densité. Les conditions oligotrophes persistent tout au long de la saison et les densités de plancton sont extrêmement faibles, bien que cela soit attendu dans un système à débit élevé comme la rivière Niagara. Le temps de séjour du plancton dans la rivière Niagara est de seulement 11-28 heures, mais pourrait être beaucoup plus long si le plancton est entraîné dans les réservoirs hydroélectriques. Étant donné les résultats de cette enquête, aucune dégradation des populations de plancton n'est indiquée.

EXECUTIVE SUMMARY

This report documents the data collected in 2014 by Fisheries and Oceans Canada (DFO) to assess the effect of the Niagara River environment on zooplankton and phytoplankton community composition, in order to recommend a status of the plankton populations BUI for the Niagara River Area of Concern (AOC). To accomplish this, six monitoring sites were sampled monthly for water chemistry, phytoplankton and zooplankton composition along the river including one site at the outflow of Lake Erie. The Welland River watershed was not included in this study.

In 2014 the Niagara River exhibited the conditions of a low-productivity, oligotrophic, clear-phase system. The water chemistry values are similar to the water that enters the river from Lake Erie, including values of chlorophyll *a* below 2.5 $\mu g.L^{-1}$. While plankton densities in the Niagara River are very low compared to the adjacent lakes, reduced densities of phytoplankton and zooplankton are expected in high flow riverine environments, given a well-documented relationship between increased current speed and decreased plankton biomass. The low plankton biomass within the river should thus not be of concern. There is some evidence that entrainment time in the hydroelectric reservoirs might be promoting an increase in phytoplankton and zooplankton growth, though it was outside the scope of this monitoring survey to include them in the sampling program. In general, the phytoplankton and zooplankton communities found in the Niagara River are similar to those in other lentic environments and predictably, dominated by species better suited to highly turbulent conditions. The phytoplankton community within the river is dominated by diatoms, particularly by filamentous or colonial forms that are suited to high-energy flow systems such as *Fragilaria crotonensis* and *Skeletonema potamos*. There is no evidence to suggest that the small diatom peak (August), or blue-green algae peak (September), were persistent or were likely detrimental to the system. Overall, levels of peak algal biomass did not exceed 503 mg m^{-3}, significantly less than the definition of a eutrophic algal bloom.

The Niagara River zooplankton community is dominated by dreissenid veligers throughout the summer, though this matched the pattern found from Lake Erie, and the Niagara River itself is known to have high densities of adult dreissenid mussels. The rest of the zooplankton community biomass comprised mostly adult and juvenile forms of calanoid copepods, which are known to be resilient in high flow environments. While the decrease in zooplankton biomass from 103.9 to 4.19 mg m^{-3} is precipitous down the river, the loss of zooplankton occurs across all groups and some natural mortality is expected in rivers, especially one with a large waterfall mid-river. Furthermore, planktivorous fish populations are high in the upper river, dominated by Emerald Shiner, which likely contribute to the reductions in zooplankton. Copepods were found at higher densities at stations below the hydroelectric plants suggesting the reservoir system may be a suitable location for zooplankton reproduction, but no sampling occurred within these reservoirs for this study.

Any reductions in biomass and changes in species compositions are consistent with expectations for a large river system, indicating no impairment of phytoplankton or zooplankton populations in the Niagara River. Any future sampling should include the hydroelectric reservoirs on both sides of the river, in particular on the Canadian side, since the Sir Adam Beck reservoir receives input from both the Welland River and the Niagara Falls Wastewater Treatment Plant, which fall within the watershed of the Welland River.

INTRODUCTION

The Niagara River is a 58 km long connecting channel from Lake Erie to Lake Ontario, flowing north over the Niagara Escarpment at Niagara Falls. It also serves as the international boundary between Canada and the United States. More than half of the flow is diverted for electrical power generation on both sides of the river and is held in the Lewiston Reservoir on the American side and the Sir Adam Beck Power Reservoir on the Canadian side. Thus, 60% of the river water has a lentic (lake-like) existence for a portion of time before entering the lower river. Areas of Concern (AOCs) which are connecting channels (e.g. Niagara River, St. Clair River, Detroit River, St. Lawrence River) are particularly challenging to manage compared to other AOCs because they require strong binational cooperation and a basin-wide ecosystem perspective for their restoration and protection (Great Lakes Connecting Channels 2009). The Canadian section of the Niagara River was originally listed as an AOC under the 1987 Binational Great Lakes Water Quality Agreement (GLWQA; International Joint Commission 1989) because available data at the time indicated degraded water quality and environmental conditions from contaminated sediments and nutrient rich runoff from agricultural areas. The Niagara River AOC has both a Canadian and American Remedial Action Plan (RAP) process, with the Canadian section of the Niagara River representing the entire length of the western side of the river, including the Canadian side of Niagara Falls. The Canadian focus is on loss and degradation of wetlands and fish habitat due to non-point sources of rural pollution. In contrast, most environmental concerns in the United States are associated with toxic contamination and the discharge of municipal wastes.

In the Stage 2 report of the Niagara River RAP (April, 1995) and in the follow up Status of Beneficial Use Impairments Niagara River (September, 2010), the status of the Beneficial Use Impairment (BUI) 'Degradation of phytoplankton and zooplankton populations' has been identified as *requires further assessment*. Previous work around this topic has been a study of chlorophyll *a* levels in the Welland River as an indicator of eutrophication, more suited to the Eutrophication or undesirable algae BUI. Until now, there have been no extensive assessments of the status of phytoplankton or zooplankton communities in the Niagara River. This report focuses on the plankton of the Niagara River as defined by the Niagara River RAP, therefore the Welland River was only examined in a cursory fashion and is only briefly discussed.

Phytoplankton and zooplankton play an important role in the transfer of energy through aquatic trophic food webs. The role of phytoplankton in converting nutrients and light into biomass through photosynthesis is understood by most people, as is the fact that zooplankton consume this primary production. However, the interconnections within the planktonic food web are complex, driven by a number of factors and are ever changing (Sommer et al. 2012). Furthermore, the role of the other heterotrophs in this food web: ciliates, nanoflagellates and other protists grouped into the term "microbial loop" are even less understood. What is known is that proper food web function relies on the contribution of each of these groups, and that an excess of one or more of them can lead to an unstable community (Legendre and Rassoulzadegan 1999).

There are a variety of potential factors which can disrupt phytoplankton and zooplankton communities and change community composition, including toxic influence from historical contamination (notably heavy metals and chlorinated hydrocarbons; Walsh 1978; Durham and Oliver 1983; Munawar et al. 1983), influences of eutrophication, sewer overflow and agricultural runoff, influences from residence time in the hydroelectric reservoirs (Akopian et al. 1999; Williams et al. 2003), increased surface irradiance in very clear water (Reynolds et al. 1994), as well as physical damage due to turbulence from the turbines and the falls themselves (Horvath and Lamberti 1999).

Connecting channels between closely adjacent large lakes are very uncommon outside of the Laurentian Great Lakes (Edwards et al. 1989). Connecting channels are different from other large rivers in that, while they have high discharge rates, they are short in length. One parallel can be found in the straits between ocean basins, but beyond their characteristic high salinities, these are usually much larger in size and very deep (e.g., Øresund strait connecting the Baltic Sea and the North Sea), and rarely considered "rivers". The transition from one lentic system to another via a strong flowing connection with a short retention time makes connecting channels very difficult to assess (Walks and Cyr 2004).

There is a general consensus in the scientific community that the transition from a lentic (lake-like) to a lotic (river-like) ecosystem has a powerful effect on the community composition of phytoplankton and zooplankton; lotic ecosystems contain less phytoplankton and zooplankton as compared to lentic environments (Pace et al. 1992) and certain species (termed potamoplankton) show better success in riverine conditions than others (Pace et al. 1992; Rojo et al. 1994; Walks and Cyr 2004). Shallow systems, including rivers can generally be grouped into two phases: turbid, phytoplankton dominated, or clear, macrophyte dominated systems (Vis et al. 2007). Low nutrient rivers tend to have the primary producer community dominated by aquatic plants (Reynolds et al. 1994; Hilt et al. 2011). Zooplankton biomass is lowest in nontidal rivers, followed by tidal rivers, estuaries and then lakes (Pace et al. 1992). In riverine environments, the rapidly changing water provides little or no time for plankton to adapt to the changing conditions (Köhler 1994). River conditions are not ideal for the survival of plankton; increased turbidity, high concentrations of organic and inorganic particles, and limited high-quality food are all regulating phytoplankton and zooplankton growth (Pace et al. 1992). In fact, all aspects of plankton growth, feeding and reproduction are negatively affected by water currents (Wahl et al. 2008). As water currents increase downstream of the river mouth, noting that this distance is related to river size (Walks and Cyr 2004), it is common for zooplankton populations to drop off. This is likely caused by avoidance of high velocity areas, increased predation and interference with feeding activity due to the advective processes of the river (Pace et al. 1992).

Increased flow is more detrimental to zooplankton populations compared to phytoplankton, since zooplankton have longer generation times and cannot compensate for losses as quickly as phytoplankton. In slow moving rivers, as residence time increases, so does plankton biomass (Pace et al. 1992). Walks (2003) suggested that water residence times correlate well with zooplankton biomass but less well with phytoplankton, therefore flushing rates are acting as a controlling factor in phytoplankton biomass. In fast moving rivers, such as the Niagara River, residence times are very low, therefore benthos, eddies, back waters, reservoirs and low-flow areas become important refugia for phytoplankton (Reynolds et al. 1994; Speirs and Gurney 2001; Walks 2003; Genin et al. 2005; Walks 2007). Pace et al. (1992) hypothesized that smaller zooplankton species would be favored in riverine ecosystems due in part to their shortened generation times, their ability to feed and grow more successfully in the presence of filamentous or toxic algae, and their survival advantage in turbid waters (notably rotifers). Reynolds et al. (1994) suggested that successful phytoplankton species will be those that can survive high-frequency irradiance fluctuations, have fast growth rates and show resilience in high flow systems, notably diatoms and chlorococcal green algae.

The purpose of this report is to assess the effect of the Niagara River environment on zooplankton and phytoplankton community composition and to recommend status of the plankton populations BUI. This was accomplished by surveying sites in the upper and lower river to determine plankton biomass, taxonomic composition and productivity over the 2014 growing season (June – Oct.) and comparing these estimates to other riverine systems.

METHODS

Study sites

The Niagara River consists of three distinct zones: the upper river, from Lake Erie to Niagara Falls which contains relatively shallow, fast moving laminar flow, vertically mixed water with flow in mid-channel approximately twice that found at the margins; above the turbines, from Niagara Falls to the turbine outflows which consists of a deep narrow gorge transporting water through rapids with flow at mid-channel ~3x that found at the margins and a large eddy at the whirlpool; and from the turbines outflows to Lake Ontario (below the turbines), where the river widens and with a deep channel, the current slows, and eddies are common [A. Thompson and S. Rodrigues, National Hydrologic Service of Environment and Climate Change Canada (ECCC), personal communication] (Figure 1). Contributing factors outside the AOC important to plankton ecological dynamics are the hydroelectric reservoirs, although not sampled, will be discussed. Water is removed from the river flow just above the falls and pumped into large holding reservoirs which are recharged primarily during the night and released from the reservoirs gradually throughout the day for peak power generation (Figure 2). The amount and timing of water diverted into the reservoirs is highly regulated by the Niagara River Water Diversion Treaty (1950) and creates strong day-night flow dynamics in the river. The zones in the upper river and above the turbines offer very few opportunities for plankton refugia, unlike the downstream system eddies, deep channels and the lentic environments in the reservoirs.

The average daily Niagara River flow rate is 5,800 m^3s^{-1}, and varies little (±20%) throughout the year. The required minimum scenic flow over Niagara Falls is 2,832 m^3s^{-1} during the daytime (08:00 to 22:00) of tourist season, April through October, but during the night and non-tourist season, November to March, the required minimum flow is reduced to 1,416 m^3s^{-1}. Excess water is permitted to be taken from the Niagara River for power generation, which accounts for up to 60% of the overall flow, drawn from the river 4 km above Niagara Falls on the US side and 2 km above the Falls and from the Welland River (via the Chippawa-Queenston Canal) on the Canadian side (Figure 2). At night, a substantial fraction (2,300 m^3 s^{-1}) of the river flow is diverted into the Robert Moses Niagara Power Station (NY Power Authority) forebay on the US side, with excess pumped into the upper Lewiston Reservoir (770 ha, $8.3x10^7$ m^3). The same pattern exists on the Canadian side for the Ontario Power Generation (OPG) Sir Adam Beck Hydroelectric Generating Stations with water being pumped into the smaller (300 ha, $1.9x10^7$ m^3) reservoir (Williams et al. 2003).

Complete filling of either reservoir can take up to 8 hours, but the water is taken in a cyclical method, being pumped up in the night when excess flow is made available and reservoir is drawn down during the day when power generation is at its maximum. The water level of the reservoir peaks during the weekend and gradually reduces until late Friday evening (Miller and Kappel 1987). This makes determination of residence time very difficult for the individual reservoirs. Knowledge of the pumped volume and water levels/volume must be known to calculate residence time, but it will fall into the range of days-weeks. The volume of the reservoir can drop considerably each day (down ~7-8 m) but the water is always taken from one end of the basin, meaning that plankters may have a refugium if they occur on the opposite side away from the main outflow.

From June to October 2014 DFO staff from the Great Lakes Laboratory for Fisheries and Aquatic Sciences in Burlington, Ontario, surveyed the river approximately once a month in Lake Erie and each of the three river zones; the upper river above the falls (Lake Erie to river km 30), the lower river below the falls above the turbines (km 30 to km 39), and the lower river below the turbines (km 39 to Lake Ontario; see Figure 1 and Table 1). The initial June survey was exploratory and included a number of land-based stations as well as mid-river stations. Based

on the sites surveyed in June, six stations were selected [NIA10 (mouth of Lake Erie), NIA11 (upstream of the Fort Erie train bridge), NIA12 (Grand Island), NIA13 (upstream of the turbines), NIA14 (Queenston Bridge), and NIA4 (lower river stretch downstream of turbines)] to collect zooplankton samples for the rest of the season. Water samples for phytoplankton production and taxonomy and water chemistry were collected from NIA10, NIA12, NIA13 and NIA4. Sites above (NIA13) and below the turbine outflows (NIA14) were chosen because there was an expected influence from the reservoirs and matching river discharge measurements from ECCC were available.

Physico-chemical

Over nine sampling excursions from June to October 2014 (see Appendix 1), sonde profiles were collected at multiple stations along and across (transects) the river in order to determine how the physical and biological properties of the river change based on location, relative to the two hydroelectric generating stations in particular (note the location of the hydroelectric plants and reservoirs on Figure 1). Multiparameter sondes [an EXO2 (YSI), a FluoroProbe (bbe-Moldaenke) and Hydrolab HL4] were used to collect data on chlorophyll *a*, phycocyanin, turbidity, temperature, conductivity, dissolved oxygen, pH, and phytoplankton-group pigments. These sondes were used concurrently due to difficulties with instrument reliability working in rugged conditions in the Niagara River. In particular, the EXO2 was susceptible to instrument reset when bumped due to a power issue, which resulted in a company recall the following winter. Due to the speed of the current at all stations, the vessel was allowed to drift in order to take the most vertical profile possible. In a flowing river, the standard method of determining water clarity with a Secchi disc is problematic. Instead, the vertical light attenuation coefficient (k_d) was estimated using Licor quantum irradiance sensor.

Water column averages were calculated for each station. Horizontal cross-river transects were also done at selected stations (NIA12, NIA18 (Queenston boat launch), NIA4) to verify the relevance of values at the station locations. In late July an additional upper river transect (NIA11) was also completed. Transects could not be performed near the turbines (NIA13 and NIA14) due to the strong current and exclusion zones. Occasionally, sonde malfunctions occurred, resulting in no salvageable data being available from any of the probes.

Due to the speed of the current at all stations, the vessel was allowed to drift in order to take the most vertical profile possible. In spite of this, the samples were still more oblique than would have been expected at a station with less current. This made targeting specific depths with bottle samplers very difficult. Water samples were instead collected with a “glug-glug” bottle integrator and a best attempt was made to integrate the sample over the estimated euphotic depth. However due to the strong water current, the maximum possible sample depth was ~7 m (Table 2). This is expected to be representative because the water column at all of the stations was well mixed to near bottom based on sonde profiles and Acoustic Doppler Current Profiler (ADCP) data. Samples were stored in the dark and kept cool until analysis. Water samples for chlorophyll *a*, DIC, DOC, POC, PON, NH_3, NO_3^-+ NO_2^-, TN, SRP, TP, SiO_2, Na^+, Mg^{+2}, K^+ and Ca^{+2} were collected at NIA10, NIA12, NIA13 and NIA4 and processed the next day back at the laboratory in Burlington. Analysis of nutrients and major ions was conducted according to the standard protocols of the Environment Canada’s National Laboratory for Environmental Testing (NLET 1997). Results underwent QA/QC for questionable values, and any outliers (e.g., DOC of 11.6 mg L^{-1} and SRP 772 µg L^{-1} and resulting TP in early July at NIA10) were confirmed with corresponding data from ECCC Niagara phosphorus monitoring program at Fort Erie (D. Burniston, ECCC, March 2016 personal communication), and excluded from analysis. Chlorophyll *a* concentrations were determined by cold acetone pigment extraction and spectrophotometric analysis (Strickland and Parsons 1968) at the DFO laboratory.

Current speed at the surface at all stations and transects was collected using a General Oceanics mechanical flow meter mounted on a pole directed into the current. The boat was kept as stationary as possible during flow measurements. Eddies or backwater flows were noted and quantified when possible. Acoustic Doppler Current Profiler (ADCP) flow cross-sections typical of conditions at NIA12 (upper river), NIA13 (cableway above power stations) and NIA14 (below power stations) were obtained from ECCC (A. Thompson and S. Rodrigues, National Hydrologic Service of ECCC, personal communication). The Niagara River flow is very consistent over the year due to its status as a connecting channel, and is controlled almost entirely by the water level of Eastern Lake Erie. This is quite different from other large rivers, which can vary in discharge by more than 30x (Broderick 2009).

Phytoplankton and microbial loop

Water was collected as described for water chemistry above. Primary productivity and bacterial growth experiments were undertaken the next day back at the DFO laboratory.

Whole water was fixed with Lugol's iodine upon collection for analysis of phytoplankton communities at stations NIA10, NIA13 and NIA4. Enumeration and measurement followed the HPMA (2-hydroxypropyl methacrylate) technique described by Crumpton (1987) which is broadly compatible with the Utermöhl (1958) inverted microscope technique. A minimum of 200 units were counted to achieve an acceptable counting efficiency (Lund et al. 1958). Within each sample, cell dimensions were measured directly and the average cell volume for each species was determined by applying the average cell dimensions to a standard geometric shape that most closely resembled the species. In the case of colonial forms, the average number of cells per colony was determined. Cell volume was converted to biomass assuming a specific gravity of 1.0 (Strickland 1960).

Microbial loop samples, including bacteria, autotrophic picoplankton and heterotrophic nanoflagellates, were fixed with 1.6% formaldehyde and enumerated using DAPI staining (Porter and Feig, 1980) under epi-fluorescence microscopy (Munawar and Weisse 1989). Size fractionated primary productivity was estimated for three size categories of phytoplankton (<2 µm, 2-20 µm and >20 µm) by the ^{14}Carbon technique as per the standard protocol of Munawar and Munawar (1996). Whole water samples were spiked with $Na^{14}CO_3$, incubated for 4 h at surface temperature and exposed to a constant light level of 240 µE s^{-1} m^{-2}. Because light and temperature levels are constant in these experiments, the results should be interpreted as potential productivity rather than actual. After incubation, size classes were determined by filtration of the sample through polycarbonate filters, all filters were rinsed with hydrochloric acid (0.5N) in order to remove excess ^{14}C-CO_2. Radioactivity was determined by liquid scintillation.

Bacterial growth rates were estimated by ^{3}H-Leucine incorporation into bacterial proteins following the protocol of Jørgensen (1992) and radioactivity was determined by liquid scintillation. Detailed procedures are available in Heath and Munawar (2004). The growth measurements for both bacteria and phytoplankton estimated by these techniques represent optimal growth rather than in-situ growth, because they occur in motionless bottles rather than the energetic conditions found within the river.

Zooplankton and rotifers

Zooplankton samples were collected monthly from NIA10, NIA11, NIA12, NIA13, NIA14and NIA4. Animals were collected using a metered 30 cm diameter, 64 µm mesh Wisconsin style net, approximately 1.2 m long. In an attempt to have the net sink as deep in the water column as possible, up to two 1 kg dive weights were affixed to the net hoop in addition to the weighted cod end, however due to the speed of the current near the hydroelectric plants, the entire water column could not be sampled (Table 2). Water was flowing strongly and well mixed vertically so this is unlikely to be problematic. Net casts were achieved by letting out line, allowing the net to

sink through the water column (or pulled in the current), and retrieving it as an oblique tow. Flow rates through the net were determined by a General Oceanics flow meter and maximum depth recorded by a Wildlife Computers MK9 tag affixed to the hoop. Beginning in August, two replicate nets were collected and pooled in the field due to inadequate sample volume concerns. All samples were preserved in 4% sugar buffered formalin solution, counted and identified to standard taxonomic groupings: Cladocerans including bosminids (*Bosmina* sp. and *Eubosmina* sp.), *Daphnia* sp., predatory species (*Bythotrephes longimanus*, *Cercopagis pengoi* and *Leptodora kindti*), calanoid copepods, cyclopoid copepods, copepod nauplii and dreissenid veligers. Loose and attached copepod and cladoceran eggs were also counted in each sample. At NIA10, NIA12 and NIA4, zooplankton were also enumerated and identified to the lowest possible taxonomic level (usually species) by a trained taxonomist. Zooplankton lengths were measured at NIA10 and weights determined using the length-weight relationships in Bowen (2017). On each date, the mean weight of each taxonomic group at NIA10 was applied to densities of that taxon at the rest of the stations to calculate biomass. For taxa that only occurred a few times, the seasonal mean weight was used. Total seasonal zooplankton production values (June to October) were determined using the production/biomass (*P*/*B*) equations from Shuter and Ing (1997) for copepods and Stockwell and Johannsson (1997) for cladocerans. Details on enumeration methods and production calculations are given in Bowen (2017).

At each of NIA10, NIA12, NIA13 and NIA4, rotifers were collected by filtering 10 L of integrated water (described above) through a 20 µm sieve. Samples were narcotized with carbonated water and preserved as above. For each station, a June to October seasonal composite was created by combining half of each rotifer sample taken on each date. Rotifers in these seasonal composites were identified to species whenever possible, counted and measured for biomass estimation (Bowen, 2017). Presence of larger rotifer species were also noted in the zooplankton samples collected on each date at NIA10, but these were not quantified.

RESULTS

Physico-chemical

The monthly weather data from the Niagara Airport (IAG, Buffalo) for 2014 are seen in Figure 3 (National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NOAA-NCEI), https://www.ncdc.noaa.gov/, accessed Jan. 2016). While April was a wet month, July had an exceptionally high precipitation value and a slightly depressed maximum temperature value. Daily weather values for date of sampling and the four previous days, illustrating when precipitation occurred just prior to the sampling date. High levels of precipitation occurred on the two days preceding the early July sampling while there was very high precipitation on two days prior to the late July sampling date, but also on the day of sampling. The mean air temperature on sampling days was not very different June-September (19-22 °C) and only slightly cooler in October at 17 °C.

Flow rates within the river increased downriver, but were reduced in the lower river past the power plants approaching NIA4. Despite difficulties getting measurements in high current areas, current speeds at any given station in the Niagara River remained fairly consistent over the sampling period, never varying more than 0.2 m s^{-1}. On average, the slowest currents were recorded at NIA10 (0.47 m s^{-1}) while the fastest currents were found in the lower river at NIA13 (1.84 m s^{-1}). Average current speeds from all six stations are presented in Figure 4. In general, current speed increased with distance down river. The current data remained fairly comparable at a number of cross-river transects at stations in the upper and lower river, therefore we only present data from three transects (NIA4, NIA18, NIA12) on each of two sampling days (June

10th and October 14th) (Figure 4). Our surface flow measurements are comparable to whole water column ADCP measurements conducted by ECCC (Tables 2 and 3). Current speed is highest at the center of the river, with tendencies for current speed to be marginally greater on the American side (Table 3). This was confirmed by ADCP transect data for NIA12, 13 and 14 from Oct-Nov 2013, which also verified that the entire water column was well mixed to near bottom (A. Thompson and S. Rodrigues, National Hydrologic Service of ECCC, personal communication). It should be noted that the river flow at NIA18 illustrates an example of a very pronounced counter current eddy nearest to the Canadian side.

The water-column flow measurement from each of the ADCP transects were used to calculate residence time within the river, which ranged from 11-28 hrs for the entire length of the river (Table 4). Two scenarios were considered: that any organism would be well-mixed across the river, or if they spent the majority of their time in the central, fast-flowing channel of the river.

