Challenges and Opportunities for Managing Eutrophication in St. Paul's Como Lake

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Introduction

Eutrophication in urban lakes

Urban lakes provide numerous ecosystem services including recreational opportunities, aesthetic benefits, wildlife habitat, and municipal water supplies. However, in many urban lakes, these benefits are degraded as a result of eutrophication. Nitrogen (N) and phosphorus (P) from sources such as lawns, gardens, leaves, and pet waste, are transported into these lakes from stormwater runoff. These nutrients fuel excessive algal growth, which can diminish a lake's recreational and aesthetic value, and also potentially decrease property values. As this algae dies and decomposes, it consumes oxygen in the hypolimnion (deep water), potentially causing stress or mortality for fish populations. Excess P can also fuel cyanobacteria blooms, which in some cases leads to toxins released in the water, endangering municipal drinking water supplies and posing a public health risk. General approaches to managing eutrophication in urban lakes include the management of nutrients and stormwater runoff at the watershed scale, treatments within lakes to reduce P availability, or treating the symptoms of eutrophication. Phosphorus often accumulates in lake sediments and release of this P to the lake water, known as internal loading, can occur for years after watershed inputs are reduced, hindering efforts to restore eutrophic lakes.

Como Lake Case Study

Como Lake in Saint Paul is among the most visited lakes in Minnesota. It has been classified as impaired due to excessive levels of chlorophyll and total P since 2002. The watershed contains a high proportion of impervious surface, and the lake is entirely fed by stormwater runoff (Figure 1).

A variety of efforts have been made to improve water quality in the lake. Restrictions on use of lawn fertilizer in the seven county metro area began in 2004 has led to reduced P application throughout the watershed[1], although the resultant decrease in P loading to Como Lake is not well-quantified. The Capitol Region Watershed District (CRWD) has funded a variety of projects designed to reduce stormwater runoff and P loading from the watershed. Between 2005-2007, CRWD installed eight rain gardens, eight underground infiltration trenches, an underground stormwater storage and infiltration system, and a regional stormwater pond, in the Como 7 subwatershed for a total cost of $2.7 million[2]. These BMPs are nested and have

[1] Report to the Minnesota Legislature: Effectiveness of the Minnesota Phosphorus Lawn Fertilizer Law. http://www.mda.state.mn.us/Global/MDADocs/protecting/waterprotection/07phoslawreport.aspx

[2] Capitol Region Watershed District BMP Performance and Cost-Benefit Analysis: Arlington Pascal Project 2007-2010. http://www.capitolregionwd.org/wp-content/uploads/2012/09/2007_2010_BMP_Performance_MainBody.pdf

a cumulative drainage area of approximately 190 acres, relative to the 1,855-acre lake watershed, and prevent approximately 77 pounds of P from entering Como Lake each year.

One of the primary sources of external P loading to Como Lake is from leaves and other material from boulevard trees that enter storm drains. The Como Active Citizen Network organizes neighborhood leaf cleanup each fall, aimed at removing leaves (and associated nutrients) from curbsides[3]. This effort supplements the municipal street sweeping, which occurs only once during the fall in the Saint Paul portion of the watershed.

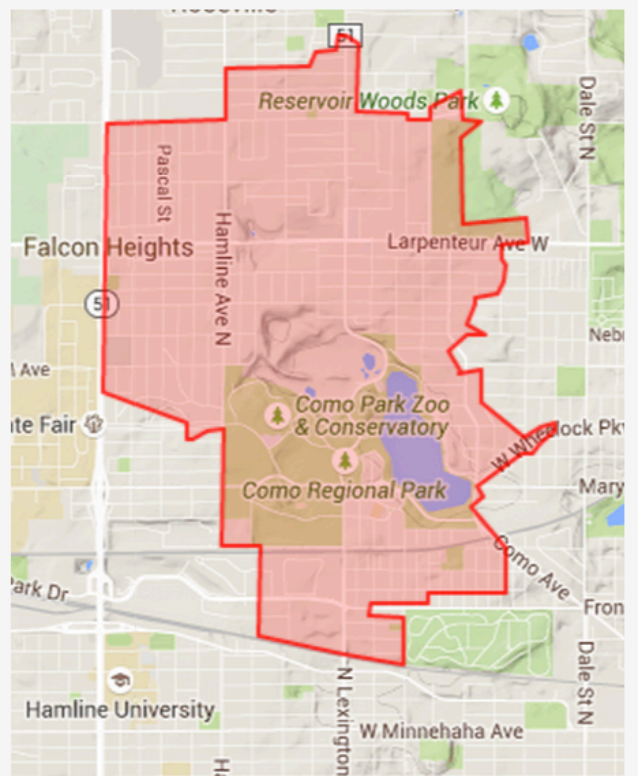

Figure 1. Como Lake in Saint Paul, MN, is fed by stormwater runoff from the 1,855-acre watershed, which includes three different municipalities.

The Como Lake TMDL (2013)[4] calculated that 625 pounds of P per year enter Como Lake from the watershed, and that a 60% reduction in external loading is required as part of the plan to achieve water quality standards. However, the bulk of P loading to Como Lake comes from internal P loading (P release from lake sediments), accounting for 1210 pounds per year. The TMDL requires a 97% reduction in internal P loading, which will be difficult to achieve. The TMDL describes a treatment strategy focused on shifting the lake from a turbid, phytoplankton-dominated state to a clear state dominated by aquatic macrophytes (vascular plants). In clear lakes, macrophytes can outcompete phytoplankton for nutrients, but may be shaded out by phytoplankton. Specific management strategies proposed in the TMDL include controlling populations of benthivorous fish (to minimize disturbance of sediments) and increasing the abundance of piscivorous fish (aimed at reducing populations of planktivourous fish, in turn increasing zooplankton abundance, which in turn decreases phytoplankton abundance).

