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Onondaga to Ontario: Management of bioavailable phosphorus in municipal wastewaters for control of *Cladophora*

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ABSTRACT

Phosphorus (P) concentrations in the open waters of Lake Ontario have been reduced markedly through load management. Yet, nuisance growth of *Cladophora* persists in the nearshore where urban P inputs are received. Elimination of nuisance conditions will require application of more effective phosphorus treatment technologies with particular attention to phosphorus bioavailability. One such technology, ballasted flocculation, was implemented in 2005 at the Metropolitan Syracuse Wastewater Treatment Plant (Metro) in Syracuse, NY which discharges 68 MGD (257 MLD, million liters per day) to Lake Ontario via the Seneca–Oneida–Oswego River system. Wet chemistry measurements and soluble- and particulate-phase bioassays of phosphorus bioavailability are used here in assessing the efficacy of the technology. Effluent total (TP) and soluble reactive (SRP) phosphorus concentrations using ballasted flocculation technology over the period 2005–2012 averaged 86 and 3 μg P/L, respectively, and the effluent BAP (bioavailable phosphorus) concentration was 10 μg P/L. In operation now for a decade, Metro has reduced its effluent total phosphorus by 86%, soluble reactive phosphorus by 99% and bioavailable phosphorus by 97% compared with the conventional chemical treatment used previously (iron salts and gravity clarification). The reduction in BAP was accomplished through direct removal of the SRP, dissolved organic (DOP) and particulate (PP) phosphorus fractions, but also by reducing the bioavailability of DOP and PP. Retrofit implementation of ballasted flocculation at Metro is described and the effectiveness of load reductions in altering the trophic state of the immediate receiving water, Onondaga Lake, is examined. The role of ballasted flocculation in an integrated phosphorus management program for the Lake Ontario nearshore is considered.

Introduction

Target phosphorus (P) loads established under the Great Lakes Water Quality Agreement of 1983 (GLWQA) have failed to maintain levels of algal biomass below those constituting nuisance conditions. Proliferation of cyanobacteria (Steffen et al., 2014) and the resurgence of the filamentous, green alga *Cladophora* (Kuczynski et al., submitted) have once again drawn the attention of water quality managers to the control of phosphorus loads to the Great Lakes. This failure was addressed in the Great Lakes Water Quality Protocol of 2012 by calling for revision of target phosphorus loads to the Great Lakes to eliminate nuisance algal growth in both nearshore (*Cladophora*) and offshore waters (cyanobacteria). The 2012 Protocol has also recognized the limitations of the total phosphorus (TP) analyte for use as a Substance Objective for algal environmental response indicators, specifying that revision of target loads takes into account P bioavailability. The focus on bioavailable phosphorus (BAP) is appropriate from both an ecosystem function perspective (all forms of phosphorus are not equally available to algae) and in management applications (focusing reductions on P-forms that are available to algae).

The phosphorus–*Cladophora* dynamic in the Great Lakes has changed dramatically in the time since load management targets were established under the 1983 GLWQA. Prior to that time, *Cladophora* growth in Lakes Erie and Ontario was driven by whole lake phosphorus concentrations, i.e. colonization occurred to the depth of light penetration wherever solid substrate was available. *Cladophora* growth in the P-rich central and western basins of Lake Erie remains whole-lake forced (and light limited) and that in the eastern basin likely controlled by a combination of point and nonpoint source P delivered by tributaries (Nutrients Annex Subcommittee, 2015). In Lakes Huron and Michigan, open waters did not historically support nuisance growth of the alga and management focused on point sources and large river systems. More recently, attention has turned to the comparative importance of pelagic and nearshore P sources in mediating *Cladophora*

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growth (Bootsma et al., 2015). The lake-specific nature of the phosphorus–*Cladophora* dynamic will be appropriately considered in developing management plans.

Significant changes have been observed in Lake Ontario where stimulation of nuisance conditions by localized urban influences has replaced whole-lake forcing (Higgins et al., 2012). Open lake SRP concentrations in Lake Ontario have been reduced from the 10–15 μg P/L characteristic of the 1970s to 1–2 μg P/L in the first decade of the 21st century (Dove and Chapra, 2015). As a result, *Cladophora* in Lake Ontario has transitioned from a state of P saturation (see Fig. 8b of Tomlinson et al., 2010) to one of strong P limitation (Higgins et al., 2012). While invasive mussels have had an impact on phosphorus cycling in the Lake Ontario nearshore (Hecky et al., 2004; Dayton et al., 2014), Higgins et al. (2012) concluded that there was little evidence that mussel excretion could produce severe *Cladophora* blooms in the absence of localized phosphorus enrichment. However, where local phosphorus sources are present and where habitats are strongly impacted by mussels, more stringent P management may be required (Hecky et al., 2004). Thus, in urban areas where municipal wastewater treatment effluents play a major role in phosphorus provenance, localized sources become the appropriate focus for management (Higgins et al., 2012).

With nuisance growth of *Cladophora* in Lake Ontario now suggested as being locally forced (Higgins et al., 2012), efforts to establish revised loads must take into consideration the interplay between direct inputs to coastal waters and exchange with the offshore (Auer et al., 2014). Specifically, the impact of phosphorus discharges to the nearshore, prior to dilution by and assimilation within the open lake, must be addressed. Coastal jets have the potential to broadly distribute phosphorus loads along the nearshore, including environmentally-sensitive habitat colonized by *Cladophora*. As made evident through the persistence of nuisance levels of *Cladophora* growth in oligotrophic Lake Ontario, levels of phosphorus removal previously identified as being satisfactory for addressing trophic state conditions lakewide (i.e., the 1 mg TP/L Great Lakes effluent standard presently in force and the 0.5 mg TP/L effluent standard proposed for Lake Ontario under the 2012 Protocol) fall far short of what is necessary to avoid proliferation of *Cladophora* where effluent discharges impact shallow, nearshore waters.

