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Hydrologic processes regulate nutrient retention in stormwater detention ponds

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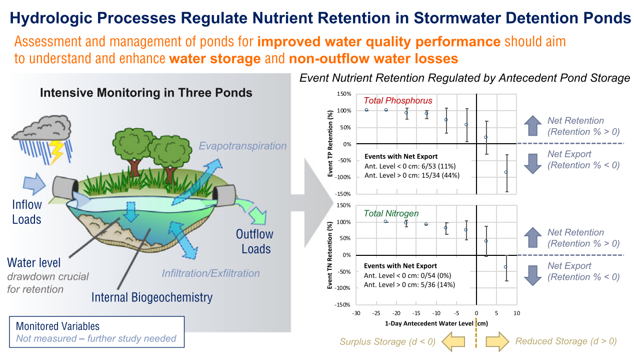
HIGHLIGHTS

- We assessed annual water and nutrient budgets for 3 ponds with intensive monitoring.
- Ponds were anoxic and eutrophic, indicating risk for poor nutrient retention.
- Concentration reduction was poor for many forms but mass reduction met expectations.
- Nutrient retention was enhanced by natural water losses (e.g., evapotranspiration).
- Pond retention performance could be improved by enhancing storage and water loss.

GRAPHICAL ABSTRACT



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ABSTRACT

Managed stormwater ponds are abundant in urban landscapes in much of the world, performing vital but understudied functions for attenuation of urban runoff and nutrient pollution. Water quality improvements are widely assumed to arise from settling of nutrients and other contaminants bound to particulates, with less consideration of hydrological and biogeochemical processes. To inform improved management of ponds for nutrient retention, we studied three mature urban detention ponds in the Twin Cities, MN, USA using continuous monitoring of pond hydrology and concentrations of nitrogen and phosphorus, coupled with periodic measurement of physiochemical conditions in the ponds. Across the three sites, annual nutrient retention was high for both nitrogen (>58%) and phosphorus (>48%) despite expectations of poor performance for phosphorus due to old age and internal loading linked to hypolimnetic anoxia. Both annual and event-scale analyses suggested strong hydrologic controls on nutrient retention, with retention for individual storm events strongly regulated by antecedent pond storage capacity. Events with net nutrient export occurred primarily due to low volume retention rather than relatively high outflow concentrations. Together these results suggest that understanding and improving pond hydrologic function is crucial to improving managed stormwater pond performance for meeting downstream water quality goals.

1. Introduction

Stormwater ponds (i.e., retention ponds, wet ponds) are widely used for managing the negative characteristics of urban runoff and protecting the water quality of downstream surface waters. Decades of new construction and modification of existing, natural ponds and wetlands have made them a ubiquitous feature of urban landscapes. Although stormwater ponds provide a variety of important ecosystem services in human-dominated landscapes, such as carbon burial, biodiversity, habitat provision and urban heat island mitigation (Moore and Hunt, 2011; Taguchi et al., 2020b), they are primarily intended to mitigate hydrologic and water quality impacts of urban runoff on downstream lakes and rivers

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(Clar et al., 2004). By decreasing water velocity and increasing residence time on the landscape, ponds reduce flooding, erosion, and habitat degradation in receiving waters. Water quality improvements arise from retention and removal of contaminants, such as nutrients and metals. The ubiquity of ponds in urban landscapes and their often direct connection to lakes and streams via storm drains suggest they play an important role for maintenance and improvement of urban water quality. However, this role has not been extensively examined since ponds were developed as a stormwater management tool decades ago (Schueler, 1987; Marsalek et al., 1992; Loganathan et al., 1994; Taguchi et al., 2020a; Flanagan et al., 2021).

Several early studies found nutrient retention, including mechanisms both of diversion (e.g., exfiltration or sedimentation) and of permanent removal (e.g., denitrification), to be highly variable in typical stormwater ponds, with performance largely determined by water residence time and by sediment settling (U.S. Environmental Protection Agency, 1983; Walker, 1987, 1998; Gu et al., 2017). The mechanisms for retention were assumed to be primarily settling and burial of incoming particulates, combined with biological assimilation and conversion of dissolved nutrients, all processes whose rates should increase with greater residence time (Walker, 1987, 1998; Gu et al., 2017). These early results led to widespread construction over the past 30 to 40 years of artificial ponds and modifications of natural waterbodies through connection of stormwater infrastructure. However, though more recent pond performance estimates have been assembled (MPCA, 2000; Weiss et al., 2007; Koch et al., 2014; Clary et al., 2020), little work has been done to assess how pond function for water quality improvement may have changed as ponds age, creating a potentially substantial water quality issue.

Stormwater pond systems are potentially susceptible to reduced nutrient capture in years following construction for several reasons (Sønderup et al., 2016). First, intensive urban drainage to ponds often leads to high sedimentation rates, reducing storage volume and residence time (Ahilan et al., 2019). Loss of hydrologic function can be detrimental to nutrient removal performance, since water quality functions are often positively related to residence time (Shukla et al., 2017). Second, high nutrient inputs can also lead to nutrient saturation and low dissolved oxygen, which can result in internal phosphorus loading (Song et al., 2017; Frost et al., 2019; Taguchi et al., 2020a). Further, high rates of nutrient availability can lead to rapid vegetation changes for both the shoreline and within ponds, which may also affect pond function (Sinclair et al., 2021). Together, shorter water residence time and greater potential for internal loading could lead to lowered retention of phosphorus, and possibly nitrogen, relative to newly constructed ponds. Despite the likelihood for changes, little information exists to evaluate temporal changes in nutrient retention of stormwater ponds following construction (though see Gulliver et al., 2010; US EPA, 2010; Erickson et al., 2013).