Transects and station sampling

During each of the sampling cruises, transects were done to examine any cross-river trends of the Niagara River, showing little or no trends in any of the measures (Appendix 1). Transects from NIA12, NIA4 and NIA18 are summarised in Table 5 and Figure 5. Transects in early and late July both showed consistency across the river. In August, transects were completed, but data capture failed at both lower river stations. In September or October, there were again no significant changes in turbidity, temperature or conductivity along the transect (Figure 5). Occasionally, increases in measures such as chlorophyll *a* were encountered during transects which were likely related to transient macrophyte fragments. Chlorophyll *a* values for all points along each of the transects were usually comparable to the corresponding single-point profiles and were generally low (< 1 µg L^{-1}) (Table 6). No changes in temperature and only minimal changes in turbidity or conductivity were observed, usually associated with samples adjacent to the river banks.

The results from the station profiles are summarized in Table 6 and Appendix 2. The data presented are from the EXO2 sonde unless otherwise stated. In June, profiles were collected over three days (5th, 10th and 12th) as part of the initial survey of potential sampling locations, so they include stations not sampled again during the project. All profiles found the water column to be well mixed. For general trends, temperature did not vary significantly along the river, while turbidity tended to increase after going over the falls (with one exception) and conductivity tended to increase marginally (between 1.04 and 7.42 µS cm^{-1}) after going over the falls. High current speeds made light attenuation difficult to measure. The vertical light attenuation coefficient (k_d) and calculation of euphotic depth were estimated from Licor PAR quantum sensor measurements. The k_d values illustrate the very clear water conditions of the river typical of oligotrophic systems. Average values were only slightly higher in the lower river than the upper river during July (Table 7) which had elevated precipitation (Figure 3), reflecting the slightly reduced clarity of the lower river.

Chlorophyll *a* was generally very low across the sampling season (Table 6, Appendix 2), averaging 0.5 µg L^{-1} for the upper river (NIA10, 11 and 12), 0.2 µg L^{-1} above the turbines (NIA13), and 0.7 µg L^{-1} below the turbines (NIA18 and 19; Figure 6). The Welland River site during the preliminary survey showed similar chlorophyll levels to the Niagara River but higher temperatures and turbidity. High turbidity and chlorophyll *a* values were measured during July 10 at NIA18 (Appendix 2), which is likely a shoreline influence associated with the backflow on the Canadian side at this station (Figure 4).

Water chemistry

Results from water chemistry are presented in Appendix 3. Water chemistry values were not significantly different from those collected weekly June-Oct from ECCC's Niagara River

Monitoring Program, with the exception of SRP (DFO's slightly higher and more variable, t=3.35, p=0.001) and marginally lower dissolved calcium (t=2.62, p=0.01) and higher magnesium (t=2.22, p=0.03). Total phosphorus (TP) was low and varied little across the season, with an average of 0.015 mg L^{-1}. Soluble reactive phosphorus (SRP) was variable (0.0062 mg L^{-1} ± 0.16 SD) with sampling date and station. Though the Welland River enters into the Niagara River via the Chippawa Canal and power stations, there is no significant increase in TP below the hydroelectric outputs. There was some suggestion, though insignificant, of increased nitrogen ions (NOx, NH_3) below the power stations.

Average extracted chlorophyll *a* in the Niagara River was 1.3 µg L^{-1}, with chlorophyll highest at 2.5 µg L^{-1} at NIA13 on July 9th, which is similar to eastern Lake Erie at < 2 µg L^{-1}, May through October 2001-2002 (Depew et al. 2006). Lake Erie Surveillance at Station 931 (nearest Niagara River, in ~10 m water, 42.85°,-78.94°) also confirms these values; Chlorophyll *a* (uncorrected) was 1.41±1.00 (SD) from 2000-2013 (ECCC, STAR database, 2016). Dissolved inorganic carbon (DIC) showed a consistent declining trend from NIA10 to NIA13, then increase again at NIA4, with an overall average of 21.9 mg L^{-1}. Dissolved organic carbon (DOC) was usually highest at NIA10 and then fairly consistent throughout the rest of the river. The average DOC for the river was 2.57 mg L^{-1}, excluding the DOC outlier in early July at NIA10 of 11.6 mg L^{-1}. Particulate organic carbon (POC), Particulate organic nitrogen (PON), Ammonia (NH_3), Nitrate-Nitrite (NO_3-/ NO_3-), Total Nitrogen (TN), silica (SiO_2), sodium (Na^+) and total calcium (Ca^{+2}) all varied little over the sampling season, with NIA4 often having only slightly elevated concentrations.

Phytoplankton and microbial loop

The total phytoplankton biomass measurements in the Niagara River ranged from 44 to 503 mg m^{-3} over the sampling season, with an overall average of 148 mg m^{-3} (Figure 7). There was little seasonal fluctuation at NIA10, and NIA4 biomass peaked in August driven by Diatomeae (Bacillariophyta): *Fragilaria crotonensis* (45.3%) and by Cryptophyceae: *Ochromonas* sp. (21.2%; Table 8). In September, NIA13 biomass jumped (Figure 8), driven by an increase of the filamentous blue green (Cyanophyta): *Lyngbya birgei* (89.4%). Generally, diatoms were the dominant group in the river community (*F. crotonensis*, *Stephanodiscus* sp., *Cocconeis pediculus*). Cryptophytes (mainly *Rhodomonas minuta nannoplanctica*) and filamentous cyanophytes (namely *L. birgei* and *Heteroleibleinia* sp. (formerly *Lyngbya* sp.)) also contributed significantly to the total biomass, particularly in the fall (Table 8 and Appendix 4). Filamentous forms were generally more common at the downstream sites.

The primary production measurements showed that total phytoplankton productivity was very low in the Niagara River ranging from 0.87 (NIA12, September 10th) to 4.91 mg C m^{-3} h^{-1} (NIA10, October 15th), with NIA10 and NIA4 being the most productive overall (3.37 and 3.27 mg C m^{-3} h^{-1}, respectively). In general, primary productivity of the upper river (NIA12) was highest in the spring and late fall. NIA13 and NIA12 were also most productive in the fall, with the lower river (NIA4) being the most productive during the September cruise. Productivity at NIA4 was significantly higher than NIA13 (paired t(4)= 2.77, p=0.04). Primary productivity was dominated by the nanoplankton-sized fraction (2-20 µm) ranging from 40% to 75% of total production. The only exceptions occurred in late July at NIA12 and NIA10, as well as in September at NIA10. In each of these cases, picoplankton (<2 µm) were the major contributor to productivity, representing between 43 and 48% of the total, followed by nanoplankton and then netplankton (Figure 9). These values are indicative of an oligotrophic system. Phytoplankton productivity at the mouth of the river shows a strong correlation (r^2 = 0.9016) to productivity in the lower river when lagged to the next sampling event, approximately one month later. To be clear, periods of low (or high) productivity at NIA10 are followed by periods of low (or high) productivity at NIA4 during the following cruise, an average of 25 days later (Figure 9).

This trend is not seen in the phytoplankton biomass data for the same stations. Average production to biomass ratios (P/B) expressed as carbon turnover rates (d^{-1}) were nearly identical at all three stations (NIA10: 0.267±0.04; NIA13: 0.269±0.10; NIA4: 0.294±0.06). P/B was consistently highest in picoplankton (the smallest fraction <2 µm), ranging from 1.01 to 13.32 d^{-1} at all three stations. High picoplankton turnover rates are typical of oligotrophic systems and suggest that these organisms may be heavily grazed by zooplankton and other heterotrophs. However, productivity estimates reflect ideal laboratory conditions and may not reflect the more harsh conditions observed in situ within the river.

Bacterial productivity was highest at all stations in early July (Figure 10), which was the month with the highest total precipitation (Figure 3). The highest values were at NIA13, above the hydroelectric reservoirs output, at 1.2 µg C l^{-1} hr^{-1} which stayed high through July 30th then fell to levels more comparable with the rest of the river. In the later part of the year, downstream stations showed slightly higher bacterial productivity than upstream stations.

Total microbial loop biomass ranged from 0.63 to 3.05 g m^{-3} with an average of 1.3 g m^{-3} (Figure 11). The highest microbial loop biomass value occurred at NIA10 in September and consisted of bacteria and a sudden increase in autotrophic picoplankton (APP). On average, microbial loop biomass remained consistent between the upper and lower river with a tendency to have higher biomass at the mouth (NIA10) and lower river (NIA4). The majority of the total microbial loop biomass is made up of bacteria, with autotrophic picoplankton (APP) and heterotrophic nanoflagellates (HNF) contributing a maximum of 30.1% and 24.2% to the total, respectively.

Zooplankton and rotifers

Zooplankton and rotifer species found in the Niagara River were typical of eastern Lake Erie and epilimnetic waters of the Great Lakes (Tables 9A-C). Total zooplankton density ranged from 0.69 to 133 individuals L^{-1} with biomass ranging from 0.5 mg m^{-3} to a peak of 153.5 mg m^{-3} occurring on July 30th at NIA10 (Figure 12). Both density and biomass trends showed a sharp decline from NIA10 into the upper river. Zooplankton biomass and density were always lowest at NIA13, and then increased beyond the turbines at NIA14 and NIA4 (Figure 12). This decline in zooplankton biomass can be described by the following equation (r^2 = 0.937) based on distance from the mouth of the river:

$$y=95.39e^{-0.081x} \quad (1)$$

where June to October mean biomass declined by ~54% as compared to the mouth of the river after entering 10 km into the river, and by ~79% after 20 km (Figure 13). The decline of zooplankton density into the river can be described as:

$$y= 76820e^{-0.086x} \quad (2)$$

where June to October mean density declined by ~61% as compared to the mouth of the river after 10 km, and by 83% after 20 km (Figure 13). The expected trend deviates from actual data at NIA14 and NIA4 (eqn. 1 and 2) likely due to input from the hydroelectric reservoirs (shown by arrows in Figure 13). Zooplankton biomass at NIA14 and NIA4 were 3.7x (12.76 mg m^{-3}) and 5.5x (12.48 mg m^{-3}) greater respectively, than would have been expected if the turbine outflows had no effect. Zooplankton densities at NIA14 and NIA4 also increased by 2.7x (6.23 individuals L^{-1}) and 5.3x (7.73 individuals L^{-1}), respectively.

A one-way ANOVA indicated significant density differences between the Lake Erie station (NIA10), the upper river (NIA11, NIA12) and the lower river stations (NIA13, NIA14, NIA4; $F=44.48$, $DF=34$, $p<0.0001$; Tukey-Kramer $p<0.05$) and also for biomass ($F=11.20$, $DF=34$, $p<0.0001$; Tukey-Kramer $p<0.05$). There was also a significant difference in densities between NIA13 (above power stations) and NIA14 (below turbines) for calanoid copepods ($t=2.85$,

DF=10, p=0.017), and the standard error of the mean was very small for NIA13 (0.21 ± 0.08 ind·L^{-1}) throughout the year compared to NIA14 (1.56 ± 0.47 mg·m^{-3}). The extra copepod numbers were likely sourced from the hydroelectric reservoir system.

Zooplankton community composition was quite different in June compared to the other dates (Figure 12), with both cyclopoid copepods (particularly juveniles) and the small cladoceran *Bosmina* most numerous early in the season when dreissenid veliger larvae were virtually absent. Veligers were the most abundant group on the remaining dates, however due to their small size, they only dominated biomass on July 30 (>70% of the total). Calanoid copepods dominated the zooplankton biomass on the remaining dates [49% ± 17 (SD)]. Cladocerans were generally a minor component of the zooplankton biomass at 15% ± 12 (SD). Bosminids (nearly entirely *Bosmina* sp.) appeared in the zooplankton community only in the spring and fall, *Daphnia* sp. biomass peaked in early July, and the biomass of predatory cladoceran species such as *Leptodora kindti* and the invasive spiny water flea *Bythotrephes longimanus* peaked throughout July (Figure 12).

In addition to the genus/group counts presented above, enumeration of the zooplankton community was taken to the species level at NIA10, NIA12 and NIA14 (Table 9A). Although densities and biomass of zooplankton taxa dropped precipitously with increasing distance downstream, there were generally only minor differences in community composition among these three stations (Figure 14). *Daphnia galeata mendotae* was the dominant *Daphnia* species in the river, with only occasional occurrences of the smaller *D. retrocurva*. The biomass was dominated by juvenile copepods, especially cyclopoid copepodites in the early part of the year and calanoid copepodites and adults throughout the sampling season. Composition of adult cyclopoids exhibited seasonal succession, with *Diacyclops thomasi* and *Mesocyclops edax* dominating in June, *M. edax* throughout the summer and *Tropocyclops extensus* increasing from late summer into the fall. Calanoid density varied little between stations or between sampling events, and was dominated by *Skistodiaptomus oregonensis*, followed by *Epischura lacustris* with minor contributions from *D. minutus* (Figure 14; Table 9A). Starting midsummer, the proportion of adult to juvenile (copepodid) copepods often increased in the river compared to the Lake Erie site, although the densities and biomass of each group declined with increasing distance downstream.

Rotifer densities and biomass also showed declines with increasing distance downstream, with the lowest values observed below the falls, and a small subsequent increase below the reservoir discharge (Table 9B). When averaged across the season, rotifer density was 19.5 individuals L^{-1} (17% of macrozooplankton + rotifer density) at the entrance to the river, but only 2.1 individuals L^{-1} below the falls (42%). In general, rotifers did not decline as rapidly as zooplankton, although large, soft-bodied taxa such as *Asplanchna* sp. were most impacted by riverine conditions. Rotifers represented only a small fraction of macrozooplankton + rotifer biomass in the river due to their small size, totalling 0.51 mg m^{-3} (0.5%) at N1 to 0.04 mg m^{-3} (0.8%) at N4. The dominant rotifer species at NIA10 in Lake Erie were *Conochilus unicornis* (34% by density), *Keratella cochlearis* (29%), *Kellicottia longispina* (12%), *Polyarthra vulgaris* (10%) and *Synchaeta kitina* (4.1%). *Asplanchna* sp. represented 47% of total rotifer biomass. Based on qualitative evaluation of the zooplankton samples taken at this site, *Asplanchna* sp., *K. longispina* and *K. cochlearis* were observed throughout the sampling season*, Keratella quadrata and C. unicornis* were noted in June and early July, and *Polyarthra* sp. and several species of *Ploesoma* dominated in the latter part of the season (Table 9C).

At stations NIA13 and 14, copepods had more eggs per individual than cladocerans in June and early July (Figure 15). Cladoceran egg densities were significantly higher at NIA14 (pooled over time, assuming equal variances) as compared to NIA13 (One-way ANOVA; F=7.20, DF=10, p=0.02). Copepod egg numbers per individual were not different between these two stations

(F=0.074, DF=10, p=0.79). There also was no evidence of increased copepod juveniles (nauplii or copepodids of either group) downstream of the reservoirs relative to upstream (Figure 14).

When averaged across the sampling season we observed a declining trend in density and biomass from the mouth of the river towards the falls, minimal zooplankton presence above the turbines, with a small measure of recovery further downstream (Table 10). Veligers comprised the largest portion of zooplankton density and calanoids dominated the biomass at all stations. The total potential seasonal production (which assumes that all individuals in the sample were alive at time of collection) for the zooplankton community also reflects these trends (Table 10). Viability of zooplankton was not directly addressed in this report, though animals were noted to be actively swimming in the sample prior to preservation.

Hydroelectric reservoir contribution to lower river plankton

Calculation of the combined reservoirs plankton biomass can be done through a mass-balance relationship, based on combining solutions with different volumes and concentrations. This uses the assumption that 60% of the total daily flow of the Niagara River is diverted for hydroelectric purposes (Miller and Kappel 1987; URS Corporation et al. 2005) and enters the river between NIA13 and NIA14 (see Figure 1):

$$\text{Final Conc} = \frac{\text{Conc1} \times \text{Vol1}}{\text{Vol1}+\text{Vol2}} + \frac{\text{Conc2} \times \text{Vol2}}{\text{Vol1}+\text{Vol2}}$$

where,

Volume of river at NIA13 = V13 [m^3]

Vol. Reservoir Discharge = $V13 \times \frac{60}{40}$ (e.g. 60% of total volume) = $V13 \times 1.5$ [m^3]

Total volume at NIA14 = $V13 + (V13 \times 1.5)$

and,

Contribution of NIA13 = NIA13 [mg m^{-3}] $\times \frac{V13}{V13+V13\times1.5}$

Contribution of Reservoirs = Res [mg m^{-3}] $\times \frac{V13\times1.5}{V13+V13\times1.5}$

therefore,

$$\text{NIA14 [mg m}^{-3}\text{]} = \text{NIA13 [mg m}^{-3}\text{]} \times \frac{V13}{V13+V13\times1.5} + \text{Res [mg m}^{-3}\text{]} \times \frac{V13\times1.5}{V13+V13\times1.5}$$

$$= \text{NIA13 [mg m}^{-3}\text{]} \times \frac{V13}{2.5\times V13} + \text{Res [mg m}^{-3}\text{]} \times \frac{V13\times1.5}{2.5\times V13}$$

reorganised as a function of the reservoirs,

Reservoir Conc. [mg m^{-3}] = ((NIA14 [mg m^{-3}] X 2.5) – NIA13 [mg m^{-3}]) / 1.5

= **(NIA14 X 1.67) – (NIA13 X 0.67)** (3)

Any difference between the reservoirs (US and Canadian) cannot be discriminated, because both of the hydroelectric plants empty into the same location on the river. Using this relationship, the reservoir system is likely to have ~1.5x (±0.5 SD) the biomass of algae at NIA13 based on chlorophyll *a* concentration. The total phytoplankton biomass is likely ~3.5x (±5.4 SD) the value at NIA13, with chrysophytes having the greatest contribution (~22.1x ±22.8 SD). The total zooplankton biomass is likely ~6.7x (±4.1 SD) the value at NIA13, with copepods having the greatest contribution (Calanoids ~11.3x ±6.3 SD and Cyclopoids ~8.9x ±10.9 SD).

Planktivorous fishes

Results from electrofishing surveys completed in 2015 in the upper and lower Niagara River by DFO are used to characterize the typical fish communities of the river (Biodiversity Database, DFO). A full report of the fish community is forthcoming (R. Gáspárdy, pers. comm.). Data from the four closest transect stations to NIA11 and NIA12 were used in the upper river (DFO Species at Risk (SAR) Stations 11, 12, 21, 22) and NIA14 and NIA4 in the lower river (DFO SAR Stations 71, 72, 81, 82) for comparison. Overall, the Niagara River fish densities were 0.09 fish s^{-1}, intermediate compared to the Detroit (0.169 fish s^{-1}) and St. Clair River (0.063 fish s^{-1}) surveys from DFO. The fish community composition was very different between the upper and lower river, with much lower catches (density) but similar overall biomass in the lower river due to the dominance of larger sized fishes (Figure 16). Piscivorous fishes were common in the lower river dominated by salmonids, Lake Trout (*Salvelinus namaycush*), Smallmouth Bass (*Micropterus dolomieu*), and Bowfin (*Amia calva*). The primary piscivores in the upper river were Largemouth Bass (*M. salmoides*), Smallmouth Bass and Pumpkinseed (*Lepomis gibbosus*). Planktivorous fish biomass in the lower river was dominated by large-bodied Gizzard Shad (*Dorosoma cepedianum*) and Yellow Perch (*Perca flavescens*), but the smaller, but much more numerous Emerald Shiner (*Notropis atherinoides*) and Yellow Perch (*P. flavescens*) were common in the upper river. Densities of planktivorous fishes were significantly higher in the upper river 75 ± 88 (SD) CPUE(x1000) s^{-1} compared to the lower river 15.5 ± 13 (SD) CPUE(x1000) s^{-1} ($F=5.30$, $DF=23$, $p<0.03$) due to the very high densities of Emerald Shiner. However, when accounting for the larger-bodied Gizzard Shad in the lower river, there is no significant difference between upper 2.2 ± 2.6 (SD) [CPUE-Mass s^{-1}] and lower river 1.3 ± 1.4 (SD) planktivorous fishes biomass ($F=0.96$, $DF=23$, $p=0.34$).

DISCUSSION

The Canadian section of the Niagara River AOC currently includes the entire length of the western side of the river, including the Canadian side of Niagara Falls (and the Welland River watershed). The Niagara River does not act as a traditional river; instead it serves as a connecting channel between two large lakes where the flow is high, but consistent throughout the year, varying only by changes in Lake Erie levels. The high discharge, but short retention time within connecting channels makes them a challenging system to assess for plankton ecology studies. Since connecting channels between large lakes exist almost uniquely within Laurentian Great Lakes, comparing their impact on the ecology of plankton to other sites is very challenging. The only system outside of the Great Lakes that has been studied for plankton ecology are the connecting channels associated with the Sea of Marmara, which is connected to the Black Sea via the Bosphorus and with the Aegean Sea of the Mediterranean via the Dardanelles. Both of these are considered straits because the seas have different salinities, very complex flow dynamics which are dependent on the resulting density differences (surface water outflow and deep salty water inflow). These physical characteristics fundamentally drive the ecology of this system (Kovalev et al. 1999; Isinibilir et al. 2011), which do not occur in a freshwater system such as the Niagara River. Other Great Lakes connecting channel assessments of plankton are ongoing (e.g., Detroit River).

Although it has a high discharge, the Niagara River is relatively constant compared to large rivers, and does not undergo large fluctuations in flow or depth throughout the year. This consistency has allowed extensive infrastructure for shipping associated with the Erie Canal to be built on the US side of the Niagara River. These efforts to improve navigation have led to significant changes to the morphology of the river. The Niagara River receives generally high quality source water from Lake Erie, with contaminants usually locally sourced from the industry

along the river (Edwards et al. 1989). The American shores of the upper Niagara River had extensive industrial, chemical and manufacturing infrastructure compared to the Canadian side of the river (Rossi 1996). Concerns on the U.S. side include legacy of these hazardous waste sites, made notorious by the events of Love Canal. The east branch of the Niagara River flowing around Grand Island also has very high recreational boating usage. Most impacts of concern for the Canadian RAP have focused on nutrient abatement, releases of untreated wastewater discharges and some contaminated sediment pollution from industry, almost entirely within the Welland River. The Welland River empties into the Niagara River via the Chippawa Canal and hydroelectric power system, which was not sampled for this study. Instead, this report infers the impact of the reservoirs on the lower Niagara River by comparing samples collected above the turbines (NIA13) to samples collected below the turbines (NIA14); these sites were chosen deliberately because there was an expected effect of water impoundment.

The Niagara River is thermally well mixed across and vertically through the water channel with temperatures varying only ±0.2 °C at most, along the river at any one sampling event. This was expected given the high flows known within the river (URS Corporation et al. 2005). The cross-river transects showed very little difference in chlorophyll, turbidity and conductivity across the river, with the exception of occasional minor differences associated with the very nearshore of riverbanks. The flow near the banks is approximately half of the center channel, with habitat in the form of local eddies and back flows, which may provide increased residence time to plankton in the river, but overall these results suggest that the river is well mixed from top to bottom and bank to bank.

Both the EXO2 and the FluoroProbe use chlorophyll fluorescence sensors and have similar detection limits (~0.1-0.2 µg L^{-1}). The chlorophyll *a* levels reported by these sondes in the Niagara River are extremely low, ranging from 0.0 to 2.1 µg L^{-1}; with 26% and 59% of the EXO and fluorometer readings below reliable measurement limits, respectively. The chlorophyll values reported by the sondes are supported by standard extraction techniques (average of 1.3 µg L^{-1}). Small fluctuations between stations are likely a result of the probes measuring extremely low levels of chlorophyll at the detection limits of the instruments. This is not unexpected because the outflow waters of Lake Erie generally have low chlorophyll *a* levels, and given the high flows in the Niagara River, the system is likely to be dominated by attached macrophytes (Vis et al. 2007). Gunderson (2015) found that macrophytes in the Niagara River around Grand Island were common in the nearshore, being encountered up to 80% of the time depending on sediment coarseness.

There is a clear delineation between Lake Erie stations and those within the Niagara River, but the zones within the Niagara River are less well defined. Lake Erie water feeding into the River has similar chlorophyll *a* levels throughout the sampling season (less than 2 µg L^{-1}, May through October 2001-2002) (Depew et al. 2006). Generally speaking, chlorophyll *a* was lowest above the turbines, turbidity increased as water traveled over the falls towards Lake Ontario and conductivity increased by a trivial amount (~2 µS cm^{-1}) after going over the falls. Potential causes of chlorophyll *a* decline within the river could be consumption by filter-feeders such as dresseinid mussels or herbivorous zooplankton (Twiss et al. 2010). The lower river increase in chlorophyll may be from input from the hydroelectric reservoirs where algae had a refuge. The reservoirs could also be acting as a nutrient and contaminant source which could have impacts on the plankton, though no contaminants were measured for this study. Onuska et al. (1983) showed that sediment at the Niagara River mouth contained a multitude of organic contaminants. Kauss and Post (1987) and Williams et al. (2003) showed that the Sir Adam Beck Power Reservoir also contains heavy metal and organic contaminants. Through the processes of bioaccumulation and transport in zooplankton tissues and feces, pollutants may be carried

into Lake Ontario and sink into the sediment once the river current slows (Durham and Oliver 1983; Strickland 1983).

