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TECHNICAL NOTE

Improvement of phosphorus removal in bioretention cells using real-time control

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ABSTRACT

Retrofitting urban watersheds with wireless sensing and control technologies will enable the next generation of autonomous water systems. While many studies have highlighted the benefits of real-time controlled gray infrastructure, few have evaluated real-time controlled green infrastructure. Motivated by a controlled bioretention site where phosphorus is a major runoff pollutant, phosphorus removal was simulated over a range of influent concentrations and storm conditions for three scenarios: a passive, uncontrolled bioretention cell (baseline), a real-time controlled cell (autonomous upgrade), and a cell with soil amendments (passive upgrade). Results suggest the autonomous upgrade matched the pollutant treatment performance of the baseline scenario in half the spatial footprint. The autonomous upgrade also matched the performance of the passive upgrade; suggesting real-time control may provide a 'digital' alternative to existing, passive upgrades. These findings may help site- and cost-constrained stormwater managers meet their water quality goals.

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Bioretention; green infrastructure; phosphorus; real-time control; water quality

Introduction

An emerging generation of autonomous stormwater solutions promises to shrink the size of infrastructure needed to manage runoff pollution and changing weather. Retrofitting stormwater infrastructure with wireless sensors, gates, valves, and pumps will reduce flooding and improve pollutant treatment (Mullapudi, Wong, and Kerkez 2017; Berglund et al. 2020). This will be achieved by dynamically adjusting water levels to take advantage of excess storage and enhanced treatment conditions. At the core of this vision is system-level control, where tens to hundreds of individual stormwater assets will coordinate in real-time to route water and promote the uptake of pollutants across the scale of entire watersheds (Berglund et al. 2020; Eggimann et al. 2017). In lieu of new construction, this will repurpose existing infrastructure by dynamically adapting it on a storm-by-storm basis (Mullapudi, Wong, and Kerkez 2017).

Many studies have highlighted the benefits of autonomous stormwater infrastructure for gray infrastructure, including basins, ponds, and underground infrastructure (Gaborit et al. 2013), but few have explicitly evaluated real-time control of green infrastructure (Persaud et al. 2019; Mason, Mullapudi, and Kerkez 2021). Real-time control of larger and non-biologically active sites, such as detention basins, have shown significant benefits – a valve at the outlet can be used to extend retention time and drastically improve the capture of sediment-bound pollutants (Gaborit et al. 2013; Carpenter et al. 2014). Extrapolating these benefits to green infrastructure, and more specifically bioretention systems, is difficult because pollutant removal is underpinned by much more complex biological and physical processes (Davis et al. 2006). The purpose of this technical note is to begin exploring these processes for phosphorus, a runoff pollutant associated with harmful algal blooms (Michalak et al. 2013), using StormReactor, a new water quality modeling toolchain (Mason, Mullapudi, and Kerkez 2021).

Passive bioretention practices

Bioretention cells have become a popular design in the rapidly growing toolbox of green infrastructure, enabling pervious management in impervious urban areas (Hunt, Davis, and Traver 2012). Examples of bioretention cells include bioswales and rain gardens, which capture and reduce runoff by allowing it to evapotranspire or exfiltrate into surrounding soil. Bioretention cells effectively remove particulate pollutants through sedimentation and filtration by the soil media. However, they often struggle to remove dissolved pollutants, primarily through adsorption, and may even leach (i.e. release) pollutants previously stored in the soil media and vegetation (Hunt, Davis, and Traver 2012; Qiu et al. 2019).