In this study, we evaluated the performance of three old stormwater ponds (constructed 1997 or earlier), including one recently renovated to increase volume and phosphorus removal capacity, located in the Minneapolis-St. Paul metropolitan area of Minnesota, USA. We examined annual retention of nitrogen and phosphorus and identified controls over losses or retention of these nutrients at the scale of individual storm events, with the goal of informing pond management decisions. Primary research questions included: (1) is pond performance reduced for nutrient removal, especially phosphorus, relative to expectations due to anoxic conditions and internal loading from accumulated sediments? (2) how effective are typical renovations intended to improve nutrient removal when compared to un-maintained ponds? and (3) how important is pond hydrologic function (storage capacity, residence time) relative to biogeochemical processes for nutrient retention? To provide necessary data to understand the complex controls over nutrient retention, we carried out a roughly 18-month study of intensive monitoring and data collection, including quantifying event and annual nutrient loads, as well as various physical, hydrologic, and chemical conditions within the three ponds.

2. Methods

2.1. Site selection and description

Monitoring was conducted for mass balance of phosphorus (P) and nitrogen (N) in three detention ponds in Roseville, Minnesota, USA (Fig. S1). The three ponds were selected for their simple drainage configurations (one inlet, one outlet) but were typical of ponds in the region, spanning a gradient in surface area (0.057–1.17 ha) and watershed size (1.8–115 ha), and were > 25 years old. Two of the ponds (Pond C and Pond E) were natural wetlands connected to sewers in the 1960's for stormwater storage, with Pond C having been dredged and retrofitted with an iron-enhanced sand filter in 2013 (Belden and Fossum, 2018). The third pond (Pond D) was newly constructed in 1996 to collect runoff from a small parking lot. The three ponds generally met or exceeded recommended thresholds for ratios of drainage area to basin area (<125 for residential watersheds, <33 for paved watersheds; MPCA, 2000) (Table 1), suggesting that none were particularly under-sized.

The three ponds were of particular interest due to several internal and external factors that suggested high likelihood of low nutrient retention, especially for P. First, we expected that prolonged high rates of external P loading would promote internal P loading. Similar watersheds in the area have extremely high rates of phosphorus losses due to high rates of mobilization and transport of P to storm drain networks (Hobbie et al., 2017), resulting in high rates of P inputs to stormwater ponds. Second, the ponds were expected to have reduced storage capacity from accumulated sediment (in ponds D and E), as these sites had no maintenance since constructed or connected prior to 1998. Finally, a concurrent study investigating internal P loading in the ponds (Taguchi et al., 2020a) found high potential for sediment phosphorus release in all three ponds, due to combined effects of (1) moderate levels of iron-bound phosphorus in the pond sediments, (2) anoxic (and oxic) phosphorus release in the laboratory column studies of sediment collected in the ponds, and (3) persistent stratification in the ponds during most of the study period. The intense stratification, which produced extensive anoxia (normalized anoxic factors of 0.69–0.90 across ponds; Table 1) was likely set up by effects of road salt (Herb et al., 2017) and reinforced by high tree cover (mean canopy height 3.5–8.4 m; Table 1), which likely reduced water column mixing from wind.

2.2. Hydrologic and nutrient budgets

We monitored water level in each of the ponds and discharge into and out of the ponds throughout the study period (December 2016 – September 2018). Water level at Pond D was measured with Solinst pressure transducers (unvented), correcting for atmospheric pressure using a second logger mounted above water. For Pond C and Pond E, we used water level collected in the ponds by the Capitol Region Watershed District (http://waterdata.capitolregionwd.org).

Inflows and outflows were sampled with ISCO 6712 automatic water samplers (flow-paced samples composited into 1-l samples), and discharge was measured with ISCO depth-velocity probes installed in inlet and outlet storm pipes. Grab samples were occasionally taken from pond inlets and outlets when equipment malfunctioned and were especially necessary during winter. Hydrologic time series data were corrected for drift in water level using manual measurements of flow depth during site visits, interpolating linearly between dates of measurement. Inflow hydrology at Pond C required rainfall-runoff modelling (Boyd et al., 1993) to fill in gaps, particularly for small events, due to difficulties with pipe access and problems monitoring and sampling low flows. This data correction and modelling process is described in the SI.

Groundwater inputs, which were not directly measured, were present at Ponds C and E, detected as frequent baseflow input to Pond E (Herb et al., 2017) and as small but nearly year-round discharge from Pond C's IESF drain tiles. At the event scale, outflow volumes often exceeded inflow volumes at Pond C; after confirming that the rainfall-runoff relationship for the inlet site was reasonable for the level of imperviousness of the watershed

Table 1
Drainage area and physical characteristics of the three monitored ponds. Shoreline canopy height is mean within 25 m buffer and determined from raw LiDAR data; Annual Anoxic Factor calculated per Nürnberg (1995) from bathymetry and manual dissolved oxygen profiles and normalized by days in the year (July 2017 – June 2018; see Methods).

Pond	Surface Area	Max Depth	Volume	Drainage Area	SA:DA Ratio	Age	Annual Anoxic Factor	Total Impervious Area	Shore Canopy Height	Land Use
	ha	m	m^3	ha		Years		%	m	
Pond C	0.29	2.0	566	15.4	53	30+	0.90	19	7.2	Residential
Pond D	0.057	1.4	14,500	1.82	32	25	0.69	75+	3.5	Parking lot; institutional
Pond E	1.17	2.1	3682	115.3	99	30+	0.70	20	8.4	Residential

(see SI), we applied a baseflow separation analysis (local minimum method; Sloto and Crouse, 1996) to the outflow data of Pond C to isolate direct runoff of storm events from groundwater inflow (see SI for details). We chose not to apply a similar groundwater-separation approach to Pond E, as the groundwater effect was minor (i.e., event inlet volumes usually exceeded outlet volumes, unlike at Pond C).

We collected water column samples from the ponds every 1–4 weeks during the study period. Grab samples from the epilimnion (from within 10 cm of the water surface and typically excluding floating vegetation) and hypolimnion (from within 25 cm of the sediment surface) were collected into 1-L bottles from a canoe or through surface ice. Water column samples were made using a PVC tube with a rubber stopper to seal the top of the tube after lowering the sampler slowly through the water column. For hypolimnion samples, the stopper was left in place while lowering the tube to the desired depth then slowly released to retrieve water. Collection of hypolimnion water quality samples was complicated by steep chemoclines in bottom waters and the presence of unconsolidated sediment so hypolimnetic data are presented only for qualitative comparisons to the epilimnion and inflow/outflow monitoring results and should not be used infer N or P release rates.