The Sir Adam Beck hydroelectric reservoirs are not explicitly included in this study, though impoundments have been shown to potentially alter the natural community composition of the plankton in large Chinese rivers (Li et al. 2013). With about 60% of the Niagara flow being diverted the Sir Adam Beck forebay and reservoir (storage for about 1.9×10^7 m^3 of water) and Lewiston forebay and reservoir (8.5×10^7 m^3 of water) on the US side, these structures may provide plankton with a refuge from the fast-flowing river and the opportunity to recover (Williams et al. 2003). Given the correct conditions and sufficient residence time, eutrophication of the reservoirs could conceivably occur (see Li et al. 2013). This could be intensified by release of untreated wastewater into the Chippawa Canal. Eutrophication mechanics and phytoplankton assemblage dynamics have been influenced by cascading dams such as the Paranapanema River in Brazil (Nogueira et al. 2010) and a tributary of Yangtze River in China (Zhang et al. 2010).

Sedimentation is known to occur within the reservoirs (Williams et al. 2003) and Munawar et al. (1983) found that phytoplankton assemblages exposed to Niagara River sediment elutriate in increasing concentrations were increasingly inhibited in their productivity rates. When the elutriate was treated to remove metals, the phytoplankton assemblages showed increased growth over the controls since the removal of the dissolved metals removed the possibility of the synergistic interaction between dissolved metals and organic compounds released in the standard elutriate (Munawar et al. 1983). Increased time of exposure in the hydroelectric reservoirs is likely to exacerbate this effect, but this was not tested in this study (see Williams et al. 2003).

From a nutrient and hydrological perspective, the Niagara River shows many similarities to other oligotrophic systems (Stockner et al. 2005), including low nutrients, domination by small plankters, small diatoms and low primary production rates. Nutrients tended to decrease from the mouth of the river towards the falls, and occasionally rebound in the lower river (NIA4), but levels were low overall. High concentrations of organic and inorganic particles can have negative effects on the survival of certain zooplankton (Pace et al. 1992) however river levels of particulates were less or equal to that of eastern Lake Erie (Dove and Chapra 2015). Some rivers have shown seasonal fluctuations of nutrients which were inversely linked to discharge levels (Thorp et al. 1994), but as stated previously, discharge variability is low for the Niagara River. The St. Lawrence River has shown increased silica concentrations correlated to the thermal stresses in the river and increased TP with transit downstream (Twiss et al. 2010). In contrast, both parameters remained fairly consistent for the entire length of the Niagara River. The Niagara River and the St. Lawrence (Cornwall) AOC both showed similar levels of nitrite+nitrate and TP (Munawar and Fitzpatrick, 2006). Light limitation in riverine environments has been proposed as the factor controlling the development of eutrophic conditions in short-retention-time rivers (Reynolds et al. 1994; Hilton et al. 2006). The light attentuation coefficient at Niagara reflected clear water (0.2~0.7 m^{-1}) and was similar to the St. Lawrence River (0.1~0.5 m^{-1}; Twiss et al. 2010), where the euphotic depth was estimated to reach the river bottom in most places.

Phytoplankton

There are no other studies of the plankton of the Niagara River we have found, which differs from the other connecting channels, with Niagara River biota being conspicuously absent from the major review of the connecting rivers within the Great Lakes in Edwards et al. (1986). As such, there is little data to compare this study with over time, so any comparisons are to values found in other connecting channels or large rivers.

Aquatic systems with short residence times and higher flows, particularly rivers, tend to have lower abundances of phytoplankton (Chandler 1937; Pace et al. 1992; Basu and Pick 1996; Walks and Cyr 2004). Søballe and Kimmel (1987) analysed large data sets which included algal cell counts from 136 rivers (average cell abundance of 8,487±973 cells mL^{-1}), and found that residence time was an important property distinguishing differences in the abundance of phytoplankton among rivers, reservoirs and lakes. This trend is supported by the phytoplankton biomass observed in the Niagara River which ranged from 44 to 503 mg m^{-3} over the sampling season. By comparison, phytoplankton biomass in the St. Lawrence AOC (which includes an 80 km long stretch of the St. Lawrence River) ranged from 46 to 323 mg m^{-3} at mid-channel sites during surveys conducted in June, July and September of 2004 (Munawar and Fitzpatrick 2006) which were very similar to the Niagara River, although some higher values were reported at nearshore sites. The slightly wider range observed mid-channel in the Niagara River may be due to a variety of factors, including the water feeding the river or the presence of the hydroelectric reservoirs which diverts the fast moving river into a refuge of sorts and gives phytoplankton biomass an opportunity to recover. Unlike the Niagara River AOC, the St. Lawrence AOC which begins directly downstream of hydroelectric plants, instead relies on the outflow of the river. Boundary effects in the river above the turbines (NIA13) might also provide relatively slower currents which may encourage the accumulation of algal cells. In contrast, the St. Lawrence AOC also had single-species algal blooms at two nearshore sites peaking at 2,365 and 3,760 mg m^{-3}, an extent which was not observed in the Niagara River. Flow rates in the St. Lawrence are much less than those found in the Niagara River so this may be contributing factor.

In general, diatoms were the most prevalent group in the Niagara River community. In recent years (2001-2011), diatoms (particularly *Aulacoseira islandica* and *Stephanodiscus parvus*) have been a significant aspect of the phytoplankton ecology of the eastern basin of Lake Erie, particularly in the spring (Alliger and Reavie 2013). Both *Aulacoseira* sp. and *Stephanodiscus* sp. were both found in high numbers in the river. Diatom species are favoured in high flow systems (Reif 1939; Perry et al. 1990; Reynolds et al. 1994; Rojo et al. 1994), because their strong skeletal structure allows them to be more resilient to the turbulent conditions of the river than any other phytoplankton group. *Fragilaria crotonensis*, a species which was a significant contributor to summertime biomass in eastern Lake Erie in 2008 and again in 2011 (Alliger and Reavie 2013), appears to survive the entire length of the Niagara River, as shown by its presence at NIA4 in August 2014. Cryptophytes were also a significant contributor to total phytoplankton biomass, particularly upstream, being sourced from Lake Erie. However, recent Lake Erie data shows a decreasing trend of cryptophyte biomass in the eastern basin (Alliger and Reavie 2013). The Environmental Protection Agency Great Lakes National Program Office (EPA-GLNPO) data presented by Alliger and Reavie (2013) does show an increasing trend of blue-green (Cyanobacteria) biomass in the summer. The elevated biomass observed in September at NIA13 was dominated by the mat forming cyanobacteria *Lyngbya birgei,* which was not observed at any other site in the river in September. This suggests that the conditions necessary for algal success (e.g., back eddies) are present between the upriver sampling site (NIA10) and NIA13, which provide an area of low flow, relatively high levels of substrate to attach to, and increased residence time (Li et al. 2013). It is common for high concentrations of filamentous, colonial, gelatinous and/or toxic algae to be present in rivers with short water residence times (Reif 1939; Pace et al. 1992; Hilton et al. 2006). Common species in the Niagara River were chain-forming diatoms *Fragilaria crotonensis* and *Skeletonema potamos* (a tolerant species adapted to riverine systems), in addition to the filamentous cyanobacteria *Lyngbia*. However, the observed biomass of these (and indeed all) species was actually quite low. Alternatively, in the St. Lawrence AOC, filamentous species (benthic chlorophyte *Zygnema* sp. and the cyanophyte *Microcystis botrys*) were the drivers of peak algal events (Munawar and

Fitzpatrick 2006), which is likely due to the different source water from either Lake Ontario or the localized effects of the Raisin River. Finally, chlorococcal species of phytoplankton were found in the Niagara River (albeit at low concentrations), particularly *Scenedesmus* spp., which are indicators of clear water since they have higher threshold light requirements (Reynolds et al. 1994).

Primary productivity in the Niagara River was highest within Lake Erie at the mouth of the river and decreased sharply when entering the river. From a cell-size perspective, nanoplankton productivity was the highest followed by picoplankton productivity, and similar to observations from the St. Lawrence AOC and in Lake Ontario (Munawar and Fitzpatrick 2006). Primary productivity of Lake Erie also reflects a similar characteristic of nanoplankton and picoplankton dominating the production (Munawar et al. 2008). Total primary productivity declined beyond the mouth of the river but returned to near-original values in the lower river (NIA4). This trend was most apparent during the summer months, when phytoplankton biomass was greatest. A correlation was found between upper and lower river productivity, but only if there was a significant residence time (time lag) in the river. With the average residence time of the river ranging from hours to a day, and the production peaks occurring an average of 25 days apart, it suggests that the primary productivity increase seen in the lower river is due to water being retained within the hydroelectric reservoirs.

While phytoplankton community composition and biomass remain fairly consistent down the length of the Niagara River, the productivity of the Niagara community is influenced by natural or man-made riverine conditions. Excluding the occasional peaks in individual algae species, there is only a small dip in phytoplankton biomass following the falls. This suggests that low phytoplankton biomass is not predominantly caused by physical damage from the turbulence of the falls and/or the turbines (Marcy Jr. et al. 1978), increased predation (Walks and Cyr 2004), increased downstream turbidity (Basu and Pick 1996), or instream macrophyte beds causing decreases in plankton densities (Welker and Walz, 1998; Basu et al. 2000b; Walks and Cyr 2004). Rather, high flow speeds and low water residence time are driving low biomass values along the entire length of the river (see also Pace et al. 1992; Basu and Pick 1996; Walks and Cyr 2004). The result in the Niagara River is a potamoplankton phytoplankton community composed of species best able to survive lotic conditions present from the river mouth to the outlet into Lake Ontario. The productivity of this community suggests that the fast moving upper river is not conducive to phytoplankton growth. However below the falls the river is equally as swift but significantly deeper and suggests a more productive community downstream (NIA4). Furthermore, natural refugia in the lower river: benthic zone, eddies etc. (Reynolds et al. 1994), combined with the input from the hydroelectric reservoirs is creating a more productive phytoplankton community.

Bacterial production fluctuated throughout the season, with early July being of particular note. The peak in bacterial productivity coincided with a slight increase in chlorophyll *a* but not in phytoplankton biomass. High phosphorus was not recorded at the site of highest bacterial production (NIA13). The likely explanation for the increased bacterial production values in the lower river could be increased July precipitation which likely increased runoff and loadings into the power plant canal system. In particular, the Niagara Falls, ON Wastewater Treatment Plant and the Welland River empty into the Niagara River via the Chippawa Canal, both of which could lead to increased bacterial growth in the downstream stations. However, it is unknown if high precipitation in July led to any capacity exceedances or release of untreated sewage.

The increase in microbial loop biomass, which was dominated by bacteria, at NIA4 in July could also be sourced from the hydroelectric reservoirs since it was more than 2.5x the biomass above the turbines (NIA13). The increase at NIA10 in September was a localized effect from Lake Erie, and did not appear to have impacted the microbial biomass downriver. Historically,

eastern Lake Erie has shown high proportions of bacteria, but lower total microbial biomass (Munawar et al. 2008). Bacterial counts from the Eastern end of Lake Erie were found to be an order of magnitude less than those found in the Niagara River at 1.21 $x10^6$ ml^{-1} (DeBruyn et al. 2004). In comparison to the St. Lawrence AOC, where HNF were the dominant microbial loop components throughout the year and bacterial biomass ranged from only 0.04 to 0.18 g m^{-3} (Munawar and Fitzpatrick 2006), the Niagara River was dominated by bacteria in comparatively high amounts. The microbial loop biomass at Niagara is comparable to the Bay of Quinte, which is noted for its high biomass of microbial heterotrophs (M. Munawar, unpublished data). Of particular note, the presence of HNF is limited to the mouth and foot of the river (NIA10 and NIA4) where conditions in the river are calmer. Increases in bacterial productivity did not coincide with changes in bacterial biomass. Given the small size of bacteria, the effects of turbulence and advection are likely to be minimal, and as observed, the microbial loop biomass is relatively unaffected by transit through the river.

Zooplankton

There is little to no information on historic zooplankton composition in the Niagara River, with only the Patalas (1969) study, which included a Lake Ontario station near the outflow of the river, indicating a differential, warmer habitat for plankton compared to the rest of the lake. There is also very little recent information on zooplankton from the far eastern basin of Lake Erie, and relatively dated past information, with regular sampling programs in Erie ending in the mid-1990s (see Johannsson et al. 1999).

Although zooplankton community composition among the Niagara River stations in 2014 remained relatively unchanged, abundance and biomass declined significantly from Lake Erie downstream into the river. This is consistent with the findings of Walks and Cyr (2004) who found loss of most zooplankton within 50 m into rivers at four sites in Algonquin Park. In contrast to the Niagara River with an outflow of 6,500 m^3 s^{-1}, Walks and Cyr (2004) studied considerably smaller rivers (outflow discharge of 0.2-0.3 m^3 s^{-1}) with small feeder lakes. They found that lake morphology affects river input and the persistence of plankton in the river. In larger rivers, such as the Niagara, plankton communities persist much further downstream than in smaller rivers (Brook and Rzoska 1954; Rzoska et al. 1955; Cushing 1963; Talling and Rzoska 1967; Shiel et al. 1982; Saunders and Lewis 1988; Kobayashi 1997; Welker and Walz 1998; Basu et al. 2000a), suggesting that persistence is also related to river size (zooplankton density decreases faster in shallow outlet streams than in deeper ones; Walks and Cyr 2004). It is possible that their findings might scale up to larger rivers such as the Niagara, where zooplankton persisted at least 10 km into the river. There is a general consensus in the literature that rivers show a significant decline in zooplankton as compared to lentic environments such as lakes, however there lacks agreement on the cause of this decline which include increased turbidity, high concentrations of organic and inorganic particles, and limited high-quality food (Pace et al. 1992). It has been suggested that lentic zooplankton are simply not able to survive in river environments due to the advective transport of food and individuals by water currents (Wahl et al. 2008). Advection (Pace et al. 1992) and/or residence time of rivers correlates with zooplankton biomass (Basu and Pick 1996; Walz and Welker 1998; Walks 2003), but not with phytoplankton, all of which supports why zooplankton biomass drops off so quickly in the Niagara River while phytoplankton biomass is less affected.

The opportunities for zooplankton persistence in fast flowing rivers consist of refugia from the current in the form of eddies, embayments, low flow areas, slackwater areas and deadzones (Pace et al. 1992; Reynolds et al. 1994; Thorp and Casper 2003; Genin et al. 2005; Walks 2007). As with phytoplankton, there appears to be resilient zooplankton species which survive better in and dominate riverine environments (Reif 1939). Research has shown that some large zooplankters such as the calanoid copepod *Eurytemora affinis* may be strong enough swimmers

to seek refuge lower in the water column of large rivers (Jack et al. 2006), since the water current speeds approach zero near the bottom (Vogel 1981). Another copepod, *Temora longicornis* is able maintain foraging speeds of 6 mm s^{-1}, with escape bursts of up to 80 mm s^{-1} (Van Duren and Videler 2003). *Bosmina*, a common cladoceran in the Niagara River, can only briefly reach speeds of 10 mm s^{-1} so is not likely to navigate the water current (Zaret and Kerfoot 1980), which sometimes approached 2 m s^{-1} (2,000 mm s^{-1}).

Turbulence, like that in coastal shorelines and in the wake of motorized boats, has been found to cause up to 34% mortality in copepods (Bickel et al. 2011). Horvath and Lamberti (1999) found that veligers were highly susceptible to damage by physical forces in high current streams (>1.0 $m \cdot s^{-1}$), which could limit veliger survival during downstream transport. Increased current velocities have been documented to increase mortality up to 20% among cladocerans, 40% in rotifers and 50% in copepods (Telesh 1986) and it has been estimated that current speeds greater than 0.25 m s^{-1} will lead to the death of lentic zooplankton (Tang et al. 2014). Niagara River velocities are greater than 1 m s^{-1} until approximately midway through the lower river. It is likely that the plankton are not actively feeding or effectively swimming during passage through the river (transit time of hours) and are most likely just drifting along with the current, not given much opportunity to seek out food or shelter (Hart et al. 1996). The relatively short-term turbulence of the river may lead to both positive and negative effects on predator-prey contact and feeding ability of copepods (Pace et al. 1992), with larger calanoid copepods better able to cope than smaller-sized groups (Sluss et al. 2008). In general, powerful swimmers such as predatory copepods, tend to be more successful in maintaining their position and continue to feed in highly turbulent systems compared to much slower and more awkward swimmers such as cladocerans (Visser et al. 2009; Tóth et al. 2011). This corresponds with our results showing a persistence of calanoid copepods (and the juvenile stages of copepodids and nauplii) and dreissenid veligers in the river. That said, we did not observe a decline in the relative contribution of cladocerans with increasing distance downstream, so they did not appear to be impacted by the river forces any more than other zooplankton groups.

Predation is often cited as a leading potential cause of zooplankton biomass decline in rivers (Thorp and Casper 2003; Walks and Cyr, 2004) either from abundant benthic filter-feeding species, notably dreissenid mussels (Welker and Walz 1998; Twiss et al. 2010), feeding on phytoplankton and microzooplankton (rotifers) or by fishes preying on macrozooplankton. Fish planktivory is likely a major factor contributing to the rapid loss of zooplankton biomass as it enters the upper river from Lake Erie. In other rivers, Akopian et al. (1999) and Thorp and Casper (2003) noted that larger zooplankton (particularly *Daphnia* sp. and adult copepods) were being consumed by young Yellow Perch. Emerald Shiner also generally prefer the largest cladocerans, particularly, *Leptodora* or *Bythotrephes* (Pothoven et al. 2009). Emerald Shiner, which along with Yellow Perch dominate the upper Niagara River, show a consumption rate (grams of plankton per gram fish) of 0.21 g/g/d (Pothoven et al. 2009). The feeding rates of Gizzard Shad (the dominant lower river planktivore by biomass) are lower, likely ranging from 0.1-0.15 g/g/d at 20 °C (Sebring 2002). These differences in fish species composition and consumption rates suggest that planktivory in the upper river is likely much greater than below the falls, although total planktivore biomass in the two areas were not significantly different. It is expected that planktivory from Emerald Shiner in the upper river may have a considerable contribution to the decline of zooplankton densities within the river. However, Emerald Shiner are known to have a critical swimming velocity ~0.59 m s^{-1} (Jones et al. 1974), which is much less than measured within the mid-channel of the Niagara, likely restricting these fish to within close proximity of either shoreline (Allen 2015). More light on this subject may be forthcoming through study of the role of these fishes as part of a collaborative “Emerald Shiner Project” in the upper river being led by Buffalo State University (http://emeraldshiner.buffalostate.edu).

There was less evidence of planktivorous fishes altering community composition of zooplankton by selectively consuming larger individuals (Akopian et al. 1999; Thorp and Casper 2003), based on the relatively constant zooplankton community composition observed in the Niagara River. The numerical domination of the river by small taxa (veligers, nauplii, *Bosmina*) is more likely driven by the domination of these organisms in Lake Erie. In general, zooplankton are more strongly affected by residence time in rivers than phytoplankton because of their relatively longer generation times. Smaller species may have an advantage in riverine systems because they have shorter generation times which helps compensate for population losses (Pace et al. 1992), but this is likely not as relevant in the Niagara River given the short retention time.

To determine any river impacts on the zooplankton community, it is also necessary to take into account the seasonal succession patterns in zooplankton. In eastern Lake Erie in the 1990s, cyclopoid copepod species including *Diacyclops thomasi* and cyclopoid nauplii larvae peaked in late spring followed by a summer successional shift from *D. thomasi* to *Mesocyclops edax* and then *Tropocyclops extensus* in the late summer (K. Bowen, unpublished data). The eastern Lake Erie calanoid community remained fairly consistent throughout the year, except for an increased dominance of *Epischura* in the summer. This aligns extremely well with the variability of cyclopoids and calanoids seen in the Niagara River. The overall community composition of the cyclopoids tends to be driven more by seasonal changes than by the environmental conditions of the river, though there is a clear difference in copepod densities in the downstream stations following the input from the hydroelectric plants. In terms of cladocerans, *Daphnia galeata mendotae* and *Bosmina* tended to dominate in the Niagara across the sampling season. The domination of *Bosmina* and the virtual absence of *Eubosmina*, a similar but slightly larger genus, were also consistent with observations in eastern Lake Erie in the 1990s (K. Bowen, unpublished data) and in August 1998 by Barbiero et al. (2001). These sources also indicate both *D. galeata mendotae* and *D. retrocurva* were dominant summer species in the 1990s in eastern Lake Erie, along with *D. longiremis*, a *Daphnia* species not identified in the Niagara River in 2014.

Though reservoir systems have a history of being ignored scientifically, their dynamics and complexity have become an important field of study within limnology given their differences to both lakes and rivers (Thornton et al. 1990). Akopian et al. (1999) showed that the Marne Reservoir (residence time 4-6 month) acts as a zooplankton source for the river. This is relevant for the Niagara River given the presence of hydroelectric reservoirs on both sides of the border. In order for the reservoirs to act as a zooplankton (and phytoplankton) source for the lower river, a portion of the plankton must persist in the reservoir for a period of time, and be viable after having traveled through the hydroelectric turbines. The sources of mortality due to hydroelectric turbines include blade strikes, shear stress, cavitations, turbulence, and barotraumas (Schlezinger et al. 2013). The literature reports zooplankton mortality ranging from 5 to 23% (Dubovskaia et al. 2004; Schlezinger et al. 2013) resulting from passage through hydroelectric power stations, and that mortality may be directly related to animal size (Cada 1990). Our report did not specifically address viability through verification of the proportion of live zooplankton in the river; however qualitative microscopic examination of an unpreserved sample collected in July at NIA14 indicated most animals were alive. Other preserved samples did not appear to show physical damage of zooplankton carapaces, however pressure-induced mortality remains possible. In a similar manner, the primary productivity experiments detailed above clearly demonstrate that phytoplankton were alive and able to phytosynthesize after traveling over the falls and/or through the hydroelectric turbines. Our estimates based on combining waters of different plankton concentrations indicates that certain zooplankton groups, in particular copepod densities may be as much as 10x higher in the hydroelectric canal/reservoir system as found within the river, and eggs per individual are higher in cladocerans below the power plants. This suggests an overall positive influence on zooplankton populations in the lower river due to

the impoundment of water in the hydroelectric reservoirs. Future research on Niagara River zooplankton should include sampling within the reservoirs and channels themselves to directly measure this effect.

SUMMARY AND RECOMMENDATIONS

This survey examined the composition of the phytoplankton and zooplankton communities of the Niagara River during the 2014 sampling season. In this time period, the Niagara River exhibited the conditions of a low-productivity, clear-phase system with considerable primary production by macrophytes enhancing the phytoplankton. This report, which sought to examine the degradation of phytoplankton and zooplankton population for the Niagara River AOC, found that while the plankton levels in the Niagara River are very low as compared to the adjacent lakes, reduced densities of phytoplankton and zooplankton are expected in riverine environments. There is a well-documented correlation between decreased residence time (i.e., increased current speed) and decreased plankton biomass, therefore the low plankton biomass within the river should not immediately be a cause for concern. There is little evidence to suggest that the diatom peak (August), and blue-green algae peak (September), were persistent or were likely detrimental to the system. Overall, the levels of the peak algal biomass did not exceed 503 mg m^{-3}, significantly less than the definition of a eutrophic algal bloom. The phytoplankton community within the river is dominated by diatoms, particularly by filamentous or colonial forms that are suited to high-energy flow systems such as *Fragilaria crotonensis* and *Skeletonema potamos*. In general, the phytoplankton and zooplankton communities are similar to those in other lentic environments, dominated by certain species better suited to the highly turbulent conditions found in rivers. While high veliger densities were found throughout the summer, these matched the pattern found in the water entering from Lake Erie, and the Niagara River is known to have high densities of adult dreissenid mussels. Moreover, the planktivorous fish population in the upper river, dominated by Emerald Shiner, is quite high and likely contributes to the reductions in zooplankton densities. Any reductions in biomass and changes in species compositions are consistent with expectations for a large river system, indicating no impairment of phytoplankton or zooplankton populations in the Niagara River. There is some evidence that entrainment time in the hydroelectric reservoirs might be promoting an increase in phytoplankton and zooplankton growth, though it was outside the scope of this monitoring survey. If assessing the role of the hydroelectric reservoirs is deemed important, then the project should include sampling within the reservoirs over the growth period of plankton (i.e., May-October), and any exceedances from the Niagara Falls Wastewater Treatment Plant should be recorded.