Negative impacts may be mitigated by extending the discharge offshore, by removing phosphorus prior to discharge or by combinations of the two (Canale et al., 1983). As a result, management emphasis has been placed on moving the discharge further offshore, an option involving engineering and economic challenges and one that has been criticized because it offers no incentive to remove other pollutants, e.g. pharmaceuticals and personal care products.

Treatment technologies capable of achieving the requisite effluent phosphorus concentrations have the potential to reduce dependence on extending the discharge location, while easing the burden of meeting the mandate of the 2012 Protocols to control nuisance algal growth in the nearshore. Biological phosphorus removal and chemical precipitation of phosphorus with iron and aluminum salts are widely applied as a means of meeting the present TP effluent objective of 1 mg P/L and are capable of achieving the 0.5 mg TP/L limit proposed under the 2012 Protocol. In some cases (see Bott and Parker, 2011), effluent standards <0.2 mg TP/L have been met by employing chemical precipitation with filtration (e.g. Blue Plains, DC, 370 MGD; effluent TP of 0.073 mg/L and effluent SRP of 0.037 mg P/L) and by using biological phosphorus removal with chemical precipitation and filtration as employed in a polishing capacity (Clark County, NV, 100 MGD; effluent TP of 0.089 mg/L and effluent SRP of 0.033 mg P/L).

However, the mandate conferred under the 2012 Protocol makes manifest the potential value of more effective technologies. Reverse osmosis has received some attention in this regard and is being considered as part of an effort to meet a 0.02 mg TP/L effluent standard for discharge to Lake Simcoe (CRA et al., 2014). Another option, ballasted flocculation (BF) or high rate clarification has been utilized where particularly stringent phosphorus effluent objectives are in place (Table 1). Here, a coagulant (iron or aluminum salts) is added, forming microflocs and facilitating phosphorus conversion from the soluble to the particulate phase through adsorption and precipitation. A ballast (e.g. microsand) and polymer are also added to promote floc formation. The high specific gravity of the ballast, used as a continuously recycled medium, improves particle settling qualities and thus achieves a greater degree of removal in the final clarifier (U.S. EPA, 2003).

The Remedial Action Plan for the Oswego River Area of Concern (AOC; delisted in 2006), addressed beneficial use impairment in this, the second largest source of phosphorus to Lake Ontario (excluding the Niagara River; Makarewicz et al., 2012). Beneficial use impairments within the AOC included manifestations of eutrophication associated with non-AOC phosphorus sources. Prominent among those sources was the discharge from the Metropolitan Syracuse Wastewater Treatment Plant (Metro; Syracuse, NY) which delivers phosphorus to the AOC through the Seneca–Oneida–Oswego River complex. Ballasted flocculation technology was incorporated into the Metro process train in 2005 as a means of reducing the degree of P-enrichment downstream of the Metro discharge.

Here, we describe the implementation and efficacy of ballasted flocculation technology at Metro and report the results of bioassays used to quantify the removal efficiency of bioavailable phosphorus. Next, we examine the water quality benefits accrued in Onondaga Lake, Metro's immediate receiving water, through application of ballasted flocculation technology. Finally, based on results achieved at Metro, we consider the utility of this technology in reducing the impact of urban P sources impacting the Lake Ontario nearshore.

Methods

The efficacy of ballasted flocculation in removing bioavailable phosphorus is assessed using algal bioassays, an approach that directly measures the ability of various forms of phosphorus to support algal growth. Three phosphorus components, together comprising the TP analyte, are considered here: soluble reactive phosphorus, dissolved organic phosphorus and particulate phosphorus. The operationally-defined SRP analyte consists largely of orthophosphate and loosely-bound DOP and is generally accepted as being fully and freely available for algal uptake. The DOP analyte is heterogeneous in composition and its bioavailability varies with the source and exposure to biogeochemical processing. Phosphorus present in the PP analyte is released by desorption and through diagenetic activity involving microbial mineralization of organic matter, as well as by mussel processing (Ozersky et al., 2009). As measured by the techniques described below, particulate phase bioavailability refers to that resulting from desorption and microbial mineralization, i.e. does not seek to characterize potential differences in bioavailability between these processes and mussel recycling. Assay results reported here describe Metro BAP removal both within the BF process train and in comparison with results achieved using traditional chemical precipitation and gravity clarification.

Sample collection and processing

40 L grab samples of screened influent and partially treated wastewater entering (pre-BF) and leaving (post-BF) the ballasted flocculation unit were collected at Metro. Samples were stored in the dark at 4 °C until processed, usually within 2–3 days of collection. Each 40 L sample was passed through a 142 mm, 0.45 μm cellulose acetate filter (GE Osmonics Labstore) under positive pressure. Filtrate was retained for use in soluble phase assays. Particulate matter was scraped off the filters and placed in glass bottles containing a small amount of filtrate to create a slurry. Filtrate and slurries were shipped over night, on ice to the laboratory at Michigan Technological University and stored at 4 °C (filtrate) or frozen at −20 °C (slurries) until assays were performed. Holding time for soluble phase samples extended beyond that recommended

Table 1
Manufacture and application of the ballasted flocculation technology.