Based on available data spanning more than three decades, conditions in the lake were worst during the mid-1980's. Following the lawn fertilizer restrictions that began in 2004 and the stormwater infrastructure projects that occurred from 2005-2007, water quality appears to have improved for several years, but since 2010, total P and chlorophyll levels are back around their long-term averages, several times higher than regulatory limits (Figure 2).

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[3] Como Active Citizen Network. http://www.comoacn.org/

[4] Como Lake TMDL. http://issuu.com/capitolregionwd/docs/final_approved__como_tmdl

While the benefits of BMPs in the Como Lake watershed have been quantified in terms of reductions in P loading[2], the current and potential future effects on lake water quality have not been quantified. In this report, we explore the following questions:

1) How much improvement in water quality might be expected from the stormwater infrastructure initiatives implemented by CRWD between 2005-2007?

2) Are there alternative management strategies focused on P removal from the lake that might be feasible?

To address these questions, we developed a coupled hydrologic/phosphorus model for Como Lake, and used this model to simulate a variety of different management strategies. For these scenarios, we estimated cost-benefit analyses in terms of cost per gram of P removed from the lake, and cost per unit improvement in water column total P.

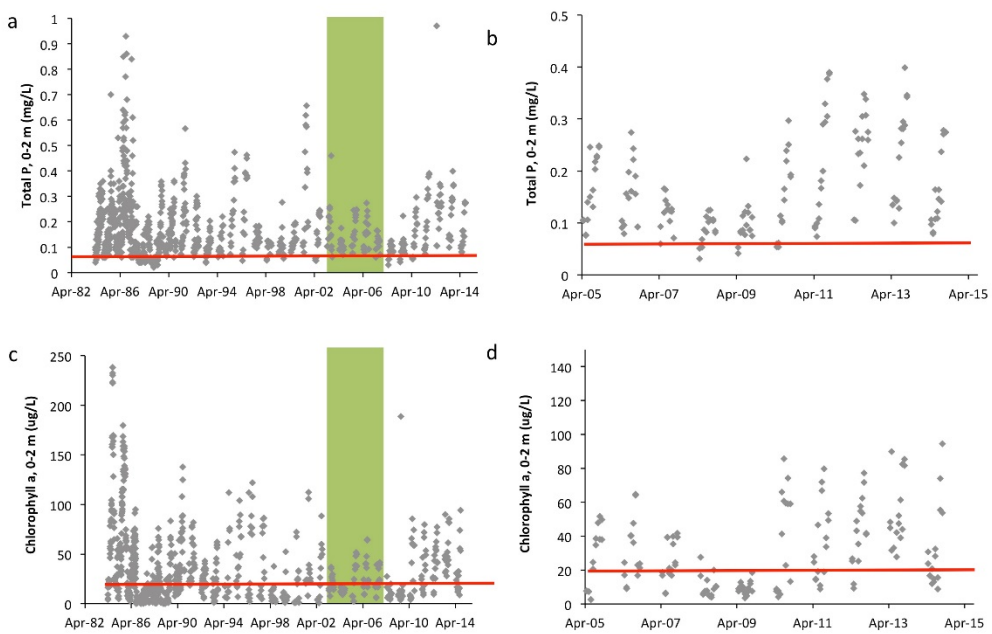

Figure 2. 30 years of observations of total P in Como Lake show levels consistently higher than the standard of 0.06 mg/L (shown by red line). The green bar illustrates the time period from 2004-2007, which included the MN lawn fertilizer restrictions and stormwater infrastructure improvements. B. Typical seasonal trends for total P show steady increases throughout the summer. C. 30-year time series for chlorophyll, with standard of 0.2 mg/L shown in red. D. Chlorophyll levels typically increase throughout the summer months.

Como Lake Phosphorus Management Model

We used a phosphorus model previously developed for a shallow, urban hypereutrophic lake[5] as the basis for our phosphorus management model for Como Lake. The zero-dimensional model (i.e. the lake is assumed to be homogenous) consisted of hydrology and phosphorus submodels.

Hydrology Submodel

The hydrology submodel simulated lake volume. Lake area was assumed to be constant, so that changes in volume resulted in changes in lake level. Inputs to the lake included direct precipitation on the lake surface, and runoff. We used daily precipitation data from the University of Minnesota St. Paul Campus Climatological Observatory[6], approximately 3 miles from Como Lake. For precipitation on the rest of the watershed, we assumed a runoff coefficient of 0.13 (i.e. 13% of rainfall reached the lake as stormwater runoff, while the remainder was returned to the atmosphere as evaporation or transpiration, or infiltrated into groundwater). To simulate the time required for stormwater from across the watershed to reach the lake, we added a second compartment in the hydrology model representing stormwater stored in the watershed. With each 1-day time step, 70% of this stormwater would enter the lake. For example, for a 1 inch rain event, 0.13 inches of rain would become stormwater, and of this amount, 0.9 inches would enter the lake that same day, with an additional 0.3 inches entering the lake the next day. We included spring snowmelt in the runoff term, based on the daily decrease in reported snow depth, assuming water content of 20% for snow in April.

There are two loss terms for water in the lake: evaporation and outflow into Trout Brook. Evaporation was modeled as a constant rate based on pan evaporation measurements made at the St. Paul Campus Climatological Observatory. Because only monthly data are available, we assumed constant daily evaporation values for each month. Outflow was modeled based on lake height. Lake volume was divided by lake area to calculate lake levels, which were converted into height above sea level. Outflow occurs only when lake level exceeds the height of the outflow pipe at 874.1 feet above sea level. Outflow was modeled as an exponential function of lake height based on available data.

