Internal loading in stormwater ponds as a phosphorus source to downstream waters

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Scientific Significance Statement

Stormwater ponds are common in many cities and are intended to slow runoff and improve water quality in downstream waterbodies. The use of stormwater ponds to capture and retain phosphorus is based on assumptions that most incoming phosphorus is particulate and prone to settling and that ponds remain fully aerated to prevent the release of sedimentary phosphorus via redox-driven internal loading. Our analysis of observations from stormwater ponds suggests that internal loading is common due to stratification, and the resulting low oxygen, as well as high sedimentary phosphorus availability. This indicates that many ponds have a reduced capacity to trap phosphorus and, in some cases, can release previously trapped phosphorus, potentially contributing to eutrophication in downstream waterbodies.

Abstract

We assessed the prevalence and causes of sediment phosphorus (P) release within urban stormwater ponds, a process that may reduce P removal by sedimentation. Data collected from surface water of 98 urban stormwater ponds in Minnesota showed that nearly 40% had median summer total P concentrations in excess of average stormwater runoff (0.38 mg L⁻¹), implying effects of internal loading. We sampled seven ponds more intensively and found four were strongly stratified with persistent hypolimnetic anoxia, despite mean depths <2 m. Sediment core incubations revealed that, unlike in most lakes, both labile organic P (NaOH minus persulfate extractions) and redox-sensitive P (NH₄Cl and Na₂S₂O₄ extractions) contribute to P release. Together, these analyses suggest P accumulated in stormwater ponds is highly susceptible to internal release and potentially contributes to downstream eutrophication. Understanding how frequently these conditions occur and how they affect different P forms is vital to improving pond design and management.

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Urban stormwater ponds are either constructed or retrofitted from natural ponds and wetlands to receive stormwater runoff (Erickson et al. 2018). Stormwater ponds (hereafter, ponds) were first designed to reduce peak flows and settle out suspended solids carrying nutrients and other pollutants (Walker 1987). They have since become ubiquitous in many regions (Schroer et al. 2018), making them a significant part of urban watershed hydrology and water quality management (Song et al. 2015). As urban watershed nutrient management focuses largely on phosphorus (P) due to its major role in inland waterbody eutrophication, ponds are widely used to retain P (Schroer et al. 2018) based on their assumed efficiency in trapping P in stormwater (Walker 1987).

As ponds age, P trapped and accumulated in sediments is susceptible to release, or “internal loading.” Internal loading has been recognized as a difficult-to-manage contributor to eutrophication in lakes (Nürnberg 2009; Song et al. 2015; Song and Burgin 2017; Steinman and Spears 2019). Internal loading has received comparatively little attention in managed ponds (Steinman and Spears 2019) because ponds are shallower and thought to be polymeric with oxygen water columns (Walker 1987), an assumption that is not widely evaluated.

Syntheses of large national databases have determined median total P (TP) removal efficiencies in ponds of 52% (Center for Watershed Protection 2007) and 55% (Clary et al. 2017). Many studies contributing to these estimates, however, were short-term evaluations (over 1 or 2 years) of newly constructed urban ponds. Older ponds, which are likely more numerous, would potentially have much lower retention rates if experiencing internal loading or reduced storage volume from accumulated sediment. Nevertheless, total phosphorus removal rates on the order of 50% are widely assumed for watershed planning and nutrient budget calculations (Walker 1987; Rossman and Huber 2016).

Stormwater pond management for TP removal relies on sufficiently long hydraulic residence time to promote particle settling, removal of accumulated sediments to reestablish storage capacity, and designs that avoid sediment resuspension by inflowing runoff (Erickson et al. 2018; Schroer et al. 2018). However, many urban stormwater ponds are undersized relative to their intensively drained watershed areas (Persson and Pettersson 2009), resulting in disproportionately high inputs of nutrients (Schueler and Simpson 2001) and organic material, such as leaf litter (Janke et al. 2017), relative to their sizes. As a result of large loading rates of organic material (Song et al. 2017; Schroer et al. 2018), many ponds accumulate substantial organic P in their sediments (Frost et al. 2019). The release of organic P is mediated by microbial activity (Gächter et al. 1988; Golterman 2001) and can occur under both low- and high-DO conditions (Frost et al. 2019). This means that conventional management strategies like dredging (Erickson et al. 2018; Schroer et al. 2018) may not occur frequently enough to prevent P export from internal loading.