ACKNOWLEDGEMENTS

All of the authors would like to acknowledge the contributions of individuals who provided data, gave support or improved the manuscript. Many people were instrumental in completing work in the field and lab and assisting with data analyses and guidance, including DFO Freshwater Ecosystem Group: Angela Wilson, Amanda Conway and Marten Koops. Fish data was provided through fieldwork by DFO SAR Group led by Robin Gáspárdy and Lynn Bouvier; and from the Niagara River Emerald Shiner Project from Alicia Pérez-Fuentetaja. Phytoplankton, primary production and microbial loop findings were carried out under the supervision of Mohi Munawar. Thanks to Claudiu Tudorancea, the St. Lawrence River Institute of Environmental Sciences and Amanda Conway for zooplankton and rotifer sample enumeration and taxonomy. Funds were secured through ECCC under the Great Lakes Action Plan, upon request from the Niagara River RAP and research base funding at DFO GLLFAS.

REFERENCES

Akopian, M., Garnier, J. and Pourriot, R. 1999. A large reservoir as a source of zooplankton for the river: structure of the populations and influence of fish predation. J. Plankton Res. **21**(2): 285-297.

Allen, I. 2015. Hydrodynamic modeling of the upper Niagara River to assess aquatic connectivity of the Emerald Shiner (*Notropis atherinoides*) population. M.Sc. thesis, University at Buffalo, State University of New York.

Alliger, L.E. and Reavie, E.D. 2013. The ecological history of Lake Erie as recorded by the phytoplankton community. J. Great Lakes Res. **39**: 365-382.

Barbiero, R.P., Little, R.E. and Tuchman, M.L. 2001. Results from the U.S. EPA's Biological Open Water Surveillance Program of the Laurentian Great Lakes: III. Crustacean Zooplankton. J. Great Lakes Res. **27**(2):167–184.

Bowen, K.L. 2017. Laboratory methods for the determination of zooplankton density, biomass and secondary production. Can. Tech. Rep. Fish. Aquat. Sci. XXXX: X + XXp.

Basu, B.K., Kalff, J. and Pinel-Alloul ,B. 2000a. Midsummer plankton development along a large temperate river: the St Lawrence River. Can. J. Fish. Aquat. Sci. **57**: 7–15.

Basu, B.K., Kalff, J. and Pinel-Alloul, B. 2000b. The influence of macrophyte beds on plankton communities and their export from fluvial lakes in the St Lawrence River. Freshwater Biol. **45**: 373-382.

Basu, B.K. and Pick, F.R. 1996. Factors regulating phytoplankton and zooplankton biomass in temperate rivers. Limnol. Oceanogr. **41**(7): 1572-1577.

Bickel, S. L., Hammond, J.D.M. and Tang, K.W. 2011. Boat-generated turbulence as a potential source of mortality among copepods. J. Exp. Mar. Biol. Ecol. **401**: 105–109.

Broderick, W. 2009. Niagara power project – A success story of international cooperation. Transactions of the Twenty Third International Congress on Large Dams, 28A, Brasilia-Brazil. International Commission on Large Dams.

Brook, A.J. and Rzoska, J. 1954. The influence of the Gebel Aulia Dam on the development of Nile plankton. J. Anim. Ecol. **23**: 101–115.

Cada, G.F. 1990. A Review of Studies Relating to the Effects of Propeller-Type Turbine Passage on Fish Early Life Stages. N. Am. J. Fish. Manage. **10**(4): 418-426.

Chandler, D. C., 1937. Fate of typical lake plankton in streams. Ecol. Monogr. **7**: 445–479.

Crumpton, W.G. 1987. A simple and reliable method for making permanent mounts of phytoplankton for light and fluorescence microscopy. Limnol. Oceanogr. **32**(5): 1154-1159.

Cushing, C.E. 1963. Filter-feeding insect distribution and planktonic food in the Montreal River. T. Am. Fish. Soc. **92**: 216–219.

DeBruyn, J.M., Leigh-Bell, J.A., McKay, M.L., Bourbonnière, R.A. and Wilhelm, S.W. 2004. Microbial distributions and the impact of phosphorus on bacterial activity in Lake Erie. J. Great Lakes Res. **30**(1):166–183.

Depew, D.C., Guildford, S.J. and Smith, R.E.H. 2006. Nearshore–offshore comparison of chlorophyll *a* and phytoplankton production in the dreissenid colonized eastern basin of Lake Erie. Can. J. Fish. Aquat. Sci. **63**: 1115–1129.

Dove, A. and Chapra, S.C. 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. Limnol. Oceanogr. **60**: 696–721.

Dubovskaia, O.P., Gladyshev, M.I. and Makhutova, O.N. 2004. Limnetic zooplankton run-off a high-head dam and their fate in a river with high current velocity (case of the Krasnoiarsk hydroelectric power station on the Yenisei river) [In Russian]. Zh Obshch Biol. **65**(1):81-93.

Durham, R.W. and Oliver, B.G. 1983. History of Lake Ontario contamination from the Niagara River by sediment radiodating and chlorinated hydrocarbon analysis. J. Gr. Lakes Res. **9**(2):160-168.

Edwards, C.J., Hudson, P.L., Duffy, W. G., Nepszy, S.J., McNabb, C.D., Haas, R.C., Liston, C.R., Manny, B. and Busch, W.D.N. 1989. Hydrological, morphometrical, and biological characteristics of the connecting rivers of the international Great Lakes: A review. pp. 240-264. *In* D.P. Dodge (ed.) Proceedings of the International Large Rivers Symposium, Can. Spec. Publ. Fish. Aquat. Sci. 106.

Environment and Climate Change Canada. 2016. Great Lakes Surveillance Program STAR database. Retrieved: April 2016, Burlington, ON.

Genin, A., Jaffe, J.S., Reef, R., Richter, C. and Franks, P.J.S. 2005. Swimming Against the Flow: A Mechanism of Zooplankton Aggregation. Science. **308**:860-862.

Great Lakes Connecting Channels: Governance, Ecosystem Science and Management conference. 2009. Final Program. June 12, 2009, Center for the Arts, University at Buffalo, Buffalo, New York. Accessed online April 2016, from http://wings.buffalo.edu/intled/trun/files/GtLksConf09Flyer.pdf

Gunderson, M.D. 2015. Habitat-assemblage relations and seasonality of aquatic macrophytes in the upper Niagara River. M.Sc. thesis. State University of New York, College of Environmental Science and Forestry, New York, NY.

Heath, R.T. and Munawar, M. 2004. Bacterial productivity in Lake Superior, 2001: Implication for food web efficiencies in oligotrophic freshwater ecosystems. Aquat. Ecosyst. Health. **7**(4): 465 - 474.

Hart, D.D., Clark, B.D. and Jasentuliyana, A. 1996. Fine-scale field measurement of benthic flow environments inhabited by stream invertebrates. Limnol. Oceanogr. **41**(2): 297-308.

Hilt, S., Kohler, J., Kozerski, H. P., van Nes, E. H. and Scheffer M. 2011. Abrupt regime shifts in space and time along rivers and connected lake systems. Oikos. **120**(5): 766–775.

Hilton, J., O'Hare, M., Bowes, M.J. and Jones, J.I. 2006. How green is my river? A new paradigm of eutrophication in rivers. Sci. Total Environ. **365**: 66–83.

Horvath, T.G. and Lamberti, G.A. 1999. Mortality of zebra mussel, *Dreissena polymorpha*, veligers during downstream transport. Freshwater Biol. **42**: 69–76.

Isinibilir, M., Svetlichny, L., Hubareva, E., Yilmaz, I. N., Ustun, F., Belmonte, G. and Toklu-Alicli, B. 2011. Adaptability and vulnerability of zooplankton species in the adjacent regions of the Black and Marmara Seas. J. Mar. Syst. **84**(1): 18-27.

International Joint Commission, 1989. Revised Great Lakes Water Quality Agreement of 1978 between the United States and Canada, as amended by protocol, signed November 18, 1987.

Jack, J.D., Fang, W. and Thorp, J.H. 2006. Vertical, lateral and longitudinal movement of zooplankton in a large river. Freshwater Biol. **51**: 1646–1654.

Johannsson, O.E., Graham, D.M., Einhouse, D.W.E. and Mills, E.L. 1999. Historical and recent changes in the Lake Erie zooplankton community and their relationship to ecosystem function. *In* State of Lake Erie (SOLE)—past, present, and future. *Edited by* M. Munawar and T. Edsall. Ecovision World Monograph Series. Backhuys, The Netherlands, pp.169-196.

Jones, D.R., Kiceniuk, J.W. and Bamford, O.S. 1974. Evaluation of the Swimming Performance of Several Fish Species from the Mackenzie River. J. Fish. Res. Board Canada. **31**: 1641–1647.

Kauss, P.B. and Post, L.E. 1987. Contaminant concentrations in bottom sediments of the Sir Adam Beck power reservoir and Niagara River bar dredgeate. Great Lakes Section Water Resources Branch. Ministry of the Environment. Queen's Printer of Ontario.

Kobayashi, T. 1997. Associations between environmental variables and zooplankton body masses in a regulated Australian river. Mar. Freshwater Res. **48**: 523–529.

Kovalev, A.V., Skryabin, V.A. Zagorodnyaya, Yu.A., Bingel, F., Kideyş, A.E., Niermann, U. and Uysal Z. 1999. The Black Sea Zooplankton: Composition, Spatial/Temporal Distribution and History of Investigations. Tr. J. Zoology. **24**: 195-209.

Köhler, J. 1994. Origin and succession of phytoplankton in a river-lake system (Spree, Germany). Hydrobiologia. **289**: 73-83.

Legendre, L. and Rassoulzadegan, F. 1999. Stable versus unstable planktonic food webs in oceans. *In* Microbial Biosystems: New Frontiers Proceedings of the 8th International Symposium on Microbial Ecology. *Edited by* Bell CR, Brylinsky M, Johnson-Green P. Atlantic Canada Society for Microbial Ecology, Halifax, Canada.

Li, J., Dong, S., Liu, S., Yang, Z., Peng, M. and Zhao, C. 2013. Effects of cascading hydropower dams on the composition, biomass and biological integrity of phytoplankton assemblages in the middle Lancang-Mekong River. Ecol. Engineering. **60**: 316-324.

Lund, J.W.G., Kipling, C. and LeCren, E.D.. 1958. The inverted microscope method of estimating algal numbers and the statistical basis of estimation by counting. Hydrobiologia. **9**: 143-170.

Marcy Jr., B.C., Beck, A.D. and Ulanowwicz, R.E. 1978. Chapter 4. Effects and Impacts of Physical Stress on Entrained Organisms. *In* Power Plant Entrainment: A Biological Assessment. *Edited by* Schubel, J.R. and Marcy, B.C. Academic Press Inc, New York. pp.135-188.

Miller, T.S and Kappel, W.M. 1987. Effect of Niagara Power Project on Ground-Water flow in the Upper Part of the Lockport Dolomite, Niagara Falls Area, New York. Water-Resources Investigations Report 86-4130. U.S. Geological Survey, Ithaca, New York.

Munawar, M. and Fitzpatrick, M. 2006. An Integrated Evaluation of the Planktonic Communities of the Cornwall Area of Concern Project Report. Fisheries and Oceans Canada. The St. Lawrence River Restoration Council Committee.

Munawar, M., Mudroch, A., Munawar I. F. and R. L. Thomas. 1983. The impact of sediment-associated contaminants from the Niagara River mouth on various size assemblages of phytoplankton. J. Great Lakes Res. **9**: 303-313.

Munawar, M., and Munawar, I.F. 1996. Phycological studies in Lakes Ontario, Erie, Huron and Superior. Can. J. Bot. **60**: 1837-1858.

Munawar, M., Munawar, I.F., Fitzpatrick, M., Niblock, H., Bowen, K. and Lorimer, J. 2008. An intensive assessment of planktonic communities in the Canadian waters of Lake Erie, 1998

In Checking the Pulse of Lake Erie. *Edited by* Munawar, M., Heath, R.T. Wayne State University Press, Detroit. pp. 297-346.

Munawar, M. and Weisse, T. 1989. Is the 'microbial loop' an early warning indicator of anthropogenic stress? Hydrobiologia. **188/189**: 163-174.

Treaty between Canada and the United States of America Concerning the Diversion of the Niagara River, U.S.-Can, Feb. 27, 1950. E100418 - CTS 1950 No. 3.

National Laboratory for Environmental Testing (NLET), 1997. Manual of Analytical Methods, Major Ions and Nutrients, Volume 1. Environment Canada, Burlington, Ontario.

Nogueira, M.G., Ferrareze, M., Moreira, M.L. and Gouvêa, R.M. 2010. Phytoplankton assemblages in a reservoir cascade of a large tropical–subtropical river (SE, Brazil). Braz. J. Biol. **70**: 781–793.

Onuska, F. I., Mudroch, A. and Terry, K. 1983. Identification and determination of trace organic substances in sediment cores from the western basin of Lake Ontario. J. Great Lakes Res. **9**(2):169-182.

Pace, M.L., Findlay, S.E.G. and Lints, D. 1992. Zooplankton in Advective Environments: The Hudson River Community and a Comparative Analysis. Can. J. Fish. Aquat. Sci. **49**: 1060-1069.

Patalas, K. 1969. Composition and horizontal distribution of crustacean plankton in Lake Ontario. Journal of the Fisheries Board of Canada. **26**(8): 2135-2164.

Perry, S.A., Perry, W.B. and Simmons Jr., G.M. 1990. Bacterioplankton and Phytoplankton Populations in a Rapidly-Flushed Eutrophic Reservoir. Internationale Revue der gesamten Hydrobiologie und Hydrographie. **75**(1): 27-44.

Pothoven, S.A., Vanderploeg, H.A., Ludsin, S.A., Höök, T.O. and Brandt, S.B. 2009. Feeding ecology of emerald shiners and rainbow smelt in central Lake Erie. J. Great Lakes Res. **35**: 190–198.

Reif, C.B. 1939. The Effect of Stream Conditions on Lake Plankton. T. Am. Microsc Soc. **58**(4): 398-403.

Reynolds, C.S., Descy, J.-P. and Padisák, J. 1994. Are phytoplankton dynamics in rivers so different from those in shallow lakes? Hydrobiologia. **289**: 1-7.

Rojo, C., Cobelas, M.A. and Arauzo, M. 1994. An elementary, structural analysis of river plankton. *In* Phytoplankton in Turbid Environments: Rivers and Shallow Lakes. *Edited by* J.-P. Descy, C. S. Reynolds, J. Padisák. Kluwer Academic Publishers, The Netherlands. pp. 43-56.

Rossi, M.C. 1996. An historical sketch of industry along the buffalo river, New York with a focus on chemical manufacturers. Middle States Geogr. **29**: 86-94.

Rzoska J., Brook, A.J. and Prowse, G.A. 1955. Seasonal plankton development in the White and Blue Nile near Khartoum. Internationale Vereinigung fur Theoretische und Angewande Limnologie. **12**: 327–334.

Saunders, J.F. and Lewis, W.M. 1988. Zooplankton abundance and transport in a tropical white-water river. Hydrobiologia. **162**: 147–155.

Schlezinger, D.R., Taylor, C.D. and Howes, B.L. 2013. Assessment of Zooplankton Injury and Mortality Associated With Underwater Turbines for Tidal Energy Production. Mar. Technol. Soc. J. **47**(4): 142-150.

Sebring, S.H. 2002. Development and application of a bioenergetics model for gizzard shad. M.Sc. thesis. Lubbock: Texas Tech University.

Shuter, B.J. and Ing, K.K. 1997. Factors affecting the production of zooplankton in lakes. Can. J. Fish. Aquat. Sci. **54**(2): 359–377.

Stockwell, J. and Johannsson, O.E. 1997. A temperature-dependent, allometric model to estimate zooplankton production in temperate, freshwater lakes. Can. J. Fish. Aquat. Sci. **54**(10): 2350–2360.

Shiel, R.J., Walker, K.F. and Williams, W.D. 1982. Plankton of the Lower River Murray, South Australia. Aust J. Freshwater Res. **33**: 301–327.

Sluss, T.D., Cobbs, G.A. and Thorp, J.H. 2008. Impact of turbulence on riverine zooplankton: a mesocosm experiment. Freshwater Biol. **53**: 1999–2010.

Sommer U., Adrian, R., De Senerpont Domis, L., Elser, JJ., Gaedke, U., Ibelings, B., Jeppesen, E., Lürling, M., Molinero, J.C., Mooij, W.M., van Donk, E. and Winder, M. 2012. Beyond the Plankton Ecology Group (PEG) Model: Mechanisms Driving Plankton Succession. Ann. Rev. Ecol. Evol. Syst. **43**: 429 -448

Søballe, D.M. and Kimmel, B.L. 1987. A Large-Scale Comparison of Factors Influencing Phytoplankton Abundance in Rivers, Lakes, and Impoundments. Ecology. **68**(6): 1943-1954.

Speirs, D.C. and Gurney, W.S.C. 2001. Population Persistence in Rivers and Estuaries. Ecology, **82**(5): 1219–1237.

Stockner, J., Langston, A., Sebastian, D. and Wilson, G. 2005. The limnology of Williston Reservoir: British Columbia's largest lacustrine ecosystem. Water Qual. Res. J. Canada. **40**(1): 28–50.

Strickland, J.D.H. and Parsons, T.R. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. Ottawa, ON, Canada.

Strickland, J.D.H. 1960. Measuring the primary production of marine phytoplankton. Bull. Fish. Res. Board Can. 122.

Strickland, R.M. 1983. Chapter 7: Plankton and Pollution In *The fertile fjord: plankton in Puget Sound*. Seattle, Washington: University of Washington Press. pp. 89-111.

Talling, J.F. and Rzoska, J. 1967. The development of plankton in relation to hydrological regime in the Blue Nile. Ecology. **55**: 637–662.

Tang, K.W., Gladyshev, M.I., Dubovskaya, O.P., Kirillin, G. and Grossart, H.-P. 2014. Zooplankton carcasses and non-predatory mortality in freshwater and inland sea environments. J. Plankton Res. **36**(3): 597-612.

Telesh, I. V. 1986. Transformation of the lake zooplankton in rivers. Dokl. Akad. [in Russian] Nauk SSSR. **291**: 495–498.

Thornton, K.W., Kimmel, B.L., Payne, F.E. 1990. Reservoir limnology: Ecological perspectives. John Wiley & Sons, Inc., Somerset, New Jersey.

Thorp, J.H. and Casper, A.F. 2003. Importance of Biotic Interactions in Large Rivers: An Experiment with Planktivorous Fish, Dreissenid Mussels and Zooplankton in the St Lawrence River. River Res. Applic. **19**: 265–279.

Thorp, J.H., Black, A.R., Haag, K.H. and Wehr, J.D. 1994. Zooplankton Assemblages in the Ohio River: Seasonal, Tributary, and Navigation Dam Effects. Can. J. Fish. Aquat. Sci. **51**: 1634-1643.

Tóth, L.G., Parpala, L., Balogh, C., Tátrai, I., and Baranyai, E. 2011. Zooplankton community response to enhanced turbulence generated by water-level decrease in Lake Balaton, the largest shallow lake in Central Europe. Limnol. Oceanogr. **56**(6): 2211–2222.

Twiss, M.R., Ulrich, C., Kring, S.A., Harold, J. and Williams, M.R. 2010. Plankton dynamics along a 180 km reach of the Saint Lawrence River from its headwaters in Lake Ontario. Hydrobiologia. **647**: 7–20.

URS Corporation, Gomez and Sullivan Engineers, P.C. and E/PRO Environmental and Engineering Consulting, LLC. 2005. Niagara River Water Level and Flow Fluctuation Study, prepared for the New York Power Authority.

Utermöhl, H. 1958. Zur vervolkommnung der quantitativen phytoplankton-methodik. [The improvement of quantitative phytoplankton methodology. In German.] Mitt. Internat. Verein. Limnol. **9**: 1-38.

Van Duren, L.A. and Videler, J.J. 2003. Escape from viscosity: the kinematics and hydrodynamics of copepod foraging and escape swimming. J. Exp. Biol. **206**: 269–279.

Vis, C., Hudon, C., Carignan, R. and Gagnon, P. 2007. Spatial Analysis of Production by Macrophytes, Phytoplankton and Epiphyton in a Large River System under Different Water-Level Conditions. Ecosystems. **10**: 293-310.

Visser, A.W., Mariani, P. and Pigolotti, S. 2009. Swimming in turbulence: Zooplankton fitness in terms of foraging efficiency and predation risk. J. Plankton Res. **31**: 121–133.

Vogel, S., 1994. Life in Moving Fluids: The Physical Biology of Flow, 2nd Ed. Princeton, NJ: Princeton University Press.

Wahl, D.H., Goodrich, J., Nannini, M.A., Dettmers, J.M. and Soluk, D.A. 2008. Exploring riverine zooplankton in three habitats of the Illinois River ecosystem: Where do they come from? Limnol. Oceanogr. **53**(6):2583–2593.

Walks, D.J. 2003. The Origin and Dynamics of River Plankton (Doctoral dissertation). University of Toronto, Toronto, Ontario, Canada.

Walks, D.J. 2007. Persistence of plankton in flowing water. Can. J. Fish. Aquat. Sci. **64**: 1693–1702.

Walks, D.J. and Cyr, H. 2004. Movement of plankton through lake-stream systems. Freshwater Biol. **49**: 745–759.

Walsh, G.E. 1978. Chapter 12: Toxic effects of pollutants on plankton. *In* Principles of Ecotoxicology. *Edited by* Butler, G.C. John Wiley & Sons, Chichester. pp. 257-274.

Walz, N. and Welker, M. 1998. Plankton development in a rapidly flushed lake in the River Spree system (Neuendorfer See, Northeast Germany). J. Plankton Res. **20**(11): 2071-2087.

Welker, M. and Walz, N. 1998. Can mussels control the plankton in rivers?- a planktological approach applying a Lagrangian sampling strategy. Limnol. Oceanogr. **43**(5): 753-762.

Williams, D.J., McCrea, R.C. and Sverko, E. 2003. The Bottom Sediments of the Sir Adam Beck Reservoir, Niagara River, Ontario. J. Great Lakes Res. **29**(4):630–640.

Zaret, R.E. and Kerfoot, W.C. 1980. The shape and swimming technique of Bosmina longirostris. Limnol. Oceanogr. **25**: 126–133.

Zhang, J.L., Zheng, B.H., Liu, L.S., Wang, L.P., Huang, M.S. and Wu, G.Y. 2010. Seasonal variation of phytoplankton in the DaNing River and its relationships with environmental factors after impounding of the Three Gorges Reservoir: a four-year study. Procedia Environ. Sci. **2**: 1479–1490.

LIST OF TABLES

LIST OF FIGURES

Table 1. Niagara River plankton project sample site coordinates (see Figure 1 for map).

Main Stations	Descriptor	Latitude	Longitude
NIA10	Lake Erie inlet	42.88201	-78.92405
NIA11	Fort Erie train bridge	42.91907	-78.90854
NIA12	Grand Island	42.96111	-78.96899
NIA13	Above turbines	43.14113	-79.04274
NIA14	Queenston Bridge	43.15923	-79.04508
NIA4	Lower river	43.20444	-79.05333

Support Sites	Descriptor	Latitude	Longitude
NR15	Crystal beach, Lake Erie	42.8586	-79.05775
NIA15	Shore at train bridge	42.9294	-78.913
NIA16	Netherby boat launch	42.9826	-79.0244
NIA17	Welland River	43.0462	-79.1231
NIA18	Queenston Boat launch	43.1657	-79.0523
NIA19	Shore site at NOTL boat launch	43.2571	-79.06371
NOTL Mid-Channel	Mid-River at NOTL boat launch	43.25825	-79.05775

Table 2. Niagara River station summary; depth, clarity (Secchi), flow rate, temperature, maximum depths for integrated water collection and zooplankton nets, and total zooplankton net volume. Beginning in August, two zooplankton nets were pooled from each station. Sonde profiles were also collected at all main stations (summary in Table 6, full details in Appendix 2).