We parameterized the model using precipitation and evaporation data for 2013. Modeled lake levels correspond reasonably well with weekly observations of lake level[7], capturing the period from mid-May through mid-July when the lake emptied into Trout Brook, and the period from mid-July through early October when no outflow occurred (Figure 3).

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[5] Ruley & Rusch (2004). Development of a simplified phosphorus management model for a shallow, subtropical, urban hypereutrophic lake. Ecological Engineering 22: 77-98.
[6] http://climate.umn.edu/doc/observatory.htm
[7] http://www.dnr.state.mn.us/lakefind/showlevel.html?downum=62005500

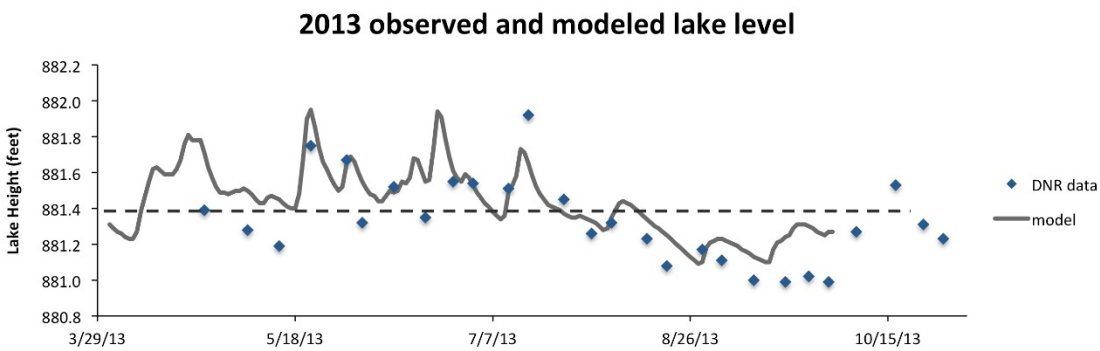

Figure 3. Modeled lake level (solid line) compared to observed lake level (blue diamonds). The dashed line represents the height of the outflow pipe; no outflow occurs when the lake level is below this value.

Phosphorus submodel

Two compartments were represented in the P submodel: water column total P and sediment P. Two external inputs were represented: direct atmospheric inputs and runoff inputs. Atmospheric inputs (from rain and dust) were represented as a small constant value, based on the value reported in the TMDL (22.7 g P/day). Runoff P inputs were based on modeled runoff hydrologic inflow to the lake multiplied by a TP concentration of this runoff. This runoff TP concentration was assumed to be constant (0.292 mg P/L), based on the mean runoff TP concentration reported in the TMDL, which is also consistent with stormwater samples collected in the watershed[8].

Phosphorus loss from the water column occurred via outflow from the lake, based on water column total P concentration. Water loss via evaporation does not remove P from the lake.

Phosphorus moves from the water column to the sediment represented by a constant sedimentation term (approximately 0.8% of water column TP entered the sediment each day). Of this sedimentation, a constant fraction (30%) was assumed to be permanently buried (lost from the system).

Phosphorus from the sediment re-enters the water column according to a temperature-dependent mineralization function. Daily lake temperature was an input to the model, interpolated from available data[9]. The areal rate of P release from sediment was modeled as:

$$k_r = c_1 \times \alpha \times T^{c_2 \times \beta}$$

where k_r is areal P flux (g/m^2/d), T is water temperature in °F, α is the constant 7.6 x 10^{-6}, and β is the constant 2.33. c_1 and c_2 were adjusted to fit observed lake total P concentration data.

[8] Unpublished data from Dr. Jacques Finlay, University of Minnesota.
[9] http://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=62-0055-00

The modeled water column total P concentrations aligned well with observed data for the 2013 season, capturing the steady increase from early June through late August (Figure 4). Although external P inputs are greatest in the spring, the internal loading resulting from warming water temperatures accounts for the rise throughout the summer.

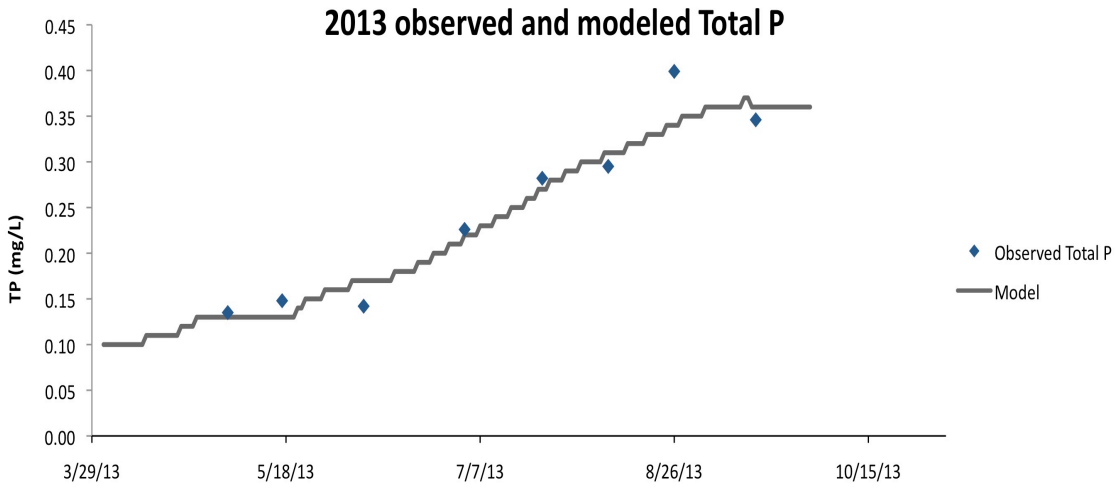

Figure 4. Observations of total P (from 2 m depth) for 2013 compared to modeled values.