All manual grab samples and profiles were taken from the deepest point of each pond (approximately near the center in all instances) every 1–4 weeks during the study period. All three ponds were sampled on the same day during field trips, generally within an hour of each other. Water samples, both water column and those retrieved from the autosamplers, were processed and analyzed at the University of Minnesota (UMN). Samples were filtered within 24 h of retrieval through pre-ashed Whatman GF/F fiberglass filters and analyzed using standard EPA laboratory methods for major forms of nitrogen (N), phosphorus (P), carbon (C), and chlorophyll-a. Specifically, analyses included total dissolved nitrogen (TDN) and dissolved organic carbon (DOC), using a Shimadzu TOC Vcpn analyzer; nitrite-nitrate nitrogen (NO_x) and ammonium (NH_4), using a Lachat autoanalyzer; and particulate nitrogen (PN) and particulate carbon (PC), using a Perkin-Elmer CHN analyzer. Phosphorus analyses included total dissolved phosphorus (TDP), soluble reactive phosphorus or orthophosphate (SRP), and particulate phosphorus (PP) using molybdate colorimetry. Chlorophyll-a was analyzed using a Turner Designs AU Fluorometer. Total phosphorus (TP) was calculated as TDP + PP, total nitrogen (TN) as TDN + PN.

2.3. Load estimates and data analysis

For pond inlet and outlet sites, nutrient loads were calculated for each event by the product of discharge volume and nutrient concentration of the event's sample (composite or grab). Roughly 31%, 44%, and 52% of all runoff events at the inlets and outlets of Pond C, Pond D, and Pond E, respectively, were sampled over the study (Table S1). For un-sampled events, characteristic concentrations were assigned by averaging the mean monthly concentration with all concentrations from observations within three weeks prior to and after the event.

All annual loads reported hereafter include both sampled and modeled events and correspond to the 12-month monitoring period July 1, 2017 – June 30, 2018. Analyses of events and in-pond data include data collected during hydrologic monitoring of the three ponds, which all had slightly different start dates but all ended in June 2018 (Table S1). Water column sampling continued beyond the end of monitoring, through the end of September 2018; these data are shown in the SI but are not included in any event analyses. Retention analyses consist of the ratio of outlet vs. inlet loads or concentrations, such that numbers greater than 1.0 indicated export (discharge > inflow) and numbers less than 1.0 indicated retention (discharge < inflow).

Other calculations include mean tree canopy height around the ponds, anoxic factor, and an estimate of gross internal loading of SRP from pond sediments. Mean shoreline canopy heights were determined from raw LiDAR point cloud data acquired from Minnesota DNR (http://arcgis.dnr.state.mn.us/maps/mntopo/), which was collected in 2011. Canopy returns were clipped to a 25-m buffer around the ponds and averaged arithmetically to approximate mean canopy heights. Anoxic factor (AF) was determined using the method of Nürnberg (1995) and calculated for the annual period of July 2017 – June 2018 using manual profiles of dissolved oxygen and hypsographic information for all three ponds. Units of AF are days; we normalized AF by days in the year (365) such that AF is reported as the fraction of the year during which an area equivalent to pond surface area is exposed to anoxic water.

Internal loading of SRP from sediments was estimated as the product of AF and the anoxic SRP release rate (RR), and restricted to the summer period (June – September) per Nurnberg (2009) due to temperature sensitivity of release rate. Anoxic SRP release rates (RR) were measured in a concurrent laboratory study of sediment cores collected from the ponds, and ranged from 1.09 mg/m^2/d (Pond C) to 3.18 mg/m^2/d (Pond E) (Taguchi et al., 2020a). These release rates, determined in a lab setting at roughly 18–21 °C (Taguchi et al., 2020a), were adjusted to observed pond water temperatures using the Van Holst relationship (Nurnberg, 2009): $RR_{adj} = RR_{ref} \times Q_{10}^{(Tadj - Tref)/10}$, where the reference ("ref") release rate and temperature refer to the column studies, and the adjusted ("adj") rate and temperature are for field (pond) conditions. We used a Q_{10} value of 4.4, which was determined by Natarajan et al. (2021) for a shallow urban lake in Minnesota and is near the middle of the expected range of this parameter. Mean summer water temperatures (T_{adj}) were determined from the anoxic portion of the summer temperature profiles (Taguchi et al., 2020a) and ranged from 15.0 °C (Pond E) to 20.5 °C (Pond D), while summer (June – September) AF values for Ponds C, D, and E were 0.88, 0.61, 0.76, respectively. The resulting adjusted RR (RR_{adj}) were 1.16, 3.24, and 1.35 mg/m^2/d for Ponds C, D, and E, respectively.

3. Results and discussion

3.1. Hydrologic processes drive stormwater pond nutrient retention

We expected poor retention of nitrogen (N) and phosphorus (P) in the three ponds studied due to several factors associated with reduced nutrient capture. In particular, all ponds were strongly stratified and anoxic throughout much of the water column for most of the year, with normalized anoxic factors ranging from 0.56–0.90 (Table 1). Combined with decades of sediment accumulation (in two ponds) and high rates of watershed loading (Table S2), we expected reduced nutrient retention, especially for P, compared to designed performance. In contrast to expectations, we observed high nutrient mass retention across the ponds during the 2017–2018 annual study period. In fact, the observed TP retention of 48%–80% across ponds and TN retention of 58%–88% (Table 2) generally met or exceeded

Table 2
Annual areal loading rates (volume or load per unit pond surface area per year) of inflows, outflows, and burial/loss (retention) for (a) water volume and forms of phosphorus, and (b) forms of nitrogen, for the three ponds over the annual study period (July 2017 – June 2018). Totals include both sampled and modeled events. Percent retention is versus inlet load. Note that DON = TDN – NO_x – NH_4 and DOP = TDP – SRP. *95% confidence interval is for event retention percentage and is determined only from completely-sampled events.