To boost performance, bioretention designers can add soil amendments (organic or inorganic) to improve pollutant treatment (Hunt, Davis, and Traver 2012; Qiu et al. 2019). For example, it is known that the phosphorus sorption capacity can be improved by amending the iron oxide and aluminum oxide contents of the soil inside a bioretention cell (Tirpak et al. 2021). Soil amendments are mixed into the bioretention soil media (5–30% of the total soil volume). Their price is highly dependent on the type of amendment, ranging from free water treatment plant residuals (a by-product of the water treatment plant) to \$16,000 USD/m^3 for iron filings. While soil amendments are excellent at removing specific pollutants, they deplete

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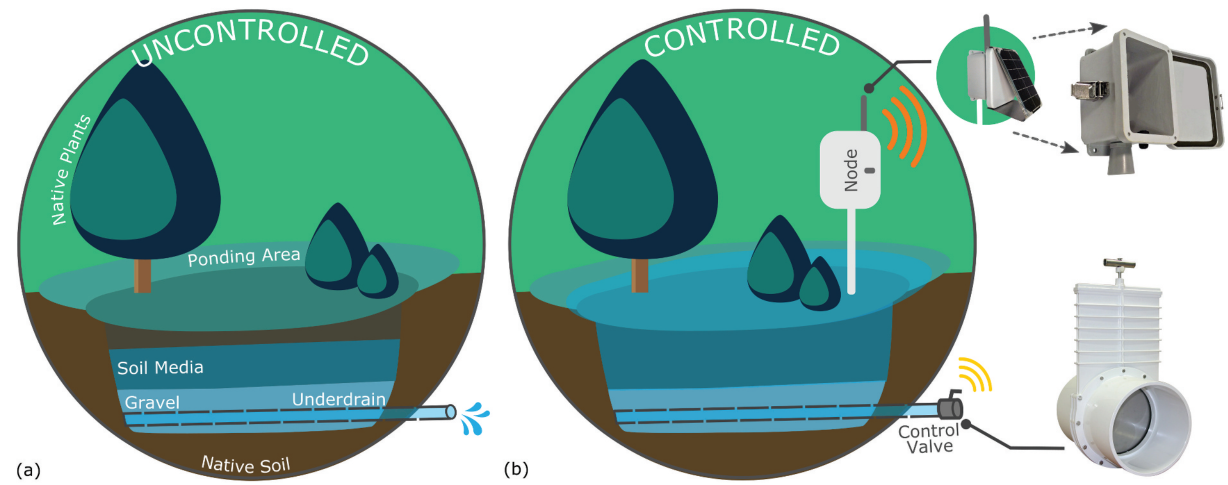

Figure 1. The cross-section of (a) a passive, uncontrolled bioretention cell (i.e., baseline) and (b) a real-time controlled bioretention cell (i.e., autonomous upgrade) with images of the sensor node and control valve installed on a bioretention cell in Toledo, Ohio, US.

over time, provide limited hydrologic benefits, and have limited or no impact on pollutants for which they were not amended (Tirpak et al. 2021). As such, discovering more flexible ways to manage bioretention design constraints is important in meeting the pollutant removal goals of land- and cost-constrained water managers.

Exploring the role of real-time control in boosting bioretention performance

Real-time control of a bioretention cell can be achieved cost effectively by adding an actuated valve and a water level sensor (Figure 1(b)). At the time of writing, a fully automated and internet-connected control system could be constructed for $1,500 USD using open-source solutions. Readers are directed to Bartos, Wong, and Kerkez (2018) and www.open-storm.org for details and best practices on implementation. The opening and closing of this valve allow for many of the trade-offs in existing bioretention designs to be dynamically balanced. Intuitively, this suggests that controlling water levels using a valve would improve infiltration and pollutant treatment due to extended residence times. However, such benefits and their practicality have yet to be quantified outside of a laboratory column study (Persaud et al. 2019).

The objective of this technical note is to compare phosphorus removal in a passive, uncontrolled bioretention cell (i.e., baseline) scenario to two upgraded scenarios: one with real-time control (i.e., autonomous upgrade) and another with water treatment plant residuals (i.e., passive upgrade). The approach ingests laboratory-measured data into a model of bioretention-based phosphorus removal under real-time control. Treatment performance is evaluated across a broad range of influent concentrations and storm conditions. Results suggest real-time control may enable bioretention cells to be built smaller without compromising pollutant treatment performance and may provide a 'digital' alternative to existing, passive upgrades like soil amendments.