Manufacturer/distributor	WWTP installations	Operating Flows (MGD)	Flagship installation (including flow)
Infilco Degremont, Inc. Technology: *DensaDeg®*	11 (12)	0.3–20	West Basin WWTP, CA 20 MGD
Veolia Krüger, Inc. Technology: *Actiflo®*	17 (25)	1.3–126	Syracuse, NY 126 MGD
Siemens Water Technologies, LLC Technology: *Co-Mag®*	6 (all US)	0.5–14	Billerica, MA 14 MGD

Numbers represent installations in the US and Canada, additional international installations in parentheses.

by U.S. EPA; however, membrane filtration and storage at 4 °C would be expected to minimize conversion of DOP to SRP.

Assays

Soluble phase assays were conducted using a modification of the Bottle Test Procedure of Miller et al. (1978). The initial SRP and TDP content of the filtrate were determined and a 2–4 L aliquot of filtrate was placed into a 4 L Erlenmeyer flask. P-starved algae (*Selenastrum capricornutum*) were added to the flask and the sample was incubated in the light (PAR = 600 μE m^{-2} s^{-1}, 24-hour photoperiod) at 20 °C. SRP and TDP concentrations were determined at intervals of 1–7 days (higher frequency at the beginning) with DOP calculated by difference. The incubation was continued for 1–3 weeks, i.e. until no further change in SRP or DOP was noted (Fig. 1a). Bioavailability of the SRP and DOP fractions was calculated as the amount of P taken up divided by the amount initially present, expressed as a percent. A total of six soluble phase assays were performed: one on pre-ballasted flocculation secondary effluent and five on effluents from the ballasted flocculation process (Table 2).

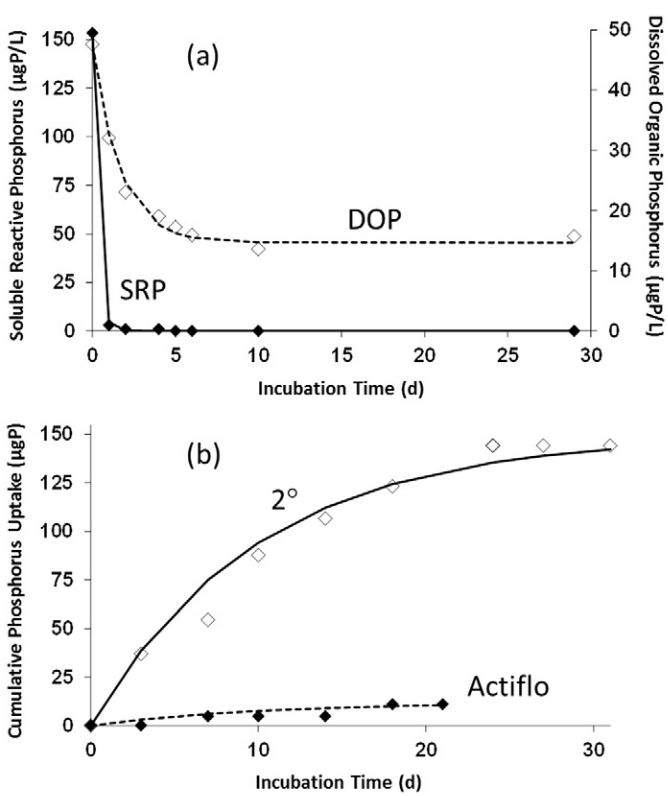

Fig. 1. Representative bioavailability assay results: (a) soluble phase assay performed on secondary effluent (2°, no Actiflo) illustrating algal uptake of soluble reactive phosphorus (SRP) and dissolved organic phosphorus (DOP) and (b) particulate phase assays performed on secondary (2°, no Actiflo) and tertiary (3°, Actiflo) effluent illustrating production of bioavailable phosphorus and subsequent uptake and sequestration by assay algae.

Particulate phase assays utilized the Dual Culture Diffusion Apparatus (DCDA) developed by DePinto (1982). The DCDA consists of two compartments separated by a black, 0.45 μm membrane filter. One compartment is completely shielded from light by black tape and receives the slurry resuspended in P-free algal growth medium. The other compartment is clear and receives P-starved algae suspended in P-free algal growth medium. The DCDA is incubated at 20 °C (PAR = 600 μE m^{-2} s^{-1}, 24-hour photoperiod). As particulate phase P becomes desorbed or solubilized in the dark compartment, it diffuses across the membrane and is taken up by the algae. At 3 to 4-day intervals, the algae are harvested, the amount of P taken up measured and fresh, P-starved algae are added. The assay continues until uptake ceases, ~30 days (Fig. 1b). Particulate phase bioavailability is calculated as the cumulative amount of P taken up over the incubation period divided by that originally added to the dark chamber, expressed as a percent. Additional details of the methodology are provided by Effler et al. (2002, 2012a). A total of eleven particulate phase assays were performed: two on pre-ballasted flocculation (i.e. secondary effluent) samples and nine on effluents from the ballasted flocculation process (Table 2).