Date	Station	Station Depth (m)	Secchi (m)	Current speed ($m\ s^{-1}$)	Surface temp (°C)	integrated water depth (m)	net depth (m)	net volume (L)
12-Jun	NIA10	9.1	5.2	nd	16.5	7	7.50	479
12-Jun	NIA11	6.0	5.2	nd	15.1	n/a	3.00	636
12-Jun	NIA12	5.2	bottom	0.98	16.2	5	3.50	715
10-Jun	NIA13	17.0	nd	1.52	16.1	0-3	1.00	776
10-Jun	NIA14	22-30	nd	1.14	16.1	n/a	1.00	667
10-Jun	NIA4	14.6	3.3	nd	16.2	0-6	14.00	747
09-Jul	NIA10	9.2	nd	0.72	22.6	7	7.00	1230
09-Jul	NIA11	8.4	1.8	1.07	22.4	n/a	7.00	327
09-Jul	NIA12	5.7	4.5	0.78	22.7	4	4.50	297
09-Jul	NIA13	15.9	nd	2.21	22.5	1.5	5.50	426
09-Jul	NIA14	40.0	1.8	1.36	22.7	n/a	6.00	664
09-Jul	NIA4	13.1	1	1.42	22.7	3	13.50	763
30-Jul	NIA10	8.9	3	0.54	21.3	6	8.50	559
30-Jul	NIA11	7.8	4.6	0.81	21.7	n/a	4.50	350
30-Jul	NIA12	5.9	4.9	1.12	21.7	4	5.50	327
30-Jul	NIA13	16.6	1.9	1.48	21.4	4	8.00	551
30-Jul	NIA14	22.0	1.6	1.32	21.4	n/a	10.50	791
30-Jul	NIA4	13.2	2.1	1.44	21.4	4	12.00	763
19-Aug	NIA10	9.0	5	0.29	22.2	7	7.00	728
19-Aug	NIA11	3.6	bottom	0.40	21	n/a	3.75	648
19-Aug	NIA12	5.0	bottom	0.77	21.7	5	4.00	494
19-Aug	NIA13	17.8	2.5	2.36	22	nd	9.00	1164
19-Aug	NIA14	39.0	2.3	1.24	21.9	n/a	8.25	1814
19-Aug	NIA4	13.8	3.3	1.22	21.9	5	10.00	1253
10-Sep	NIA10	8.2	4.5	0.40	23.1	5	7.25	1951
10-Sep	NIA11	5.6-8.7	6.9	0.23	22.6	n/a	6.25	850
10-Sep	NIA12	4.8	bottom	0.75	22.8	4.5	4.00	626
10-Sep	NIA13	14.9 - 17.6	3.25	2.04	23.5	5	3.00	848
10-Sep	NIA14	25	3.25	0.19	22.9	n/a	7.00	1436
10-Sep	NIA4	13 - 14.8	4	1.11	22.9	5	10.25	1208
15-Oct	NIA10	8.7	3	0.39	17.2	6	8.75	1812
15-Oct	NIA11	7.6	4.2	1.04	17	n/a	n/a	n/a
15-Oct	NIA12	5.3	4.2	1.01	16.9	6	4.25	594
15-Oct	NIA13	17.4	nd	1.43	16.9	5	9.75	1216
15-Oct	NIA14	18	nd	nd	16.6	n/a	7.50	1569
15-Oct	NIA4	14	2.75	1.12	16.7	6	13.75	1526

nd = no data

n/a = not applicable (nothing was collected)

Table 3. Average measured flows and discharge at NIA11, NIA13 and NIA14 using whole water column estimates summarized from Acoustic Doppler Current Profiler surveys completed in October 2014 (pers. comm. A. Thompson and S. Rodrigues, National Hydrologic Service of ECCC, Feb. 2016).

Site	CAN shore $m \cdot s^{-1}$	Mid-channel $m \cdot s^{-1}$	US shore $m \cdot s^{-1}$	Discharge $m^3 s^{-1}$
Fort Erie	1.3	1.7	1.0	5600
Above Power Stations	0.9	3.0	1.4	3300
Below Power Stations	0.8	1.3	0.3	6200

Table 4. Estimate of Niagara River residence time based on flow rates from Table 3, where average flow rates for entire river assumes equal likelihood of being in each section of the river (Canadian shore, mid-channel or US shore).

	Avg flow entire river km h^{-1}	Avg. mid-channel flow km h^{-1}	River section km	Hours for avg. river flow	Hours for mid-channel flow
Upper Niagara River	1.7	4.8	28	16.5	5.8
Falls to Power Stations	3	6.4	9	3	1.4
Power Stations to L.Ontario	1.3	2.9	11	8.5	3.8
			Total:	28	11

Table 5. Cross-river transect profile summary (average of sonde transect) for Niagara River stations.

		EXO				**FluoroProbe**
Date	Transect at Station	Chl. *a* (µg L^{-1})	Turbidity (FNU)	Temperature (°C)	Conductivity (µs cm^{-1})	Chl. *a* (µg L^{-1})
12 Jun	NIA 12	0.63±0.07	0.00±0.30	15.8±0.22	238±0.8	0.29±0.25
	NIA 18	--	--	--	--	0.23±0.21
	NIA 4	--	--	--	--	1.35±0.90
9 July	NIA 18	0.73±0.04	5.86±0.06	22.2±0.00	278±0.2	--
	NIA 4	0.93±0.17	5.10±0.08	22.2±0.02	279±0.1	--
	NIA 11[1]	0.31	0.00	22.1	271	--
30 July	NIA 11[1]	0.50±0.11	1.30±1.05	21.5±0.19	278±0.5	0.66±0.08
	NIA 12[1]	0.30±0.03	0.00±0.11	21.4±0.15	280±0.2	0.39±0.01
	NIA 18[1]	0.68±0.04	1.95±0.16	21.5±0.01	280±0.0	0.92±0.12
	NIA 4[1]	0.66±0.03	2.33±0.48	21.6±0.01	281±0.3	0.77±0.03
19 Aug	NIA 12[1]	0.29	0.00	21.3	273	0.00
	NIA 18	--	--	--	--	--
	NIA 4	--	--	--	--	--
10 Sep	NIA 12	0.09±0.02	0.00±0.13	22.1±0.03	268±0.4	--
	NIA 18	0.22±0.06	0.00±0.28	22.4±0.00	271±0.0	0.00±0.00
	NIA 4	0.20±0.02	0.00±0.03	22.4±0.00	271±0.1	0.00±0.00
15 Oct	NIA 12	0.10±0.05	2.05±0.13	16.2±0.02	224±0.5	--
	NIA 18	0.35±0.14	2.24±0.07	16.3±0.00	226±0.2	--
	NIA 4	0.10±0.06	2.39±0.10	16.3±0.00	226±0.1	--
Mean ±SE	NIA 12	0.32±0.06	0.03±0.31	18.8±0.7	251±4.8	0.28±0.11
	NIA 18	0.43±0.05	2.36±0.50	20.5±0.5	262±4.5	0.31±0.09
	NIA 4	0.52±0.08	2.74±0.42	20.5±0.5	263±4.2	0.64±0.20

[1] From transect across river

Table 6. Single-point Niagara River station summary (average ± SE of sonde profile). Upper River grouping includes NIA11 and 12 while Below Turbines grouping includes NIA 14 and 4. Double-dashes indicate no measurements were taken.

		EXO				**FluoroProbe**
Date	Designation	Chl. *a* ($\mu g\ L^{-1}$)	Turbidity (FNU)	Temperature (°C)	Conductivity ($\mu s\ cm^{-1}$)	Chl. *a* ($\mu g\ L^{-1}$)
12 Jun	Lake Erie	23.95	2.53	13.85	230.62	--
	Welland River	1.06	12.27	17.12	276.14	--
	Upper River	1.00±0.10	0.31±0.68	15.40±0.29	237.12±2.28	0.04±0.02
	Above Turbines	0.37	1.74	16.10	240.00	--
	Below Turbines	1.19±0.30	3.60±0.99	16.01±0.09	241.20±2.72	0.07±0.04
9 July	Welland River	--	--	--	--	2.14
	Upper River	0.58±0.25	1.58±0.48	22.02±0.04	270.22±0.81	0.00±0.00
	Above Turbines	--	--	--	--	--
	Below Turbines	0.72	--	22.35	277.64	--
30 July	Upper River	0.47±0.06	0.07±0.08	21.31±0.09	278.61±0.49	0.59±0.08
	Above Turbines	0.41	1.89	21.50	278.62	0.55
	Below Turbines	0.59	2.00±0.04	21.54±0.01	280.02±0.34	0.76±0.04
19 Aug	Upper River	0.61±0.12	2.14±1.48	21.18±0.09	276.02±1.01	0.47±0.37
	Above Turbines	--	--	--	--	0.00
	Below Turbines	--	--	--	--	0.01±0.01
10 Sep	Upper River	0.15±0.05	0.00±4.61	22.08±0.02	268.37±0.24	0.00±0.00
	Above Turbines	0.07	0.05	22.32	270.00	0.00
	Below Turbines	0.21	0.00	22.37	270.92	0.00
15 Oct	Upper River	0.32±0.10	2.13±0.35	16.27±0.02	223.96±0.37	0.92±0.04
	Above Turbines	0.00	2.53	16.38	225.00	1.04
	Below Turbines	0.20±0.04	2.28±0.20	16.32±0.01	226.00±0.00	0.68±0.63
Mean ±SE	Upper River	0.54±0.06	0.92±0.33	19.7±0.54	258±3.7	0.34±0.08
	Above Turbines	0.20±0.09	1.55±0.43	19.1±1.34	253±10	0.40±0.20
	Below Turbines	0.68±0.14	2.74±0.48	18.7±0.72	254±5.5	0.29±0.11

Table 7. Vertical light attenuation coefficient k_d (m^{-1}) estimates for Niagara River. Double-dashes indicate no measurement.

	June	Early July	Late July	August	September	October	Station Average
NIA10	0.275	--	0.275	0.229	0.211	0.304	0.259
NIA11	--	--	0.236	0.733	0.154	0.352	0.369
NIA12	0.233	--	--	0.266	0.216	0.241	0.239
NIA13	--	--	0.12	0.443	0.294	0.445	0.326
NIA14	0.327	--	0.646	--	0.393	0.382	0.437
NIA4	0.369	0.903	0.585	0.367	0.266	0.448	0.490
Cruise Average	0.301	0.903	0.372	0.408	0.256	0.362	

Table 8. Selected common phytoplankton species in the Niagara River by percent contribution to total biomass.

		09-Jul			30-Jul			19-Aug			10-Sep			15-Oct		
Group	Species	NIA10	NIA13	NIA4	NIA10	NIA13	NIA4	NIA10	NIA13	NIA4	NIA10	NIA13	NIA4	NIA10	NIA13	NIA4
Cyanophyta	*Heteroleibleinia* sp.												13.9			
	Lyngbya sp.					18.0										
	Lyngbya birgei											89.4				
Chlorophyta	*Sphaerocystis schroeteri*	12.0														
	Tetracystis pulchra															11.3
Chrysophyta	*Ochromonas* sp.							16.0	6.6	21.2	0.4	0.1	4.0			
Diatoma	*Aulacoseira muzzanensis*	12.0														
	Cocconeis pediculus		38.1	44.8	19.7	3.3	22.8		6.2							13.0
	Diatoma vulgaris vulgaris														15.5	
	Fragilaria construens					15.7										
	Fragilaria crotonensis		11.9					25.8		45.3	7.1			26.3	28.1	
	Gomphonema olivaceum		11.1													
	Navicula tripunctata					9.5										
	Nitzschia heufleriana			19.7												
	Nitzschia intermedia	8.6														
	Skeletonema potamos			11.3			35.0			0.2			8.7			
	Stephanodiscus alpinus				19.7									15.9		40.7
	Stephanodiscus binderanus									10.7						
	Stephanodiscus medius				13.4			8.3								5.1
	Stephanodiscus parvus	11.0	4.2													
Cryptophyta	*Rhodomonas minuta nannoplanctica*	10.0	5.5	6.3	13.7	10.3	10.3	18.6	29.0	1.3	26.0	1.8	11.8	9.9	6.5	4.8

Table 9A. Zooplankton species by major groupings for the Niagara River stations. An X indicates species was present.

			10-Jun-14			9-Jul-14*			30-Jul-14			19-Aug-14			10-Sep-14			15-Oct-14		
			NIA10	NIA12	NIA14	NIA10	NIA12	NIA14	NIA10	NIA12	NIA14	NIA10	NIA12	NIA14	NIA10	NIA12	NIA14	NIA10	NIA12	NIA14
Zooplankton	**Cladocera**	*Alona* sp.																		X
		Bosmina longirostris	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X
		Bythotrephes longimanus				X	X	X	X	X	X	X		X						
		Chydorus sphaericus					X													
		Daphnia galeata mendotae	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Daphnia retrocurva	X	X	X						X									X
		Leptodiaptomus minutus	X					X			X									
		Eubosmina coregoni	X						X							X				
		Eurycercus lamellatus		X																
		Holopedium gibberum	X																	
		Leptodora kindtii	X					X	X	X	X	X	X	X	X					
	Cyclopoids	*Diacyclops thomasi*	X	X	X							X			X			X	X	
		Cyclops vernalis									X									
		Cyclopoida copepodites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Cyclopoida nauplii	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
		Eucyclops agilis															X			
		Mesocyclops edax	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	
		Tropocyclops extensus						X			X	X	X		X	X	X	X	X	X
	Calanoids	Calanoida copepodites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Calanoida nauplii	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Leptodiaptomus ashlandi	X																	
		Leptodiaptomus minutus				X	X	X	X	X	X	X	X		X	X	X	X		
		Skistodiaptomus oregonensis	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Epischura copepodid	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Epischura lacustris	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
		Eurytemora affinis						X					X			X	X		X	X
		Limnocalanus copepodites	X																	
		Limnocalanus macrurus	X																	
		Harpacticoida						X	X	X	X		X	X		X	X	X	X	X

**Cercopagis pengoi* was noted at NIA11 on July 9th.

Table 9B. Rotifer densities and dry biomass values in June - October seasonal composite samples collected in the Niagara River in 2014. Dominant taxa at the river entrance are given in bold.

	density (no.m^{-3})				dry biomass (mg m^{-3})			
Taxa Name	**NIA10**	**NIA12**	**NIA13**	**NIA4**	**NIA10**	**NIA12**	**NIA13**	**NIA4**
Asplanchna sp.	400	133	0	0	0.237	0.101	0.000	0.000
Colurella sp.	0	133	0	0	0.000	0.001	0.000	0.000
Conochilus unicornis	6533	4933	267	600	0.120	0.071	0.006	0.008
Gastropus stylifer	133	133	0	100	0.001	0.003	0.000	0.001
Kellicottia longispina	2400	933	267	600	0.012	0.005	0.002	0.003
Keratella quadrata	400	0	0	300	0.024	0.000	0.000	0.019
Keratella cochlearis	5600	2933	667	1000	0.045	0.017	0.004	0.009
Keratella cochlearis tecta	0	133	133	0	0.000	0.000	0.000	0.000
Monostyla sp.	0	0	133	0	0.000	0.000	0.000	0.000
Pleosoma hudsoni	0	0	0	100	0.000	0.000	0.000	0.003
Pleosoma lenticulare	133	133	133	100	0.001	0.005	0.012	0.003
Polyarthra major	400	400	133	0	0.009	0.004	0.005	0.000
Polyarthra vulgaris	2000	1600	400	200	0.027	0.018	0.006	0.003
Pompholyx sulcata	133	0	0	0	0.001	0.000	0.000	0.000
Synchaeta kitina	800	0	0	500	0.008	0.000	0.000	0.006
Synchaeta pectinata	133	0	0	0	0.005	0.000	0.000	0.000
Synchaeta stylata	400	0	0	100	0.018	0.000	0.000	0.006
Total	**19467**	**11467**	**2133**	**3600**	**0.507**	**0.224**	**0.035**	**0.062**

Table 9C. Rotifer species list for station NIA10 on each sampling date developed from qualitative observations of the 64 µm zooplankton net samples.

	Species Name	12-Jun	9-Jul	30-Jul	19-Aug	10-Sep	15-Oct
Rotifers	*Asplanchna sp.*	X		X	X		X
	Conochilus unicornis	X	X				
	Kellicottia longispina	X	X		X		X
	Keratella cochlearis	X	X	X	X	XX	X
	Keratella quadrata	X					
	Ploesoma hudsoni				X	X	
	Ploesoma lenticulare				X		X
	Ploesoma truncatum				X		
	Polyarthra sp.			X	XX		X
	Trichocerca cylindrica		X		X		

X = Present, XX = Abundant

Table 10. June to October mean density, mean biomass and total seasonal production for major zooplankton groups at Niagara River stations.

Density (no L^{-1})	Bosminid	Daphnia	Predatory Cladoceran	Cyclopoid	Calanoid	Nauplii	Veliger	Total
NIA10	4.81	1.09	0.05	7.17	15.51	13.58	51.32	93.53
NIA11	3.47	0.77	0.01	6.23	5.92	5.30	28.41	50.10
NIA12	2.32	0.74	0.02	2.72	5.97	1.88	10.24	23.90
NIA13	0.28	0.19	0.01	0.16	0.21	0.18	1.88	2.92
NIA14	0.97	0.53	0.01	1.03	1.56	0.40	4.17	8.66
NIA4	1.53	0.33	0.01	0.75	1.35	0.52	4.84	9.33
Biomass (mg m^{-3})	**Bosminid**	**Daphnia**	**Predatory Cladoceran**	**Cyclopoid**	**Calanoid**	**Nauplii**	**Veliger**	**Total**
NIA10	5.40	7.76	1.97	7.44	50.28	1.42	29.66	103.94
NIA11	4.17	5.23	0.84	6.49	21.06	0.51	20.18	58.48
NIA12	1.65	5.67	3.72	1.53	13.04	2.19	7.51	35.30
NIA13	0.37	1.33	0.37	0.19	1.09	0.02	0.83	4.19
NIA14	1.20	3.68	1.52	1.09	7.59	0.04	1.83	16.96
NIA4	1.93	2.33	0.61	0.77	7.33	0.05	2.27	15.28
Production (mg m^{-3})*	**Bosminid**	**Daphnia**	**Predatory Cladoceran**	**Cyclopoid**	**Calanoid**	**Nauplii**	**Veliger**	**Total**
NIA10	69.9	88.1	46.5	101.8	326.9	12.8	415.3	1061.3
NIA11	48.2	58.4	23.2	92.7	135.1	5.2	262.5	625.4
NIA12	33.1	57.1	24.6	45.3	157.8	2.1	94.7	414.7
NIA13	3.8	14.4	12.0	3.3	6.2	0.2	11.6	51.4
NIA14	13.5	41.9	42.5	15.2	42.3	0.4	26.6	182.3
NIA4	22.3	25.7	21.2	10.2	36.6	0.4	32.9	149.4

*Production calculated based on volumetric biomass standardized production (P:B)

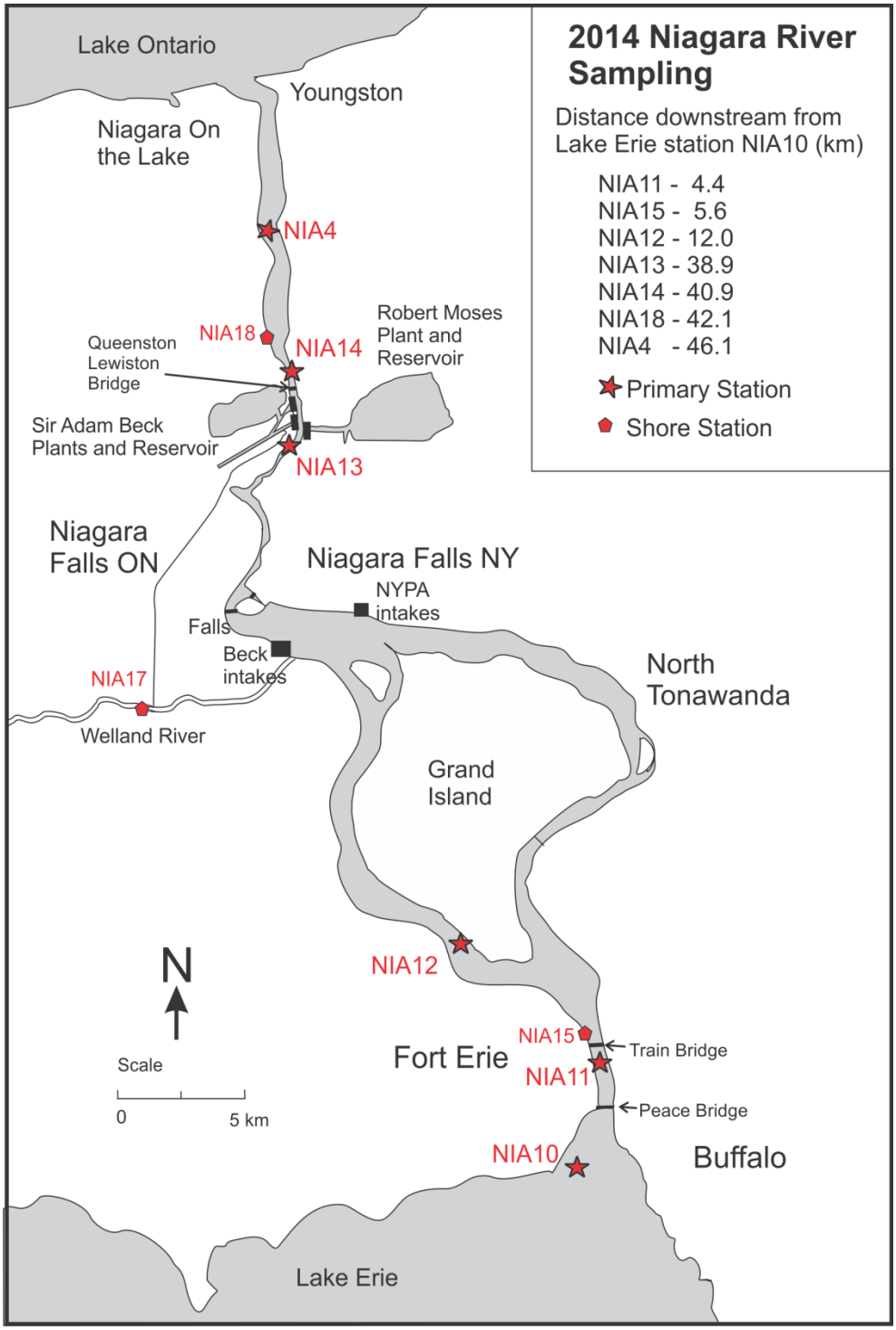

Figure 1. Map of Niagara River study site showing the location of the sampling stations relative to the hydroelectric installations on the American and Canadian side. The insert shows distance downriver of sampling sites relative to NIA10.

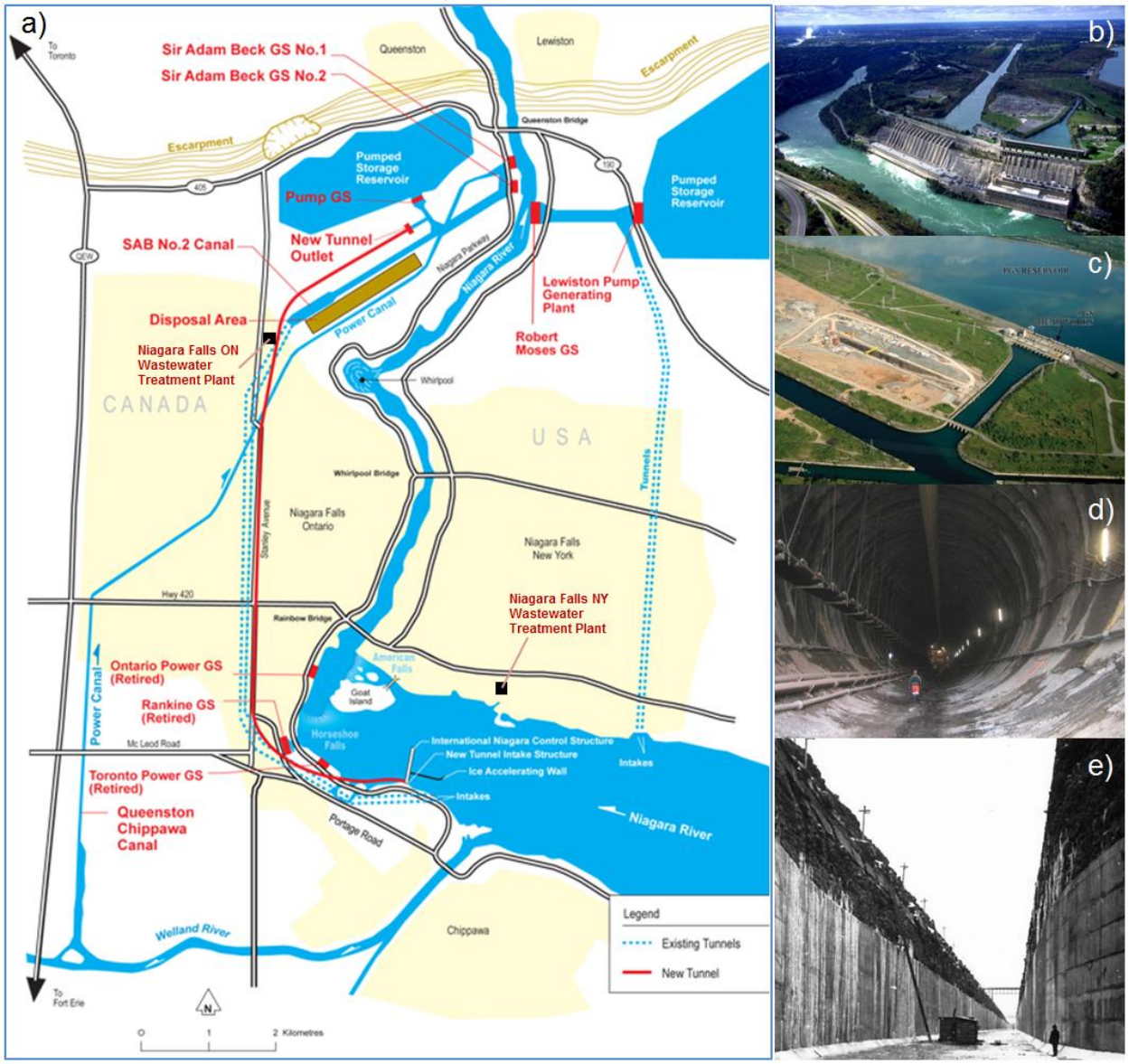

Figure 2. Map showing locations of hydroelectric power stations, water supply tunnels and wastewater treatment plants (a); and photographs of Sir Adam Beck Power Stations, canals and reservoir (b), detail of the pumped reservoir system (c), the new Niagara Tunnel completed 2013 (d) and the original Chippawa-Lewiston canal originating from the Welland River (e). Images are modified from Ontario Power Generation Niagara Tunnel Project portal (http://www.opg.com/generating-power/hydro/projects/niagara-tunnel-project/).

