J. Aquat. Plant Manage. 55: 26–34

Aquatic plant harvesting: An economical phosphorus removal tool in an urban shallow lake

WILLIAM M. BARTODZIEJ, SIMBA L. BLOOD, AND KEITH PILGRIM*

ABSTRACT

The mechanical harvesting of nuisance macrophytes in shallow lakes is frequently conducted to improve recreational opportunities and aesthetics. This management approach also removes phosphorus from lake systems. We assessed the effectiveness and relative cost of phosphorus removal by plant harvesting in a shallow (mean depth 0.6 m), small (5-ha), urban lake in Minnesota from which common carp (*Cyprinus carpio* L.) had previously been eradicated by drawdown. In 2014, two harvesting efforts (July and August) were effective at reducing infestations of water net [*Hydrodictyon reticulatum* (L.) Bory] and common elodea (*Elodea canadensis* Michx.) in Casey Lake. A total of 3,600 kg dry weight of plant material and 16.4 kg of total phosphorus (TP) were removed through harvesting. The phosphorus removed by harvesting was equivalent to 53% of the TP inflow (load) to Casey Lake. The cost of this phosphorus removal was \$670 kg^{-1} of TP, which was more expensive than in-lake alum treatment (\$480 kg^{-1} of TP), but considerably less expensive than many watershed best-management practices (\$2,800 to \$49,800 kg^{-1} of TP). Phosphorus removal costs were figured over the life of each practice. Our results show that macrophyte harvesting can be a cost-effective means to remove phosphorus from an urban shallow lake system, and this management tool has the potential to factor into dynamic and creative lake and watershed management plans.

Key words: Common elodea, common carp, *Cyprinus carpio*, *Elodea canadensis*, *Hydrodictyon reticulatum*, mechanical harvesting, phosphorus, water net, watershed, watershed best-management practices

INTRODUCTION

Managing shallow lakes (< 4 m) can be challenging because of extensive littoral zones, substantial nutrient inputs from developed watersheds (Cooke et al. 2005), and internal nutrient loading (Søndergaard et al. 2013). Because of eutrophication, these systems are typically either phytoplankton or macrophyte dominated (Uhlmann 1980, Scheffer 1998). In macrophyte-dominated lakes, aquatic plant control is common and usually driven by the need to improve aesthetics and recreational opportunities (Moss et al. 1997). Although urban lakes are altered by many factors, citizens sometimes set great expectations for these water resources that later prove to be unrealistic. In the Upper Midwest, management goals for urban shallow lakes commonly include moderate aquatic plant coverage, sustainable game fish populations, patches of natural shore providing diverse habitat, and water-quality parameters that meet or exceed state standards.

Because phosphorus limits primary production in most midwestern lakes, management plans usually focus on reducing total phosphorus (TP) inputs from tributary watersheds and, in some cases, from internal loading. Simple mass balances and models are typically used to predict external and internal load changes on in-lake phosphorus concentrations (Canfield and Bachmann 1981, Walker 1987, Heiskary and Walker 1995, Walker 2000). Rarely is the uptake of phosphorus by aquatic plants included in these mass balances or models, likely because of modeling convention and lack of solid aquatic plant data. Thus, plant harvesting is seldom included as a component in comprehensive watershed and shallow-lake phosphorus reduction plans.

Implementing watershed best management practices (hereafter BMPs) such as bioretention systems, also referred to as "rain gardens," is an increasingly popular approach to reduce phosphorus loads in urban lakes (Davis et al. 2009). In developed watersheds, these practices are expensive, mainly because of complicated engineering retrofits and associated land prices (Weiss et al. 2007). When internal phosphorus loading is a concern, managers typically rely on aluminum salt (e.g., alum) treatments for in-lake phosphorus control. Another in-lake management option to remove phosphorus is aquatic plant harvesting.

Nutrient removal through harvesting has traditionally been considered relatively expensive (Neel et al. 1973, Burton et al. 1979) and ineffective at changing the trophic state of a lake (Madsen 2000). James et al. (2002) and Cooke et al. (2005) were among the first to advocate that, in certain lake systems, harvesting may be a useful component of integrated nutrient management plans. When used repeatedly, plant removal has the potential to deplete phosphorus levels in lake-bottom sediments (Chen and Barko 1988). Over the last decade, the idea of nutrient reduction through harvesting has gained more attention. In a total maximum daily load study, Reisinger et al. (2008) included the harvest

---

*First and second authors: Natural Resources Specialist and Natural Resources Technician, Ramsey–Washington Metro Watershed District, 2665 Noel Drive, Little Canada, MN 55406. Third author: Senior Water Resources Scientist, Barr Engineering, 4300 MarketPointe Drive, Suite 200, Minneapolis, MN 55435. Corresponding author's E-mail: bill.bartoziej@rwmwd.org. Received for publication April 14, 2015 and in revised form August 30, 2016..