Table 2
Impact of ballasted flocculation (BF) at Metro on (a) measured concentrations of phosphorus components (μg P/L), (b) the bioavailable fraction of each phosphorus component (f_{bio}, 0 → 1, dimensionless) and (c) the calculated concentration of bioavailable phosphorus for each component (BAP, μg P/L). Component concentrations for 1996 are annual averages for the 1995–1997 interval. Results of assays performed in 1996 are those of Tomasoski (1997). Values of f_{bio} for DOP and SRP were not measured at Metro in 1996. For SRP, a value of $f_{\text{bio}} = 1$ is assumed for 1996 as confirmed by multiple subsequent assays later performed at Metro. The DOP f_{bio} value for 1996 was derived from measurements made at the Portage Lake, Michigan WWTP, a system using the same treatment technology as Metro. These values are included here to facilitate comparison.

	1996 effluent w/o BF	2010 effluent w/ BF	2012		
			BF influent	BF effluent (iron)	BF effluent (alum)
(a) P, as measured					
TP	436	102	393	74	59
PP	213	67	192	52	36
DOP	137	30	48	21	22
SRP	86	5	153	2	1
(b) f_{bio}					
TP	0.68	0.26	0.54	0.07	0.16
PP	0.58	0.01	0.14	0.01	0.02
DOP	*0.62*	0.71	0.67	0.14	0.36
SRP	*1.00*	1.00	1.00	1.00	1.00
(c) BAP, calculated as (a) · (b)					
TP	294	27	212	5	10
PP	124	1	27	1	1
DOP	85	21	32	3	8
SRP	86	5	153	2	1
(d) Number of assays performed					
Soluble	See note	1	1	2	2
Particulate	1	5	1	2	2

Analysis

SRP was measured spectrophotometrically by the ascorbic acid method (APHA, 2005, 4500-P). PP and TDP samples were digested by the persulfate method (APHA, 2005, 4500-P), converting the phosphorus to SRP, and then measured spectrophotometrically. Dissolved organic phosphorus is defined operationally as TDP minus SRP.

Ballasted flocculation: the Onondaga Lake case study

Onondaga Lake and Metro

Onondaga Lake is a hard water, alkaline, dimictic system located in metropolitan Syracuse, NY (lat. 43°06′54″; long. 76°14′34″). This medium size lake (surface area of 12.0 km^2, mean and maximum depths of 10.9 and 20 m) flushes rapidly, ~4 times per year on average (Effler, 1996), and thus is quite responsive to changes in loading (Doerr et al., 1994). The lake was oligomestrophic before European settlement in the late 1700s (Rowell, 1996). Increasing inputs of domestic and industrial wastes as the area developed led to severe degradation and loss of beneficial uses (Effler, 1996).

Onondaga Lake was culturally hypereutrophic, primarily as a result of the direct discharge of municipal wastewater effluent from the regional treatment facility, Metro, since the 1920s (Effler and O'Donnell, 2010; Effler et al., 2013). This facility's discharge is extraordinary in the context of the lake's hydrologic budget (Rucinski et al., 2007), representing ~20% of the total inflow on an annual basis, the largest such contribution nationally. Manifestations of cultural eutrophication included: (1) high concentrations of phytoplankton and severe blooms of nuisance forms (Sze and Kingsbury, 1972; Effler, 1996; Matthews et al., 2001), (2) low clarity (S.W. Effler et al., 2008), (3) rapid loss of dissolved oxygen (DO) from the hypolimnion (Matthews and Effler, 2006a), (4) elevated depositional fluxes of particulate organic matter from the epilimnion (Effler et al., 2012b), (5) high hypolimnetic accumulation rates of P and reduced by-products of anaerobic metabolism (Matthews et al., 2008), and (6) depletion of DO in the upper waters during the approach to fall turnover (Matthews and Effler, 2006b).

Phosphorus removal at Metro

At present, Metro provides conventional treatment (activated sludge), advanced ammonia and phosphorus removal and disinfection for average, design and peak flows of 68.0, 84.2 and 126.3 million gallons per day (MGD; equivalent to 257, 319 and 478 million liters per day, MLD). The history of P loading from Metro is well represented by the effluent TP concentration (Fig. 2a, with inset), as the average discharge flow rate has remained essentially unchanged. Mostly progressive decreases in TP have occurred since 1970 in response to a series of management actions taken to abate cultural eutrophication in the lake, including: (1) a ban on high P content detergent within the service area in 1971 (Murphy, 1973), (2) an upgrade to secondary treatment (1979), (3) an upgrade to tertiary treatment (ferric chloride addition) in 1981, and (4) optimization of tertiary treatment over the 1982–2002 interval. Approximately an 80-fold reduction in the Metro P effluent has been achieved between 1970 and the early 2000s.

In 2004–2005, Metro completed a project that would provide increased levels of ammonia and phosphorus removal as well as other plant upgrades. Metro chose ballasted flocculation (Actiflo®, Veolia Treatment Technologies) as the phosphorus treatment technology to achieve compliance with a 1998 Amended Consent Judgment requiring reduction in effluent TP levels to 100 μg P/L by 2010 (Martin et al., 2014). The ballasted flocculation unit consists of four process trains where ferric chloride, polymer and micro-sand are added. The capital cost of the BF retrofit was \$3.65 million; installation and interconnection costs for the BF component are estimated to have brought the total cost of implementing BF to \$12.3 million. The project was completed over a period of 37 months (Oct 2001–Dec 2004) with no interruption or degradation in plant performance. Installation of ballasted flocculation as a standalone retrofit is estimated to require 18 months. Operationally, dosage with ferrous sulfate (2000–3000 gal/day at 45 mg/L) used with conventional chemical treatment to achieve an effluent with <1 mg/L TP was replaced under ballasted flocculation with a lesser dosage of ferric chloride (1200 gal/day at 25 mg/L) and a small amount of polymer to attain an effluent concentration <0.12 mg/L TP. The change from a high dosage of less expensive ferrous sulfate to a lower dosage of more expensive ferric chloride left chemical costs largely unchanged.