(a) Volume, phosphorus		Water	TP	PP	TDP	SRP	DOP
Site		m	g/m^2	g/m^2	g/m^2	g/m^2	g/m^2
Pond C	Inflow	6.4	2.6	1.7	0.88	0.53	0.35
	Outflow	5.6	0.90	0.61	0.29	0.14	0.15
	Burial/loss	0.7	1.7	1.1	0.59	0.39	0.20
	Retention %	11%	66%	64%	67%	74%	58%
	Event ret 95% CI*	13%	22%	32%	34%	50%	72%
Pond D	Inflow	12	1.3	0.79	0.53	0.32	0.20
	Outflow	2.6	0.27	0.19	0.08	0.03	0.05
	Burial/loss	9.4	1.1	0.60	0.45	0.30	0.15
	Retention %	79%	80%	76%	85%	92%	73%
	Event ret 95% CI*	9%	16%	18%	17%	13%	41%
Pond E	Inflow	5.8	1.45	0.89	0.57	0.42	0.15
	Outflow	4.3	0.76	0.37	0.39	0.24	0.15
	Burial/loss	1.5	0.70	0.52	0.18	0.18	0.00
	Retention %	26%	48%	59%	31%	43%	-2%
	Event ret 95% CI*	31%	19%	20%	23%	21%	42%

(b) Nitrogen		TN	PN	TDN	NO_x	NH_4	DON
Site		g/m^2	g/m^2	g/m^2	g/m^2	g/m^2	g/m^2
	Inflow	20	12	7.3	1.9	2.6	2.8
	Outflow	7.1	3.2	3.7	0.44	1.7	1.5
Pond C	Burial/loss	13	9.2	3.6	1.4	0.85	1.3
	Retention %	64%	75%	49%	76%	33%	45%
	Event ret 95% CI*	24%	17%	29%	6%	50%	65%
	Inflow	17	9.3	8.5	2.5	3.9	2.1
	Outflow	2.0	1.2	0.78	0.18	0.15	0.45
Pond D	Burial/loss	15	8.0	7.7	2.3	3.8	1.6
	Retention %	88%	87%	91%	93%	96%	78%
	Event ret 95% CI*	8%	8%	10%	8%	13%	20%
	Inflow	12	7.3	4.4	1.7	1.2	1.5
	Outflow	4.9	1.9	2.9	0.24	0.78	1.9
Pond E	Burial/loss	6.7	5.3	1.5	1.4	0.43	−0.39
	Retention %	58%	73%	34%	86%	35%	−26%
	Event ret 95% CI*	14%	11%	18%	6%	21%	64%

Table 3
Event mean concentrations (mg/L) in the three study ponds over the annual study period (July 2017 – June 2018), for (a) Phosphorus, and (b) Nitrogen and molar ratio of total N:P. Reduction is relative to inlet concentration; DON = TDN – NO_x – NH_4, DOP = TDP – SRP.

(a) Phosphorus		n	TP	PP	TDP	SRP	DOP
Site			mg/L	mg/L	mg/L	mg/L	mg/L
Pond C	Inlet	19	0.507	0.325	0.183	0.125	0.057
	Outlet	25	0.345	0.285	0.061	0.028	0.033
	Reduction		32%	12%	67%	78%	43%
Pond D	Inlet	20	0.142	0.081	0.061	0.041	0.020
	Outlet	13	0.176	0.139	0.037	0.014	0.023
	Reduction		−24%	−71%	39%	66%	−15%
Pond E	Inlet	39	0.322	0.176	0.146	0.111	0.034
	Outlet	27	0.194	0.107	0.087	0.050	0.037
	Reduction		40%	39%	40%	55%	−7%

(b) Nitrogen		n	TN	PN	TDN	NO_x	NH_4	DON	TN:TP
Site			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	molar
Pond C	Inlet	19	4.71	2.50	2.21	0.340	0.893	0.978	23.5
	Outlet	24	2.00	0.99	1.01	0.051	0.487	0.472	15.2
	Reduction		58%	60%	54%	85%	46%	52%	36%
Pond D	Inlet	19	2.00	1.05	0.950	0.317	0.375	0.258	37.4
	Outlet	12	1.25	0.878	0.375	0.095	0.088	0.191	16.8
	Reduction		37%	16%	61%	70%	76%	26%	55%
Pond E	Inlet	36	2.75	1.45	1.29	0.310	0.251	0.732	20.4
	Outlet	26	1.25	0.554	0.694	0.057	0.200	0.437	14.3
	Reduction		55%	62%	46%	82%	20%	40%	30%

the expected removal performance for wet ponds for TP (~50%; Weiss et al., 2007) and TN (~30–40%; MPCA, 2000; Koch et al., 2014).

Water retention emerged as the key factor for pond performance, as differences in annual nutrient retention across the ponds were primarily affected by volume retention and residence time, and less so by reductions in nutrient concentration. In fact, comparisons across our sites of inflow vs. outflow EMC (−24% to 40% for TP, 37% to 58% for TN; Table 3), a widely used metric of pond performance, were lower than expected relative to literature values for P (51% for wet pond TP concentration reduction; Clary et al., 2020), due to outflow concentrations of total P and N (Table 3) that exceeded expectations (wet pond outflow TP and TN of 0.120 mg/L and 1.20 mg/L, respectively; Clary et al., 2020). Annual retention of TP and TN were approximately proportional to water losses, with the largest TP (80%) and TN (88%) mass reductions occurring in the site (Pond D) with the highest volume retention (79%; Table 2), and with lower observed annual retention for the other two ponds due to much lower volume retention (11% for Pond C, 26% for Pond E).

