Phosphorus Provenance and *Cladophora* Growth in Lake Ontario

Martin T. Auer, Anika Kuczynski and Rasika K. Gawde, Michigan Technological University

October 2014

MOTIVATION

The filamentous, green alga *Cladophora* has been present at nuisance levels in Lake Ontario, fouling beaches and resulting in beneficial use impairment, for more than 80 years (Figure 1). Proliferation of the alga has long been linked to the availability of phosphorus, the growth-limiting nutrient (Auer and Canale 1982; Higgins et al. 2008; Higgins et al. 2012). As recently as the 1980s, *Cladophora* growth in Lake Ontario was considered to be 'whole-lake forced', i.e. phosphorus levels were sufficiently high that, wherever solid substrate was available for attachment, *Cladophora* grew to the maximum depth of light penetration. This is not the case today. Striking reductions in phosphorus (Figure 2), achieved pursuant to the mandate of the Great Lakes Water Quality Agreement of 1972, have resulted in phosphorus-limited conditions in the open waters of the lake and a transition to a state of oligotrophy (Dove and Chapra 2015). Today, the occurrence of nuisance levels of *Cladophora* growth is seen as a response to local, urbanized influences (Higgins et al. 2012) rather than the whole-lake forcing of prior decades. Appropriately, the Great Lakes Water Quality Protocol of 2012 calls for the maintenance of levels of algal biomass below those constituting a nuisance condition and the establishment of load reduction targets to meet that objective (Governments of the U.S. and Canada 2012).

Figure 1. *Cladophora* at Humber Bay, Lake Ontario in 1933. Neil and Owen 1964.

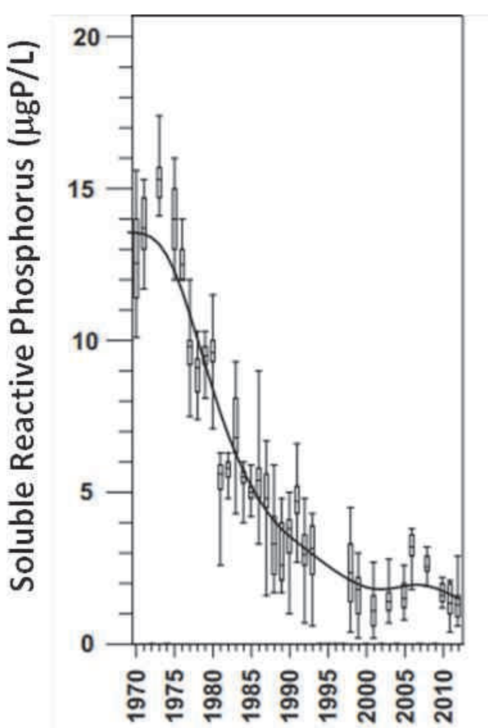

Figure 2. Soluble reactive phosphorus in Lake Ontario. Dove and Chapra 2015.

PHOSPHORUS PROVENANCE

Given the widespread awareness of phosphorus as the nutrient limiting *Cladophora* growth and the shift from whole-lake to local forcing, attention now appropriately turns to identification of the provenance or origin of that phosphorus. This, as prelude to development of management strategies that would eliminate nuisance conditions and restore lost beneficial uses. For the case of the Great Lakes nearshore, four potential sources are of particular interest,

- recycling by mussels
- exchange with offshore waters
- exchange through longshore transport
- discharges from tributaries and point sources

Here, we examine these potential sources with reference to the proliferation of *Cladophora* in the Lake Ontario nearshore at Ajax, Ontario, drawing upon information available from the primary, peer-reviewed literature and from field and laboratory measurements made at the site by our team in 2013 and 2014.

<u>Recycling by mussels</u>

Cladophora colonizes cobbles, boulders and bedrock to depths at which sunlight reaches the bottom. Where the requirements for solid surfaces and light are met, the presence and level of growth of *Cladophora* is determined by the availability of phosphorus. Acting as ecological engineers (Karatayev 2002; Hecky et al. 2004), mussels have transformed physical conditions in the Lake Ontario nearshore in two ways beneficial to *Cladophora* growth. First, mussel beds developing over sandy bottoms provide solid substrate for attachment by *Cladophora*. Second, filter-feeding by mussels increases water clarity and thus the depth to which sunlight penetrates. This, in turn, adds to the amount of bottom area available for colonization by *Cladophora* and the total amount of algal biomass that may be produced each season. In this way, the activity of mussels has made the Great Lakes nearshore more sensitive to discharges of phosphorus.

Mussels also influence phosphorus cycling in the lake through their filter-feeding activity. Here, mussels ingest particulate- phosphorus, a form not directly available to *Cladophora* and transform a portion of that solid-phase phosphorus to soluble reactive phosphorus (SRP), the form directly available. SRP made available in excess of the nutritional needs of mussels is then excreted and may be taken up by *Cladophora*. This process has been termed the nearshore phosphorus shunt (Hecky et al. 2004) and can create a near-bottom SRP boundary layer with phosphorus levels capable of stimulating *Cladophora* growth (Dayton et al. 2014). As with the engineering of physical conditions, this capacity for recycling makes the nearshore more sensitive to phosphorus discharges.