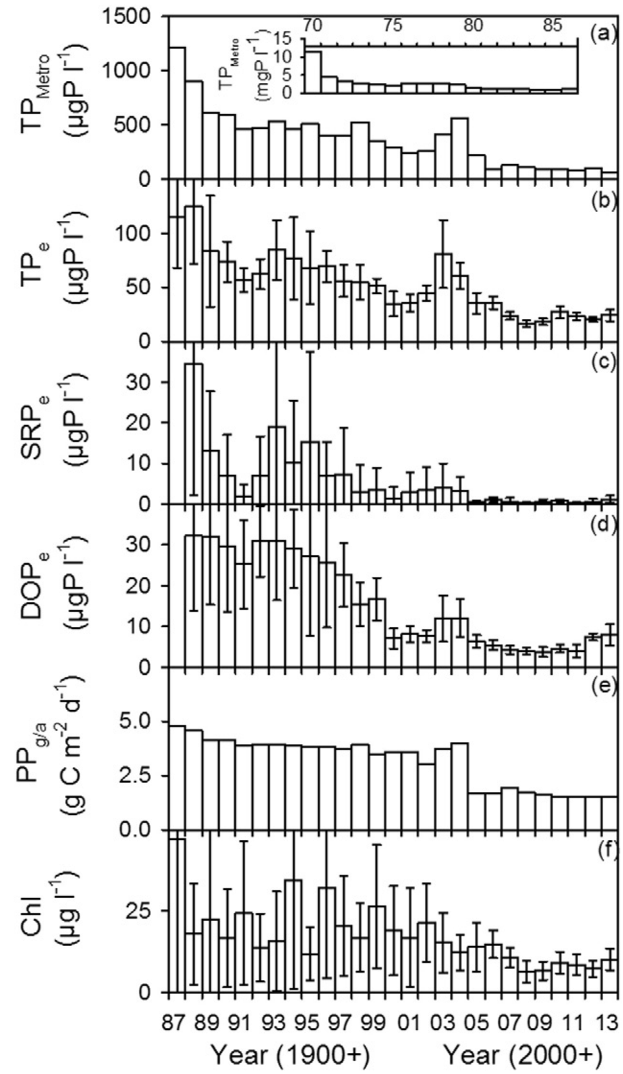

Fig. 2. Time series of annual summer average conditions for the Metro effluent and the epilimnion of Onondaga Lake: (a) Metro effluent total phosphorus, TP_{Metro}, (b) epilimnetic total phosphorus, TP_e, (c) epilimnetic soluble reactive phosphorus, SRP_e, (d) epilimnetic dissolved organic phosphorus, DOP_e, (e) gross, areal primary production, $PP_{g/a}$, and (f) epilimnetic chlorophyll, Chl_e. Dimensions of vertical lines correspond to ±1 standard deviation in (b), (c), (d), and (f), representing temporal variability within individual years (revised from Effler and O'Donnell, 2010).

Results achieved through the application of ballasted flocculation have been striking (Fig. 3a), with the average effluent TP falling from 482 ± 94 μg P/L (2003–2004) to 86 ± 32 μg P/L (2007–2012), a reduction of 82%. However, the benefit of adding BF relative to the potential to support algal growth was greater than can be portrayed by the TP results alone. Fifty-five percent of the Metro effluent TP was in dissolved (accessible) forms before the BF upgrade, while only 35% was in a dissolved form after the upgrade (Effler et al., 2012a). Most importantly, average effluent SRP (freely and fully accessible) concentrations fell from 217 ± 82 μg P/L (2003–2004) to 3 ± 8 μg P/L (2007–2012), a