The influence of hydrology on pond nutrient retention, evident in the annual mass retention results, was especially apparent at the runoff event scale, as antecedent pond storage capacity was tightly related to retention percentage of nutrients (TP, TDP, TN, and TDN) for an event across all three ponds (Fig. 1). Net nutrient export was far likelier to occur if the pond was near or above its permanent pool (antecedent pond level = 0 cm) at the onset of a storm or melt event, with 14%–45% of these events producing net export across these nutrient forms (TP, TDP, TN, TDN). Water level in all three ponds, during prolonged dry periods especially, could fall below permanent pool levels, resulting in 'surplus' storage capacity and a greater likelihood of net retention for an event: 81%–100% of events with surplus storage resulted in net retention across nutrient forms. In these plots (Figs. 1 and S6), most events fell into the upper-left quadrant (net retention with surplus storage capacity), with some in the upper right quadrant (net retention relying only on treatment volume, i.e., no surplus storage). In the latter case, net nutrient retention was achieved through delayed release of the pond's treatment volume, as intended in its design. Events for which outflow loads exceeded inflow loads (net export), while rarer overall, were indicative of internal loading and included events with surplus antecedent storage capacity (lower left quadrant) and events with no surplus storage (lower right quadrant). Overall, greater antecedent storage capacity resulted both in lower outflow volumes and in greater likelihood of net nutrient retention.

Pond storage volume is primarily controlled by evapotranspiration and by loss of volume to groundwater (exfiltration) during antecedent periods. These hydrologic processes reduced the water surface levels below the pond outlets, providing for storage that could capture runoff from smaller storms and substantially decrease pond discharge due to larger storms. These water fluxes were not observed directly, yet we can infer their relative importance from the ponds' hydrologic settings and dynamics. Pond D, the smallest pond by volume and by drainage area-to-surface area ratio (Table 1), also lacked groundwater inflows or outflows and had the greatest rates of drawdown (water loss). These factors enabled the high volume retention observed at this pond, which contrasts with the relatively lower water retention at the larger ponds, C and E. In these ponds, lower drawdown rates were observed, likely affected by greater depth and volume, potential groundwater inputs (see Methods), and the effect of surrounding trees, which were tall (>7 m; Table 1) and likely suppressed wind-driven evaporation. Seasonality of hydrologic processes also impacted pond storage dynamics. Runoff events resulting in net TP, TDP, TN, and TDN export from all three ponds (Figs. 1, S6) tended to occur during the shoulder seasons (e.g. during heavy snowfall and snowmelt in April 2018) when evapotranspiration rates were low and recovery of pond treatment capacity (volume) between events was reduced, as well as during wet periods with rapid succession of storms, such as during August 2017 and June 2018

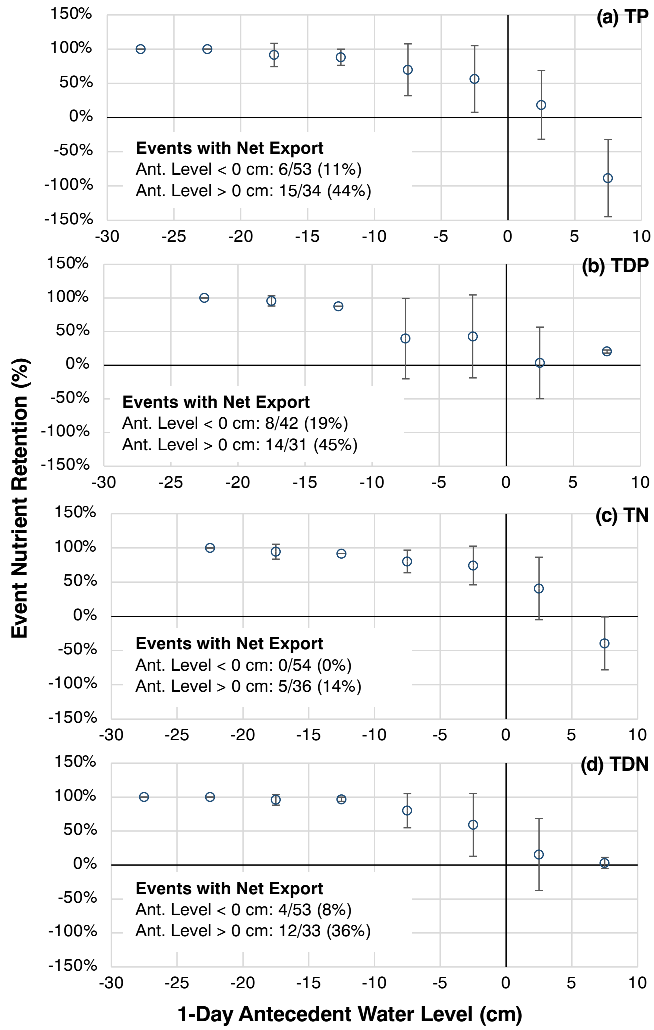

Fig. 1. Mean and standard deviation of event retention (%) vs. 24-h antecedent water level (0 cm = elevation above which pond outflow occurs) in the three ponds for TP, TDP, TN, and TDN; each point is the summary of all events across all three ponds within the given bin range of antecedent water level, plotted at the bin center (bin size = 5 cm).

(see Figs. S7, S8 for Ponds C, E). Overall, while we did not measure specific mechanisms of water losses, generation of storage volume emerged as a major factor for maintaining high rates of nutrient capture in ponds.

Increased storage volume from water losses would also effectively increase water residence time, which contributes to greater in-pond and in-lake processing of nutrients from settling, uptake, and burial (Walker, 1987; MPCA, 2000; Erickson et al., 2018; Schroer et al., 2018). Annual hydraulic residence time (pond volume / mean outflow rate) was highest in Pond D at 124 days, roughly twice the value at the other two, larger ponds (61 days for Pond C, 77 days for Pond D; Table 4). This longer residence time likely contributed to the generally higher nutrient retention of Pond D relative to the other two ponds, but further analysis of the effect of residence time would require a longer data record or inclusion of more ponds than in this study.