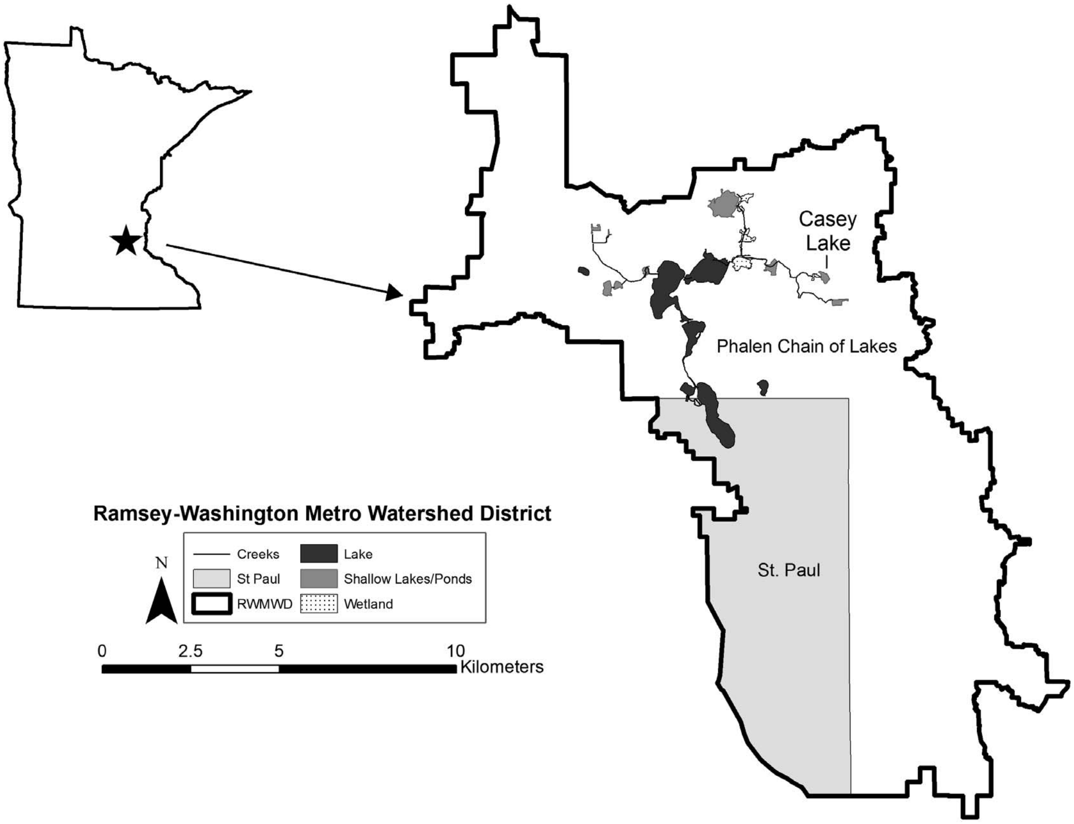

Figure 1. Casey Lake is within the Ramsey–Washington Metro Watershed District (RWMWD), MN, and comprises part of the Phalen Chain of Lakes headwaters. This is the most popular chain of lakes near the city of St. Paul.

of a floating plant, water hyacinth [*Eichornia crassipes* (Mart.) Solms], as an effective method for TP removal in the St. Johns River, Florida. Evans and Wilke (2010) build the case that hydrilla [*Hydrilla verticillata* (L. f.) Royle] harvesting is a suitable and cost-effective management strategy for many nutrient-impaired waters. Additionally, the harvest of submersed macrophytes for nutrient removal in water treatment systems is now being considered (Zhu et al. 2012, Souza et al. 2013).

We contend that macrophyte harvesting is an economical way to remove phosphorus from shallow lakes. Furthermore, harvesting should be considered in concert with watershed BMPs as harvesting has the potential to permanently remove a significant quantity of phosphorus from watershed systems. We present a management case study that investigates aquatic plant harvesting on a shallow lake in a developed watershed, including phosphorus removed by harvesting, phosphorus inflow and outflow, and the measured in-lake water quality before and after harvesting. In this study, we evaluate harvesting that was conducted in 2014 to control the invasive filamentous alga water net [*Hydrodictyon reticulatum* (L.) Bory] and common elodea (*Elodea canadensis* Michx.), which reached nuisance levels 1 yr after common carp (*Cyprinus carpio* L.) eradication (henceforth carp). We compared expenditures associated with harvesting with the cost of BMPs currently used in our watershed. This information will be useful to managers when evaluating cost and effectiveness of a range of phosphorus management tools. We also discuss our management approach and the perceived risks associated with macrophyte harvesting in shallow lakes.

MATERIALS AND METHODS

Study site

Located in the Ramsey–Washington Metro Watershed District (RWMWD), Casey Lake (45°01′19″N, 93°00′44″W) is at the headwaters of the Phalen Chain of Lakes in Minnesota (Figure 1). Casey Lake is a favorite local destination for the residents of North St. Paul. A city park with ball fields, picnic areas, a walking path, and lake access points encompasses the eastern half of the shore. The lake is 5-ha and shallow, with a mean depth of 0.6 m and a maximum depth of 1.1 m. An outlet control structure minimizes flood events (< 1 m) and allows for drawdown. Casey's watershed (95 ha) is fully developed with a dominance of residential suburban housing and 27% impervious surface area.

In 2010, Casey Lake was identified as a productive carp nursery area (Osborne 2012). The carp population was extremely high ($n \approx 6{,}000$), with a mean individual weight of 0.43 kg, and a total biomass estimated at 500 kg ha^{-1} (Dauphinais, pers. comm., 2016). In Midwestern shallow lake systems, carp biomass over 100 kg ha^{-1} is considered damaging to macrophytes (Bajer et al. 2009, Bajer and

Sorensen 2015). In addition to having adverse effects on Casey's water quality and biota, substantial numbers of invasive carp could travel downstream into the Phalen Chain of Lakes (Koch 2014); see Figure 1. As part of a comprehensive carp management plan, Casey Lake was drawn down in the winter of 2012 to 2013. In the spring of 2013, netting and electrofishing surveys suggested a complete kill of the fish community (Dauphinais, pers. comm.). Subsequently, the Minnesota Department of Natural Resources introduced gamefish[1] species, specifically bluegill sunfish (*Lepomis macrochirus* Raf.), green sunfish (*Lepomis cyanellus* Raf.), and largemouth bass (*Micropterus salmoides* Lac.), to restore the fishery and provide biotic resistance against carp recruitment. An aeration system was installed to increase the survival of game fish over the winter months.

Aquatic plant harvesting

After the carp eradication, Casey switched from a phytoplankton-dominated state to one blanketed by macrophytes. In 2013, rooted aquatic plants became established and covered a majority of the lake bottom. In most areas, plants did not reach the surface and were at levels where recreation and aesthetics were not affected. However, in 2014, nuisance levels of common elodea and the invasive water net first became apparent in June. This prompted the RWMWD to employ a private contractor to conduct mechanical harvesting. Two harvesting efforts began on 11 July and 20 August 2014 and lasted 30 h and 36 h, respectively. The majority of the lake surface area, 5 ha, was harvested during each effort. A paddlewheel harvester[2] with a cutting swath of 1.5 m and the harvesting depth set at 0.3 m was used at Casey Lake (the boat draft was 0.5 m with a full load). Harvested plant material was hauled off site to a local public works yard for composting. The total wet weight of each harvesting effort was calculated using the total number of trailer loads and the average plant material payload weight (measured in triplicate).

Aquatic plant and water-quality sampling

Plant and water-quality sampling began in 2010 as part of a related study on carp, and continued through 2014, mainly because of the aquatic plant management effort. In mid-June of each growing season, we used the point-intercept method (Madsen 1999) to document and survey the submersed macrophyte community. On 11 July and 20 August 2014, common elodea and water net were sampled for phosphorus analysis. Before mechanical harvesting, polyvinyl chloride quadrats (0.5 m by 0.5 m) were randomly placed ($n = 6$) in representative patches of surfaced common elodea and water net. Vegetation in the quadrats was harvested by hand down to a depth of 0.3 m (mimicking the harvester cutting depth). The common elodea and water net were separated and bagged individually for analysis. In addition, on 22 August, six representative composite samples (common elodea and water net), approximately 300 g wet weight, were collected by hand from the harvester payload area during six different harvesting trips. Samples were sent to a private certified laboratory for analyses. Samples were oven dried overnight at 100 C and ground. Subsamples (0.5 g) were digested with sulfuric acid, potassium sulfate, and mercuric sulfate, and analyzed for TP using a Westco SmartChem discrete analyzer following Environmental Protection Agency (EPA) 365.4 methods (USEPA 1983). All reported plant phosphorus values hereafter are dry weight.