Differences in P forms in pond sediments relative to lakes likely affect the cycling of P because specific P fractions have different mobilization potentials. Other sediment factors influencing P mobility include the relative abundances of iron, sulfur, calcium, and aluminum (Hupfer and Lewandowski 2008). In a review of internal loading research in lakes, Søndergaard et al. (2003) identified both iron-bound P and labile organic P as mobile forms of sediment P (hereafter, mobile-P = redox-P + labile organic P), which are the most readily soluble and accessible to biota (Hansen et al. 2003; James 2011). Degradable (i.e., labile) organic P is one of the main recyclable forms in sediments (Paraskova et al. 2014) and is abundant in many stormwater ponds (Song et al. 2017). While not all labile organic P is bioavailable, even small increases in labile organic P have consequences for eutrophication (Frost et al. 2019).

We therefore hypothesize that urban ponds can have high internal loading rates during warm summer conditions. Ponds are subject to high external mobile-P loading in urban watersheds (Janke et al. 2017; Schroer et al. 2018) and the associated accumulation of organic sediments. Dissolved oxygen (DO) concentrations are typically low in the bottoms of ponds (Søndergaard et al. 2003; Song and Burgin 2017), particularly during summer when warm temperatures promote stratified conditions (McEnroe et al. 2013). As a result, low DO could drive internal loading from redox-P release (Søndergaard et al. 2003; Liboriussen et al. 2011; Song et al. 2013), and warm temperatures are likely to increase microbial processing of the organic matter in pond sediments (Song et al. 2017; Schroer et al. 2018).

We tested our hypothesis using three approaches. First, we analyzed data from 98 ponds sampled over 3 years (RPBCWD 2014) to assess internal loading prevalence within a large developed watershed. Second, we examined seven ponds representing a wide range of trophic states to directly identify mechanisms controlling internal loading in ponds. We intensively monitored five of these seven ponds (located close to the University of Minnesota) to better understand the variability of in situ mixing and stratification dynamics and their influence on P release. Third, we incubated intact sediment cores from all seven ponds to measure sediment P release rates and sediment oxygen demand (Smax), as an evaluation of the potential for a pond to release P under oxic and anoxic conditions, and analyzed the sediment P fractionation to identify mechanisms responsible for P release under different chemical and biological conditions. Understanding how frequently these conditions occur and how they affect different P forms is vital to improving pond design and maintenance, which is important to reduce nutrient fluxes to receiving waterbodies.

**Materials and methods**

**Approach 1: Variation of total phosphorus in surface water across stormwater ponds**

To evaluate the potential for internal P loading in ponds, we analyzed TP concentrations in surface water from repeated
measurements across 98 ponds, using data collected by the Riley Purgatory Bluff Creek Watershed District (RPBCWD) in the Minneapolis – St. Paul Metropolitan Area (Twin Cities Metro) (RPBCWD 2014). The data set was generated by an intensive sampling program during spring and summer conditions over 3 years that collected an average of six samples per pond (Supporting Information Tables S1 and S2, Method S1).

We compared these pond surface TP concentrations to a robust data set representing typical stormwater runoff in the Twin Cities Metro (Janke et al. 2017), making the assumption that pond surface TP concentrations in excess of typical inflow TP concentrations indicated the influence of internal loading. Typical runoff TP for the Twin Cities Metro was characterized using data assembled by Janke et al. (2017) for over 2000 warm-season storm events at 19 urban Twin Cities sites from 2005 to 2014 (Supporting Information Table S1). Runoff TP resembled stormwater runoff from other regions of the USA, as characterized by Pitt et al. (2008) (Supporting Information Table S1). We fit the Janke et al. (2017) data to a log-normal distribution, where the upper 95% confidence interval of expected values (95% CI) represents the maximum value for approximately 97.5% of the distribution (Supporting Information Method S2 and Table S1). Pond TP measurements were then compared to this upper 95% CI. Such a comparison is subject to several assumptions: that the inflow P concentrations to the ponds are represented by the Janke et al. (2017) data set, that concentrations in pond outflows are equal to the measured in-pond concentrations, and that the ponds are hydrologically neutral (inflow volume = outflow volume). While these assumptions require further exploration, we consider this approach a reasonable assessment of the prevalence of internal loading and the potential for net P export from ponds, which would be indicated by outflow concentrations greatly exceeding inflow concentration estimates.