3.2. Influences of internal processes on pond nutrients

While we observed relatively high rates of nutrient load reduction in all ponds, driven by non-outflow water losses, nutrient concentration reductions, measured as changes from pond inlets to outlets, contrasted sharply between P and N. Phosphorus concentration reductions were low, with observed reductions of −24% to 40% for TP and 39% to 67% for TDP across the ponds (Table 3) versus expected reduction of roughly 50% for both TP and TDP (median values for detention ponds; Clary et al., 2020). TN concentration reductions, however, greatly exceeded literature values (26%; Clary et al., 2020), with observed reductions of 37% to 58% across the ponds (Table 3), while NO_x and NH_4 reductions also exceeded median values from the International BMP Database (Clary et al., 2020). Thus, while pond hydrologic retention drove load reductions overall, pond conditions had contrasting effects on cycling of P vs. N within the ponds.

Strong year-round thermal and chemical stratification (Taguchi et al., 2020a) combined with high levels of organic matter (dissolved organic carbon, DOC, and particulate carbon, PC; Table S3) produced anoxic conditions throughout much of the water column in all three ponds (Tables 1, 3). These anoxic conditions favored sedimentary recycling of P and helped maintain high rates of biological production in the ponds, while also potentially promoting N losses through denitrification. Consistent changes in nutrient stoichiometry from inlet to outlet across the ponds, especially the pattern of decreasing TN:TP (Table 3), suggested P enrichment relative to N, consistent with internal recycling of P and removal of N via denitrification and other processes (e.g., uptake, burial). While most of these processes were not measured directly, these drivers account for the reductions of total nutrient concentrations across the ponds and help explain the contrast in TP vs. TN reductions, i.e., stronger removal of N compared to P.

For phosphorus, internal loading of SRP from anoxic sediments was potentially substantial, as suggested by the concurrent laboratory study of pond sediments in the three ponds (Taguchi et al., 2020a). Using the approach of Nurnberg (2009) (see Methods), we estimated summer (June – September) SRP release from the anoxic portion of pond sediments to be 0.12, 0.24, and 0.13 mg/m^2 for Ponds C, D, and E, respectively, which corresponded to roughly 23%, 75%, and 30% of the annual inflow SRP loads for the three ponds (or 5%, 19%, and 9% of annual inflow TP loads; Table 2). This internal P load was consistent with observed elevated hypolimnetic P concentrations relative to epilimnion, inlet, and outlet locations (Figs. S3, S5), and is likely a conservative estimate of actual P release given that anoxic conditions were present much of the year.

Though sedimentary SRP release rates were potentially large, the contribution of internal loading to outflow SRP loads was minimal since surface water and outflow concentrations were not strongly elevated, indicating high rates of assimilation and possibly luxury uptake of bioavailable P. All ponds had moderate levels of dissolved organic carbon (DOC = 7.6–8.3 mg/L across ponds; Table S3) and elevated chlorophyll *a* (66–201 μg/L; Fig. S4) typical of eutrophic to hypereutrophic conditions. All sites were also covered by free floating plants (predominantly *Lemna* spp.) during summer (unpublished data), representing an additional, but unquantified biomass pool at the pond surface. Together, the high levels of autotrophic biomass and organic matter (DOC and PC; Table S3) suggested high rates of productivity in the ponds, which would convert most inorganic P from inflows and sediment release to organic P, explaining the dominance of particulate P in outflows.

Patterns of inorganic nitrogen were also consistent with strong effects of stratification and anoxia, but with opposite outcomes for TN retention

Table 4
Hydrologic characteristics of the three monitored ponds, including hydraulic residence time and dry-weather drawdown rates for four periods: early summer (May–June 2017), Mid-Summer (July 2017), Late Summer (September 2017), and Late Fall (November 2017). Residence time calculated as pond volume divided by mean outflow rate over the length of the data record.

Site	Dry-period water level drawdown rates				Hydraulic
	Early Summer	Mid-Summer	Late Summer	Late Fall	Residence Time
	cm/day	cm/day	cm/day	cm/day	days
Pond C	0.75	0.92	0.70	n/a	61
Pond D	1.01	1.02	0.75	0.45	124
Pond E	0.65	0.60	0.64	0.25	77

compared to TP. NH_4 concentrations were elevated (Table 3), due to both anoxic sedimentary release and inflows, indicating lack of N limitation to primary producers. In contrast, NO_3 concentrations were strongly reduced in surface water and outflows relative to inflows (Table 3, Fig. S5). Conditions in the ponds, especially the strong anoxia in the sediments and bottom waters, were highly favorable for NO_3 removal via denitrification (Bettez and Groffman, 2012; Hohman et al., 2021), contributing overall to TN concentration reductions in the ponds. In contrast, recent studies have found that some ponds can serve as N sources, potentially due to high rates of biological N fixation and other factors (Gold et al., 2017a, 2017b). The variable removal of nitrogen in ponds across studies requires further attention.

The combination of sedimentary release of bioavailable P and N (SRP and NH_4), high in-pond productivity (e.g., abundant duckweed), and high levels of organic matter inputs (DOC and PC; Table S3) contributed to poor concentration reduction of organic forms of nutrients, for P especially (Table 3). DON concentration reduction was variable (26% to 52% across the three ponds) though generally lower than reduction of inorganic N, while for two ponds (D and E), the concentration of the non-SRP fraction of dissolved P (TDP-SRP, which is mostly organic), increased from inlet to outlet across the ponds (Table 3). Total nutrient reductions were negatively impacted by the prevalence of organic forms of N and P in the ponds, though the relationship of these forms to productivity, stratification, and oxygen dynamics warrants further study.