Water-quality parameters were monitored every 2 wk, starting in April and ending in September (2012 to 2014). Water sampling occurred at a fixed site in the center of the lake. A YSI 600 XLM V2 sonde[3] was used to measure temperature, dissolved oxygen, and pH at the surface, 0.5 m, and just above the substrate at 0.8 m. A 2.0-m plastic pipe was used to collect a composite sample of the water column. Water samples were analyzed at a commercial laboratory for TP and orthophosphorus using method EPA 365.1 (USEPA 1983). Chlorophyll *a* analysis followed Standard Methods 10200 H. (Eaton et al. 1998).

Phosphorus inflow and outflow modeling

The mass of phosphorus inputs to Casey Lake were calculated by multiplying the daily averaged P8-modeled TP concentration by the daily averaged modeled flows (Walker 2000). The mass of phosphorus exiting Casey Lake was estimated assuming that the lake inflows were equal to lake outflows. This is a reasonable assumption given the size of Casey Lake and no substantial outlet restrictions. The mass exiting Casey Lake was calculated by multiplying in-lake phosphorus concentrations by daily average outflows. In-lake phosphorus concentrations between monitoring points were estimated by linear extrapolation. Internal phosphorus loading likely occurred in Casey, but it was beyond the scope of this study to investigate sediment chemistry in relation to drawdown, carp eradication, and aeration.

Phosphorus removal cost calculations

The cost per kilogram of TP removed per year was estimated for harvesting, alum treatment, and BMPs used by the RWMWD. The cost of phosphorus removed through harvesting was determined by estimating the total wet weight of plants removed, and then converting to dry weight with a conversion factor of 0.068 (or 93.2% moisture content for composite samples). The mean TP concentration in the harvested plant tissue was then multiplied by the total dry weight of the harvest to determine the TP removed by harvesting.

The RWMWD treated Kohlman Lake, a shallow lake in the connected Phalen Chain of Lakes (Figure 1), with alum in 2012. A cost assessment of this treatment included an estimate of the quantity of phosphorus inactivated over a 10-yr treatment lifetime and expenditures such as the alum product, field application, dosing model development, and project management (Barr Engineering 2007, 2010).

Expenditures and estimated annual phosphorus removal rates were tracked for various BMP projects within the RWMWD, starting in 1990. We tabulated capital costs, which included project engineering, design, and construction expenditures. To annualize the capital costs, compound

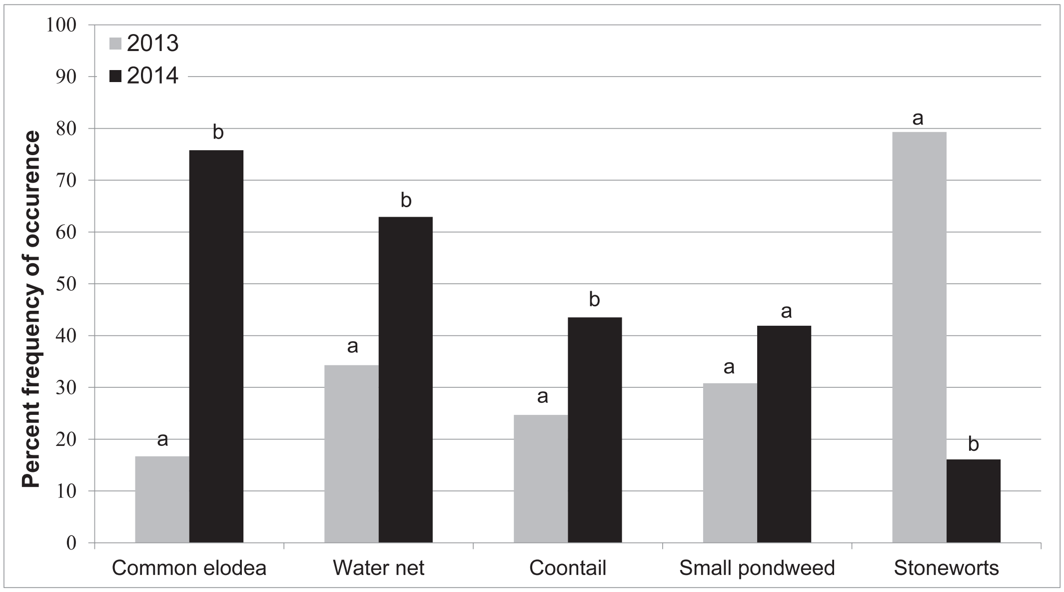

Figure 2. Macrophyte percent frequency of occurrence data (point-intercept method) for Casey Lake, June 2013 to 2014. Differences by year were tested for each species using a chi-square test of goodness of fit. For each species, bars with different letters above are significantly different ($P < 0.05$).

interest factors were applied, assuming a 4% interest rate and a projected 35-yr project life span (Newnan 1991). Land acquisition and easement costs were extremely variable, so they were left out of the calculations. Capital, operation, and maintenance costs (actual and estimated) were adjusted to 2014 dollars using the historic construction cost indices published by the Engineering News-Record (ENR 2014). Phosphorus removal rates were calculated by either the P8 urban catchment model (Walker 2000) or the Minnesota Stormwater Manual's minimal impact design standards model (Minnesota Pollution Control Agency 2014). The mean annual phosphorus removal costs were calculated for the following BMP categories: alum injection into storm water, storm water ponds, iron-enhanced sand infiltration, tree trenches, rain gardens, and pervious pavement. It should be noted that watershed BMPs have multiple benefits, such as reduction of storm water volume, suspended solids, and heavy metals; however, for this study, cost calculations were only related to TP reduction.

RESULTS AND DISCUSSION

In 2013, the year after carp were eliminated from Casey Lake by drawdown, a macrophyte community became established with two stoneworts prevalent, *Chara* sp. and *Nitella* sp., whereas small pondweed, (*Potamogeton pusillus* L.), water net, coontail (*Ceratophyllum demersum* L.), and common elodea were at low to moderate levels (Figure 2). This macrophyte response after carp eradication is similar to what others have reported (Weber and Brown 2009, Bajer and Sorensen 2015). However, the appearance and rapid growth of water net in Casey Lake was unique and unexpected. In June 2014, water net and common elodea showed significant expansion from 2013 to 2014, and were the dominant species with frequency-of-occurrence values at 62 and 75%, respectively (Figure 2). Water net quickly colonized common elodea stems that reached the water surface, creating dense floating mats. This condition impeded all water recreation and was considered unsightly by many neighborhood residents. Shoreland owners and lake users were frustrated, and some commented that they wanted the invasive carp to be stocked back into the lake. The significant expansion of water net and common elodea prompted aquatic plant management.