The Como Lake TMDL reports calculated average total P inputs of 652 lbs/year from the watershed (34%), 20 lbs/year from the atmosphere (1%), and 1190 lbs/year (65%) from internal loading. Our baseline model run for 2013 (which only spanned April-September) calculated watershed inputs of 377 lbs (41%), atmospheric inputs of 9 lbs (1%), and P inputs from internal loading of 529 lbs (58%).

The baseline model simulation for 2013 illustrates several important features about the seasonal dynamics of P loading in Como Lake. Runoff from snowmelt and rainfall (external inputs) dominates in the spring and early summer. From April-June, runoff accounted for 70% of P inputs (293 out of 421 pounds). The colder water temperatures keep rates of sediment P release low.

From July-September, runoff accounts for only 17% of P inputs (84 out of 494 pounds). Drier conditions result in less runoff, but warmer water temperatures lead to greatly increased rates of internal P loading.

While the total P loading is similar during the April-June and July-September periods, the steady increase in water column total P occurs during the later period. This is because stormwater inputs are only slightly higher in total P (0.292 mg P/L) compared to the lake water (which is approximately 0.150 mg P/L) in early summer, and, importantly, inputs of stormwater result in outflow from the lake, which removes P and essentially negates some of the impact of these P inputs. During April-June in the

simulation, 146 lbs P were exported from the lake into Trout Brook. By contrast, during the drier summer months, the lake level is generally below the height of the outflow pipe, and evaporation (which does not remove P) accounts for nearly all the water losses from the lake. During July-September, only 28 lbs P was exported from the lake.

The late systems scientist Donella Meadows noted that humans have a tendency to try to control systems by managing inputs[10], but we often forget how important outputs can be in controlling important variables. Como Lake exemplifies this adage: the characteristic rise in Total P throughout the summer is primarily a result of diminished losses of P rather than increased inputs of P.

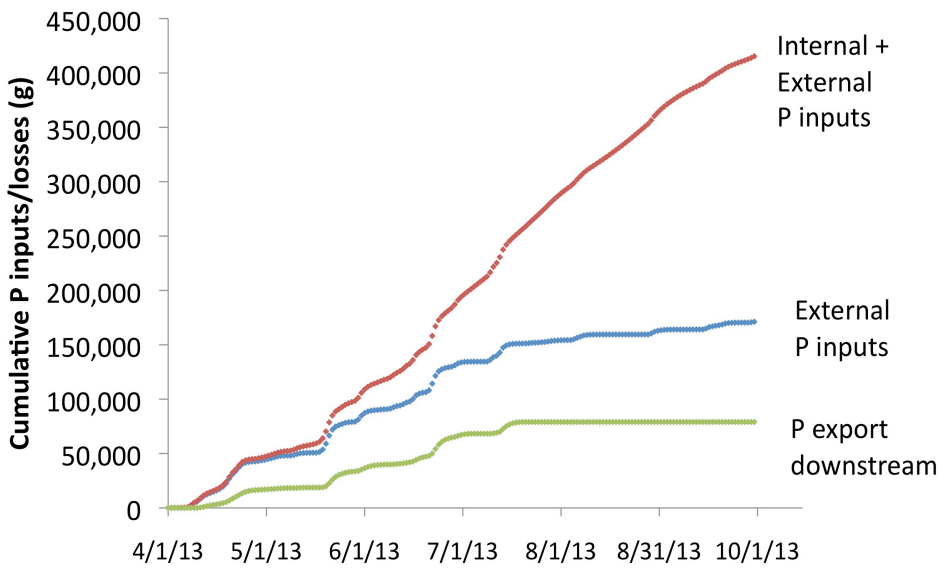

Figure 5. Cumulative P inputs/losses (g) from April 2013 to October 2013

Using the Como Lake model to simulate effects of stormwater management projects

We recognize that the goals of the Arlington Pascal Stormwater Improvement Project (APSIP) were not limited to reduction of P inputs, but also include stormwater volume reduction, public education and outreach, aesthetics, and wildlife habitat[11]. However, the goal of our project was to apply the Como Lake P management model to evaluate the predicted impact on lake water quality from the stormwater infrastructure improvements that were implemented between 2005 and 2007, as well as other potential projects.

[10] Donella H. Meadows. Thinking in Systems: A Primer. 2008.
[11] Capitol Region Watershed District. Stormwater BMP Performance Assessment and Cost-Benefit Analysis.

Note that in the baseline model described above, we assumed that the 190 acres of the Como Lake watershed that drains into the infiltration trenches, rain gardens, underground stormwater infiltration tank, and stormwater retention pond, are completely removed from the watershed. That is, all stormwater in these 190 acres is captured and completely infiltrates into groundwater, which does not enter Como Lake on a timescale relevant to our simulations. The Arlington-Hamline Stormwater Facility and the infiltration trenches are reported to have very high efficiencies of stormwater and total P retention, with the Como Park Regional Pond having a somewhat lower efficiency[12]. To the extent to which stormwater and associated total P from these 190 acres does enter Como Lake, we may be somewhat overestimating the effect of APSIP on lake water quality.

To estimate the effects of the APSIP project on lake water, we added back in these 190 acres to the effective watershed to simulate the watershed in the absence of APSIP. This change resulted in an additional 20.4 kg (45 lbs) of P inputs from runoff to the lake from April-September, consistent with estimated annual TP load reductions of approximately 75 pounds[13]. However, the reduction of stormwater inputs to the lake resulted in slightly diminished outflow from the lake, so that 12.7 kg (30 lbs) less P was exported downstream. As a result, the net reduction in decreased P loading was only 7.7 kg (17 lbs), or 38% of the gross reduction in P loading.