It must be noted, however, that mussels are not a *source* of phosphorus; they simply transform the phosphorus introduced to the lake such that it becomes available to *Cladophora*. (Higgins et al. 2012, p. 116) recognized this in concluding that, "there was little evidence that phosphorus from metabolic waste products of dreissenid mussels was sufficient to produce severe blooms in absence of localized phosphorus enrichment." Thus the significance of mussels in regard to the phosphorus – *Cladophora* dynamic is one of sensitivity, not source: no phosphorus, no *Cladophora*.

<u>Exchange with offshore waters</u>

Phosphorus is delivered to Lake Ontario from 136 tributary and 49 point source (water pollution control plants) discharges (Makarewicz et al. 2012). Acted upon by mass transport and in-lake loss processes such as settling, whole lake phosphorus levels provide a reflection of nutrient conditions lake wide. Where these concentrations exceed those required to support *Cladophora* growth (i.e., phosphorus is no longer limiting), the system is said to be whole lake forced and the impact of local inputs to the nearshore is masked by these whole lake effects. It naturally follows that, under these conditions, management focus on a single point source would not be effective as phosphorus removed from that source would be replaced by mixing with phosphorus -rich offshore waters. Whole lake forcing has been offered as an argument in opposition to focus on any individual point source in Lake Ontario pending better lakewide management of phosphorus.

Once valid, this argument is no longer supportable as phosphorus concentrations lakewide have been reduced (Figure 2) to levels deemed phosphorus limiting (Higgins et al. 2012). Concentrations of SRP at the Environment Canada open lake station 22 km offshore of Ajax, Ontario have ranged from 1.0 – 2.5 µgP/L over the interval 2001 - 2010, averaging 1.5 ± 0.6 µgP/L. These levels are consistent with conditions of phosphorus-limitation of *Cladophora* (Figure 3).

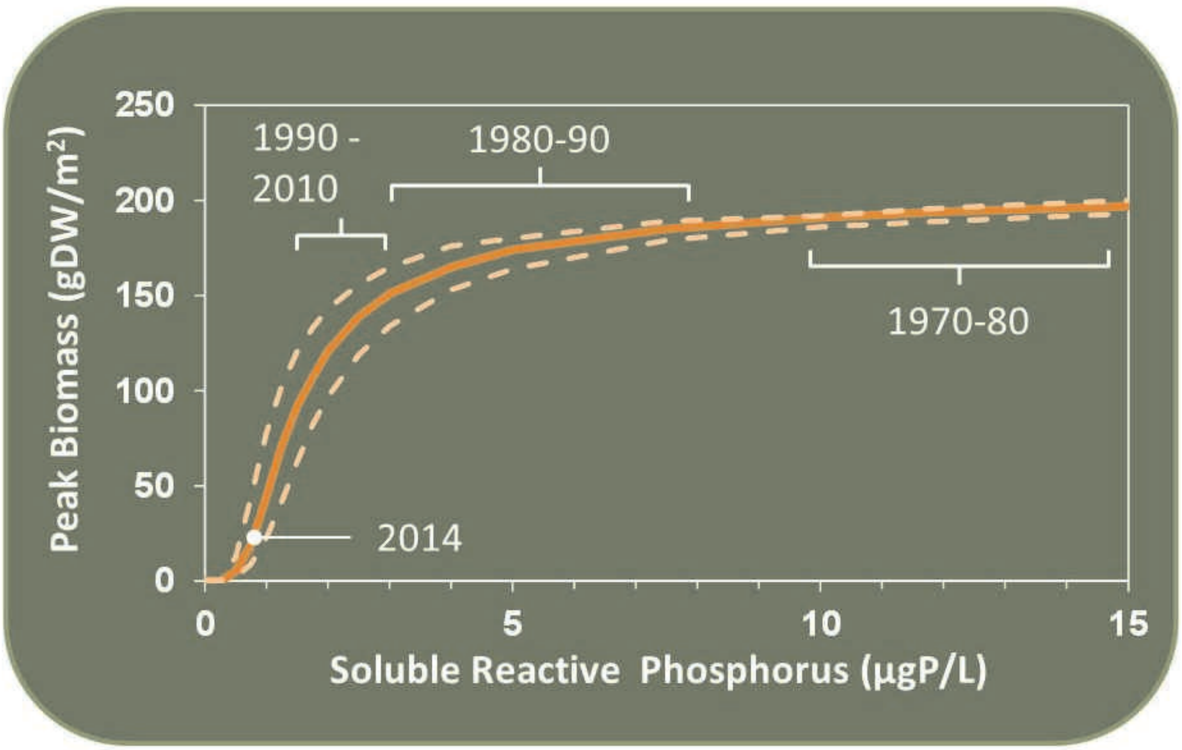

Figure 3. Relationship between the soluble reactive phosphorus concentration and model-calculated peak Cladophora biomass. Dashed lines represent ±10% of Q_0, the most sensitive model coefficient. Bracketed intervals identify soluble reactive phosphorus concentrations based on Dove and Chapra (2015) for 1975-2010 and Auer (unpublished) for 2014.