To minimize disruption of the shallow Casey Lake system, mechanical harvesting was selected over herbicide use. This decision was not swayed by the possibility of studying phosphorus removal through harvesting. Our main concern with herbicides was that decaying plant material may cause a significant reduction in dissolved oxygen and an increase in water-column phosphorus (Brooker and Edwards 1975, Carpenter and Gasith 1978, Hodgson and Carter 1982, Engel 1990, Murphy and Barrett 1990). Harvesting was effective at reducing the cover of water net and common elodea in Casey Lake. A total of 25,000 kg wet weight of plant material was harvested in July 2014. However, water net quickly expanded and covered nearly 100% of the lake water surface in less than a month after the initial harvest. The second harvesting effort in August removed another 27,000 kg wet weight of plant material. This additional control effort was not initially planned or anticipated.

Water net is widespread in the United States but rarely reaches nuisance levels in comparison with other filamentous algae, such as *Cladophora* and *Spirogyra* (Wells et al. 1999). More typically, in midsummer, macrophyte dominated shallow lakes in the Twin Cities area harbor substantial patches of the aforementioned algae species. Casey Lake is the first published occurrence of water net reaching nuisance levels in the Twin Cities metropolitan area. In the late 1980s, a major outbreak of water net in New Zealand caused substantial economic and recreational impacts. A variety of control measures, including mechan-

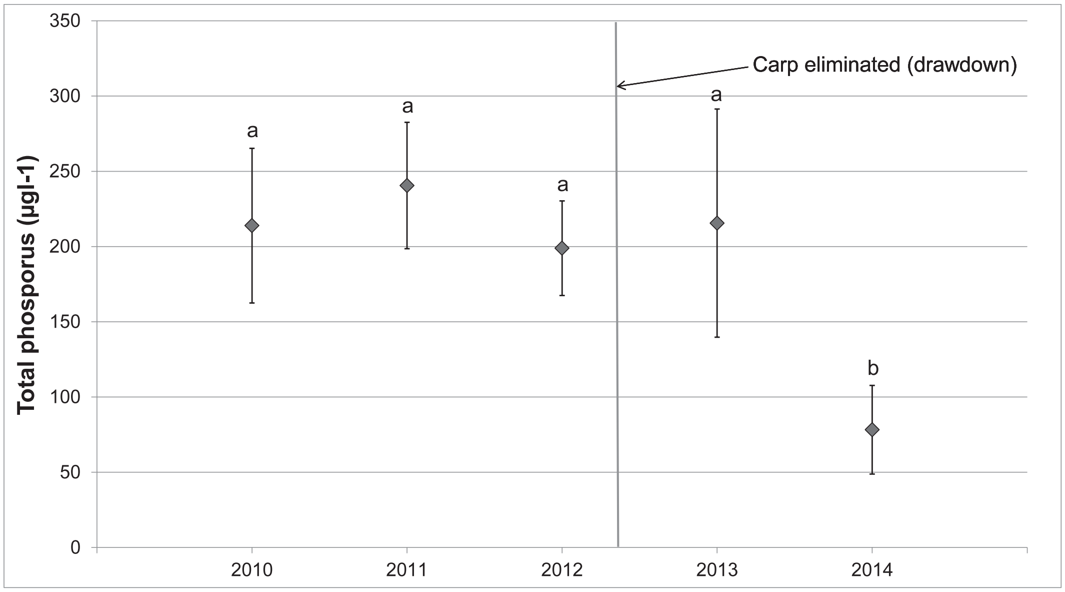

Figure 3. Mean total phosphorus concentrations (µg L^{-1}) in Casey Lake during the growing season, April to September 2010 to 2014. Means with different letters are significantly different ($P < 0.05$, Kruskal–Wallis test).

ical harvesting, were used to reduce the abundance of this invasive species (Wells el al., 1999). Water net in New Zealand was found to have a low nitrogen requirement and a high affinity for dissolved inorganic nitrogen (Hall and Payne 1997). However, this occurrence has not been documented in the United States. We did not sample nitrogen in our study, but did find that Casey Lake TP levels significantly decreased ($P < 0.05$, Kruskal–Wallis test) in 2014 (Figure 3). One possible explanation for this decrease may be related to the substantial water net blooms extracting phosphorus out of the water column. Because of its rapid rate of growth and ability to efficiently extract nutrients from water, this species is used in wastewater treatment and is being explored for biofuel production (Lee et al. 2014). Wang et al. (1999) reported over a 70% reduction of TP in reservoir water samples exposed to water net colonies for 2 to 6 d.

TP concentrations were determined for common elodea and water net during July and August 2014 harvesting (Table 1). Phosphorus values for these plant species are not reported in the literature; however, our values are within the range of those reported for other macrophyte species growing in eutrophic lakes in the Upper Midwest—600 to 13,000 mg kg^{-1} (Gerloff and Krombholz 1966, Gerloff 1975, Carpenter and Adams 1977). Using mean TP concentrations of 4,200 mg kg^{-1} (July) and 5,000 mg kg^{-1} (August) for harvested dry-weight composite material (common elodea and water net), we estimate that 16.4 kg of TP was removed through mechanical harvesting.

The quantity of phosphorus removed through harvesting was substantial when compared with TP inflow and outflow estimates for Casey (Table 2). In 2014, the phosphorus removed by harvesting was equivalent to 53% of the TP inflow (load) to Casey Lake. These observations point to harvesting being an important mechanism for phosphorus removal from Casey Lake. We can look at this phosphorus originating from both the water column and the sediments, since both water net and common elodea were harvested. Although we did not measure sources of phosphorus in the plant tissues, it is plausible that water net extracted phosphorus from the water column (discussed above) and common elodea exploited phosphorus from the sediments (Barko and James 1997).

Our phosphorus removal estimate is relatively high in comparison with other studies that focused on eutrophic lake systems. Peterson et al. (1974) found that harvesting

Table 1. Mean ($N = 6$) total phosphorus (TP) in the tissue of water net, common elodea, and composite samples of water net and common elodea collected from the payload of the harvester, July and August 2014 in Casey Lake. Values are expressed as milligrams of tp per kilogram of dry-weight plant material. One standard deviation is reported in parentheses. Composite samples were not collected in July. Values rounded to the nearest 100. na, not applicable.

Sample	July (TP, mg kg^{-1} dry wt)	August (TP, mg kg^{-1} dry wt)
Water net	3,100 (300)	4,300 (1,400)
Common elodea	5,300 (2,800)	6,700 (2,800)
Composite	na	5,000 (900)

Table 2. Casey Lake parameters and total phosphorus (TP) inflow and outflow.