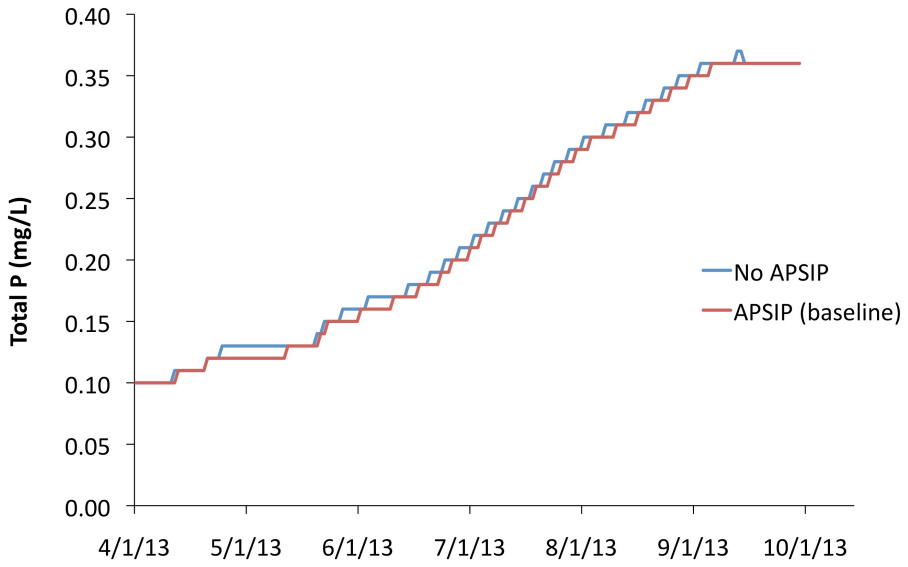

Figure 6. The effects on water quality were small, with a difference in mean water column total P of only 4 ug/L.

[12]Capitol Region Watershed District. Stormwater BMP Performance Assessment and Cost-Benefit Analysis.
[13] ibid.

Because these results were largely due to decreased flushing of the lake when storm flows are reduced, it is important to examine the effects of an important assumption in our model: that water infiltrated from APSIP does not end up in the lake on a time scale relevant to our simulation. While this seems to be largely true, we ran another simulation in which the total amount of stormwater intercepted by APSIP from April-September 2013 was added to Como Lake at a constant rate over the course of the simulation (388 m^3/d) , to simulate additional groundwater baseflow. Even when returning all stormwater to the lake via groundwater (but assuming that all P was retained), this scenario still resulted in reduced outflow from the lake (because this fraction of stormwater entered at a constant rate, where it was subject to evaporation, rather than as pulses, which raise lake level and generate outflow). Compared to the simulation without APSIP, the APSIP with additional groundwater scenario still resulted in 7.7 kg (17 lbs) less P export from the lake, reducing the impact of its 20.4 kg (45 lbs) of gross P removal. The effects on mean lake total P were still small: 216 ug/L versus 227 ug/L in the no APSIP scenario.

To understand the potential effects of additional large stormwater infrastructure projects on water quality in Como Lake, we simulated removing the entire Como 3 subwatershed (517 acres). Such a project would reduce P inputs to the lake by 35.1 kg (77 lbs) during the simulation period compared to the current watershed configuration, but would also reduce P exported from the lake (due to reduced outflow) by 32.8 kg (72 lbs), greatly reducing the net impact of this project. Mean water column total P would decrease only from 223 ug/L to 215 ug/L.

We also considered the hypothetical scenario in which the entire lake was cut off from the watershed, so that the only inputs of water were from direct precipitation, and the only P inputs were from internal loading and atmospheric deposition. Under this scenario, all 171.2 kg (377 lbs) of P inputs from runoff were eliminated, but this also led to a reduction in P exported by 90.5 kg (200 lbs). Mean water column total P improved to 173 ug/L in this scenario.

Finally, we considered a hypothetical scenario in which runoff from the entire watershed entered the lake but contained no P. This scenario was of course the most favorable for water quality, improving mean lake total P to 137 ug/L over the simulation period. This level is still more than double the shallow lake standard of 60 ug/L, indicating the necessity of controlling internal loading to achieve this standard. Nevertheless, this result also indicates that strategies to reduce the P concentration of runoff, such as through curbside leaf cleanup, may be the most cost effective in achieving additional improvements in water quality. Results from these scenarios are summarized in Table 1.

Hydroponic gardens: an alternative approach for nutrient mitigation in urban lakes?

Current management efforts have been focused on reducing nutrient loading to Como Lake. While these initiatives can be successful in reducing nutrient inputs to lakes,

they are less successful in achieving the primary goal of improving water quality because they are not actively removing nutrients from the lake itself. Phosphorus in particular poses a difficult challenge, as internal loading can often exceed external P loading, and continue to fuel excess algal growth for years or decades after management efforts are implemented. Como Lake cannot meet water quality standards solely through reductions in watershed P loading; a 97% reduction in internal loading would be required to achieve necessary water quality improvement. To help reduce internal P loading, the lake management plan recommends management activities such as stabilizing lake-bottom sediments, manage populations of benthic-feeding fishes, improving the abundance of aquatic plants, and increasing the density of zooplankton. However, while these approaches may temporarily lead to lower P levels in the lake water column, they do not deal with the issue of excess P in the lake ecosystem, which is the primary problem. In fact, for much of the summer, Como Lake has no outflow, so any P entering the lake can only build up in the water column or collect in the sediment. To achieve significant improvements in water quality, active removal of nutrients from the lake itself may be required.