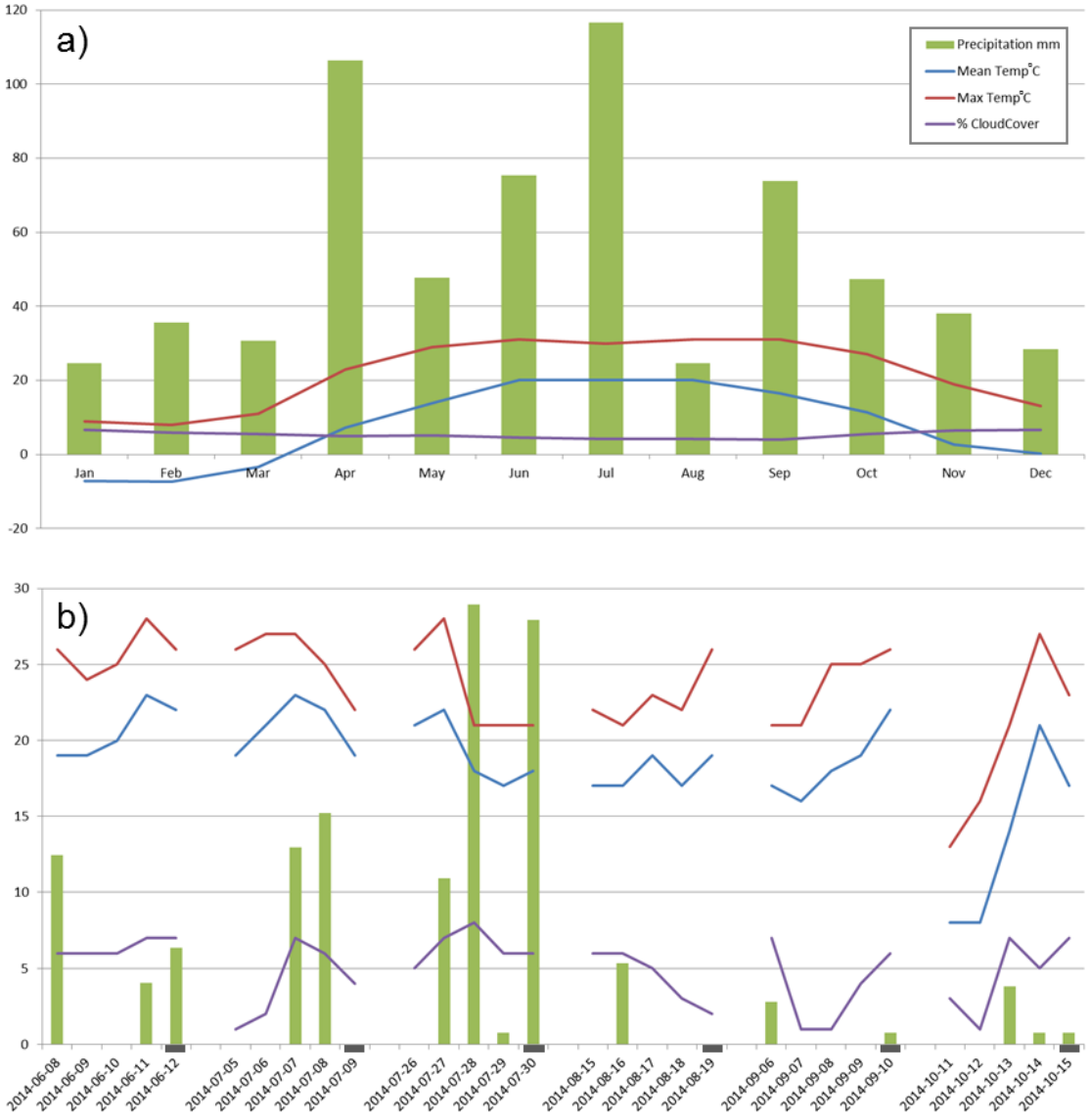

Figure 3. Monthly 2014 mean temperatures (daily mean and maxima °C), % cloud cover and total precipitation (green bar, mm) (a) taken from Niagara airport (IAG), and daily values (b) for the four days preceding the date of sampling indicated by the dark bar. Data taken from NOAA-NCEI database.

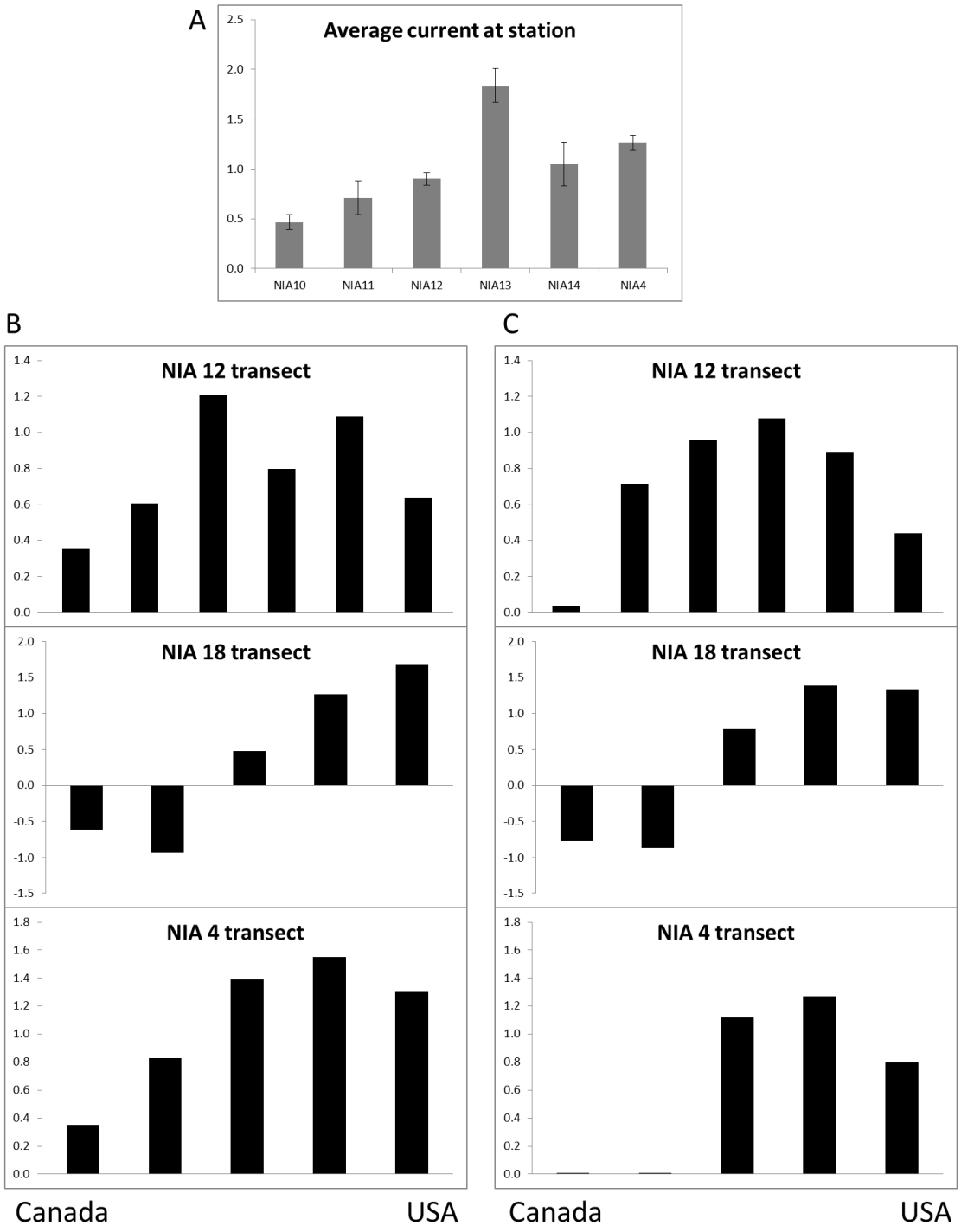

Figure 4. A) Average downstream current speeds (m s^{-1}) from the primary sampling stations, B) current speeds from above the falls (NIA12) and below the turbines (NIA18 and NIA4) on June 10th, and C) current speeds on October 15th. Note the back-eddy closest to the Canadian shore at NIA18.

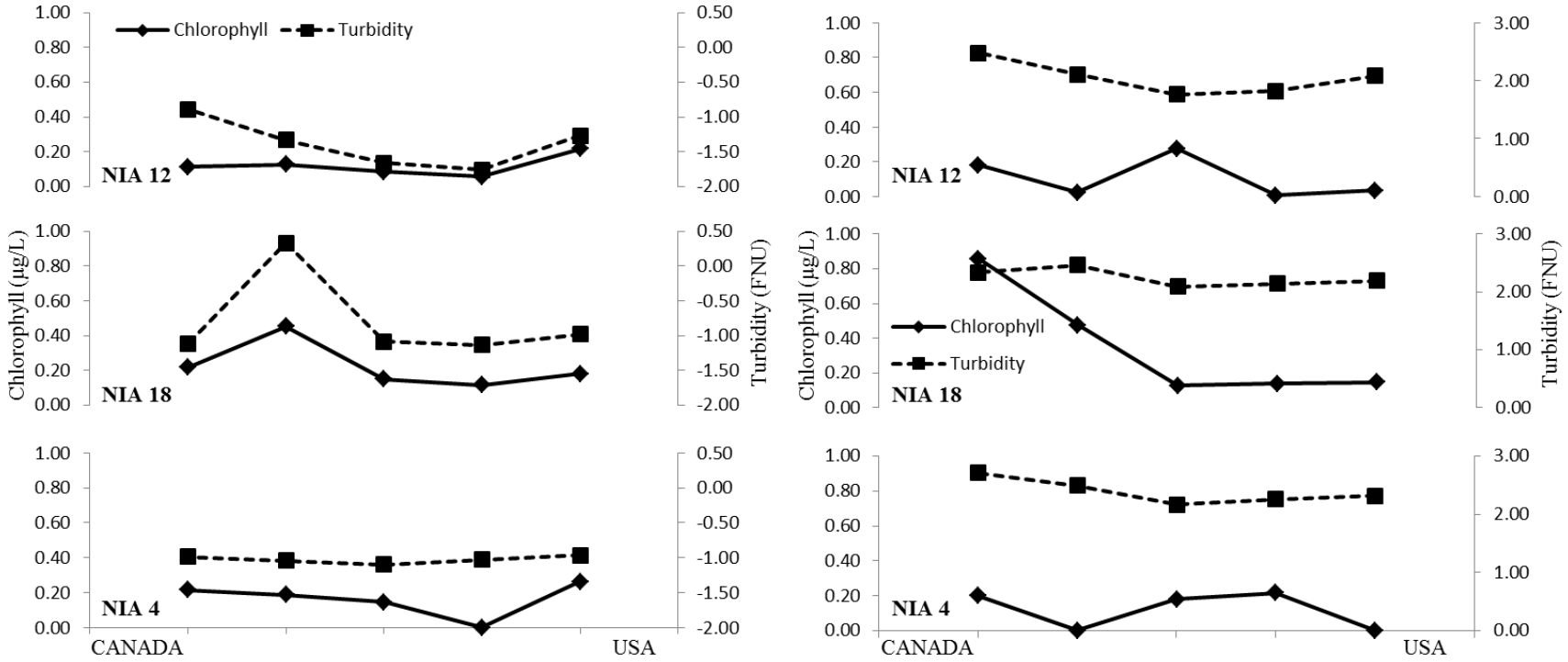

Figure 5. Cross-river transects from above Niagara Falls (NIA12) and below the turbines (NIA18 and NIA4) on September 10th, 2014 (left) and October 15th, 2014 (right).

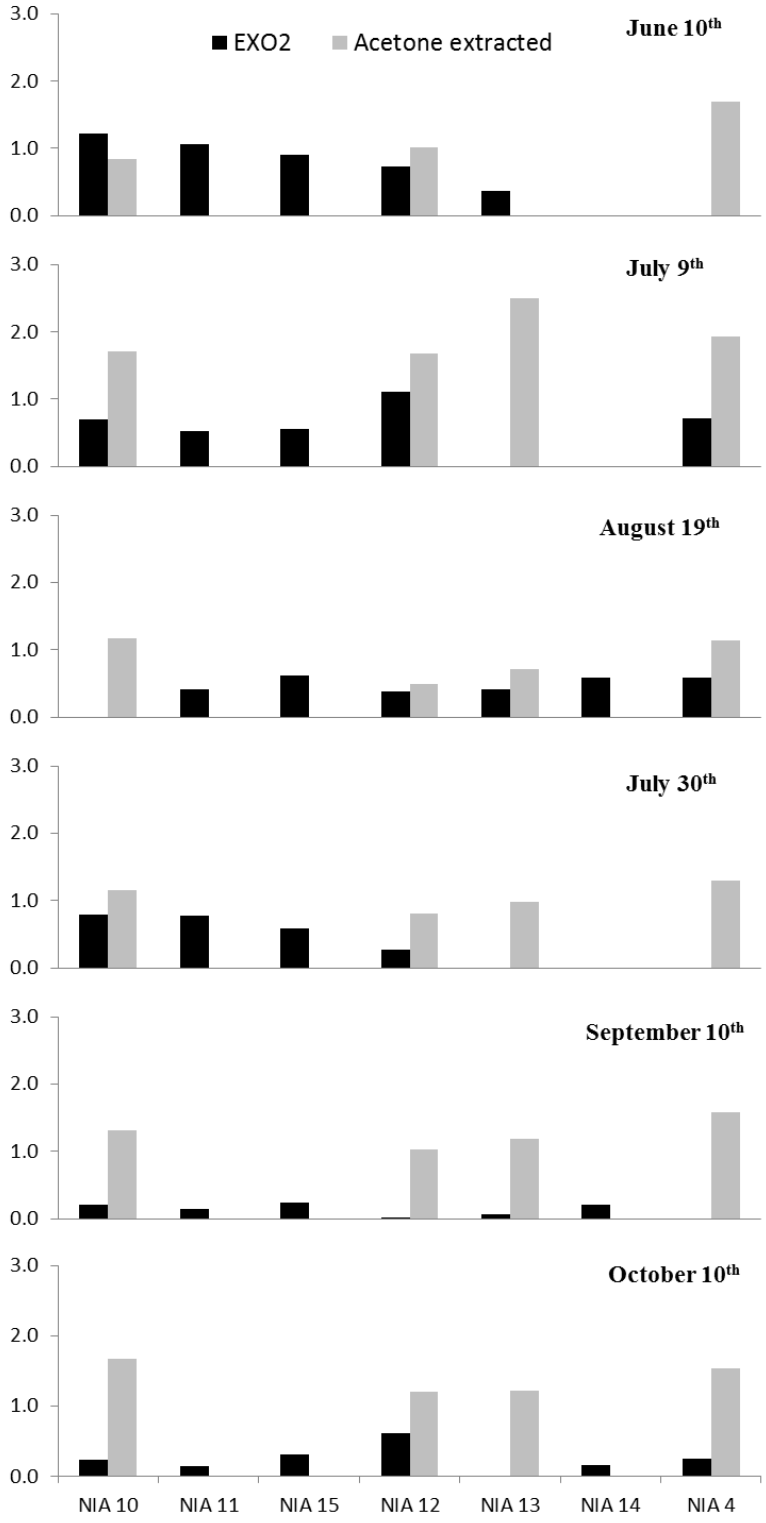

Figure 6 Comparison of chlorophyll *a* (µg L^{-1}) by cruise for seven stations from the upper to lower river as determined by the EXO2 sonde and by acetone extraction (total uncorrected). Values are consistently very low (< 2 µg L^{-1}).

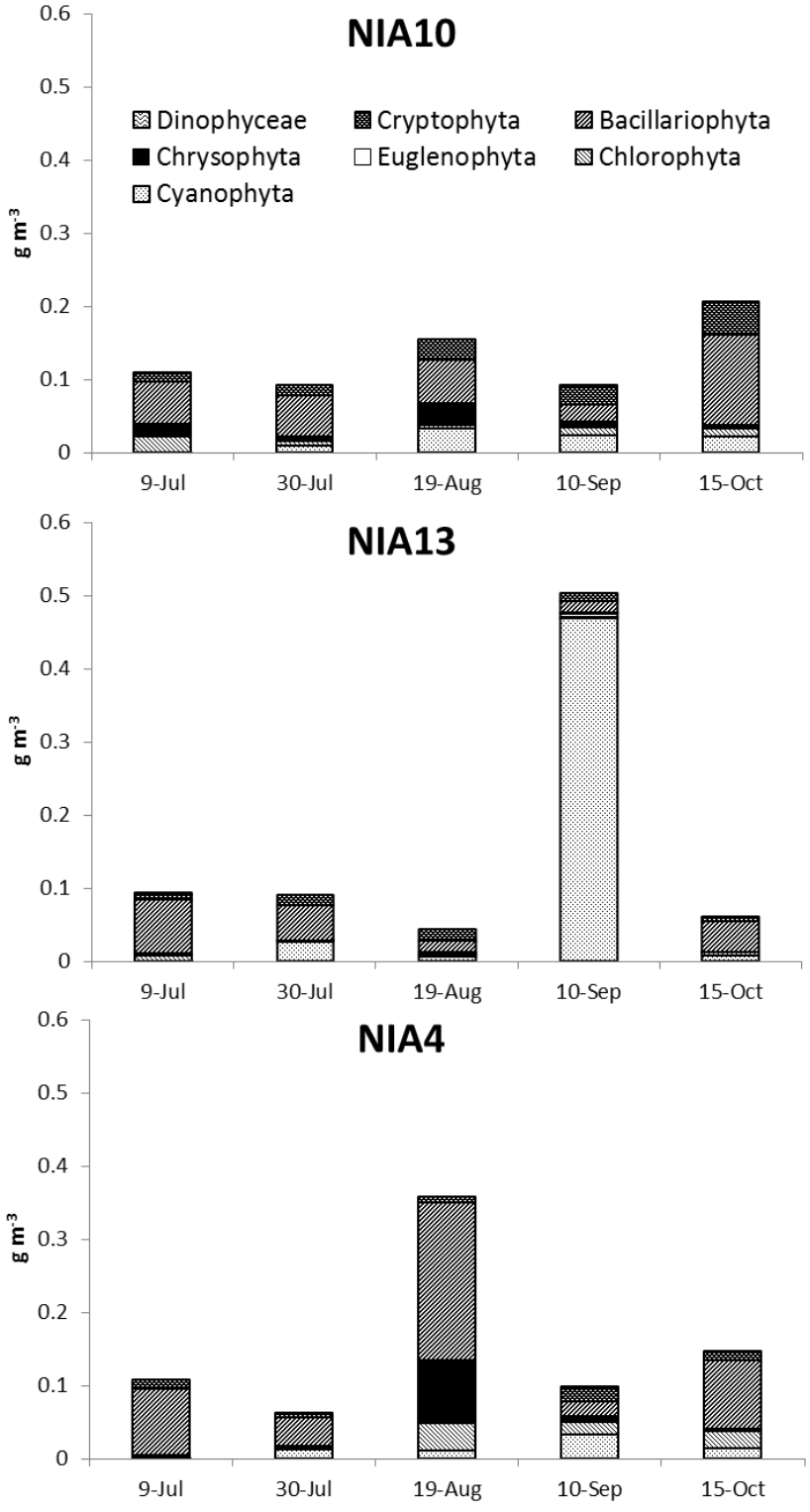

Figure 7. Niagara phytoplankton biomass (g m^{-3}) for major groups by station for each date.

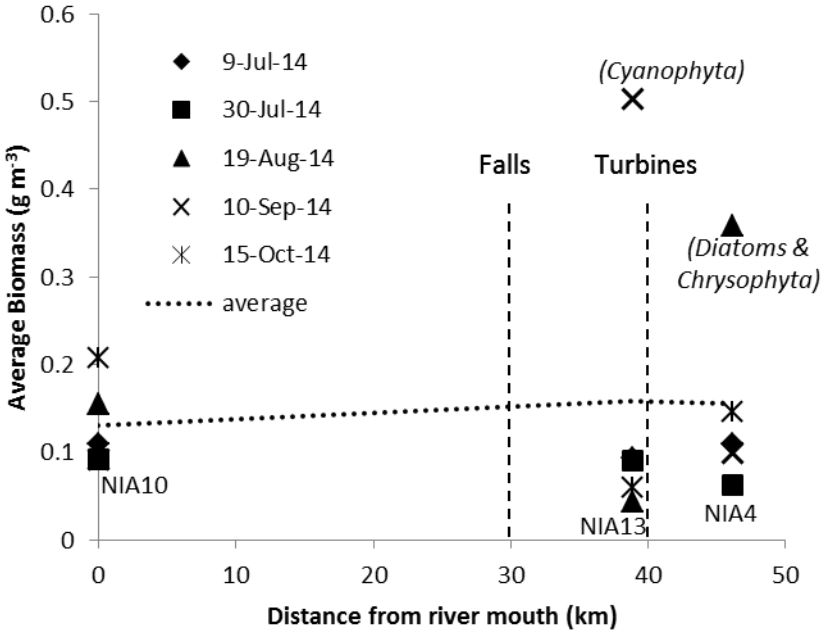

Figure 8. Phytoplankton biomass (g m^{-3}) by distance from the Niagara River mouth. Extreme values at NIA13 and NIA4 were caused by peaks in algal biomass (groups noted in parentheses and discussed in text). Locations of Niagara Falls and hydroelectric plant turbines are noted by vertical dashed lines.

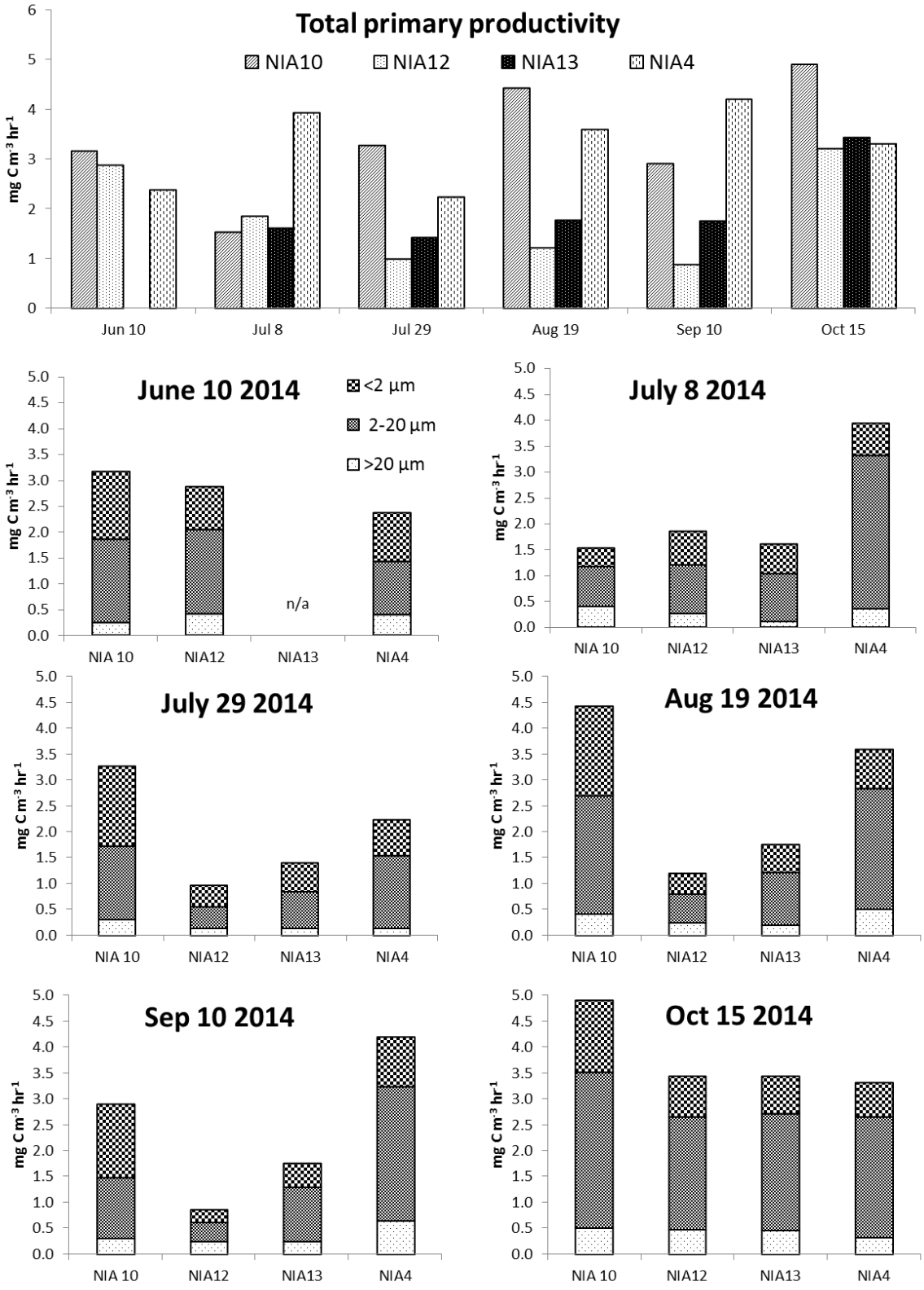

Figure 9. Total and size-fractionated primary productivity by Niagara River station and date.