	Modeling Year (May 1 through September 30)		
Parameter	2012	2013	2014
Inflow volume (m^3)	127,741	103,375	98,360
Hydraulic residence time (d)	35.2	43.5	45.7
Average lake volume (m^3)	29,357	29,480	29,480
Average lake depth (m)	0.61	0.61	0.61
Average lake TP (µg L^{-1})	191	216	89
TP inflow (kg TP yr^{-1})	28.7	26.7	31.2
TP outflow (kg TP yr^{-1})	23.6	21.4	6.0

TABLE 3. ESTIMATED ANNUAL COST OF PHOSPHORUS REMOVED THROUGH HARVESTING, ALUM TREATMENT, AND WATERSHED BEST MANAGEMENT PRACTICES (BMPS) USED BY THE RAMSEY–WASHINGTON METRO WATERSHED DISTRICT BETWEEN 1990 AND 2014. FOR BMPS, PROJECT ENGINEERING, DESIGN, AND CONSTRUCTION EXPENDITURES WERE ADJUSTED TO 2014 DOLLARS, AND COSTS WERE CONSIDERED OVER A 35-YR LIFE SPAN. LAND PRICES ARE NOT INCLUDED IN THESE CALCULATIONS. TOTAL PHOSPHORUS (TP) REMOVED BY BMPS WAS ESTIMATED BY THE P8 URBAN CATCHMENT MODEL OR THE MINNESOTA STORMWATER MANUAL'S MINIMAL IMPACT DESIGN STANDARDS MODEL. COSTS WERE ROUNDED TO THE NEAREST $100. NA, NOT APPLICABLE.

Method	TP Removal Cost (US Dollars kg^{-1})	Std. Dev.	No. of Projects
In-lake practice			
Alum treatment (Kohlman)	$480	na	1
Harvesting	$670	na	1
Watershed BMP			
Alum injection into storm water	$2,800	na	1
Storm-water ponds	$3,000	$3,900	9
Iron-enhanced sand infiltration	$7,400	$6,200	2
Tree trenches	$10,700	na	1
Rain gardens	$20,500	$13,900	146
Pervious pavement	$49,800	$39,300	9

only accounted for 1.0% of the net phosphorus load in Lake Sallie, a eutrophic Minnesota lake. This low contribution from harvesting was mainly due to extremely high nutrient loading from the Lake Sallie watershed. Model estimates for harvesting in Lake Wingra, Wisconsin suggest a 37% reduction in phosphorus net balance (or the phosphorus contained in all plants) if harvesting were to occur during the optimal period in late summer (Carpenter and Adams 1977). Morency and Belnick (1987) reported the removal of 60 kg of phosphorus through harvesting on a small Washington lake, accounting for 9% of the TP load on an annual basis.

Macrophyte harvesting will have the maximum effect on lake phosphorus budgets when plant nutrient concentrations and biomass are high, the harvesting process is effective, and loading from the watershed is relatively low. In Casey, phosphorus loading was comparable with other urban lakes in the watershed (RWMWD 2007). The relatively high phosphorus removal was attributable to the successful harvest of the entire lake twice during the growing season and the substantial plant phosphorus concentrations reported during both July and August harvesting periods. If harvesting only occurred once in Casey Lake, percent load reduction estimates would be quite comparable wih those reported for the Lake Wingra study (Carpenter and Adams 1977).

The cost of phosphorus removal through harvesting in Casey was economical and comparable with estimates from other investigations. In 2014, the total macrophyte harvesting expenditure was $11,000 or $670 kg^{-1} of TP removed. Our harvesting costs were relatively modest due to Casey Lake being 5 ha in size. This allowed the operator to spend a majority of his time cutting. In addition, time used for plant disposal was minimal because of the composting site being less than 2 km from Casey Lake. Morency and Belnick (1987) had a TP removal cost of $700 kg^{-1} (adjusted to 2014 dollars) when targeting *Ceratophyllum* sp. in a 150-ha Washington lake. Reisinger et al. (2008) estimated that the cost of phosphorus removal through water hyacinth harvest in a Florida lake would be $580 kg^{-1} of TP (adjusted to 2014 dollars). However, the authors note that logistics of a nearby dump site location were in question. If an alternate dump site became necessary, this would escalate the phosphorus removal cost estimate.

Phosphorus removal via watershed BMPs was more costly than removal through plant harvesting (Table 3). The most cost-effective BMP currently used in the RWMWD is alum injection into storm water (Pilgrim et al. 2007) at $2,800 kg^{-1} of TP removed (excluding land cost). Rain gardens were the most common BMP used in the RWMWD, with an average cost of TP removal at $20,500 kg^{-1}. In 2014, a large rain garden project was initiated in the Casey Lake watershed. A retrofit plan called for the strategic placement of 15 rain gardens that accept street runoff from an eight city-block area (4.2 ha). Modeling suggested that this project would remove 1.6 kg of phosphorus on an annual basis, or 5% of the TP load to Casey Lake. We stress that other storm-water management benefits are gained through rain gardens, such as volume reduction. However, if we assess the project cost only in terms of phosphorus reduction, this equates to $10,000 kg^{-1} of TP removed per year (excluding land cost). This is a pertinent example that highlights the expense of managing phosphorus in urban watersheds, and in contrast, points to aquatic plant harvesting being a cost-effective option.

The use of mechanical harvesting as an in-lake phosphorus management tool may be able to support challenging watershed management directives. In urban watersheds, phosphorus management is difficult because of limited land availability and the high cost of BMP retrofits (Weiss et al. 2007). In addition, persistent internal loading tends to occur in urban lakes (Søndergaard et al. 2013). In a study spanning 25 yr, Huser et al. (2016) found that in-lake measures for phosphorus control, mainly alum treatment, were by far the most cost-effective means of water-quality management in four Minneapolis lakes. In Casey, harvesting was able to remove roughly 10 times the total phosphorus, compared with a large-scale rain garden project taking place in the watershed. In addition to the limitations of individual projects, the implementation of BMPs watershed wide is not economically feasible (RWMWD 2007). Therefore, it becomes imperative to consider in-lake methods, such as harvesting, to effectively manage phosphorus in shallow lakes.

During the growing season, common elodea and water net accumulated large amounts of phosphorus. In shallow systems like Casey Lake, aside from the sediments, the standing stock of aquatic plants contains the largest reservoir of nutrients (Carpenter and Lodge 1986). We acknowledge that this applied study is limited by not measuring sources of phosphorus in the plant material, forms of phosphorus, or the timing of phosphorus release and availability in Casey Lake. However, in terms of operational watershed management, we believe that it is reasonable to still find intrinsic value in removing TP through harvesting. Because of the quantity of TP removed through harvesting, it is possible that repeated plant removal will deplete phosphorus from the Casey Lake bottom sediments (Chen and Barko 1988). This depletion, in turn, may reduce aquatic plant growth and phosphorus release from the sediments (Barko et al. 1991). Removal will also result in less soluble phosphorus being released into the water from plant decomposition (Carpenter and Lodge 1986, Barko and James 1997, Asaeda et al. 2000). This practice, along with the use of watershed BMPs, has the potential to improve the water quality of Casey Lake and lakes downstream. Harvesting represents a permanent removal of phosphorus from the overall watershed system. The downstream watershed benefits are often overlooked with stand-alone lake plans. However, the Watershed Restoration and Protection Strategy planning process that is now being implemented in Minnesota could readily incorporate the use of harvesting as part of this watershed-wide approach (Minnesota Pollution Control Agency 2016).