Methods

Hydrologic and control model

A bioretention cell at the Toledo Zoo in Toledo, Ohio, US was retrofitted for real-time control (Figure 1). To estimate site performance, a hydrological model was built and calibrated using the hydraulic conductivity rate of the existing site (-~5.1 cm/hr). This site is considered oversized by most US design guidelines, which stipulate that bioretention cells should generally capture the runoff of no more than 8,094 m^2 (2-acres), and that the surface area of a cell should be 5–10% of this contributing impervious area (Mathews 2006). Therefore, the hydrological model assumed a contributing impervious area of 4,047 m^2 (1-acre) and cell surface area of 405 m^2 (0.1-acre).

The hydrologic model was built using the U.S. EPA's Stormwater Management Model (SWMM), a physically-based, discrete-time, storm-runoff simulation model (Rossman 2015). While recent updates to SWMM feature a tool for modeling green infrastructure, the tool does not include the ability to dynamically control the flow through the underdrain. To circumvent this issue, the bioretention hydrologic model was built following the methodology vetted by Lucas (2010), which represents the individual components of the cell (i.e., ponding area, soil media, gravel storage, underdrain, and surrounding soil) using SWMM junctions, conduits, orifices, outlets, weirs, and outfalls (Figure 2).

A level controller was designed as an initial step in exploring bioretention control. The controller released water from the underdrain at a rate proportional to the cell's ponding height (i.e., the deeper the ponding height, the larger the valve opening). Specifically, the controller sets the underdrain's valve to a position between closed (0%) and open (100%) based on the following formula: $valve\_position = 10\% \times ponding\_height$. Control decisions were made once every 15 minutes, as implemented in the field. The controller promotes improved hydrologic conditions and, by extension, improved pollutant removal. Readers can access the simulation documentation from the GitHub online repository (github.com/bemason/RTC_GreenInfrastructure).

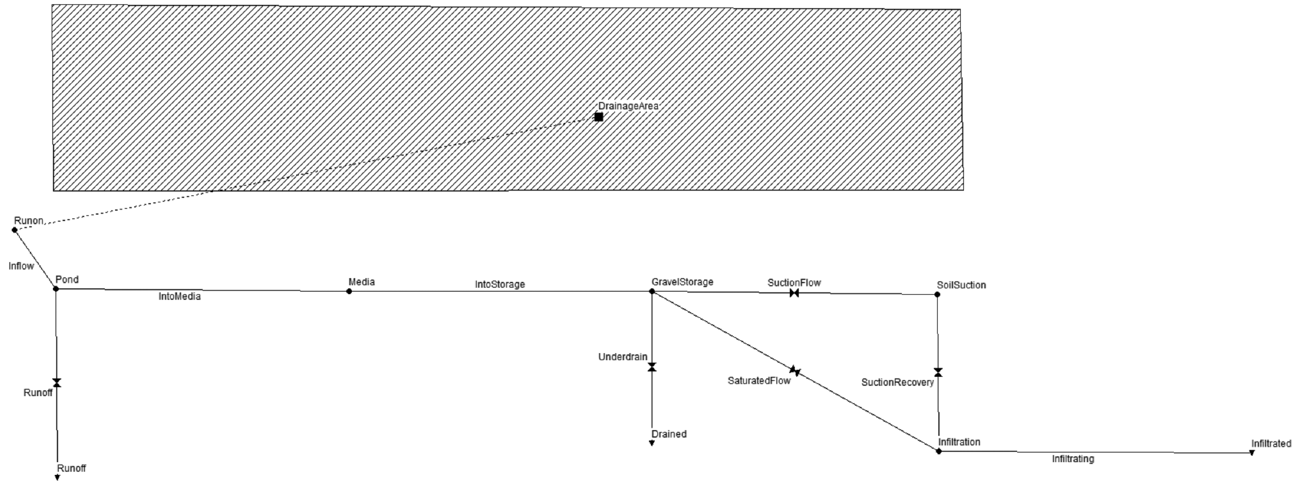

Figure 2. A bioretention cell hydrologic model was built following the methodology vetted by Lucas (2010), which represents the individual components of the cell (i.e., ponding area, soil media, gravel storage, underdrain, and surrounding native soil) using SWMM junctions, conduits, orifices, outlets, weirs, and outfalls. An orifice is used to simulate a controllable valve on the underdrain.