We explore a novel approach to urban lake remediation, using hydroponic gardens to sequester excess nutrients in lake water[14]. Hydroponic plants grow in aqueous media (a nutrient-rich water solution) rather than in soil. Hydroponic plant production has been implemented both in open-system aquaculture[15] and in closed system aquaculture[16] (i.e., aquaponics), effectively removing nutrients while producing an economically viable product. Hydroponic production systems can achieve nutrient removal rates comparable to advanced water treatment technology such as ion exchange or reverse osmosis, and unlike these other technologies, hydroponic vegetable production generates income rather than waste products[17]0.27 mg P. The opportunity to produce vegetables to be sold or distributed amongst the community is an appealing result of lake water remediation. Furthermore, a hydroponic garden presents unique opportunities for public engagement. Potential for community participation and educational outreach further bolsters the appeal of a hydroponic approach to lake water remediation and represents the novelty of hydroponic gardens. To our knowledge, our project is the first to assess the potential possibilities and challenges involved with using hydroponic gardens to simultaneously reduce P levels in lakes and generate food.

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[14] This project was supported by a grant from the U.S. Environmental Protection Agency's People, Prosperity, and the Planet (P3) Student Design Competition for Sustainability.

[15] Adler, P. R. 2000. Phytoremediation of aquaculture effluents. 2000. In E. L. Foo, T. Della Senta, and K. Sakamoto (ed.) Material Flow analysis of Intergrated Bio-Systems. Proc. Internet Conf. on Material flow analysis of Integrated Bio-Systems (March-Oct, 2000)

[16] Graber, A., Junge, R. 2009. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. Desalination 246: 147-156.

[17] Adler, P. R., J. K. Harper, F. Takeda, E. M. Wade, S. T. Summerfelt. 2000. Economic evaluation of hydroponics and other treatment options for phosphorus removal in aquaculture effluent. HortScience 35: 993-999.

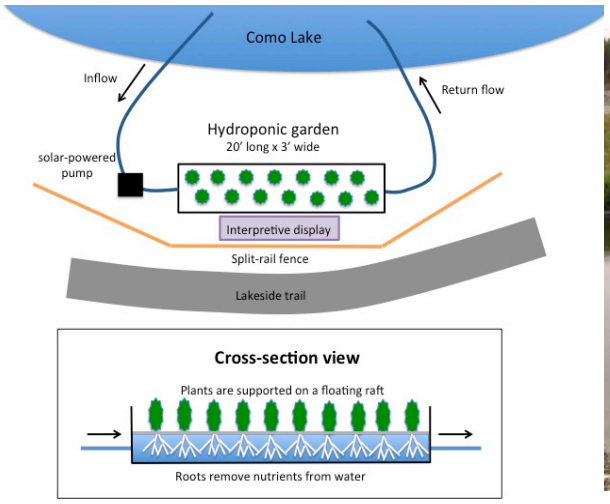

Figure 7. Example of the lakeside hydroponic system

Figure 8. Example of a floating island (BioHaven)

Hydroponic gardens could either be built alongside a lake or on a lake as a floating island. A lakeside design could include a raised bed lined with pond liner, with a solar-powered pump bringing lake water into the bed. Plants would be supported on floating rafts, with roots extending into the water, and a gravity-fed outflow would return cleaner water into the lake (Figure 7). Alternatively, vegetables could be planted directly on a floating island (made from recycled polyethelyene), with roots extending directly into the lake. These floating islands are increasingly being used for habitat restoration and water quality improvement in small lakes and ponds, but are typically planded with native wetland plants (Figure 8).

Our analysis focused on answering three central questions about the feasibility of implementing a hydroponic garden in Como Lake:

1. Would vegetables growing in lake water accumulate heavy metals at unsafe levels?

2. Would vegetable production, and P sequestration, be limited by the availability of other nutrients such as nitrogen?

3. What scale of hydroponic garden could be necessary to make significant improvements in lake water quality?

During the summer of 2014, we grew several varieties of vegetables (green peppers, green beans, peas, basil, and cucumbers) hydroponically in Como Lake water in buckets at the University of St. Thomas. At the end of the 10-week experiment, we used an X-ray fluorescence spectrometer to measure concentrations of heavy metals that could potentially be present in a stormwater-fed lake, including lead, zinc, copper, nickel, cobalt, manganese, chromium, and cadmium. Most values were below the level of