**Approach 2: Physiochemical conditions in stormwater ponds**

To understand mechanisms behind P release, we studied seven ponds (A to G) (Supporting Information Figs. S1 and S2 and Table S3). All ponds were at least 10 years old, had single primary inlets and outlets, and were easily accessible for sampling. We monitored five of the seven ponds (C to G) intensively to document physical and biochemical conditions affecting each pond. We periodically collected water samples and vertical profiles of temperature and DO concentration from each pond center; we did this for an entire year including winter for ponds C, D, and E. We also continuously recorded water temperatures in a vertical profile using thermistor chains in ponds C, D, and E to observe stratification dynamics and verify assumed conditions between profiling events.

**Approach 3: Sediment core incubation experiments**

We collected and placed five to six intact sediment cores with overlying pond water in polycarbonate tubes from each of the seven ponds to directly measure sediment P release (Natarajan et al. 2017) (Supporting Information Method S3). In the laboratory, we drained the overlying water, filtered it to remove particulates, and refilled core tubes prior to incubation. We then bubbled the water columns with air to simulate aeration during a single mixing event (Supporting Information Fig. S3). After approximately 1 month, we halted aeration and left the water above the sediments unmixed for 1 month to allow an estimate of sediment oxygen demand. We then extended incubations for two additional months with the addition of ultrapure nitrogen gas bubbling to force low-DO conditions (<1 mg L\(^{-1}\)) (Supporting Information Method S3). We calculated an overall sediment orthophosphorus (ortho-P) flux for each phase by fitting a linear regression to water column ortho-P concentrations measured over each phase. During the high-DO phase, we sampled ponds A and B every 2 weeks, but later determined that the highest oxic P flux occurred in the first week. Therefore, samples taken 1 week apart were used for ponds C to G. Thus, oxic P fluxes from ponds A and B may have been underestimated and could be double the magnitude of reported fluxes (Supporting Information Table S4). Release rates for the subsequent low-DO phase were similarly calculated from periodic ortho-P measurements over the initial 2 weeks of the monitoring period, after which an approximate equilibrium concentration was reached (Fig. 3a). At the conclusion of the monitoring period for each sediment core, we sequentially extracted sediment P fractions (Supporting Information Method S4) to examine differences in P speciation among ponds with varied loading conditions and morphologies.

![Fig. 1. Distribution of TP concentrations in RPBCWD (2014) pond data. Three lines represent, respectively, the median, the top 25th percentile, and the maximum values of TP concentration measurements for each of the 98 ponds in the data set. The x-axis gives the percentage of ponds with values in excess of TP concentrations listed on the y-axis. Box plots of the same data are presented in Supporting Information Fig. S4. Median TP concentration values from the seven intensively studied ponds (A to G) are plotted with error bars representing minimum and maximum TP concentrations. Numerical median values and numbers of samples are presented in Supporting Information Tables S2 and S3 for the 98 RPBCWD ponds and ponds A to G, respectively.](image)
Results
Approach 1: Variation of total phosphorus in surface water across stormwater ponds
Elevated TP levels in urban ponds were widespread: 39% of the 98 ponds sampled by RPBCWD (2014) had median surface TP concentrations greater than the upper 95% CI of typical Twin Cities Metro summer stormwater of 0.38 mg L\(^{-1}\) (Fig. 1; Janke et al. 2017), which is several times higher than the regional surface water quality standard (0.10 mg L\(^{-1}\); Anderson et al. 2018). The 95% CI value represents the upper extremes of inflow TP concentrations; we note, also, that TP concentrations on the pond surface tend to be lower than hypolimnion TP concentrations where the internal loading is occurring (Nürnberg 2009). Together, these results suggest that at least 39% of the sampled ponds may experience internal loading.

Fig. 2. Contour plots of (a) water temperature and (b) DO at pond E, developed by linearly interpolating manually recorded temperature and DO profiles from 2017 at 0.25-m vertical intervals (Supporting Information Method S5). Contour plots for ponds C, D, F, and G are presented in Supporting Information Figs. S5, S6, S7, and S8, respectively. Vertical dotted lines show times when profiles were measured.