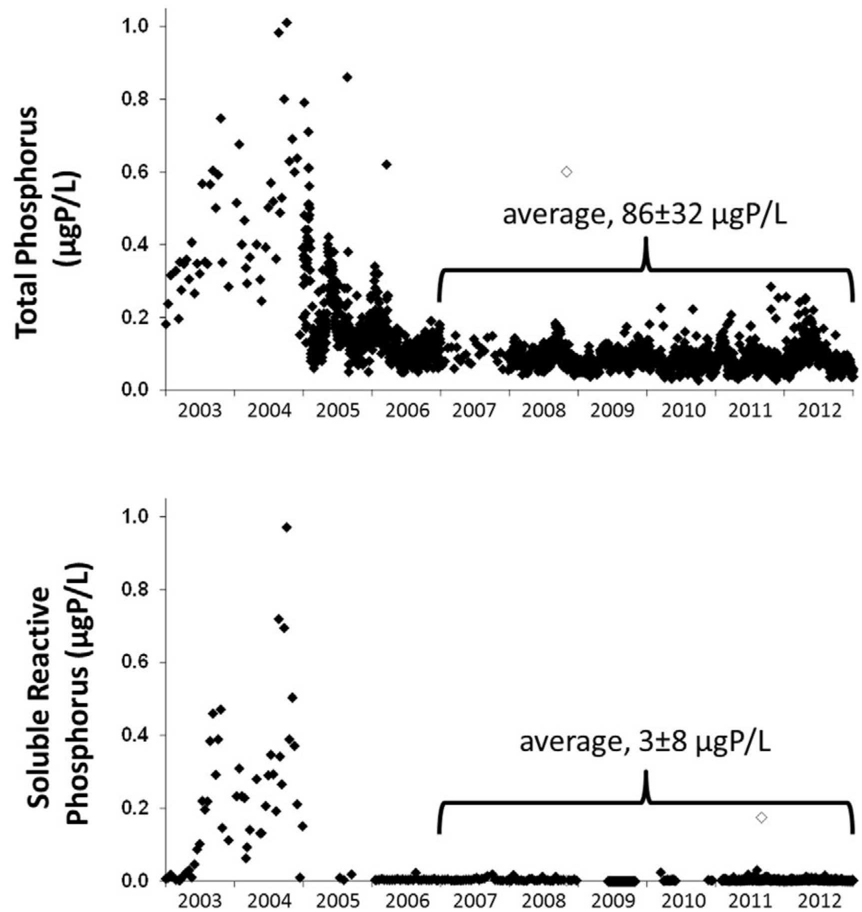

Fig. 3. Concentrations of (a) total phosphorus, TP and (b) soluble reactive phosphorus, SRP in the Metro effluent, 2003–2012.

reduction of 98% (Fig. 3b). The significance of these reductions is reflected most clearly in the results of bioavailable phosphorus assays.

Efficacy of bioavailable P removal

Assays were performed in 1996 (conventional ferric chloride treatment) and 2010 (following upgrade to ballasted flocculation) to compare the bioavailability of the respective Metro effluents (Table 2 and Fig. 4). Implementation of BF reduced effluent TP concentrations from 436 to 102 μg P/L (77% reduction), SRP concentrations from 86 to 5 (94%) and BAP concentrations from 294 to 27 μg P/L (91%). The mechanism for reduction in BAP varied with the phosphorus component. Reductions in BAP as SRP (100% bioavailable) and DOP (62–71% bioavailable) were achieved by the direct removal of those phosphorus components. Reductions in particulate P (PP) were achieved by a combination of direct removal and a reduction in PP bioavailability from 58% to 1% (Table 2), apparently due to alteration of the physicochemical nature of the particulate matter achieved with use of BF.

A second set of assays was performed in 2012, when the system had achieved characteristics of routine operation, to compare the efficacy of iron versus aluminum addition (Fig. 4). Final effluent values for ballasted flocculation with iron are again compared to those achieved with conventional ferric chloride treatment (1996). The BF process reduced effluent TP concentrations from 436 to 74 μg P/L (83%), SRP concentrations from 86 to 2 μg P/ (98%) and BAP concentrations from 294 to 5 μg P/L (98%). The overall bioavailability of the TP analyte was 7%. Here, the bioavailability of the SRP and PP fractions was as in 2010, but the bioavailability of the DOP fraction dropped to 14% (as opposed to 71% in 2010). It is noteworthy that the effluent BAP concentration was 10 μg P/ and that of SRP, the most bioavailable fraction, ~1 μg P/L. There was no significant difference in P-removal capabilities for the iron and alum additions.

The lake response

The ability of ballasted flocculation to remove BAP from municipal effluents in a cost-effective manner has been demonstrated here for the case of the Metropolitan Syracuse Wastewater Treatment Plant. The reduction in BAP is sufficiently striking to encourage a re-thinking of approaches to phosphorus management in lakes. Potential benefits to be derived through application of this technology are now examined for the case of Metro's immediate receiving water, Onondaga Lake, NY. Representation of the lake's response to P management actions at Metro focuses here on summer (mid-May to mid-September) average epilimnetic conditions (targeted by the regulatory community) for the 1987 to present period. Decreases in concentrations of multiple forms of P generally tracked the decreases in the Metro effluent TP (Fig. 2a), including epilimnetic: (1) total P (TP, $r^2 = 0.819$; Fig. 2b), (2) soluble reactive P (SRP, $r^2 = 0.618$; Fig. 2c), and (3) dissolved organic P (DOP, $r^2 = 0.674$; Fig. 2d). However, primary production in the lake was not highly responsive through earlier portions of the record because the reductions in loading were inadequate to establish a substantial degree of P limitation of phytoplankton growth. Connors et al. (1996) reported the degree of P limitation of phytoplankton growth was small for the 1989–1992 period. Effler et al. (2005) concluded that only a 30 to 40% decrease in primary production had been achieved from the late 1970s to early 2000s, despite the 80-fold reduction in the Metro effluent TP over that period.

Temporally detailed direct in situ measurements of primary production in the lake in five years over the 1978–2005 interval, representing a