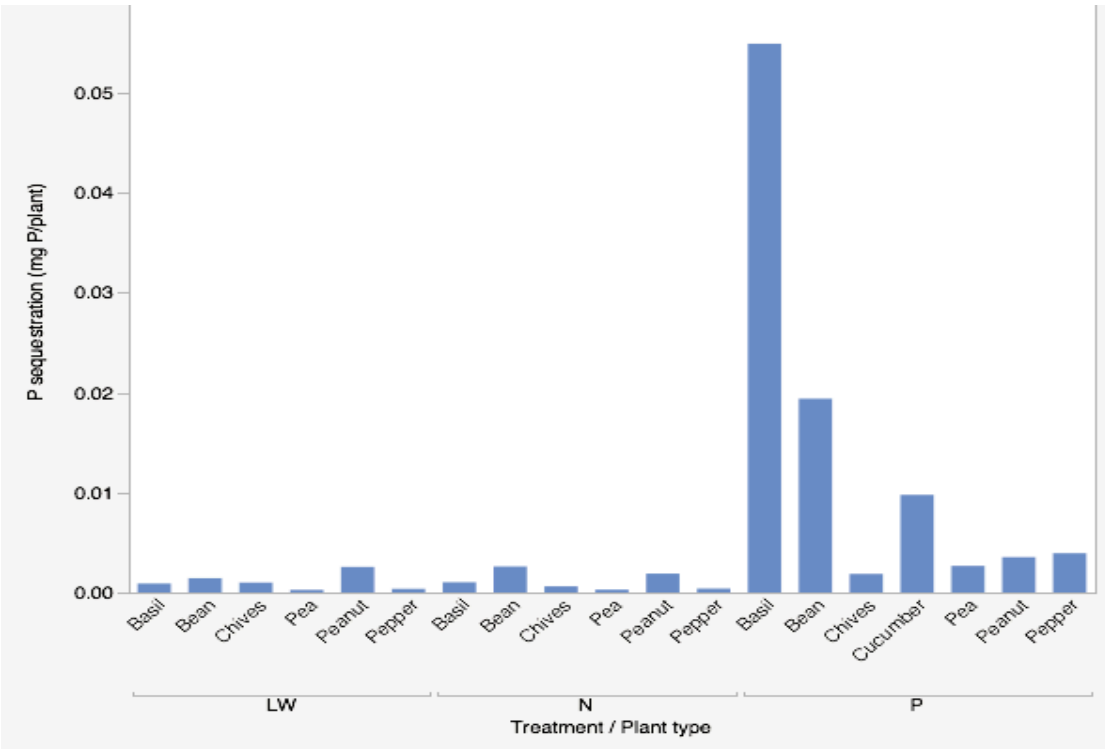

Figure 9. Preliminary results show that some plant varieties are capable of sequestering significant amounts of P under high-P conditions (P). However, under ambient nutrient conditions (LW), plant production and P sequestration was low.

detection of the instrument. Only copper showed elevated levels, with a mean concentration in plant tissue of 56 ppm (range 18-174 ppm). For reference, EU standards for permissible levels of copper are 20 ppm[18] (copper in vegetables is not regulated by the US FDA). Further tests are warranted using more precise instrumentation. We also note that we did not assess the potential for accumulation of organic compounds, or microbial contamination, in vegetables growing in lake water. A thourough assessment of these variables would be needed before these vegetables could be considered safe for human consumption.

The 2014 trial indicated that potential P sequestration was high for some plants (Figure 9), but nutrient limitation in lake water limited plant growth. Dissolved P and especially dissolved N levels in Como Lake are low relative to typical hydroponic media. Follow-up experiments examined potential strategies to overcome nutrient limitation without contributing nutrients to lake water, including: growing N-fixing legumes, foliar application of fertilizer solutions to plants, and growing vegetables in soil on floating islands. Legumes inoculated with N-fixing bacteria performed marginally better than non-legumes, but only plants in the floating island treatment performed substantially

[18] Taghipour, H., and M. Mosaferi. 2013. Heavy metals in the vegetables collected from production sites. Health Promot. Perspect. 23: 185-193.

better. In this case, however, plants are likely pulling nutrients from the soil rather than from the lake water, so it is difficult to assess the potential water quality benefit.

Simulating effects of hydroponic gardens on Como Lake water quality

The coupled hydrology and phosphorus model, previously described, was used to simulate the effects of hydroponic gardens on Como Lake P concentration. An additional sink of phosphorus was created to represent the hydroponic garden. Rate of phosphorus outflow or plant uptake was determined using data collected from the preliminary growth experiments in Como Lake water (0. 27 mg P per plant per day). Scaling from the density of plants in our prototype hydroponic gardens, we estimated 8000 plants/acre, leading to an estimated P uptake of 2 g/acre/day. We ran model simulations assuming 1-acre, 10-acre, and 100-acre gardens (Figure 10). The 1-acre, 10-acre, and 100-acre hydroponic gardens actively removed 1.29 kg (2.84 lbs), 12.87 kg (28.37 lbs), and 128.73 kg (283.80 lbs) of phosphorus respectively. Substantial impact was caused by the 100-acre garden, however, a hydroponic garden of that size is not realistically achievable. A more reasonable size for a hydroponic garden is 10-acres. The 10-acre garden was able to reduce average concentration of total dissolved P in the lake by approximately .005 mg/L independently.

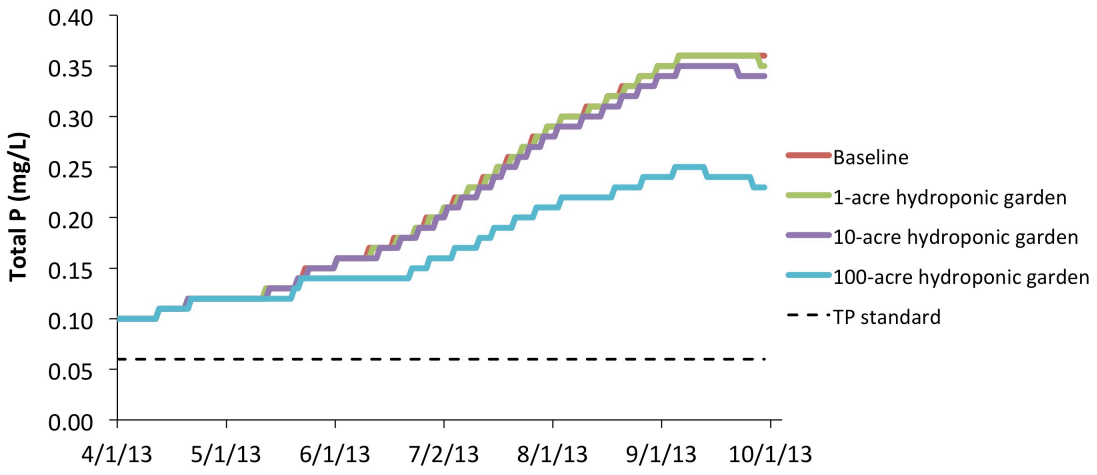

Figure 10. Concentration of P from April 1, 2013 to October 1, 2013. Comparing 1-acre, 10-acre, and 100-acre hydroponic gardens to baseline (no garden).