In shallow lakes, substantial macrophyte control carries the risk of shifting a system back to a phytoplankton-dominated state, and it is difficult to predict how much management will cause a shift (van Donk et al. 1990, Moss et al. 1997, Scheffer 1998, van Nes et al. 2002, Morris et al. 2006). With this in mind, our objectives were to harvest a majority of the water net and cut the common elodea, without having the cutting blades work close to the lake bottom substrate. The operational method was to set the target cutting depth at 0.3 m, which minimized substrate disturbance and strategically limited common elodea biomass harvest. It is possible that a deeper cutting swath and a more thorough harvesting may have circumvented the need for a second harvest; however, we decided to be very cautious in our approach. We did not intensively sample water before and after the harvesting. However, our bimonthly water-quality monitoring did not detect effects from harvesting. Dissolved oxygen and TP were consistent throughout the growing season (Figures 4a and 4b). Chlorophyll *a* levels remained low after harvesting (Figure 4c) and Secchi transparency was to the bottom on all sampling dates, suggesting that phytoplankton growth was not stimulated by the plant removal. Others have reported that the elimination of benthivorous fish adds ecological stability to shallow lakes (Hosper and Meijer 1993, Hanson and Butler 1994). In Casey Lake, the carp eradication may have reduced the risk of moving back to a phytoplankton-dominated system after the macrophyte harvest. Nevertheless, the conservative harvesting tactic was effective in that Casey Lake remained in a macrophyte-dominated state throughout the 2014 growing season.

It should be noted that plant harvesting is different from in-lake alum treatment and watershed BMPs in that the opportunity for phosphorus removal may vary considerably from year to year. Aquatic plant community composition and biomass are often variable and difficult to predict on an annual basis (Barko et al. 1986). Repeated harvesting efforts may reduce plant abundance in future years (Neel 1973, Nichols 1974, Cooke et al. 2005). Also, water net seems to have a boom-and-bust life cycle and it may or may not continue to be a nuisance in Casey Lake (Wells et al. 1999). Thus, harvesting for nutrient reduction should be looked at opportunistically. With Casey Lake, for instance, a management plan that accounts for the possibility of future harvesting appears reasonable.

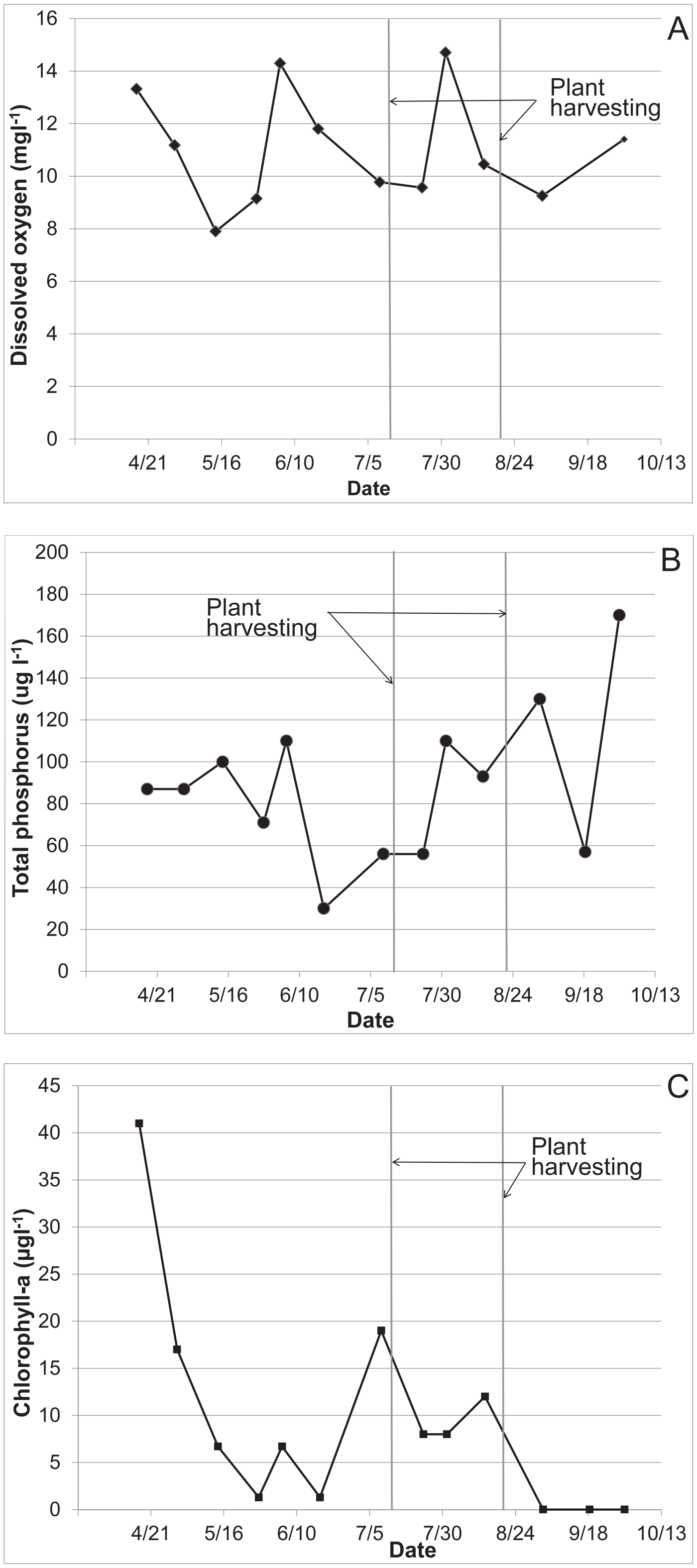

Figure 4. (a) Dissolved oxygen (mg L^{-1}), (b) total phosphorus (µg L^{-1}), and (c) chlorophyll *a* (µg L^{-1}) in Casey Lake before and after plant harvesting, 2014.

Our results show that strategic macrophyte harvesting can meet in-lake management objectives and remove phosphorus at a reasonable cost. In urban shallow lakes where macrophyte harvesting may be a feasible management tool, coupling aquatic plant management with urban watershed and lake management objectives seems prudent. Additionally, our cost comparisons suggest that it may be worthwhile to investigate the periodic harvest of large surfaced mats of algae and macrophytes for phosphorus reduction alone. A common scenario in the Twin Cities area is that substantial patches of filamentous algae will go untreated if they are far from lakeshore residences and do not inhibit recreational activity. Targeting these patches of algae for phosphorus reduction may be a reasonable in-lake management approach in shallow lakes. Harvesting, whether aligned with other lake management objectives or not, may present cost-effective opportunities for phosphorus removal, and has the potential to factor into more dynamic and creative lake and watershed management plans for urban shallow lakes.