In April of 2014, Michigan Technological University performed a survey of phosphorus concentrations along a 10-station transect extending 22 km from the Ajax, Ontario nearshore to a position proximate to the region's Environment Canada open lake station. Spring surveys of this type are conducted to determine the maximum amounts of phosphorus present, i.e. before seasonal algal production draws down phosphorus reserves, and thus the potential for algal production. Soluble reactive phosphorus concentrations in April 2014 ranged from 0.4 – 1.1 µgP/L and averaged 0.8 ± 0.2 µgP/L. These concentrations are clearly phosphorus-limiting

(Figure 3) and represent levels appropriate for elimination of nuisance growth of *Cladophora*. Measurements made in offshore waters by Environment Canada from 2001 - 2010 and by Michigan Technological University in 2014 are consistent with the findings of Higgins et al. (2012) that *Cladophora* growth in Lake Ontario is no longer driven by whole lake nutrient conditions and that the appropriate management focus for the nearshore is now tributary and point source discharges.

Exchange through longshore transport

As with offshore exchange, transport through longshore mass transport has the potential to deliver phosphorus to the Ajax, Ontario nearshore from adjacent areas. In this regard, discharges from the Highland Creek WPCP (to the west) and the Corbett Creek WPCP (to the east) are of particular interest. The total phosphorus (TP) loads for the Highland Creek and Corbett WPCPs are 46% and 12% of the Duffins Creek WPCP, respectively (Makarewicz et al. 2012). In 2014, surveys were performed, tracking the electrical conductivity of the water as an indicator of the presence of a WPCP plume (method as described below). One objective of the surveys was to determine if any influence from either neighboring discharge was evident in the Ajax, Ontario nearshore. Plumes associated with the Highland Creek and Duffins Creek WPCPs were observed, but there was no evidence of the presence of the Corbett Creek WPCP under the current structure present on that day (Figure 4). The results of this survey suggest that, under certain hydrodynamic conditions, currents may transport some fraction of the Highland Creek WPCP plume into the area also influenced by the Duffins Creek WPCP. The fractional contribution of the Highland Creek WPCP discharge and the frequency of its presence in the Ajax, Ontario nearshore is not known at present, but may be quantified through the application of a hydrodynamic model.

Discharges from tributaries and point sources

The Duffin Creek Water Pollution Control Plant discharges an annual TP load of 90.8 mta (metric tons per annum), the 3rd largest point source input to Lake Ontario and the 2nd largest point source input within the Greater Toronto Area (Makarewicz et al. 2012). If operated at its