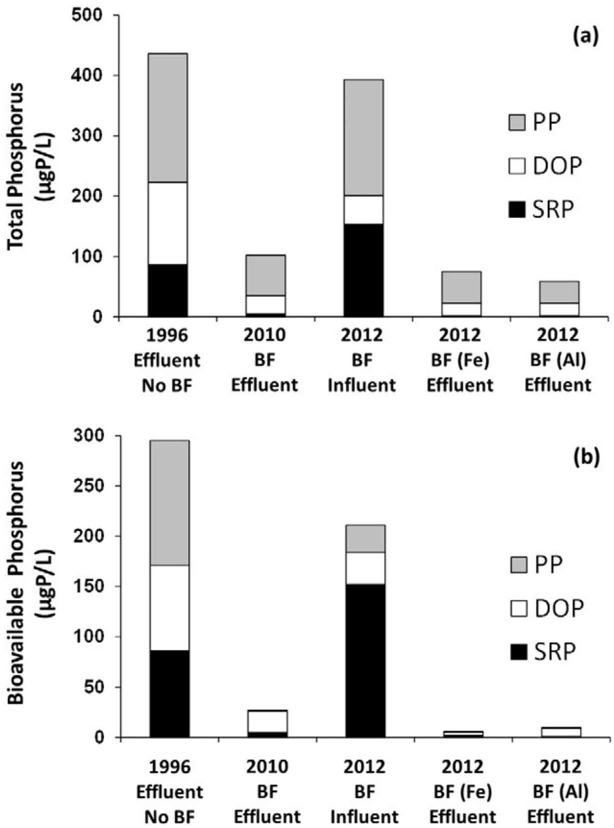

Fig. 4. Changes in (a) total phosphorus, TP and (b) bioavailable phosphorus, BAP removal at Metro using ballasted flocculation.

wide range of conditions, supported the development of a rectangular hyperbolic expression (P limitation → P saturation) that describes the relationship between gross areal primary production ($PP_{g/a}$) in the lake and Metro P loading (A.J.P. Effler et al., 2008). This functionality is consistent with the kinetics of the limiting nutrient physiology of algal growth (Gotham and Rhee, 1981; Auer and Canale, 1982a,b; Connors et al., 1996; A.J.P. Effler et al., 2008 and Tomlinson et al., 2010). Application of the relationship to the record of primary production (Fig. 2e) depicts only a modest degree of P-limitation through the early 2000s, despite major reductions in the Metro effluent TP (Fig. 2a). However, the implementation of ballasted flocculation treatment caused an abrupt decrease in primary production starting in 2005 (Fig. 2e), associated with a shift to a distinctly P-limited state (A.J.P. Effler et al., 2008). The prevalence of P-limited conditions since 2005 is also supported by SRP levels (Fig. 2c) that remain below 1 µg/L more than 90% of the summer. This conservative SRP threshold for P-limitation (Effler and O'Donnell, 2010) was supported by system-specific paired measurements of alkaline phosphatase activity (Connors et al., 1996). The decreases in DOP (Fig. 2d) are also consistent with an increased degree of P-limitation, as such limitation promotes utilization of this pool mediated by enzymatic hydrolysis (Bentzen et al., 1992).

The reductions in the Metro effluent TP achieved through implementation of ballasted flocculation treatment have substantially ameliorated Onondaga Lake's cultural eutrophication problem, transforming it from hypereutrophy to upper mesotrophy (Effler and O'Donnell, 2010). Surrogate metrics of primary production, including the trophic state indicators of epilimnetic TP, the summer average epilimnetic concentration of chlorophyll *a* (Fig. 2f), and summer average Secchi depth, are all presently consistent with mesotrophy (Effler and O'Donnell, 2010). Moreover, features of the oxygen resources of the lake have improved (Effler et al., 2013). The lake is now positioned along the linear portion of a hyperbolic P loading response curve (A.J.P. Effler et al., 2008), and thereby poised for further proportional reductions in algal growth, and related improvements in water quality, from additional fractional reductions in bioavailable forms of P (e.g. through nonpoint source control).

Managing the phosphorus–*Cladophora* dynamic in Lake Ontario

Concentrations of soluble reactive phosphorus, the form considered to be 'freely bioavailable' to algae (Reynolds, 2006, p. 154), have been reduced in the offshore waters of Lake Ontario from the growth-saturating levels characteristic of the 1970s and 1980s (median values of 12–15 µg P/L) to the growth-limiting conditions observed today (median value 1.7 ± 0.7 µg P/L, 2001–2012, Dove and Chapra, 2015; average concentration 0.8 ± 0.2 µg P/L, 2014, Auer, unpublished data). It is clear from contemporary measurements of SRP in the offshore that *Cladophora* growth in Lake Ontario is no longer whole-lake forced. The shift from P-saturated to P-limited conditions parallels the expected hyperbolic response observed for Onondaga Lake, NY and developed specifically for *Cladophora* by Tomlinson et al. (2010). In Lake Ontario, the change has been sufficiently dramatic as to have oligotrophication counted among the stressors to the lake's food web and fish community (Mills et al., 2003; Holeck et al., 2015). The conclusion that algal growth in Lake Ontario is no longer whole-lake forced, but is now driven locally by point source and tributary discharges is consistent with the observations of Higgins et al. (2012) that stored P levels in *Cladophora* at three sites in the U.S. waters of the lake (Oak Orchard, Rochester and Mexico Bay, NY) have approached the minimum cell quota (i.e. starvation level).

Yet, symptoms of eutrophication persist at certain locations in the Lake Ontario nearshore (Higgins et al., 2012), with nuisance growth of *Cladophora*, beach fouling and attendant lost beneficial use. The highest *Cladophora* biomass densities reported in the Higgins et al. (2012) survey of Lake Ontario were observed at locations near Toronto and Ajax, ON. *Cladophora* at these sites also had the highest levels of stored phosphorus (Higgins et al., 2012), symptomatic of exposure to elevated levels of bioavailable P in the water column. The occurrence of elevated stored P levels is consistent with measurements of SRP made by our group in August 2014 at locations with depths favorable for colonization by *Cladophora* (0–12 m) near Ajax, ON. SRP concentrations in the August 2014 survey ranged from 0.4 µg P/L (limit of detection) to 18 µg P/L (n = 52), with 35% of the values exceeding the mean offshore spring surface water SRP concentration by more than two standard deviations. This local enrichment, with SRP levels well above those of the lake's open waters, is consistent with the conclusion of Higgins et al. (2012) that nuisance blooms of *Cladophora* in the Lake Ontario nearshore are limited to sites with urban influences.