The surprising extent of thermal and chemical stratification in all three ponds (Taguchi et al., 2020a) likely affected internal processes that influenced nutrient retention in complex ways that are not yet completely understood (McEnroe et al., 2013). Despite their small size and shallow depth, the ponds mixed only during short periods of the fall, with stratification dominant throughout the rest of the year due to combined effects of wind sheltering, winter ice, and road salt inputs (Herb et al., 2017; Taguchi et al., 2020a). On one hand, stratification effectively isolated upper and lower waters of each pond, potentially moderating effects of internal loading by trapping released P in the hypolimnion, while also promoting particulate P burial. Incoming storm water would likely interact primarily with the upper water levels, flushing the surface mixed layer rather than internally-released nutrients in the hypolimnion. On the other hand, this reduced water column interaction by inflows is likely to reduce water residence times, providing less opportunity for particulate settling. The net outcome of these effects cannot be addressed in this study but deserve further consideration as lentic systems become increasingly stratified due to human-driven change. Stratification in shallow water bodies appears to be a common yet underappreciated feature of ponds that has not yet been thoroughly investigated (Condie and Webster, 2001; McEnroe et al., 2013; Song et al., 2013).

3.3. Hydrologic retention vs. biogeochemical processing for nutrient retention

The balance of hydrologic retention versus biogeochemical processing is illustrative of the controls on pond nutrient retention and thus potentially useful to guide management actions. In Fig. 2, this balance is shown as outlet/inlet concentration ratio vs. outlet/inlet volume ratio for all sampled events at each site, with a line for neutral retention (outlet load = inlet load) to illustrate the breakpoint between net retention and net export: as outlet concentration becomes greater than inlet concentration (positive x-axis), greater volume retention is required to achieve net load retention. While events with net export of TP and TDP were uncommon, these tended to occur when outlet concentrations were far higher than inlet concentrations, which would indicate flushing of accumulated or internally released (redox) P from anoxic sediments. Net export also tended to occur when volume retention was low, i.e., outlet/inlet volume ratios near to or greater than 1.0. The importance of volume retention was especially evident for Pond D, as outlet concentrations were nearly always higher than inlet concentrations (i.e., concentration ratio > 1.0) for both TP and TDP, yet only a few events produced net export. Volume retention was also a key indicator for Pond C, as most net export events of both TP, TDP, and TDN occurred for low volume retention (outlet/inlet volume ratio > 0.80), regardless of concentration. Conversely, in-pond sources may have been important for Pond E, as concentration ratio was a strong indicator of performance: nearly all events with net TP, TDP, or TDN export occurred for scenarios of high outlet-inlet concentration ratios (>1.0), regardless of volume retention, which was generally poor at Pond E (outlet-inlet ratio > 0.70 for most events).

Together these results show that pond hydrologic function (i.e., high water retention) was crucial for N and P capture by these ponds, at both the annual scale (Table 2) and event scale (Figs. 1, 2). The latter analysis illustrated the greater importance of water retention relative to biogeochemical processing (as concentration reduction), a conclusion reached also by Shukla et al. (2017) in a study of agricultural ponds. Water retention, and the resulting longer hydraulic residence times, affect both physical retention processes (water loss, settling) and biogeochemical retention (uptake, redox), and therefore are not mutually exclusive. However, there are clear benefits to nutrient retention performance stemming from hydrologic retention in ponds.

The specific fate of N and P retained in the study ponds cannot be determined from our dataset, yet given high rates of accumulation of nutrient-rich sediment in ponds (Brainard and Fairchild, 2012; Griffiths and Mitsch, 2020), most N and P seems likely to be deposited in sediments, with some losses of N via denitrification. Exfiltration and associated nutrient transport in the study ponds is likely minor, due both to the prevalence of particulate nutrient forms (Table 2) and to the presence of thick sediment layers in the ponds (Taguchi et al., 2020a; noting the exception of the dredged pond, Pond C). Seasonality of drawdown rates, with water loss rates during warm summer periods more than twice those in late fall (Table 4), also suggests a greater influence of evapotranspiration than exfiltration on pond water losses. Future research should confirm this water balance since the loss of dissolved nutrients via exfiltration, if occurring at high rates, would represent a shift of pollution from surface water to groundwater rather than indicate a more permanent loss mechanism such as denitrification or sedimentation and burial. Though groundwater transport provides opportunities for nutrient sorption or uptake in soil, shallow groundwater flow paths that intersect storm pipes would transport nutrients to downstream water bodies (Kaushal and Belt, 2012; Snodgrass et al., 2017), negating perceived retention benefits of the ponds.

3.4. Conclusion: management implications

In our study, we observed the benefits of pond management to both volume capture and concentration reduction (Research Question 2). While Ponds D and E had little or no maintenance since construction, at Pond C, renovations six years prior to our study included an iron-enhanced sand filter (IESF) outlet bench and dredging to improve volume control. Despite groundwater inputs causing poor annual volume retention at this site (11%; Table 2), the enhanced storage from dredging and the water level drawdown aided in part by the IESF drain tiles likely helped produce surplus storage for many events at the pond (Fig. S6). Importantly for water quality management, the pond's IESF was effective for reducing dissolved P, as expected (Erickson et al., 2012; Belden and Fossum, 2018). We observed substantial concentration reductions of TDP (67%) and especially of SRP (78%) from inlet to outlet (Table 3), resulting in sizeable annual mass retention of SRP (74%), which accounted for roughly 22% of the TP retention at the pond (Table 2). While Pond C's annual retention was average, it was subjected to the highest watershed P loading of the study sites (Table S2) and almost certainly benefited from maintenance and retrofits.

More generally, water retention in our studied ponds compensated for several factors that could have led to reduced functioning for nutrient removal (i.e., old age, lack of maintenance, high watershed loading, intense stratification, persistent anoxia, and internal loading; Research Question 1). We believe that our results apply broadly to stormwater ponds and that a greater understanding of a pond's water budget, especially of mechanisms of non-outflow water losses, could be applied towards design and management of ponds for improved water storage (Eger et al., 2017) and nutrient retention. Such water losses, occurring via exfiltration and evapotranspiration,