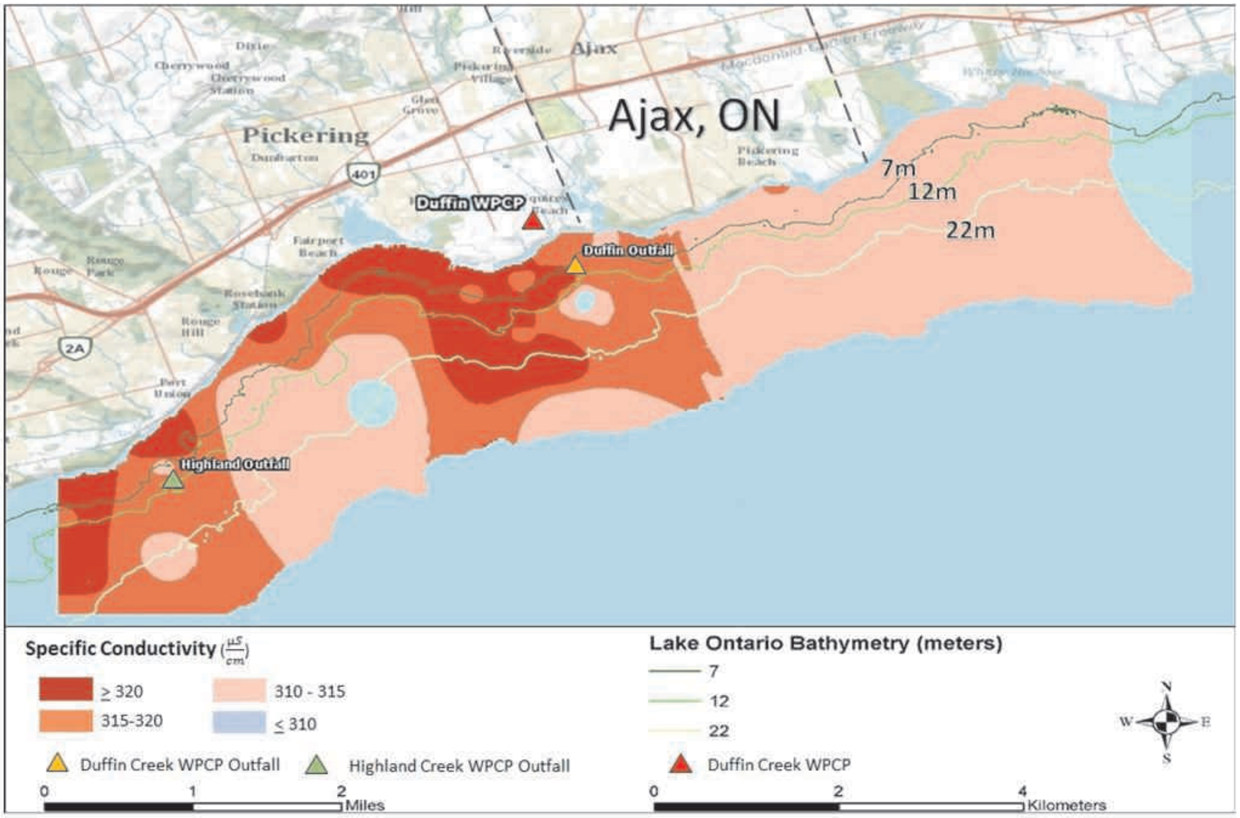

Figure 4. Map of conductivity at a depth of 3 m in the Ajax, ON nearshore on 14 July 2014. Background levels (Higgins et al. 2014) are in blue and the plumes in shades of red.

maximum rated capacity, at the current phosphorus removal efficiency, the plant would become the largest point source discharge of phosphorus to Lake Ontario. Yet, viewed on a whole lake basis, the Duffin Creek WPCP discharge is less striking, contributing 12% of the point source TP load and 3% of the overall TP load to Lake Ontario (Makarewicz et al. 2012). Calculations such as these, placing the Duffin Creek WPCP contribution in a whole lake context, have been offered as evidence that the facility is not a major player in the phosphorus – *Cladophora* dynamic in the Ajax, Ontario nearshore of Lake Ontario.

It must be noted, however, that the impact of the Duffin Creek WPCP is manifested not in its contribution to whole lake phosphorus concentrations, but in its discharge directly to and assimilation within the environmentally sensitive nearshore region. With respect to the phosphorus – *Cladophora* dynamic, the impact of the WPCP must be considered within that local context and its load compared to other local sources. Makarewicz et al. (2012) provide TP loading data for 2008, showing that the Duffin Creek WPCP contributes 85% of the annual load, with the balance added by two tributary streams, Duffins (14.8 mta, 14%) and Carruthers (1.1 mta, 1%) Creeks. The estimate for Duffins Creek is consistent with that reported by Malkin et al. (2010) for the interval 1990-2008, averaging 16.5 ± 8.2 mta, a finding that was later confirmed by Booty et al. (2013) using an alternative calculation methodology.

In application to the *Cladophora* issue, however, comparison of loading sources must consider seasonality in discharge patterns vis-à-vis seasonality in algal growth in the nearshore. This is clear from the work of Booty et al. (2013) where estimates of the Duffin Creek TP load for 1990-2010 ranged from 10 – 90 mta, occasionally approaching equivalence to the Duffin Creek WPCP load. It is important here, however, to consider the timing of delivery of these loads within the context of the seasonal cycle of *Cladophora* where growth begins in late May – early June and continues through August (Malkin et al. 2008). Examination of the daily hydrograph for 2006 (Figure 5), a wet, high load year in the analysis of Booty et al. (2013), indicates that only 16% of the annual load is delivered during the *Cladophora* growth season.