Fig. 3. (a) Ortho-P concentration, (b) DO concentration in sediment cores, and (C) ortho-P flux (mg m\(^{-2}\) d\(^{-1}\)) and sedimentary oxygen demand (g m\(^{-2}\) d\(^{-1}\)) during the unmixed low-DO phase (Supporting Information Method S3). Error bars give the 67% CI of the mean. A version of Fig. 3a extending beyond the 2-week period used for ortho-P release rate calculations is presented in Supporting Information Fig. S10. Additional plots of the other incubation phases are presented in Supporting Information Figs. S9, S11, and S12.
Approach 2: Physiochemical conditions in stormwater ponds

In contrast to expected polymictic conditions in shallow ponds, we found that three of the five intensively monitored ponds (C, D, and E) were stratified for much of the monitoring period. For example, Fig. 2 shows weak, yet persistent, temperature stratification in pond E. Ponds C and D were similar (Supporting Information Figs. S5 and S6). This may have contributed to observed strong and sustained DO deficiency in the hypolimnion for all but 1 or 2 months of 2017 (Fig. 2b, Supporting Information Figs. S5b and S6b); infrequent observations of pond B indicated similar behavior. Conversely, no

**Fig. 4.** Phosphorus speciation in core sediments as dry weight concentrations (error bars = 67% CI of the mean): (a) loosely bound P = porewater P + CaCO₃-bound P, mineral-bound P = calcite- and apatite-bound P, and other forms defined in text; (b) redox-P = loosely bound P + iron-bound P, mobile-P = redox-P + labile organic P, and total-P = the sum of all six P fractions.

**Fig. 5.** (a-d) Mean anoxic ortho-P release rates and (e-h) mean surface water TP concentrations vs. mean redox-P (a and e), mean labile organic P (b and f), mean mobile-P (c and g), and mean sediment TP (d and h) sediment fraction concentrations in the top 4 cm of each core. Plotted points represent mean values (error bars = 67% CI of the mean).
temperature or DO stratification was observed in ponds F or G over four warm season months of 2018 (Supporting Information Figs. S7 and S8), nor in pond A in our infrequent observations. The mean hypolimnion DO concentrations measured in each pond are listed in Supporting Information Table S3.

**Approach 3: Sediment core incubation experiments**

**P release rates from pond sediment cores**

We directly evaluated the influence of pond oxygen status in ponds (A to G) by measuring P release from incubated sediment cores under decreasing DO conditions. The well-known inverse relationship between sediment DO levels and P release rates from the sediments (Mortimer 1941) was confirmed (Fig. 3a,b). Ortho-P release was negative (net capture of ortho-P) under high-DO conditions for all but one pond (G) (Supporting Information Table S4). Under low-DO conditions (<1 mg L\(^{-1}\)) (Supporting Information Table S5). These trends are expected further later.

**Sediment-P composition in stormwater ponds**

Sequential P extractions revealed that pond surface sediments were dominated by labile organic P in six out of seven ponds (all but G), while loosely-bound P was very low in all ponds except B (Fig. 4a). This result contrasts with lakes, where loosely-bound and iron-bound P are typically the dominant forms (Ostrofsky 1987; Søndergaard et al. 2003; Natarajan et al. 2017). Compared to lakes, stormwater pond sediments appear to have a larger percentage of organic material, suggesting that labile organic P is important in ortho-P release (Song et al. 2015; Song et al. 2017).

Analyses of anoxic sediment release rates with data for sediment P fractions revealed that anoxic ortho-P release from pond sediments was largely dependent on sediment P composition (Fig. 5a-d). The only statistically significant regression (\(\alpha = 0.05\)) for ortho-P release rate was with labile organic P (Fig. 5b), although regressions with redox-P (Fig. 5a) and mobile-P (Fig. 5c) were significant at the \(\alpha = 0.10\) level. The regressions for TP grab samples with redox-P (Fig. 5e), labile organic P (Fig. 5f), and mobile-P (Fig. 5g) were all significant (\(\alpha = 0.05\)). No regressions with sediment TP (Fig. 5d,h) were significant at the \(\alpha = 0.05\) level.

**Discussion**

Analysis of an extensive pond data set (approach 1) indicated that a large number of ponds in our northern temperate study region have elevated summertime P in the water column, which is at risk of flushing downstream to receiving waterbodies during storms. These higher-than-expected P levels during summer suggest the presence of sediment P release, which is driven by physiochemical conditions (approach 2) that affect microbial activity and diverse sediment P forms differently (approach 3).