Model Scenario	Effective watershed (non lake) area (acres)	External P inputs (kg)	P export downstream (kg)	Gross P reduction (kg)	Net P reduction (kg)	Mean water column total P (ug/L)
APSIP (baseline)	1593	171	79	20	8	223
no APSIP (hypothetical)	1783	192	92	0	0	227
APSIP with groundwater	1593	171	87	20	15	216
Como 3 subwatershed	1266	136	59	56	23	215
cut off entire watershed	0	0	1	192	101	173
APSIP, runoff with 0 TP	1593	0	40	192	140	137
APSIP + 1 acre hydroponic	1593	171	79	1	1	222
APSIP + 10 acre hydroponic	1593	171	78	13	12	217
APSIP + 100 acre hydroponic	1593	171	69	129	119	172

Cost benefit analysis

Table 1. Summary of model scenarios.

Cost-Benefit Analysis

Our analysis shows that P uptake from hydroponic gardens, even implemented at large scales, are not able to overcome the P loading from sediment in Como Lake. However, active removal by plants may be part of a larger strategy of lake nutrient management. We considered the cost of net P removal from a large-scale (8-acre) hydroponic greenhouse, in comparison with values reported for the Arlington Pascal Stormwater Infrastructure Project (APSIP).

The capital cost of an 8-acre hydroponic greenhouse was determined to be $800,000[19]. Annual cost was subjectively fixed at $22,571 (payment $800,000 of over 35 years) to compare with the present CRWD's BMP projects[20]. In addition, annual

19 Brown, Tony. (2015). Lettuce dream launches capital campaign. Maryville Daily Forum. Retrieved from http://www.maryvilledailyforum.com/news/article_3495291e-d6dc-11e4-aa04-53d871d0981e.html

20 Capital Region Watershed District. (2010). Stormwater BMP performance assessment and cost-benefit analysis.

maintenance cost was arbitrarily set at $5000, however, potential profits from produce sales were not factored into the final calculations.

Gross P reduction for the different components of APSIP (the Arlington Hamline Underground Stormwater System, infiltration trenches, and the rain gardens) was presented as the amount (grams) of phosphorus input the respective strategy reduced. Net P reduction was the adjusted P reduction when taking into account the decrease in outflow caused by each respective strategy. Gross P reduction for the hydroponic facility was presented as the amount (grams) of P that was actively removed from the water. Net P reduction for the hydroponic facility was the adjusted P reduction when taking into account the decrease in P outflow caused by the pumping of lake water into the hydroponic facility.

	Drainage Area/Total Acreage	Gross P reduction (g)	Net P reduction (g)	Capital Cost	Maintenance Cost/Year	Total Annual Cost	Cost/g net P reduction
Underground stormwater facility	27	5,443	1,303	$799,087	$2,025	$24,605	$18.88
Underground facility + 4 Trenches	50	8,079	2,197	$974,322	$7,907	$30,487	$13.88
Rain Gardens	16	2,522	874	$160,244	$7,544	$12,122	$13.87
Hydroponic greenhouse	8	2,928	2,446	$800,000	$5,000	$27,857	$11.39

Table 2. Cost-benefit analysis of phosphorus removal strategies in Como Lake. Gross and net P reduction was modeled and total annual cost for each respective strategy was obtained to determine the cost per gram of phosphorus reduction.

Results indicate that the cost per gram of P reduction for the hydroponic facility (Table 2) would be less than that of the current strategies being implemented for Como Lake. In addition, the hydroponic facility has the potential to produce economically viable produce to be sold or distributed to the community. However, an 8-acre hydroponic facility is still a sizable venture. More research must be conducted to further determine the feasibility of cleaning urban lakes using hydroponic gardens.

Conclusions

The results of our model highlight the difficulty of managing Como Lake water quality. In particular, it illustrates the importance of lake flushing; during the summer, when the often has no outflow, P is released from lake sediments at a high rate and is concentrated in the water due to evaporation. Stormwater management efforts, while necessary, undermine much of their potential effectiveness in water quality improvement if outflow from the lake is reduced. Efforts that reduce P loading to the

lake without reducing water volume (such as neighborhood curbside leaf cleanups) are most promising in this regard, but P inputs are dominated by internal loading and even complete removal of external inputs will not bring water quality into compliance with standards.

Although we have identified potential for a hydroponic system to remove phosphorous from Lake Como, further research is necessary to fully determine its feasibility. Furthermore, a hydroponic garden on its own cannot remove enough phosphorous to bring the lake into compliance with water quality standards. The results of our research indicate that hydroponic gardens may be worth considering as part of an integrated lake nutrient management strategy. Further research is needed to assess whether food grown in lake water could be safe for human consumption.

Currently, management efforts have been focused on reducing P inputs. By exploring a strategy such as hydroponic garden, we begin to understand the importance of actively removing P from the lake itself. By coalescing P input reduction strategies and potential P removal strategies, we can prevent future P inputs while eliminating P already in the lake.

The model we have created is an effective tool to understand the dynamics of the lake and to better understand how management decisions will affect water quality in the lake. Expanding upon the model will provide a useful foundation for future management decisions in regards to Como Lake. By accurately modeling the lake we can predict how management practices may affect water quality before making any monetary decisions. Opportunities to expand the model may include accounting for the dynamic balance between N, P, phytoplankton, and other plantswithin the lake.

It is imperative that we holistically analyze strategies to remediate Como Lake of excess nutrients. Both P inputs and P outputs need to be considered when determining impact of any management strategies on lake water quality. By modifying our metric of efficacy we can further advance towards the goal of decreasing excess nutrient concentrations. By carefully deliberating all sources of P and assessing the dynamics of the lake system, new strategies can be developed and management approaches can be adapted.