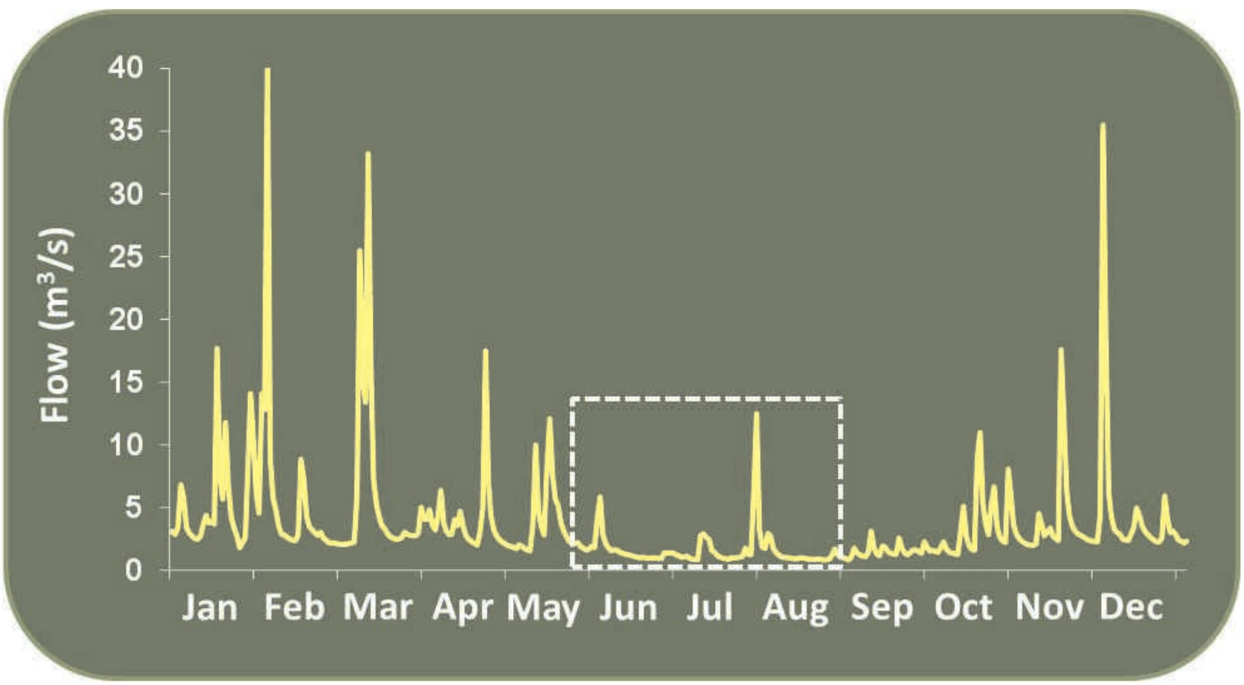

Figure 5. Duffins Creek discharge 2006. Shaded area indicates interval of *Cladophora* growth.

In addition, more than one-third of that seasonal load was delivered by three, short-term wet weather events, phenomena having a 7 - 14 hour residence time in the 5 km Ajax, Ontario nearshore for current velocities of 10 – 20 cm/s (8 – 17 km/d; Helm et al. 2012). In contrast, the effluent from the Duffin Creek WPCP is discharged to and remains present within the Ajax nearshore continuously.

Finally, the Great Lakes Water Quality Protocol of 2012 stipulates that, when establishing phosphorus loads, the bioavailability of the various forms of phosphorus be taken into consideration. Of the three phosphorus forms (soluble reactive, SRP; dissolved organic, DOP; and particulate, PP) SRP is considered to have the highest bioavailability (100%). DOP and PP are less bioavailable, on the order of two-thirds and one-third, respectively (Lambert et al., In Review). Here, we consider the load of SRP, the form directly and freely available to algae. Auer (2011) calculated summer (Jun-Sep) SRP loads for the Duffin Creek WPCP, Duffins Creek and Carruthers Creek yielding estimates of 39.1 mta (97.8%), 0.8 mta (1.9%) and 0.1 mta (0.3%), respectively. On the basis of its annual average TP load, the Duffin Creek WPCP contributes 85% of the total delivered to the Ajax waterfront. When the load is calculated within the context of its potential to stimulate *Cladophora* growth, i.e. the local, seasonal, bioavailable contribution, it accounts for essentially all (97%) of the phosphorus discharged to this environmentally sensitive nearshore region (Figure 6).

Figure 6. Contribution of the Duffins Creek WPCP to the regional, seasonal soluble reactive phosphorus load.

<u>Field and laboratory evidence of phosphorus provenance</u>

To this point, the question of phosphorus provenance has been addressed largely through consideration of phosphorus-sources, e.g. exchange with offshore waters, longshore transport and tributary and point source inputs. Provenance may also be considered with respect to the effects of those sources on the nearshore ecosystem, i.e. signals reflecting the nature of phosphorus provenance. Such evidence is considered here as provided by the results of field and laboratory measurements of three phenomena made within the Ajax, Ontario nearshore: the distribution of the Duffin Creek WPCP effluent plume, patterns in the stored phosphorus content of *Cladophora* and variability in rates of phosphorus uptake by *Cladophora*. A satellite map of the distribution of *Cladophora* in the Ajax, Ontario nearshore, supplemented by direct observations and biomass measurements is provided here for reference (Figure 7).

Figure 7. Remote sensing of Submerged Aquatic Vegetation (http://geodjango.mtri.org/static/sav/) illustrating the distribution of Cladophora in the Ajax, ON nearshore at depths within the detection limit of the satellite sensor (~7 m). Direct observation of algal density by remotely operated vehicle and divers shows that dense growth (>50 gDW/m²) occurs to a depth of 5-10 m (dark green line at 7 m), moderate growth (25-50 gDW/m²) from depths of 10 to 15 m (medium green line at 12 m) and sparse growth (≤25 gDW/m²) from depths of 15 to 25 m (light green line at 22 m). Cladophora growth is negligible at depths ≥25 due to light limitation.

<u>Plume tracking</u>

The effluents discharged by wastewater treatment plants are typically 'saltier' than the waters receiving them. That 'saltiness,' measured as its effect on the electrical conductivity of water, can be reliably measured using field and laboratory probes. Conductivity is considered a conservative property, i.e. it does not grow or decay in the water and thus changes in concentration occur only through dilution following discharge. These features make conductivity a particularly useful tracer of wastewater effluents.