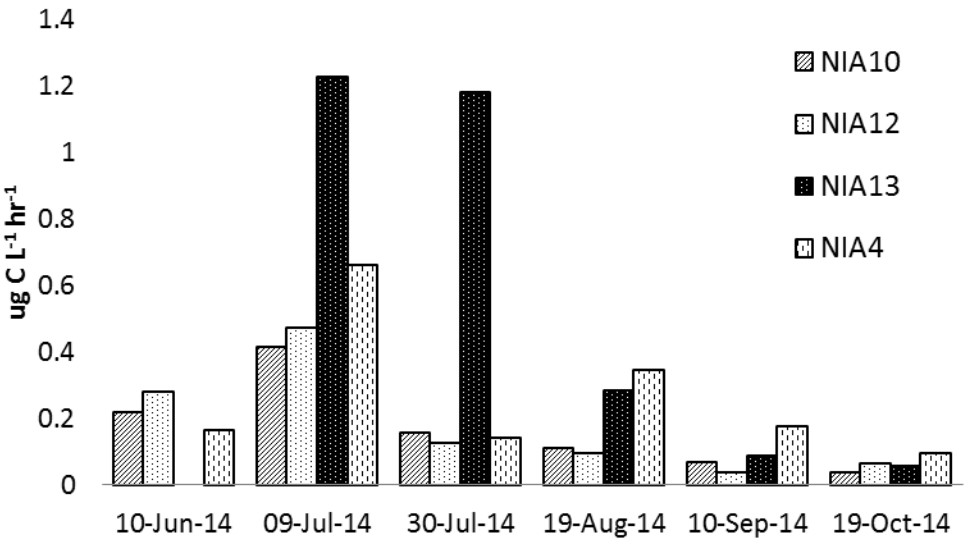

Figure 10. Bacterial potential growth rate for selected Niagara River stations by date.

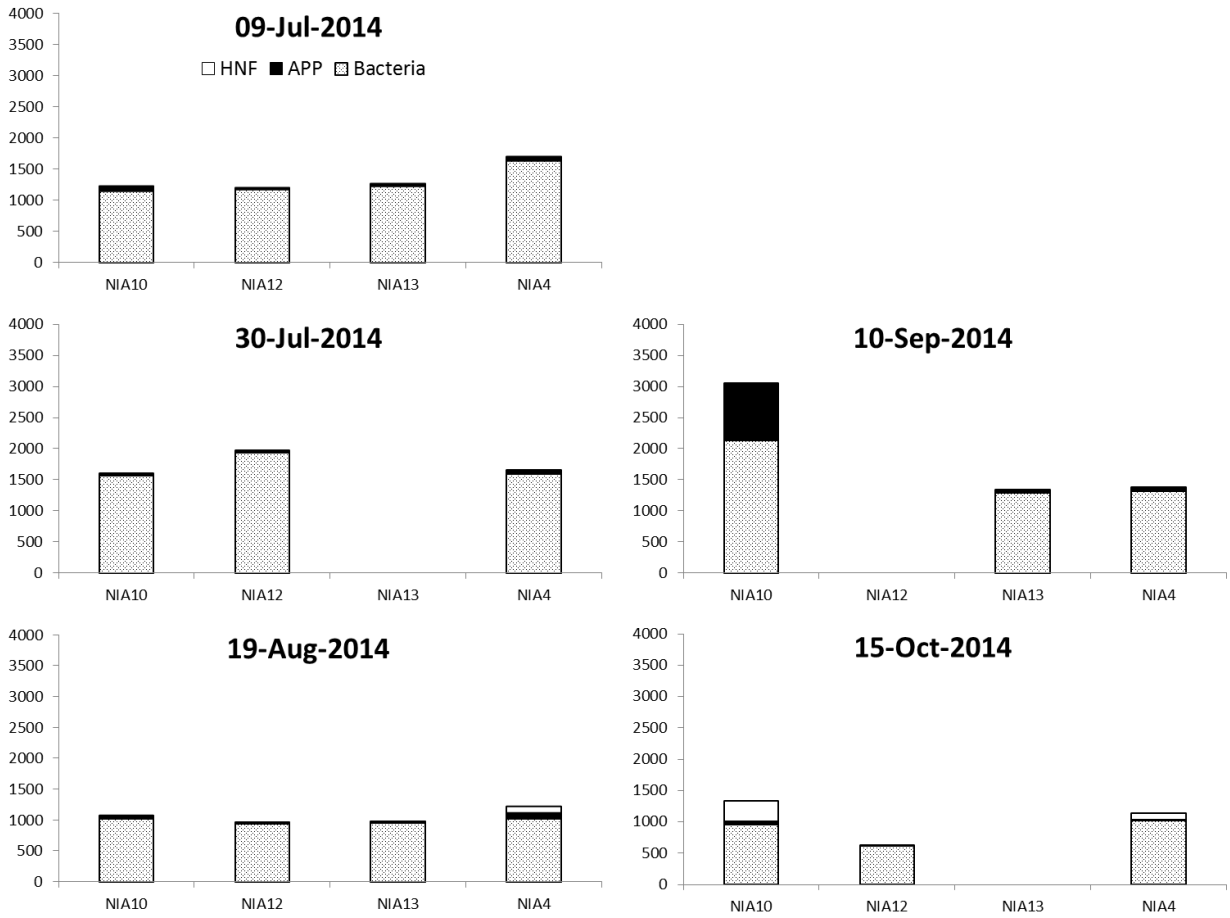

Figure 11. Microbial loop biomass (mg m^{-3}) by major group: heterotrophic nanoflagellates (HNF), autotrophic picoplankton (APP) and bacteria for stations in the Niagara River by date.

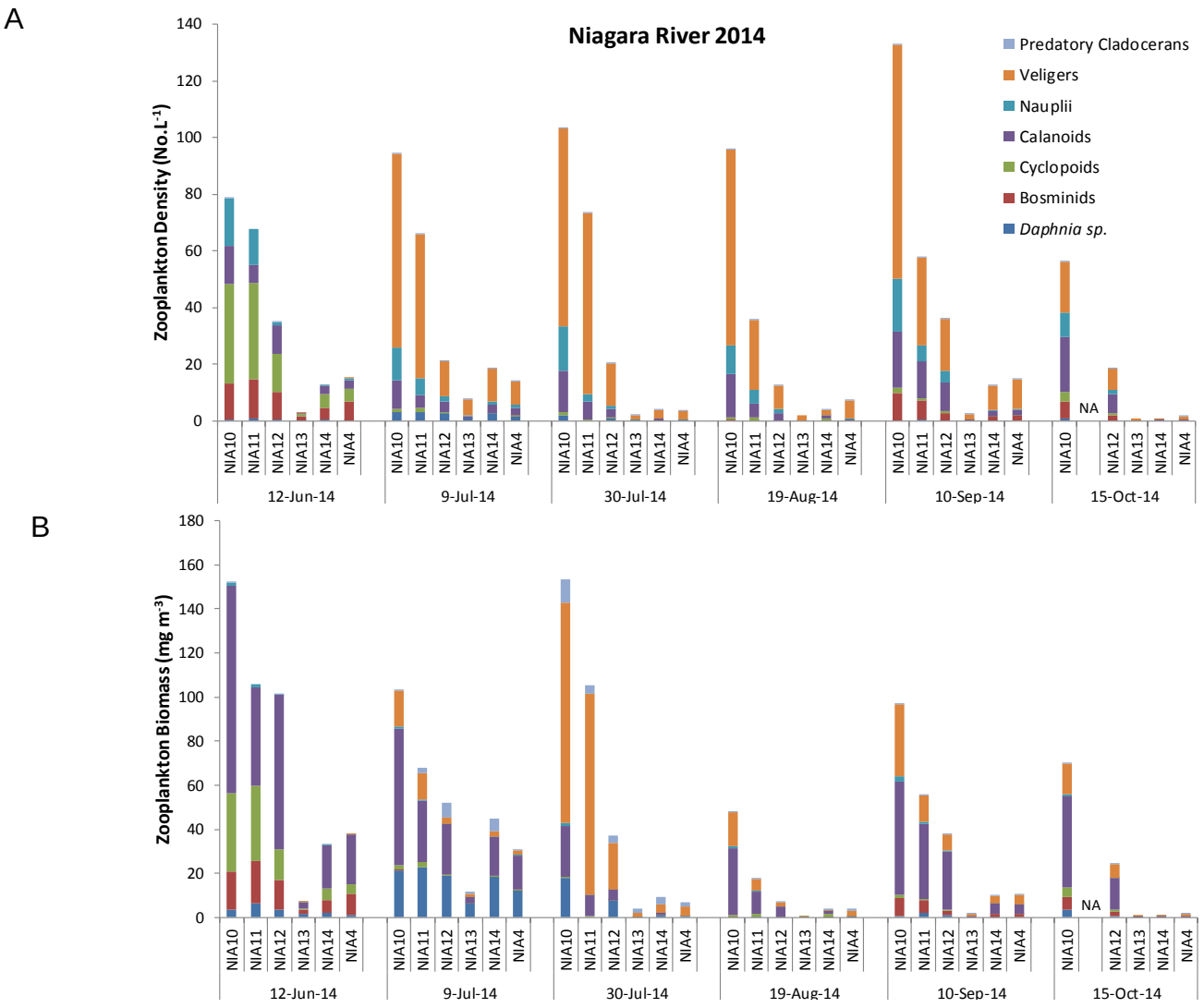

Figure 12. A) Zooplankton density (No m^{-3}) and B) Zooplankton biomass (mg m^{-3}) for major groups (see text).

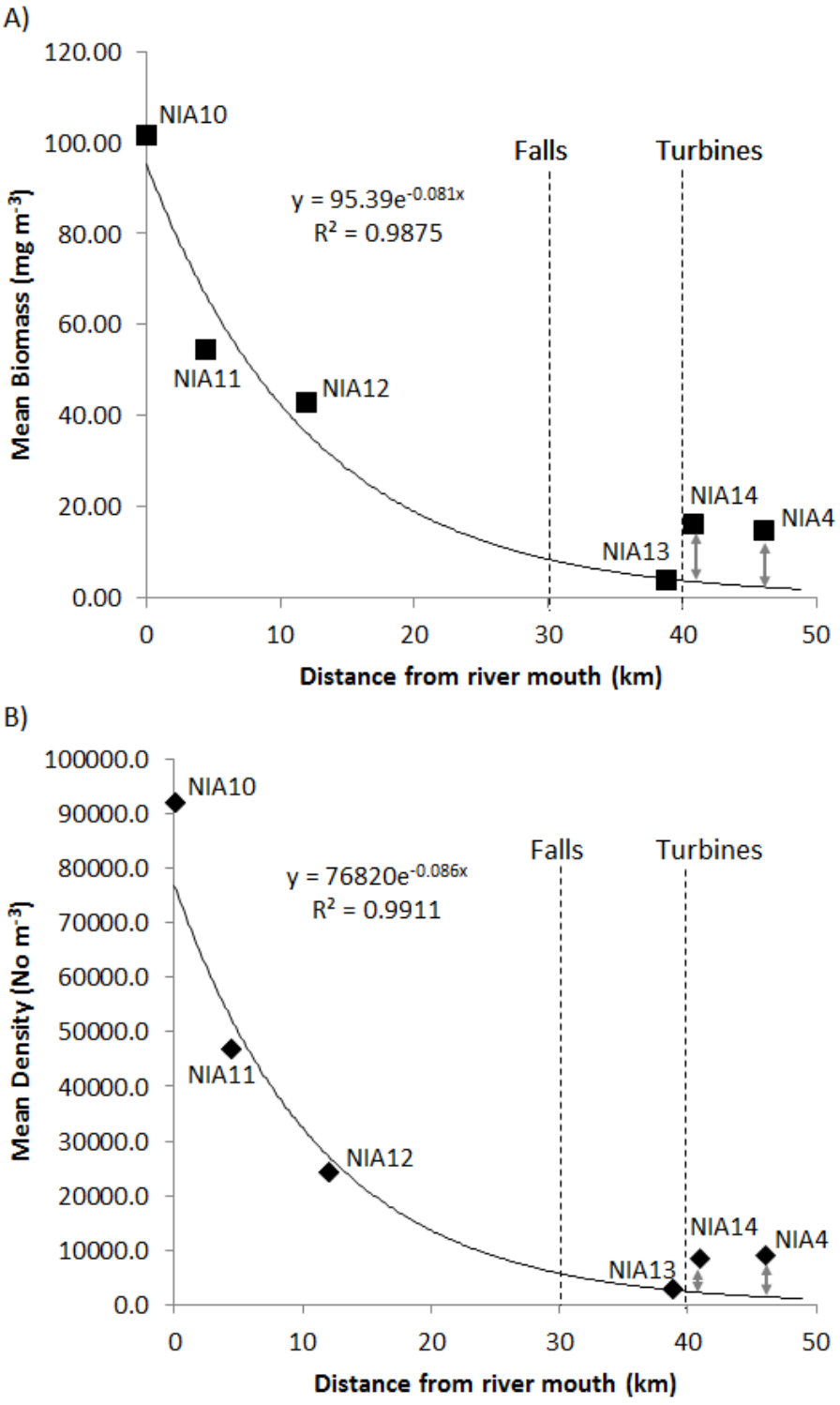

Figure 13. June to October seasonally weighted mean A) zooplankton biomass and B) density, by distance from Niagara River mouth. Grey arrows indicate deviation from the anticipated trend at NIA14 and NIA4 below the hydroelectric plant output (see text).

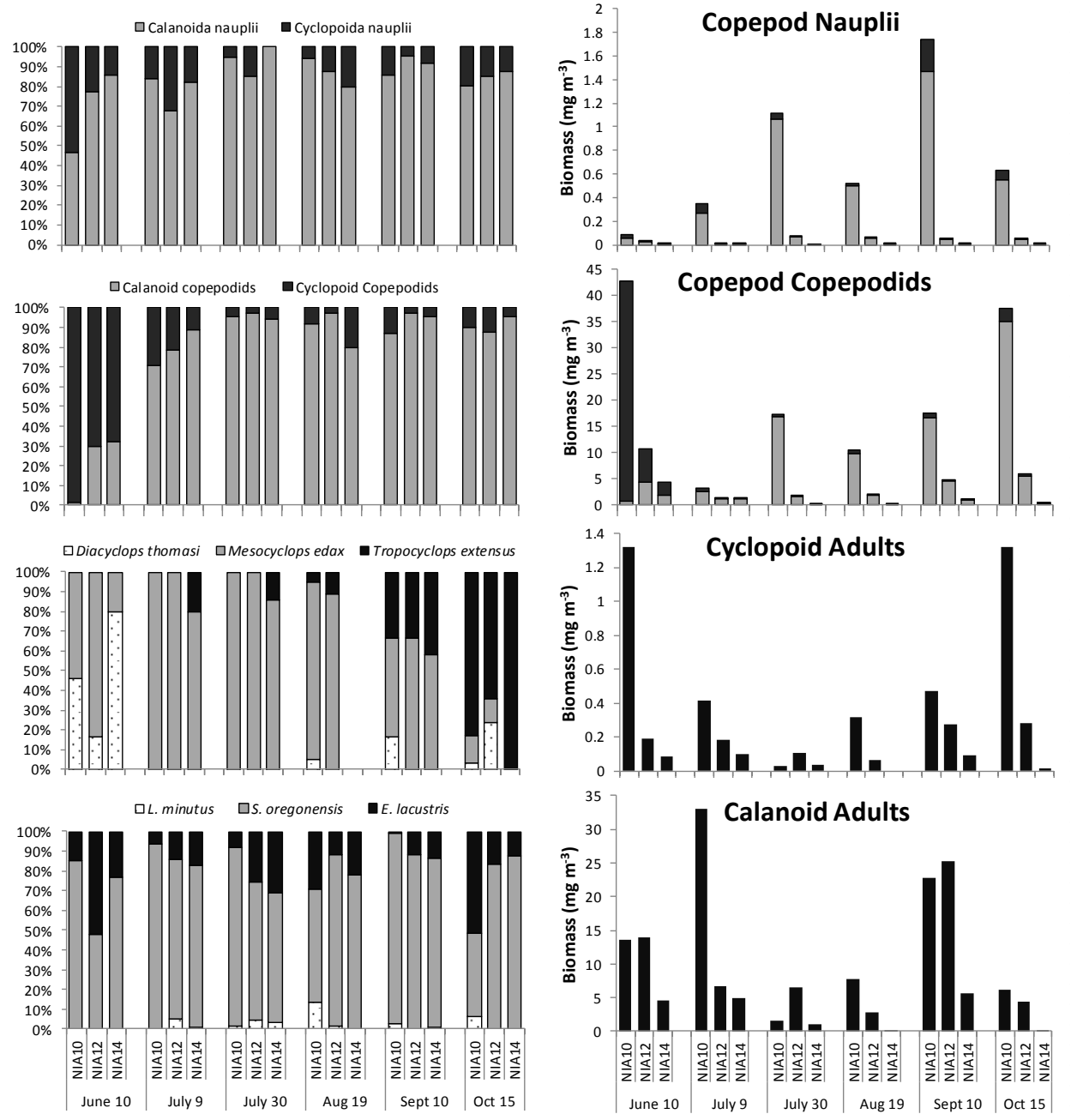

Figure 14. Proportions by density (left) and biomass (right) of dominant copepod taxa across the sampling season, including juvenile stages (nauplii and copepodids), adult cyclopoids and adult calanoids for Lake Erie (NIA10), upper (NIA12) and lower Niagara River (NIA14) stations by date. Calanoid copepods dominated density and biomass at all stations except in June.

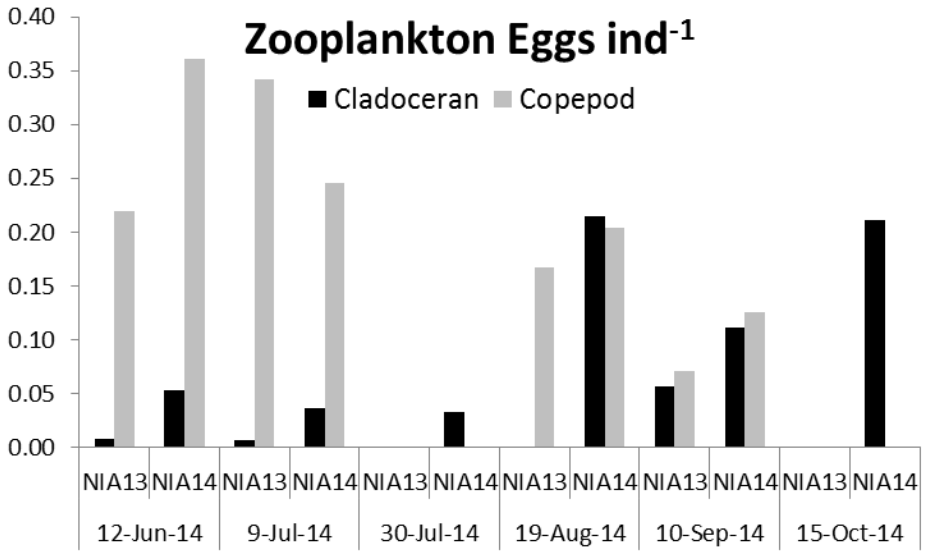

Figure 15. Cladoceran and copepod eggs per individual comparing the above turbine station (NIA13) and below turbine station (NIA14) for the Niagara River by date.

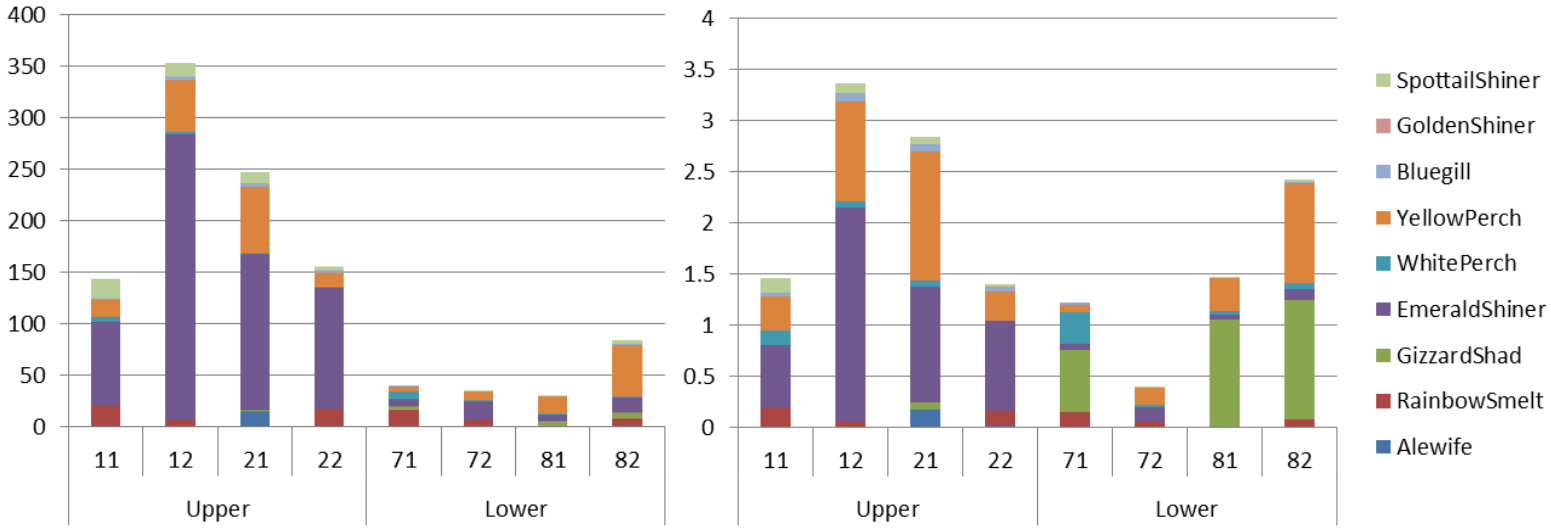

Figure 16. Density in catch per unit effort (CPUE) (left) and biomass as CPUE·Mass·1000 (right) for each species of planktivorous fishes at DFO electrofishing transect stations from the Canadian side of the upper and lower Niagara River in 2015 (DFO SAR database). Emerald Shiner comprise the dominant density and biomass in the upper river, but Gizzard Shad dominate the biomass of the lower river.

Appendix 1. Dates and sampling sites for sonde profiles.

Date	Station	Single Point	Transect
05-Jun-14	NR 15	√	
	NIA15	√	
	NIA16	√	
	NIA17	√	
	NIA18	√	
	NIA19	√	
10-Jun-14	NIA13	√	
	NIA14	√	
	NIA18	√	√
	NIA4	√	√
	NIA19	√	
	NOTL	√	
12-Jun-14	NIA10	√	
	NIA11	√	
	NIA15	√	
	NIA12	√	√
	NIA18	√	
09-Jul-14	NIA10	√	
	NIA11	√	
	NIA15	√	
	NIA12	√	
	NIA13	√	
	NIA14	√	
	NIA18		√
	NIA4	√	√
10-Jul-14	NIA10	√	
	NIA11	√	√
	NIA15	√	
	NIA12	√	
	NIA17	√	
	NIA18	√	

Date	Station	Single Point	Transect
30-Jul-14	NIA10	√	
	NIA11	√	√
	NIA15	√	
	NIA12	√	√
	NIA13	√	
	NIA14	√	
	NIA18		√
	NIA4	√	√
19-Aug-14	NIA10	√	
	NIA11	√	
	NIA15	√	
	NIA12	√	√
	NIA13	√	
	NIA14	√	
	NIA18		√
	NIA4	√	√
10-Sep-14	NIA10	√	
	NIA11	√	
	NIA15	√	
	NIA12	√	√
	NIA13	√	
	NIA14	√	
	NIA18		√
	NIA4	√	√
15-Oct-14	NIA10	√	
	NIA11	√	
	NIA15	√	
	NIA12	√	√
	NIA13	√	
	NIA14	√	
	NIA18		√
	NIA4	√	√

Appendix 2. Individual Niagara River plankton survey station sonde profile data for 2014.