DO concentration is a primary control of internal loading via anoxic release of sediment-bound P and microbiologically mediated processes. Although ponds are designed to be well-mixed (Walker 1987; McEnroe et al. 2013) and thus at least periodically re-oxygenated, recent studies have shown that this is not always the case (Song et al. 2013). We observed strong and lasting stratification in ponds B, C, D, and E but not in ponds A, F, and G where a relative lack of topographical and vegetative sheltering from wind may have contributed to increased mixing (McEnroe et al. 2013; Markfort et al. 2014). For the strongly stratified ponds, three (B, C, and E) turned over only once in the fall, while a much shallower (0.8-m max. depth) pond (D) also had spring turnover (Supporting Information Fig. S1 and Table S3). These unanticipated stable stratification patterns for shallow ponds strongly impact whether different P forms remain in sediments or are released into the water column (Fig. 5a vs. b) due to both redox-mediated release and organic P degradation.

Ortho-P release from pond sediments is largely dependent on sediment P composition (Fig. 5a,b). In ponds with a substantial fraction of sediment redox-P (Fig. 4b), ortho-P was released under low-DO conditions and captured under high-DO conditions (Supporting Information Table S4), as found in many previous lake studies. A frequently-mixed pond with anoxic hypolimnion would therefore be expected to retain sediment P, whereas persistent anoxic conditions would be expected to cause P release. However, the ponds with the highest anoxic sedimentary P release rates (Fig. 3) did not also have the highest surface water TP concentrations (Supporting Information Table S3) as might be anticipated. The realization of internal loading depends on both the availability of releasable P and the presence of conditions that facilitate that release.

Organic P likely plays a role in P release in ponds because of the high organic matter content in pond sediments. In many ponds, organic matter concentrations in sediments can be much higher (19–79%; Supporting Information Table S5) than in larger lakes (Sobek et al. 2009), likely facilitating high microbial processing (Liboriussen et al. 2011; Song and Burging 2017). We suggest that mobile-P (i.e., redox-P + labile organic P) is an informative metric of sedimentary P fractions in ponds, incorporating the important roles of both redox-P and labile organic P under variable redox conditions. Considering
labile organic P and redox-P together (as mobile-P) yielded good predictions of internal P loading potential as indicated by sedimentary ortho-P release (Fig. 5). These fractions together are also increasingly recommended to calculate alum dosing for internal P loading management in lakes (de Vicente et al. 2008; James 2011). Note that our definition of labile organic P refers to the difference between the P fractions extracted by NaOH and persulfate (Supporting Information Method S4), an important consideration because previous studies have used variable extraction methods with the intent of distinguishing between biologically available or biologically unavailable P (Paraskova et al. 2014).

Mobile-P, as an integrated metric, may help bridge the gap in relating sediment characteristics to P release rates and surface water P. The two integral components of sediment mobile-P (redox-P and labile organic P) are released via different mechanisms. We therefore propose the hypothesis, which could be examined experimentally, that oxygen may have opposing effects on P release. Where sedimentary labile organic P concentrations are high, oxygen exposure may have the effect of increasing labile organic P decomposition and microbial P release (Hupfer and Lewandowski 2008; Orihel et al. 2017) while reducing redox-P flux, as in the case of pond A. Meanwhile, low oxygen exposure may reduce labile organic P decomposition and increase redox-P flux, as in the case of ponds B and E. Given the broad range of conditions and responses encountered in seemingly similar urban ponds, we recommend comparing pond sediments on the basis of mobile-P content.

Conclusion
Stormwater ponds are designed to trap and store phosphorus through burial in pond sediments. This and other recent studies (Song et al. 2015; Song et al. 2017; Song and Burgin 2017) indicate that ponds may experience internal loading as they age and accumulate P. Ortho-P released from sediments into the water column may then be readily exported from ponds to downstream waterbodies during storm events. Our findings suggest that redox dynamics alone cannot account for observed phosphorus release rates from pond sediments, and that an integrated metric of mobile-P (redox-P plus labile organic P) is a better predictor of internal loading risk. This study makes a contribution toward a scientific understanding of how to effectively predict and manage internal phosphorus loading in urban stormwater ponds. Additionally, the problem of internal loading in shallow ponds appears to be considerably more prevalent than previously assumed, in part due to widespread hypolimnetic anoxia despite shallow pond depths. Our findings explore a rationale for assessing internal phosphorus loading risk in urban stormwater ponds (through the assessment of sediment mobile-P) and can ultimately contribute to improved design and maintenance of urban water quality management structures.

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