The position of an effluent plume in the nearshore is determined vertically by differences in temperature between the effluent and the lake and horizontally through transport by currents. The plume structure illustrated here (Figure 8) reflects measurements made at a depth of 3m for the current regime present on 19 July 2014.

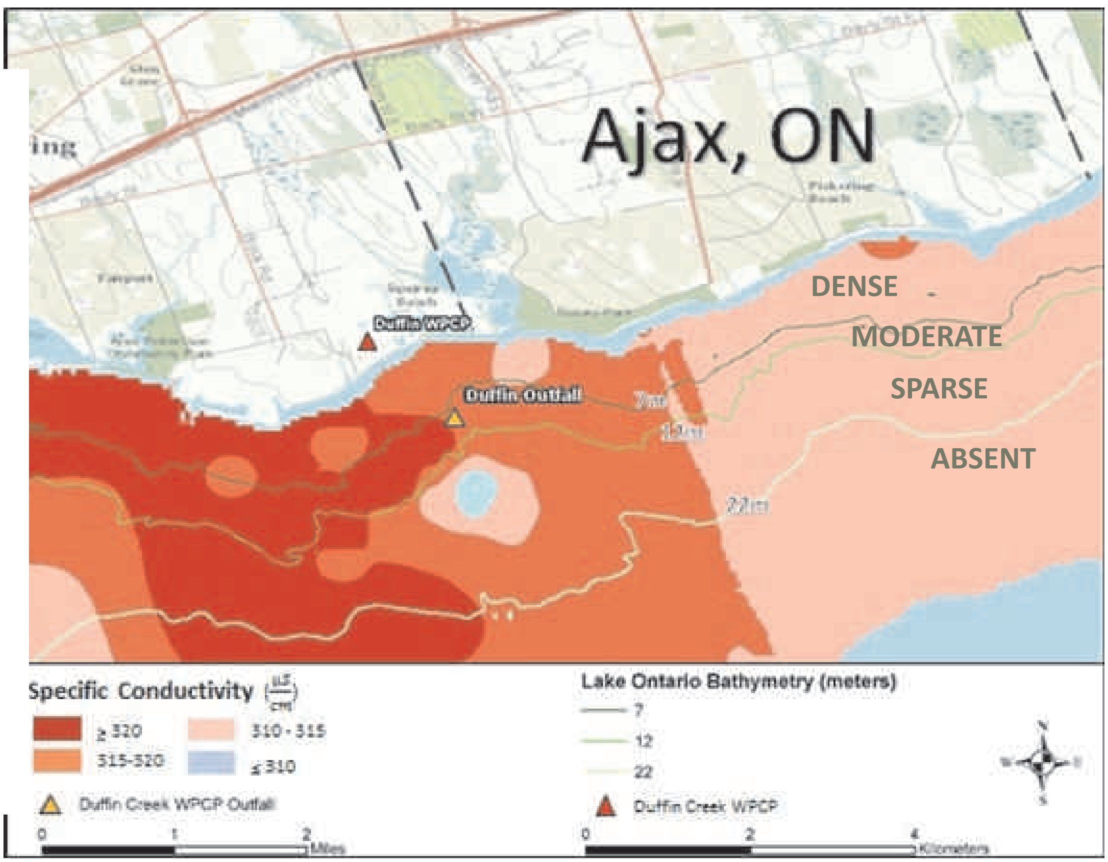

Figure 8. Map of the Duffins Creek WPCP plume at a depth of 3m as tracked by conductivity measurements made on 14 July 2014. Background levels (Higgins et al. 2012) are indicated by the blue color and, within the plume, conductivity increases pink to red.

The Duffins Creek effluent plume is evident as elevated levels of conductivity extending westward past Frenchman's Bay (~4 km) and eastward, at lower levels, past Veteran's Point (~2 km). The position of the plume relative to the Duffin Creek WPCP discharge indicates that currents were moving in an east to west direction on the day of sampling. Currents in the Ajax, Ontario nearshore are predominantly west to east (40% of the time) and east to west (30% of the time; Auer 2014). A reversal of current direction from that present on 19 July 2014 would be expected to flip the plume position as a mirror image extending ~4 km eastward to a location within 2 km of the Ajax town line. A comparison of the plume map (Figure 8) with that for *Cladophora* distribution (Figure 7) illustrates the potential for the Duffin Creek WPCP discharge to represent a regular and essentially continuous presence within this environmentally-sensitive habitat.

Phosphorus Nutrition

In the absence of companion measurements of phosphorus, the simple presence of an effluent plume over environmentally sensitive habitat does not confirm an impact. Such confirmation requires a reflection of impact within the ecosystem, e.g. in the phosphorus physiology of *Cladophora*. Here we apply the results of field and laboratory studies of the phosphorus nutrition of *Cladophora* across the Ajax, Ontario nearshore as a means of assessing the degree of nutrient limitation and the impact of phosphorus provenance on growth.