SOURCES OF MATERIALS

[1] Gamefish, Minnesota Department of Natural Resources, East Metro Area Fisheries Office, 1200 Warner Road, St. Paul, MN 55106.

[2] Aquamarine paddlewheel harvester (10 m in length)—20-horsepower Hatz diesel engine. Aquamarine Company, 586 Third Line, Oakville, ON L6L 4A7, Canada.

[3] YSI 600 XLM V2 sonde, YSI Incorporated, 1700/1725 Brannum Lane, Yellow Springs, OH 45387.

ACKNOWLEDGEMENTS

We appreciate Dr. Peter Sorensen's effort in leading the carp research on Casey Lake and contributing to this paper. We thank the following reviewers who provided comments that substantially improved this manuscript: Justine Dauphinais, Rob Langer, James Johnson, Chip Welling, Mark Gernes, and Przemyslaw Bajer. We also thank the RWMWD Board of Managers for supporting this applied study. The comments of three anonymous reviewers substantially improved this manuscript.

LITERATURE CITED

Asaeda T, Trung VK, Manatunge J. 2000. Modeling the effects of macrophyte growth and decomposition on the nutrient budget in shallow lakes. Aquat. Bot. 68:217–237.

Bajer PG, Sorensen PW. 2015. Effects of common carp on phosphorus concentrations, water clarity, and vegetation density: A whole system experiment in a thermally stratified lake. Hydrobiology 746:303–311.

Bajer PG, Sullivan G, Sorensen PW. 2009. Effects of a rapidly increasing population of common carp on vegetative cover and waterfowl in a recently restored Midwestern shallow lake. Hydrobiology 632:235–245.

Barko JW, Adams MS, Clesceri NL. 1986. Environmental factors and their consideration in the management of submersed aquatic vegetation: A review. J. Aquat. Plant Manage. 24:1–10.

Barko JW, Gunnison D, Carpenter SR. 1991. Sediment interactions with submersed macrophyte growth and community dynamics. Aquat. Bot. 41:41–65.

Barko JW, James WF. 1997. Effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation, and resuspension, pp. 197–214. In: In: E. Jeppesen, M. Søndergaard, M. Søndergaard, and K. Christoffersen (*eds.*). The structuring role of submerged macrophytes in lakes. Springer Verlag, New York.

Barr Engineering. 2007. Kohlman Lake Dredging Feasibility Report—Ramsey–Washington Metro Watershed District. Barr Engineering, Minneapolis, MN.

Barr Engineering. 2010. Kohlman Lake Total Maximum Daily Load Report—Ramsey–Washington Metro Watershed District. Barr Engineering, Minneapolis, MN.

Brooker MP, Edwards RW. 1975. Aquatic herbicides and the control of water weeds. Water Res. 9:1–15.

Burton TM, King DL, Ervin JL. 1979. Aquatic plant harvesting as a lake restoration technique, pp 177–185. In: Lake restoration: proceedings of a national conference. EPA 440/5-79-001. USEPA, Washington, DC.

Canfield DE, Jr., Bachmann RW. 1981. Prediction of total phosphorus concentrations, chlorophyll *a*, and Secchi depth in natural and artificial lakes. Can. J. Fish Aquat. Sci. 38:414–423.

Carpenter SR, Adams MS. 1977. The macrophyte tissue nutrient pool of a hardwater lake: Implications for macrophyte harvesting. Aquat Bot. 3:239–255.

Carpenter SR, Gasith A. 1978. Mechanical cutting of submersed macrophytes: Immediate effects on littoral chemistry and metabolism. Water Res. 12:55–57.

Carpenter SR, Lodge DM. 1986. Effects of submersed macrophytes on ecosystem processes. Aquat. Bot. 26:341–370.

Chen RL, Barko JW. 1988. Effects of freshwater macrophytes on sediment chemistry. J. Freshwat. Ecol. 4:279–289.

Cooke D, Welch E, Peterson S, Nichols S. 2005. Restoration and management of lakes and reservoirs. 3rd.ed. CRC Press, Boca Raton, FL. 616 pp.

Davis AP, Hunt WF, Tarver RG, Clar M. 2009. Bioretention technology: Overview of current practice and future needs. J. Environ. Eng. 135:109–117.

Eaton AD, Clesceri LS, Greenberg AE, Franson MAH, American Public Health Association, American Water Works Association, & Water Environment Federation. 1998. Standard Methods for the Examination of Water and Wastewater. Washington, DC: American Public Health Association.

Engel S. 1990. Ecosystem responses to growth and control of submerged macrophytes: A literature review. Technical Bulletin 170. Bureau of Research, Department of Natural Resources, Madison, WI. 20 pp.

[ENR] Engineering News-Record. 2014. New York. Dodge Data & Analytics. http://enr.construction.com/economics/. Accessed February 2, 2016.

Evans JM, Wilke AC. 2010. Life cycle assessment of nutrient remediation and bioenergy production potential from the harvest of hydrilla (*Hydrilla verticillata*). J Environ Manage. 91(12):2626–2631.

Gerloff GC. 1975. Nutritional ecology of nuisance aquatic plants. USEPA-660/3-75-027. USEPA, National Environmental Research Center, Corvallis, OR. 78 pp.

Gerloff GC, Krombholz PH. 1966. Tissue analysis as a measure of nutrient availability for the growth of angiosperm aquatic plants. Limnol. Oceanogr. 11:529–537.

Hall J, Payne G. 1997. Factors controlling the growth of field populations of *Hydrodictyon reticulatum* in New Zealand. J Appl. Phycol. 9:229–236.

Hanson MA, Butler MG. 1994. Responses of plankton, turbidity, and macrophytes to biomanipulation in a shallow prairie lake. Can. J Fish Aquat. Sci. 51:1180–1188.

Heiskary SA, Walker WW, Jr. 1995. Establishing a chlorophyll-*a* goal for a run-of-the-river reservoir. Lake Reserv. Manage. 11(1):67–76.

Hodgson LM, Carter CC. 1982. Effect of hydrilla management by herbicides on a periphyton community. J. Aquat. Plant Manage. 20:17–19.

Hosper SH, Meijer ML. 1993. Biomanipulation, will it work in your lake? A simple test for the assessment of chances for clear water, following drastic fish stock reduction in shallow, eutrophic lakes. Ecol. Eng. 2:63–72.