			EXO					FluoroProbe				Hydrolab			
Station	Date	Sounding (m)	Range (m)	Chl (µg L^{-1})	Turb (FNU)	Temp (°C)	Cond (µS/cm)	Range (m)	Green	Blue-Green	Total (µg L^{-1})	Range (m)	Temp (°C)	SpCond (µS/cm)	DO (mg L^{-1})
	12-Jun	9.1	0-8.27	1.22	-0.99	15.31	231.32	0-8.62	0.000	0.021	0.021				
	09-Jul	9.2	0-8.87	0.70	2.75	21.88	268.01	--	--	--	--				
	10-Jul	9.1	0.6-9.3	0.64	0.95	22.01	271.48	0-9.44	0.000	0.000	0.000				
NIA10	30-Jul		--	--	--	--	--	0-9	0.000	0.007	0.633				
	19-Aug	9	0.8-9.4	0.79	6.23	20.99	278.77	0.3-9	0.000	0.000	0.024	0-9	21.00	241.23	8.38
	10-Sep	8.2	0-8.5	0.21	-0.30	22.04	269.00	0-8.4	0.00	0.00	0.00	0-8.3	22.01	253.98	7.88
	15-Oct	8.7	0-8.7	0.23	1.40	16.32	224.00	0-5.4	0.00	0.46	0.93	0-9.3	16.27	235.75	9.64
	12-Jun	6	0-4.9	1.06	-0.55	15.02	235.00	0-4.96	0.000	0.063	0.094				
	09-Jul	8.4	0-7.32	0.53	2.67	21.89	267.38	--	--	--	--				
	10-Jul	7.1	0-6.7	0.32	-0.03	22.07	273.29	0-6.69	0.000	0.001	0.001				
NIA11	30-Jul		0-5	0.41	0.12	21.15	278.82	0-4.6	0.080	0.000	0.520				
	19-Aug		0.9-4	0.78	0.09	21.09	275.38	0.2-3.5	0.503	0.193	1.573	0-8.5	20.99	185.85	8.54
	10-Sep	5.6-8.7	0-9.1	0.15	-1.79	22.06	268.47	0-8.8	0.00	0.00	0.00	0-7.6	22.04	253.12	7.79
	15-Oct	7.6	0-8.6	0.14	1.67	16.28	224.01	0-4.8	0.00	0.41	0.82	0-7.8	16.24	233.97	9.21
	12-Jun	5.2	0-5.11	0.73	-0.75	16.20	240.00	0-5.32	0.000	0.000	0.000				
	09-Jul	5.7	0-5.61	1.11	2.51	22.05	269.84	--	--	--	--				
	10-Jul	5.6	0-5.5	0.42	0.21	22.23	270.91	0-5.59	0.000	0.000	0.000				
NIA12	30-Jul		0-6	0.39	-0.10	21.51	279.47	0-5.8	0.069	0.025	0.427				
	19-Aug	5	0.1-6	0.27	-0.16	21.24	273.94	0.3-4.9	0.000	0.014	0.014	0-6	21.24	222.78	8.12
	10-Sep	4.8	0-5.9	0.02	-1.33	22.14	268.00	0-0.5	0.00	0.00	0.00	0-5.2	22.12	253.00	7.68
	15-Oct	5.3	0-5.6	0.60	2.80	16.23	223.00	0-8.8	0.00	0.22	0.98	0-5.6	16.17	235.34	9.83
	10-Jun	16-18	0.7-2.5	0.37	1.74	16.10	240.00	--	--	--	--				
	09-Jul	15.9	--	--	--	--	--	--	--	--	--				
NIA13	30-Jul		0-12.3	0.41	1.89	21.50	278.62	0-11	0.166	0.034	0.548				
	19-Aug	17.8	--	--	--	--	--	0.4-12	0.000	0.000	0.000	--	--	--	--
	10-Sep	17.6	0-13.4	0.07	0.05	22.32	270.00	0-12.9	0.00	0.00	0.00	0-7.6	22.29	248.20	9.66
	15-Oct	17.4	0-12.3	-0.04	2.53	16.38	225.00	n/a	0.179	0.393	1.039	0-10.5	16.43	190.58	11.10
	10-Jun	22-30	--	--	--	--	--	--	--	--	--				
	09-Jul	40	--	--	--	--	--	--	--	--	--				
NIA14	30-Jul		0-7.8	0.59	1.96	21.54	279.68	0-7.7	0.125	0.034	0.800				
	19-Aug	13.8	--	--	--	--	--	0.6-5.6	0.000	0.024	0.024	--	--	--	--
	10-Sep	25	0-10	0.21	-0.02	22.37	270.92	--	--	--	--	0-6.1	22.87	146.23	8.36
	15-Oct	18	0-6.2	0.16	2.08	16.32	226.00	n/a	0.00	0.38	1.32	0-12.7	16.61	156.59	10.20
	05-Jun	2	0-1.56	0.56	0.82	14.45	234.18	--	--	--	--				
	12-Jun		0-3.4	0.90	-0.13	15.14	235.24	0-3.64	0.000	0.010	0.010				
	09-Jul		0-3.85	0.56	3.28	21.90	268.00	--	--	--	--				
NIA15	10-Jul		0-3.7	0.34	0.31	22.15	272.89	0-3.7	0.000	0.000	0.000				
	30-Jul		0-3.7	0.61	0.19	21.28	277.55	0-3.4	0.320	0.000	0.780				
	19-Aug		0.1-3.5	0.58	2.40	21.39	276.00	0.2-3.4	0.000	0.096	0.255	--	--	--	--
	10-Sep	4.3	0-3.7	0.23	-1.54	22.08	268.00	0-3.6	0.00	0.00	0.00	--	--	--	--
	15-Oct	3.2	0-3.8	0.31	2.66	16.26	224.82	0-3.3	0.00	0.42	0.96	--	--	--	--
NIA16	05-Jun		0-0.6	0.91	3.44	16.30	246.99	--	--	--	--				
NIA17	05-Jun	2	0-2.82	1.06	12.27	17.12	276.14	--	--	--	--				
	10-Jul	3-4	--	--	--	--	--	0-3.31	0.487	0.472	2.139				
	05-Jun	2	0-1.12	1.27	6.84	15.86	246.00	--	--	--	--				
NIA18	10-Jun		--	--	--	--	--	0-1.51	0.000	0.003	0.003				
	12-Jun		0-0.5	2.01	1.78	16.30	232.33	1.14-0	0.055	0.092	0.218				
	10-Jul		0-0.5	50.99	35.07	22.54	276.99	--	--	--	--				
NIA19	05-Jun	1.5	0-0.73	0.30	2.19	15.88	245.26	--	--	--	--				
	10-Jun		--	--	--	--	--	1-2.44	0.000	0.038	0.038				
	10-Jun	14.6	--	--	--	--	--	--	--	--	--				
	09-Jul	13.1	1.3-14.8	0.72	5.27	22.17	278.30	--	--	--	--				
NIA4	30-Jul		0-13	0.59	2.04	21.55	280.36	0-12.7	0.137	0.005	0.712				
	19-Aug		--	--	--	--	--	0.39-15	0.000	0.000	0.000	0-14.7	21.51	207.81	8.95
	10-Sep	13-14.8	--	--	--	--	--	0-11.4	0.00	0.00	0.00	0-13.9	22.37	226.65	8.60
	15-Oct	14	0-14.6	0.24	2.48	16.33	226.00	0-12.4	0.00	0.05	0.05	0-14.2	16.35	229.59	10.31
NOTL	10-Jun		--	--	--	--	--	0-18.67	0.000	0.041	0.041				
NR 15	05-Jun		0-1.09	23.95	2.53	13.85	230.62	--	--	--	--				

Appendix 3. Niagara River station NLET water chemistry by date.

Date	Station	Chl. a µg.L^{-1}	TP µg.L^{-1}	SRP µg.L^{-1}	TKN mg.L^{-1}	NO_{3}+NO_{2} mg.L^{-1}	NH_3 mg.L^{-1}	POC mg.L^{-1}	PON mg.L^{-1}	DIC mg.L^{-1}	DOC mg.L^{-1}	SiO_2 mg.L^{-1}	Na^+ mg.L^{-1}	Mg^{+2} mg.L^{-1}	K^+ mg.L^{-1}	Ca^{+2} mg.L^{-1}
Jun-06	NIA10	0.835	11.9	0.7	0.244	0.256	0.013	0.195	0.034	21.1	2.8	0.33	12.4	8.95	1.58	34.2
	NIA12	1.006	13.1	1.9	0.224	0.245	0.018	0.141	0.023	20.7	2.5	0.32	12.4	8.96	1.59	34.2
	NIA13	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	NIA4	1.693	15.3	1.7	0.284	0.310	0.018	0.289	0.051	21.3	2.7	0.40	12.9	8.89	1.59	33.9
Jul-09	NIA10	1.710	~~755.0~~	~~772.0~~	0.261	0.144	0.019	0.285	0.045	21.2	~~11.6~~	0.47	11.1	8.60	1.69	33.5
	NIA12	1.680	19.2	9.9	0.273	0.165	0.030	0.298	0.049	21.0	2.5	0.46	10.8	8.66	1.61	33.3
	NIA13	2.499	25.3	9.8	0.255	0.181	0.025	0.288	0.046	20.9	2.6	0.46	10.9	8.62	1.60	33.4
	NIA4	1.925	19.5	6.8	0.265	0.195	0.039	0.349	0.055	21.0	2.6	0.54	11.8	8.66	1.63	33.6
Jul-30	NIA10	1.172	13.5	2.8	0.225	0.187	0.014	0.182	0.028	21.7	2.9	0.49	11.4	8.86	1.52	34.2
	NIA12	0.490	7.8	2.9	0.221	0.182	0.017	0.136	0.018	21.6	2.9	0.48	11.3	8.82	1.50	34.0
	NIA13	0.711	18.5	5.7	0.245	0.192	0.027	0.163	0.021	21.5	2.7	0.53	11.4	8.73	1.52	33.8
	NIA4	1.140	23.5	11.1	0.285	0.196	0.039	0.341	0.047	21.6	2.9	0.53	11.5	8.74	1.55	33.9
Aug-19	NIA10	1.162	13.5	3.3	0.260	0.144	0.012	0.229	0.038	22.4	2.6	0.39	11.1	8.95	2.18	33.9
	NIA12	0.801	16.1	8.5	0.421	0.139	0.019	0.172	0.028	22.3	2.3	0.36	10.8	8.93	1.63	33.7
	NIA13	0.974	12.6	3.8	0.271	0.144	0.015	0.206	0.031	22.2	2.5	0.38	11.1	8.88	1.58	33.5
	NIA4	1.297	13.7	4.4	0.262	0.154	0.022	0.275	0.042	22.6	2.5	0.39	11.1	8.96	1.61	33.9
Sep-10	NIA10	1.309	24.3	12.9	0.255	0.092	0.020	0.278	0.048	22.3	2.6	0.34	10.5	9.03	1.46	34.4
	NIA12	1.031	13.3	5.8	0.250	0.095	0.021	0.160	0.024	22.2	2.5	0.26	10.4	9.05	1.46	34.3
	NIA13	1.192	9.4	2.4	0.249	0.098	0.016	0.206	0.028	22.0	2.5	0.28	10.4	9.02	1.46	34.2
	NIA4	1.579	10.9	2.2	0.252	0.105	0.019	0.213	0.031	22.2	2.5	0.31	10.6	9.03	1.47	34.4
Oct-15	NIA10	1.665	12.8	6.0	0.239	0.111	0.025	0.698	0.047	22.9	2.4	0.43	10.5	8.88	1.56	33.8
	NIA12	1.194	12.8	6.7	0.232	0.109	0.024	0.601	0.053	22.7	2.3	0.37	10.3	8.78	1.54	33.5
	NIA13	1.215	19.1	13.1	0.251	0.116	0.023	0.651	0.044	22.7	2.5	0.38	10.4	8.78	1.56	33.5
	NIA4	1.527	24.4	13.8	0.250	0.129	0.029	0.726	0.073	22.9	2.3	0.42	10.8	8.91	1.57	33.9
Mean ± SE	NIA10	1.31±0.14	15.2±2.3	5.14±2.1	0.247±0.006	0.156±0.024	0.017±0.002	0.31±0.08	0.040±0.003	21.9±0.3	2.66±0.09	0.41±0.03	11.2±0.2	8.88±0.06	1.67±0.11	33.9±0.1
	NIA12	1.03±0.16	13.7±1.6	5.95±1.3	0.270±0.031	0.156±0.022	0.022±0.002	0.25±0.07	0.033±0.006	21.8±0.3	2.50±0.09	0.38±0.03	11.0±0.3	8.87±0.06	1.56±0.03	33.9±0.2
	NIA13	1.32±0.31	17.0±2.8	6.96±2.0	0.254±0.004	0.146±0.018	0.021±0.002	0.30±0.09	0.034±0.005	21.9±0.3	2.56±0.04	0.41±0.04	10.8±0.2	8.81±0.07	1.54±0.02	33.8±0.2
	NIA4	1.53±0.11	17.9±2.2	6.67±2.0	0.266±0.006	0.182±0.030	0.028±0.004	0.37±0.07	0.050±0.006	21.9±0.3	2.58±0.08	0.43±0.04	11.5±0.3	8.87±0.06	1.57±0.02	34.0±0.1
Mean ± SE	FE *		14.7±2.2	1.94±0.5	0.31±0.011	0.166±0.017	0.024±0.002			21.3±0.2	2.62±0.05	0.47±0.05	11.2±0.3	8.75±0.04	1.55±0.01	33.4±0.2
	NOTL*		26.0±6.9	3.88±0.4	0.33±0.000	0.179±0.014	0.022±0.002			21.9±0.2	2.61±0.03	0.48±0.04	11.0±0.2	8.75±0.04	1.54±0.02	33.4±0.2

* Environment Canada Niagara River Monitoring Program sampled weekly June-Oct, 2014 for upper river Fort Erie (FE) and lower river Niagara-on-the-Lake (NOTL) stations.

Appendix 4. Niagara River phytoplankton species biomass (mg m^{-3}) by station and date. Taxonomic groups are: (1) Cyanophyta, (2) Chlorophyta, (3) Euglenophyta, (4) Chrysophyta, (5) Bacillariophyta, (6) Cryptophyta, (7) Dinophyceae.

NIA10

Group	Name	July 9	July 30	Aug 19	Sept 10	Oct 15
1	*Anabaena lemmermannii*			10.22		
	Aphanizomenon flos-aquae			8.51		
	Aphanocapsa delicatissima	0.13	0.30	2.08	2.76	1.39
	Aphanocapsa elachista			0.11	0.03	
	Aphanocapsa holsatica		0.56	0.88	0.67	0.22
	Aphanocapsa incerta				1.37	
	Aphanothece nidulans		1.09	0.89	6.04	0.12
	Cylindrospermopsis raciborskii		0.54			
	Microcystis aeruginosa					0.11
	Pseudanabaena galeata		0.26			18.28
	Pseudanabaena limnetica	1.38	2.74	0.36	4.63	
	Pseudanabaena mucicola		0.29			
	Synechococcus elongatus	0.03			0.05	
	Synechococcus sp 1	0.05	0.49	5.17	2.42	
	Synechocystis sp.					1.11
	Unknown Cyanophyte	1.78	2.59	3.78	5.86	0.98
2	*Ankistrodesmus falcatus*			0.36		
	Chlamydomonas sp.	0.33	0.43	2.80	3.31	5.19
	Coelastrum microporum		2.05		0.63	
	Coelastrum pseudomicroporum		0.69			
	Monomastix minuta				0.28	
	Monoraphidium arcuatum	0.44				1.89
	Monoraphidium capricornutum	2.86	0.18	0.12	0.42	
	Oocystis parva	0.88	3.55			
	Scenedesmus bijuga		0.08	0.36	0.62	1.24
	Scenedesmus quadricauda		0.11		0.38	
	Scenedesmus serratus					0.03
	Sphaerocystis schroeteri	13.16				
	Stichococcus bacillaris			0.10		
	Unknown Chlorophyte	0.04	0.10	1.06	5.08	2.06
4	*Chromulina* sp.	1.05	0.44	0.78	0.55	0.11
	Chrysochromulina parva	1.31	0.25	3.45	1.76	1.97
	Dinobryon sp.	15.76	1.53		3.06	1.23
	Dinobryon bavaricum			0.08		
	Dinobryon sertularia			1.48		
	Dinobryon sociale americana		0.58			
	Mallomonas sp.		3.63			
	Ochromonas sp.			24.70	0.36	
	Unknown Chrysophyte					0.96
	Uroglena sp.				1.32	1.18
5	*Achnanthes minutissima*	0.64				
	Asterionella formosa		0.93			
	Aulacoseira crenulata					2.78
	Aulacoseira muzzanensis	13.16				
	Cocconeis pediculus		18.10			
	Cyclotella atomus			0.38	5.21	2.10
	Cyclotella comensis	0.89			2.25	11.97
	Cyclotella comensis 1	5.16	0.52	1.05	3.14	1.33

	Cyclotella ocellata				2.20	6.76
	Cyclotella pseudostelligera	1.40	0.38	0.38		
	Fragilaria crotonensis			39.83	6.56	54.32
	Navicula cryptotenella	3.84				
	Nitzschia gracilis			2.66		
	Nitzschia intermedia	9.46				
	Nitzschia palea			1.44		
	Nitzschia recta	11.23	4.37			11.07
	Rhoicosphenia curvata				4.19	
	Stephanodiscus alpinus		18.14			32.77
	Stephanodiscus medius		12.31	12.85		
	Stephanodiscus parvus	11.91				
	Synedra filiformis		0.74			
6	*Cryptomonas erosa*	1.70				23.34
	Rhodomonas minuta		1.44		1.03	1.71
	Rhodomonas minuta nannoplanctica	10.94	12.57	28.73	23.82	20.52
7	*Gymnodinium* sp 2				1.79	
Total		**109.52**	**91.99**	**154.60**	**91.78**	**206.74**

NIA13

	Name	**July 9**	**July 30**	**Aug 19**	**Sept 10**	**Oct 15**
1	*Aphanocapsa delicatissima*			0.17	0.35	0.19
	Aphanocapsa elachista		0.07	0.60		0.03
	Aphanocapsa holsatica			0.97		
	Aphanocapsa incerta			0.50	0.92	
	Aphanothece nidulans				0.65	0.39
	Chroococcus minimus				0.32	
	Lyngbya sp.		16.19			
	Lyngbya birgei				450.24	
	Microcystis aeruginosa				11.26	
	Phormidium sp.					0.44
	Pseudanabaena sp.		2.30	0.83	0.18	0.04
	Pseudanabaena galeata					4.16
	Pseudanabaena limnetica		2.07	0.77	0.56	0.52
	Synechococcus elongatus		0.10			
	Synechococcus sp 1	0.77	1.72	1.32	1.58	0.06
	Synechocystis sp.		0.03	0.08	0.65	0.10
	Unknown Cyanophyte	0.62	3.69	1.47	1.70	1.11
2	*Chlamydomonas*	5.47	0.10	1.19		2.46
	Coelastrum microporum					1.05
	Lagerheimia quadriseta					0.28
	Monoraphidium capricornutum	0.15	0.12	0.08	0.17	0.06
	Scenedesmus bijuga		1.42			0.56
	Scenedesmus denticulatus			0.23		
	Scenedesmus quadricauda					0.27
	Scenedesmus serratus				0.11	
	Unknown Chlorophyte	0.64	0.59	0.66	1.09	0.06
3	*Euglena* sp.				4.64	
4	*Chromulina* sp.	0.28	0.13		0.40	
	Chrysochromulina parva	1.85		1.06	0.37	0.25
	Dinobryon sp.	1.54				
	Mallomonas sp.				1.06	0.96
	Ochromonas sp.			2.93	0.28	

5	*Achnanthes delicatula*					0.15
	Achnanthes minutissima	2.08				0.71
	Cocconeis neodiminuta	0.76				
	Cocconeis pediculus	35.47	2.94	2.75		
	Cocconeis placentula lineata	6.09	11.07	1.72	3.42	
	Cyclotella atomus				1.24	0.43
	Cyclotella comensis	3.81				
	Cyclotella ocellata					0.79
	Cymbella caespitosa					1.99
	Diatoma vulgaris vulgaris					9.25
	Fragilaria capucina vaucheriae			1.58		
	Fragilaria construens		14.18			
	Fragilaria crotonensis	11.08				16.76
	Gomphonema olivaceum	10.38				
	Gomphonema parvulum				0.51	
	Navicula cryptotenella		1.77	0.88	1.42	0.27
	Navicula pupula					1.39
	Navicula salinarum				4.56	
	Navicula tripunctata		8.51			
	Navicula viridula rostellata			4.73		1.32
	Nitzschia dissipata					3.70
	Nitzschia gracilis			2.47		
	Nitzschia palea			0.91		1.00
	Nitzschia perminuta					0.46
	Nitzschia recta		9.37		4.26	2.02
	Stephanodiscus parvus	3.94				
	Synedra filiformis					0.67
6	*Cryptomonas erosa*		3.08	2.53	0.59	0.85
	Rhodomonas minuta		1.44	1.03	2.06	
	Rhodomonas minuta nannoplanctica	5.13	9.23	12.82	8.79	3.85
7	*Gymnodinium* sp 2					1.05
	Gymnodinium sp 3	3.08				
Total		**93.13**	**90.12**	**44.30**	**503.38**	**59.66**

NIA4

	Name	July 9	July 30	Aug 19	Sept 10	Oct 15
1	*Aphanocapsa delicatissima*			0.28	0.30	0.23
	Aphanocapsa elachista			2.43	0.06	0.02
	Aphanocapsa holsatica		1.00	1.40	0.80	0.19
	Aphanothece nidulans		0.64	0.41	3.21	0.72
	Heteroleibleinia sp.				13.86	
	Merismopedia punctata				5.11	
	Oscillatoria sp.				2.67	
	Pseudanabaena sp.			0.16	0.18	0.40
	Pseudanabaena acicularis				1.13	
	Pseudanabaena galeata					10.22
	Pseudanabaena limnetica		1.11		0.42	1.50
	Pseudanabaena mucicola		0.66			
	Synechococcus elongatus	0.06	4.01	0.14	0.06	
	Synechococcus sp 1	0.37	1.74	0.62	2.28	0.26
	Synechocystis sp.			1.35	0.48	0.06
	Unknown Cyanophyte	1.72	2.74	4.31	2.26	0.76

2	*Chlamydomonas* sp.	0.30	0.27	14.56	7.13	1.22
	Chlorogonium sp.				0.34	
	Coelastrum microporum			6.65	1.14	
	Lagerheimia quadriseta				0.05	
	Monomastix minuta					0.14
	Monoraphidium arcuatum					0.50
	Monoraphidium capricornutum		0.10	0.15	0.18	
	Oocystis parva				0.20	1.27
	Pyramichlamys dissecta				3.18	
	Scenedesmus bijuga			0.93	0.25	0.72
	Scenedesmus denticulatus					1.90
	Scenedesmus quadricauda			0.40		
	Scenedesmus serratus				0.18	0.22
	Stichococcus bacillaris	0.09			0.05	
	Tetracystis pulchra					16.45
	Unknown Chlorophyte	0.54	0.43	14.41	3.71	0.38
4	*Chromulina* sp.	0.04	1.11	0.28	0.11	
	Chrysochromulina parva	1.31	0.41	1.85	1.72	0.70
	Dinobryon sp.		2.14		1.18	
	Mallomonas sp.			5.03	1.02	
	Ochromonas sp.			75.89	4.02	
	Unknown Chrysophyte			3.74		
	Uroglena sp.					3.11
5	*Achnanthes minutissima*				1.33	
	Cocconeis pediculus	48.70	14.19			18.99
	Cocconeis placentula lineata		2.13	1.30	0.64	
	Cyclostephanos invisitatus			4.16		1.22
	Cyclotella atomus				1.77	0.14
	Cyclotella comensis		1.31		3.15	0.47
	Cyclotella comensis 1	2.66		1.66	0.33	
	Cyclotella michiganiana			2.13	1.54	
	Cyclotella ocellata	1.41				4.11
	Fragilaria crotonensis			162.14		
	Gomphonema pumilum	1.29				
	Navicula sp.			0.51		
	Navicula cryptotenella			1.23	1.83	
	Nitzschia heufleriana	21.42				
	Nitzschia palea			1.80	1.97	0.81
	Nitzschia recta	2.30				
	Skeletonema potamos	12.26	21.75	0.87	8.62	
	Stephanodiscus alpinus					59.36
	Stephanodiscus binderanus			38.47		
	Stephanodiscus medius					7.42
6	*Cryptomonas erosa*	7.11		4.43	5.25	2.89
	Rhodomonas minuta				0.72	2.06
	Rhodomonas minuta nannoplanctica	6.84	6.41	4.49	11.80	6.23
7	*Gymnodinium* sp 2				2.66	
	Peridinium umbonatum					1.28
Total		**108.77**	**62.16**	**358.17**	**99.66**	**145.95**