Measurements of two features of the phosphorus nutrition of *Cladophora* were made in August of 2014: radioisotope assays of the rate of phosphorus uptake by the alga and chemical measurement of the alga's stored phosphorus content. Rates of phosphorus uptake reflect the degree of phosphorus sufficiency in *Cladophora*, with high rates being associated with algae having lower stored phosphorus reserves and low rates being associated with algae having higher levels of stored phosphorus (Auer and Canale 1982a). Thus the degree of contribution of a particular source to phosphorus provenance may be inferred from spatial variation in phosphorus uptake rates. Where requirements for light, temperature and hard substrate for attachment are met, the growth rate of *Cladophora* is governed by levels of stored phosphorus (Auer and Canale 1982b). Thus, in a fashion similar to that described for phosphorus uptake, the spatial distribution of stored phosphorus in *Cladophora* can reflect both phosphorus provenance and the potential for *Cladophora* growth associated with that provenance.

The results of field and laboratory measurements of phosphorus nutrition made in 2014 point to the Duffins Creek WPCP effluent as the major contributor to phosphorus provenance in the Ajax, Ontario nearshore. Levels of stored phosphorus were higher and attendant rates of phosphorus uptake lower in the immediate vicinity of the outfall, declining/increasing with distance from the source in a manner consistent with a conclusion that the outfall is the major source of phosphorus (Figure 9). The results of the stored phosphorus survey are particularly supportive of that conclusion (Figure 10). Here, levels of stored-phosphorus in *Cladophora*, and thus growth potential, reach a peak in the vicinity of the Duffin Creek WPCP outfall and then decline with distance east and west, reaching a local minimum offshore of Frenchman's Bay to the west and Whitby Harbor to the east. The location of the maximum stored phosphorus content at the Duffin Creek WPCP, bookended concentration minima to the east and west, serves to spatially define the contribution of the Duffin Creek WPCP to the Ajax, Ontario nearshore.

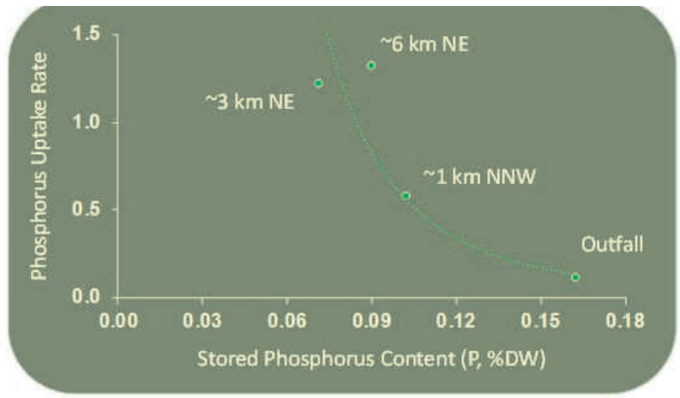

Figure 9. Rate of phosphorus uptake by *Cladophora* as a function of position relative to the Duffins Creek WPCP outfall.

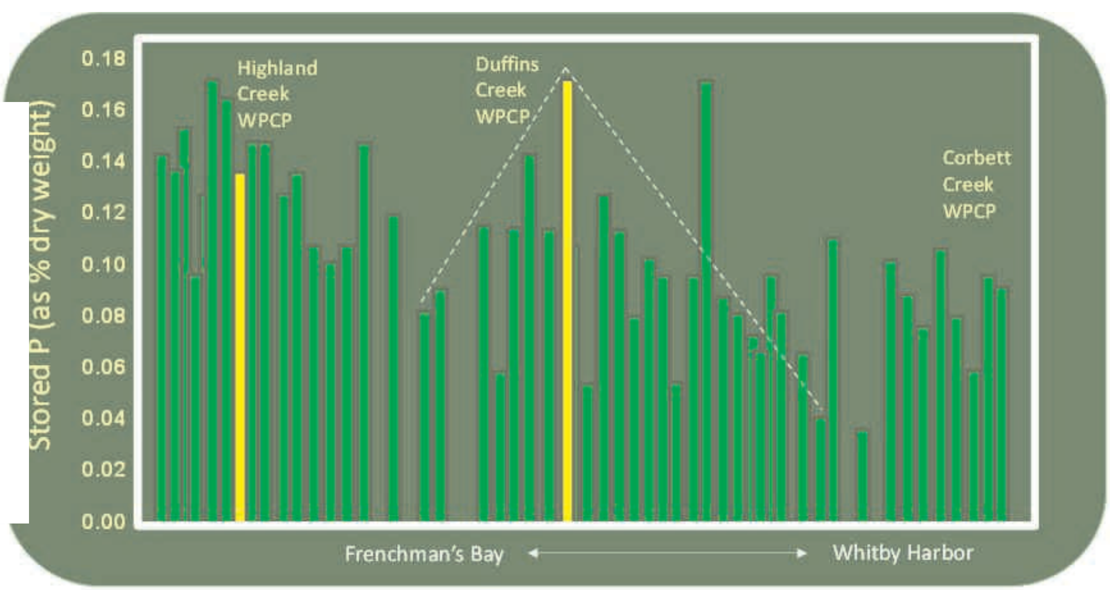

Figure 10. Distribution of stored phosphorus in *Cladophora* relative to point source discharges in the Ajax, ON nearshore.