Huser BJ, Futter M, Lee JT, Perniel M. 2016. In-lake measures for phosphorus control: The most feasible and cost-effective solution for long-term management of water quality in urban lakes. Water Res. 97:142–152.

James WF, Barko JW, Eakin HL. 2002. Phosphorus budget and management strategies for an urban Wisconsin lake. Lake Reserv. Manage. 18:149–163.

Koch JD. 2014. Source–sink population structure of invasive common carp in a model Midwestern watershed: Empirical evidence and notes on management. Master's thesis. University of Minnesota, St Paul, MN. 105 pp.

Lee K, Chantrasakdakul P, Kim D, Kong M, Park KY. 2014. Ultrasound pretreatment of filamentous algal biomass for enhanced biogas production. Waste Manage. 34:1035–1040.

Madsen JD. 1999. Point and line intercept methods for aquatic plant management. APCRP Technical Notes Collection (TN APCRP-M1-02). U.S. Army Engineer Research and Development Center, Vicksburg, MS. 16 pp.

Madsen JD. 2000. Advantages and disadvantages of aquatic plant management techniques. Aquatic Plant Control Research Program. ERDC/EL MP-00-1. U.S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Minnesota Pollution Control Agency. 2014. Minimal Impact Design Standards Calculator. http://stormwater.pca.state.mn.us/index.php/MIDS__calculator. Accessed February 8, 2016.

Minnesota Pollution Control Agency. 2016. Watershed Restoration and Protection Strategy (WRAPS). https://www.pca.state.mn.us/water/watershed-approach-restoring-and-protecting-water-quality. Accessed February 8, 2016.

Morency DA, Belnick TJ. 1987. Control of internal phosphorus loading in two shallow lakes by alum and aquatic plant harvesting. Lake Reserv. Manage. 3:31–37.

Morris K, Bailey P, Boon P, Hughes L. 2006. Effects of plant harvesting and nutrient enrichment on phytoplankton community structure in a shallow urban lake. Hydrobiology 571:77–91.

Moss B, Madgwick J, Phillips G. 1997. A guide to the restoration of nutrient-enriched shallow lakes. Broads Authority, Norwich, UK. 180 pp.

Murphy KJ, Barrett PRF. 1990. Chemical control of aquatic weeds, pp. 136–173. In: A. Pieterse and K. Murphy (*eds.*). Aquatic weeds: The ecology and management of nuisance aquatic vegetation. Oxford University Press, Oxford, UK. 593 pp.

Neel JK, Peterson SA, Smith WL. 1973. Weed harvest and lake nutrient dynamics. EPA-660/3-73-001. U.S. Environmental Protection Agency, Washington, DC. 91 pp.

Newnan DG. 1991. Engineering economic analysis. 4th ed. San Jose (CA) Engineering Press, San Jose, California. 578 pp.

Nichols SA. 1974. Mechanical and habitat manipulation for aquatic plant management. Tech. Bull. 77. Department of Natural Resources, Madison, WI. 33 pp.

Osborne JB. 2012. Distribution, abundance, and overwinter survival of young-of-the year common carp in a Midwestern watershed. M.S. thesis. University of Minnesota, St. Paul, MN.. 132 pp.

Peterson SA, Smith WL, Malueg KW. 1974. Full-scale harvest of aquatic plants: Nutrient removal from a eutrophic lake. J Water Pollut. Control Fed. 46:697–707.

Pilgrim KM, Huser BJ, Brezonik PL. 2007. A method for comparative evaluation of whole-lake and inflow alum treatment. Water Res. 41:1215–1224.

Reisinger DL, Brabham M, Schmidt MF, Victor PR, Schwartz L. 2008. Methodology, evaluation, and feasibility study of total phosphorus removal management measures in Lake George & nearby lakes. Fla Water Res. J. 60(9):42–50.

[RWMWD] Ramsey–Washington Metro Watershed District. 2007. Watershed Management Plan for the Ramsey–Washington Metro Watershed District 2006–2016. Little Canada, MN.

Scheffer M. 1998. Ecology of shallow lakes. Kluwer Academic Publishers, Dordrecht, the Netherlands. 357 pp.

Søndergaard M, Bjerring R, Jeppesen E. 2013. Persistent internal loading during summer in shallow lakes. Hydrobiology 710:95–107.

Souza FA, Dziedzic M, Cubas SA, Maranho LT. 2013. Restoration of polluted waters by phytoremediation using *Myriophyllum aquaticum* (Vell.) Verdc., Haloragacae. J. Environ. Manage. 120:5–9.

Uhlmann D. 1980. Stability and multiple steady states of hypereutrophic ecosystems, pp. 235–247 In: J. Barica and L.R. Mur (*eds.*). Hypertrophic ecosystems. Developmental hydrobiology 2. Springer, The Hague, the Netherlands. 349 pp.

[USEPA]U.S. Environmental Protection Agency. 1983. Methods for the Chemical Analysis of Water and Wastes. EPA-600/4-79-020. Environmental Monitoring and Support Laboratory, Cincinnati, OH. 491 pp.

van Donk E, Gulati RD, Grimm MP. 1990. Restoration and biomanipulation in a small hypertrophic lake: First year results. Hydrobiobiology 191:285–295.

van Nes EH, Scheffer M, van den Berg MS, Coops H. 2002. Aquatic macrophytes: Restore, eradicate or is there a compromise?. Aquat. Bot. 72(3):387–403.

Walker WW, Jr. 1987. Empirical methods for predicting eutrophication in impoundments. Report 4, Phase III: Application Manual. Technical Report E-81-9. USACE Waterways Experiment Station, Vicksburg, MS. 321 pp.

Walker WW, Jr. 2000. P8: Urban Catchment Model, V 2.4. Developed for the Narragansett Bay Project. http://wwwalker.net/p8/. Accessed: February 8, 2016.

Wang Z, Jiang T, Qi S, Luo Y, Qi Y. 1999. Studies on nitrogen and phosphorus removal capacity of *Hydrodictyon reticulatum* in eutrophic freshwater samples. Acta Sci. Circum. 19:448-452.

Weber MJ, Brown ML. 2009. Effects of common carp on aquatic ecosystems 80 years after "carp as a dominant": Ecological insights for fisheries management. Rev. Fish Sci. 17:524–537.

Weiss PT, Gulliver JS, Erickson AJ. 2007. Cost and pollutant removal of storm-water treatment practices. J. Water Resour. Plan. Manage. 133(3):218–229.

Wells RDS, Hall JA, Clayton JS, Champion PD, Payne GW, Hofstra DE. 1999. The rise and fall of water net (*Hydrodictyon reticulatum*) in New Zealand. J. Aquat. Plant Manage. 37:49–55.

Zhu J, Hu W, Hu L, Deng J. 2012. Variation in the efficiency of nutrient removal in a pilot-scale natural wetland. Wetlands 32:311–319.