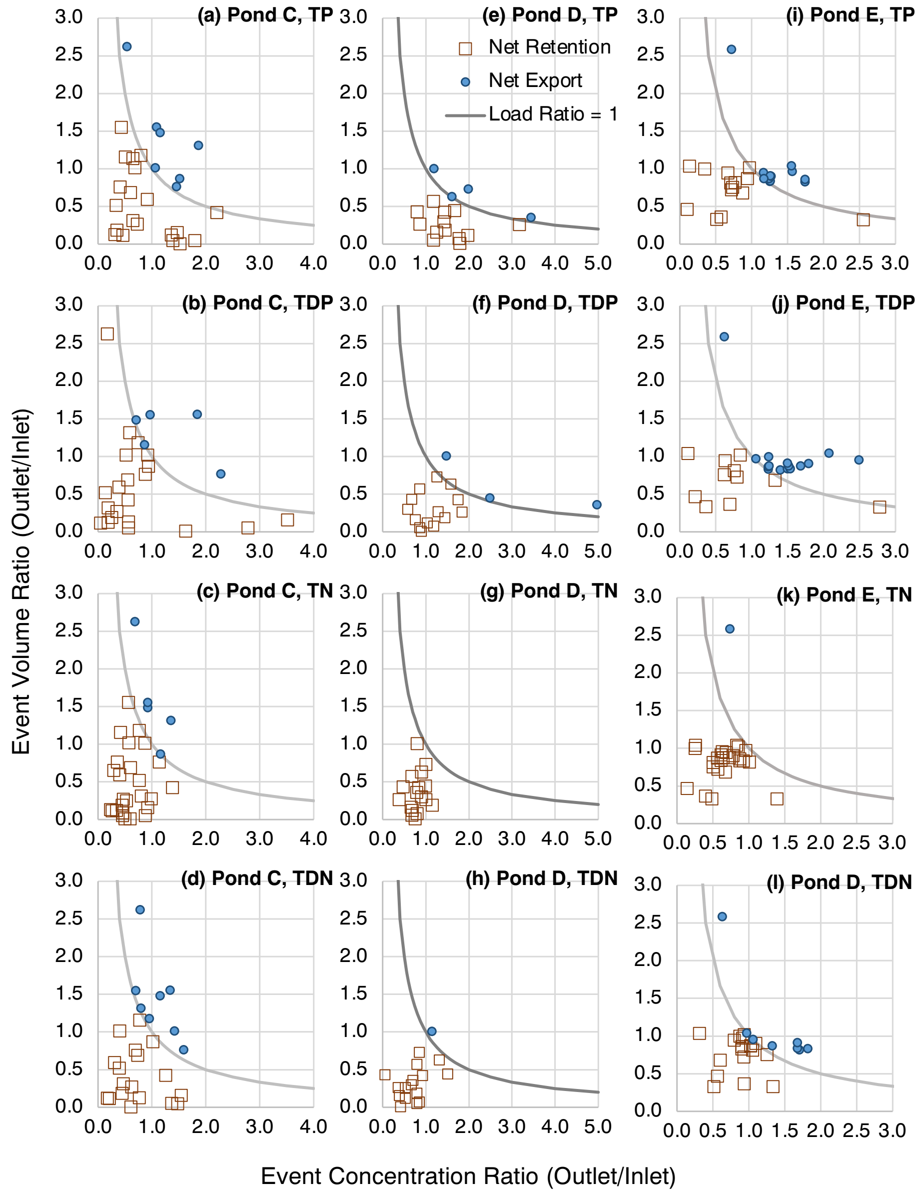

Fig. 2. Volume ratio (outflow:inflow) vs. concentration ratios (outflow:inflow) for completely-observed events at the study ponds over the monitoring period for each (18 months at Ponds C and D, 12 months at Pond E). (a–d) Pond C; (e–h) Pond D; (i–l) Pond E. Hollow squares are events for which net retention was observed (inflow load > outflow load) while shaded circles are events for which net export was observed. Solid line indicates the breakpoint between net export and net retention for given concentration and volume ratios, such that net retention was observed for events plotting below the line, net export for events above the line.

are not explicitly factored into design plans. Of these, only exfiltration represents a direct "loss" of nutrients from the pond system; evapotranspiration does not generate nutrient loss but instead promotes greater volume storage capacity for the next runoff event, lengthening residence times and allowing more time for internal processes.

More research to understand water fluxes from ponds could be used to promote the advantage of water losses (Research Question 3). Development of water balance assessment techniques based on straightforward data collection (e.g., water level), rather than the intensive monitoring undertaken in our study, would be especially beneficial. Such techniques could include analyses of fluctuations in water level or in stratification strength, which can be conducted using low-cost data collection of water level and temperature profile time series (e.g., Toran, 2016; Janke et al., 2021). Assessments of nutrient removal performance based solely on in-pond concentrations or inlet to outlet concentration reductions are at risk of over- or under-assessing a pond's nutrient (mass) retention; such an assessment would have identified our study ponds as poor performers for nutrient removal (TP and NH_4 especially; Table 3) when actual performance was in line with expectations.

Concerning stormwater management, these results highlight the importance of maintaining storage volumes in wet ponds for managing both flooding and nutrients in urban watersheds (Research Questions 2 and 3). In our study, most runoff events occurring with even small surplus storage did not lead to net export of nutrients (Fig. 1). However, since many older ponds have reduced volumes compared to initial construction due to sedimentation, and climate change drives larger or more intense storms (Forsee and Ahmed, 2011; Moore et al., 2016), maintaining or increasing volume capacity of ponds is likely necessary for many existing ponds. While the high rates of water losses help generate storage volume, dredging and expansion to increase volume and area, where feasible, can be used to increase the potential storage capacity of ponds. Increased capacity could be especially important for managing runoff during periods of low evapotranspiration, such as early open-water season in north temperate climates, as well as for managing large, intense summer storms. Controlled drawdown, another method of generating volume storage through adaptive outlet controls that remove pond water via valves ahead of storms, is a practice now used in a small number of sites (Kerkez et al., 2016). This approach requires new infrastructure but could become more effective when combined with optimizing natural processes like groundwater outflow and evapotranspiration.

CRediT authorship contribution statement

BDJ: Methodology, Investigation, Formal Analysis, Writing; **JCF:** Conceptualization, Project Administration, Formal Analysis, Writing; **VJT:** Methodology, Investigation, Writing; **JSG:** Conceptualization, Project Administration, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153722.

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