Presently, 15 wastewater treatment plants discharge to the Lake Ontario nearshore between Hamilton and Oshawa, ON (Makarewicz et al., 2012). These facilities contribute nearly two-thirds (63%) of the P discharged to this portion of the lake (Makarewicz et al., 2012) and likely a larger fraction of the bioavailable P (see Effler et al., in review). While current P discharge limits for these facilities have served well in meeting the Great Lakes Water Quality Agreement trophic state objective of oligotrophy for Lake Ontario, nuisance conditions of attached algal growth still occur and the issue is specifically identified for attention under the 2012 Protocol. The problem results from the fact that effluent discharges transit environmentally sensitive nearshore habitat, i.e. locations suitable for colonization by *Cladophora*, before P concentrations can be sufficiently diluted and assimilated into the nutrient condition of the larger lake. Thus, P discharges from wastewater treatment plants may be expected to become an appropriate focus for management in meeting the objective of the 2012 Protocol to eliminate nuisance growth of algae in the Lake Ontario nearshore.

Historically, the differing sensitivities of nearshore and offshore environments to P discharges have been met by combinations of P removal at the wastewater treatment facility and extension of the effluent outfall some distance from shore. Canale et al. (1983) applied a mathematical model in optimizing these combinations for coastal outfalls discharging to regional environments supporting *Cladophora* growth. In application today, that approach would first require that: (a) a Lake Ecosystem Objective be established with respect to *Cladophora*, (b) an environmental response indicator (ERI) be selected for *Cladophora*, e.g. levels of algal biomass or stored nutrient content and (c) a Substance Objective for SRP, the P form freely and fully available to algae, be defined. These steps are consistent with those outlined in Annex 4 of the 2012 Protocol to meet its general and specific objectives. With this guidance in place, a linked hydrodynamic-SRP model would then be utilized to test the economic and environmental efficacy of meeting the Substance Objective in the nearshore. Model simulations would be applied for various combinations of outfall length and treatment level seeking a least cost solution (Fig. 5). It is here that application of ballasted flocculation or similarly effective technologies offer their singular benefit. The exceptional level of bioavailable P removal achieved through BF has the potential to significantly reduce dependence on the costly and sometimes logistically-challenging option of extending the offshore distance for effluent discharge. Finally, it should be noted that in a fast-flushing coastal environment such as nearshore Lake Ontario, the BF component of P removal would only be required seasonally, i.e. under temperature conditions favoring *Cladophora* growth. An approach embracing seasonal operation would reduce operating and maintenance costs while offering a means for addressing concerns relating to the oligotrophication of offshore waters and attendant impacts on the Lake Ontario food web.

Today, the Lake Ontario community is well positioned to address conditions of nuisance *Cladophora* growth that have persisted for over 80 years. Through the Great Lakes Water Quality Protocol of 2012, the U.S. and Canada have provided a mandate calling for remediation of water quality degradation related to nuisance algal growth. The Province of Ontario has demonstrated leadership in environmental actions of a similar nature, developing an *Environmental Management Strategy* and a *Protection Plan* for Lake Simcoe and securing passage of the *Lake Simcoe Protection Act* (Ontario Regulation 60/08) to control P loading. The science and technology required to support management of this long-standing problem are in place today, providing an opportunity to recover lost beneficial use and fulfill the call of the Great Lakes Water Quality Protocol of 2012 to maintain levels of algal biomass below the level constituting a nuisance condition in the Lake Ontario nearshore.

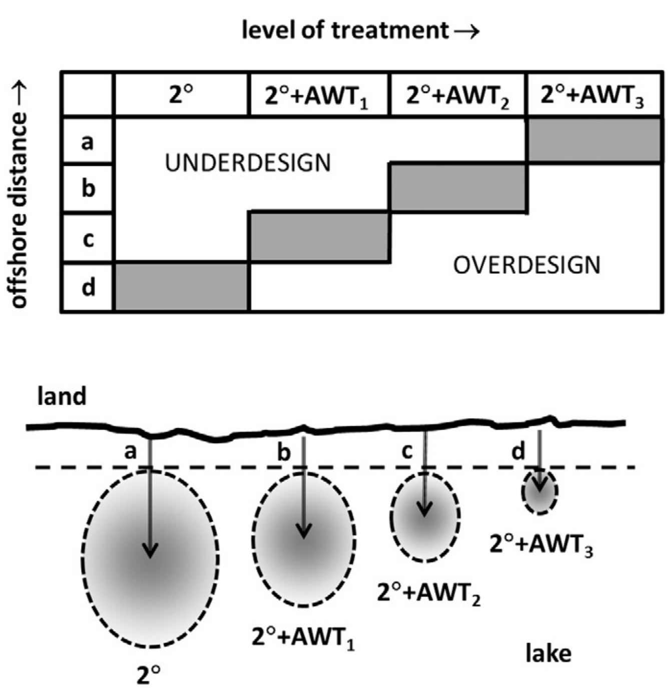

Fig. 5. An engineered design matrix for management of the phosphorus–*Cladophora* dynamic in coastal waters. Treatment levels refer to secondary treatment (2°) plus various levels (subscripts) of advanced wastewater treatment (AWT). Horizontal dashed line represents the lakeward extent of *Cladophora* colonization based on light availability.

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