Summary

A team of scientists from Canada and the U.S. recently published results from a study of *Cladophora* in Lake Ontario, concluding that growth of the alga is strongly phosphorus limited in the lake and that local phosphorus sources are responsible for differences in algal density observed from site to site (Higgins et al. 2012). The study further reported that the highest levels of algal stored phosphorus and the highest *Cladophora* biomass densities were observed at Ajax and Toronto, Ontario, among the most highly urbanized locations in western Lake Ontario. As prelude to the implementation of management actions to remediate nuisance conditions and restore lost beneficial uses, it is necessary to identify the sources or provenance of the phosphorus. It is concluded that the Duffin Creek WPCP is the appropriate focus for management actions seeking to remediate nuisance conditions of *Cladophora* growth and restore lost beneficial uses along the Ajax, Ontario waterfront.

References

Auer, M.T. 2011. Monitoring, Modeling and Management of Nearshore Water Quality in the Ajax-Pickering Region of Lake Ontario. Toronto Region Conservation Authority, 94 pp.

Auer, M.T. and Canale, R.P. 1982a. Ecological studies and mathematical modeling of *Cladophora* in Lake Huron: 2. Phosphorus uptake kinetics. *Journal of Great Lakes Research*, 8(1): 84-92.

Auer, M.T. and Canale, R.P. 1982b. Ecological studies and mathematics modeling of *Cladophora* in Lake Huron: 3. Dependence of growth rates on internal phosphorus pool size. *Journal of Great Lakes Research*, 8(1): 93-99.

Booty, W.G., Wong, I, Bowen, G.S., Fong, P., McCrimmon, C. and Leon, L. 2013. Loading estimate methods to support integrated watershed-lake modeling: Duffins Creek, Lake Ontario. *Water Quality Research Journal of Canada*, doi:10.2166/wqrjc.2013.022.

Dayton, A.I., Auer, M.T. and Atkinson, J.F. 2014. *Cladophora*, mass transport and the nearshore phosphorus shunt. *Journal of Great Lakes Research*, 40(3): 790-799.

Dove, A. and Chapra, S.C. 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. In Review. *Journal of Great Lakes Research.*

Governments of the U.S. and Canada. 2012. Great Lakes Water Quality Protocol of 2012. Washington and Ottawa, 75 pp.

Hecky, R.E., Smith, R.E., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N., and Howell, T. 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(7): 1285-1293.

Helm, P.A., Howell, E.T., Metcalfe, T.L., Chomicki, K.M. and Metcalfe, C.D. 2012. Influence of nearshore dynamics on the distribution of organic wastewater-associated chemicals in Lake Ontario determined using passive samplers. *Journal of Great Lakes Research*, 38, Supplement 4: 105-115.

Higgins, S.N., Malkin, S.Y., Todd Howell, E., Guildford, S.J., Campbell, L., Hiriart-Baer, V., and Hecky, R.E. 2008. An ecological review of Cladophora glomerata (Chlorophyta) in the Laurentian Great Lakes. *Journal of Phycology*, 44(4): 839-854.

Higgins, S.N., Pennuto, C.M., Howell, E.T., Lewis, T.W., and Makarewicz, J.C. 2012. Urban influences on *Cladophora* blooms in Lake Ontario. *Journal of Great Lakes Research,* 38, Supplement 4: 116-123.

Karatayev, A.Y., Burlakova, L.E. and Padilla, D.K. 2002. Impacts of zebra mussels on aquatic communities and their role as ecosystem engineers. pp. 443-446, In: Leppäkoski, E., Gollasch, S. and Olenin, S. (eds.), *Invasive Aquatic Species of Europe: Distribution, Impacts and Management*. Springer Publishers.

Lambert, R., Auer, M.T. and DePinto, J.V. 2015. Phosphorus bioavailability of tributary and point source discharges to Lake Erie. In Preparation for submission to *Journal of Great Lakes Research*.

Makarewicz, J.C., Booty, W.G. and Bowen, G.S. 2012. Tributary phosphorus loading to Lake Ontario. *Journal of Great Lakes Research,* 38, Supplement 4: 116-123.

Malkin, S.Y., Guildford, S.J. and Hecky, R.E. 2008. Modeling the growth response of *Cladophora* in a Laurentian Great Lake to the exotic invader *Dreissena* and to lake warming. *Limnology and Oceanography*, 53(3): 1111-1124.

Malkin, S.Y., Dove, A., Depew, D., Smith, R.E., Guildford, S.J. and Hecky, R.E. 2010. Spatiotemporal patterns of water quality in Lake Ontario and their implications for nuisance growth of Cladophora. *Journal of Great Lakes Research*, 36(3): 477-489.

Neil, J.H., and Owen, G.E. 1964. Distribution, environmental requirements and significance of *Cladophora* in the Great Lakes. pp. 113-121, In: *Proceedings of the 4th Conference on Great Lakes Research*, Publication 11, Great Lakes Research Division University of Michigan.