Phosphorus model

Although SWMM has the ability to model nutrient removal, it is limited to percent removal and first order dynamics (Rossman 2016), which cannot effectively represent the complex nutrient interactions triggered by real time control (Mullapudi, Wong, and Kerkez 2017). Therefore, a phosphorus model was added as a new custom pollutant model to the open-source Python package *StormReactor* (Mason, Mullapudi, and Kerkez 2021). *StormReactor* provides a high-level programming interface for users to model pollutant transformations while leveraging the flow and routing functionality of SWMM. *StormReactor* provides the ability to model complex pollutant transformations (e.g., higher order reaction kinetics, wastewater process models, differential equations). Readers can access the source code and documentation from the GitHub online repository (github.com/kLabUM/StormReactor).

Li and Davis's (2016) phosphorus model was implemented, which represents a bioretention cell as a plug flow reactor and one-dimensional adsorption column (Figure 3). The model allows for advective flow in and out of a horizontal differential element of the soil media and considers filtration, adsorption, and leaching reactions. The mass balances for the reactor are shown for the particulate and dissolved phosphorus concentrations (C_{PP},C_{DP}) in Equations 1 and 2, respectively (Figure 3).

The water quality model parameters were experimentally derived and calibrated by Li and Davis (2016). In the baseline and autonomous scenarios, these parameters assume the cell's soil media consists of 74% bioretention soil media, 22% additional sand, and 3% mulch, on an air-dry mass basis. In the passive upgrade scenario, 5% of the bioretention soil media was replaced with water treatment plant residuals (O'Neill and Davis 2012).

Control performance evaluation

As discussed, bioretention cells can be upgraded in a variety of ways to boost performance. An analysis was performed to compare phosphorus removal in a passive, uncontrolled bioretention cell (baseline) scenario to two upgraded scenarios: one with real-time control (autonomous upgrade) and another with water treatment plant residual soil amendments (passive upgrade). To capture the wide range of conditions a bioretention cell may experience, the scenarios were evaluated under a variety of influent concentrations and design storms. Five total phosphorus influent concentrations (0.2, 0.6, 1.0, 1.4, and 1.8 mg/L) were selected based on literature values for commercial, residential, and agricultural settings (Liu et al. 2015). Since dissolved and particulate phosphorus removal are independent of each other, equal amounts of each were used in the evaluation (for 0.2 mg/L of total phosphorus, 0.1 mg/L of both dissolved and particulate phosphorus were used). Three 6-hour Soil Conservation Service (SCS) Type II design storms were evaluated as conventional in the green infrastructure community: 12.7 mm (0.5 in), 25.4 mm (1.0 in), and 50.8 mm (2.0 in) (Rossman 2010).

In addition, a simulation using rain data from the wet summer of 2015 in Toledo, OH, US was used to evaluate performance under real, dynamic weather conditions for the same three scenarios described above. The weather data selected includes several consecutive storms, dry periods, as well as large and small storms. The total phosphorus influent concentration was assumed to be 0.38 mg/L, the average concentration for all US land use types according to the US National Stormwater Quality Database (Pitt, Maestre, and Clary 2018).

Results and discussion

Comparative analysis

The results of the comparative analysis are shown in Figure 4. Illustrated are various permutations of design storms (x-axis) and influent concentration (y-axis) across multiple scenarios: baseline (a), autonomous upgrade (b), and passive upgrade (c). For each simulation, the total phosphorus load (flow times concentration) was computed for the flows entering the bioretention cell, exiting through the underdrain, exfiltrating into the surrounding soil, and overflowing when the ponding

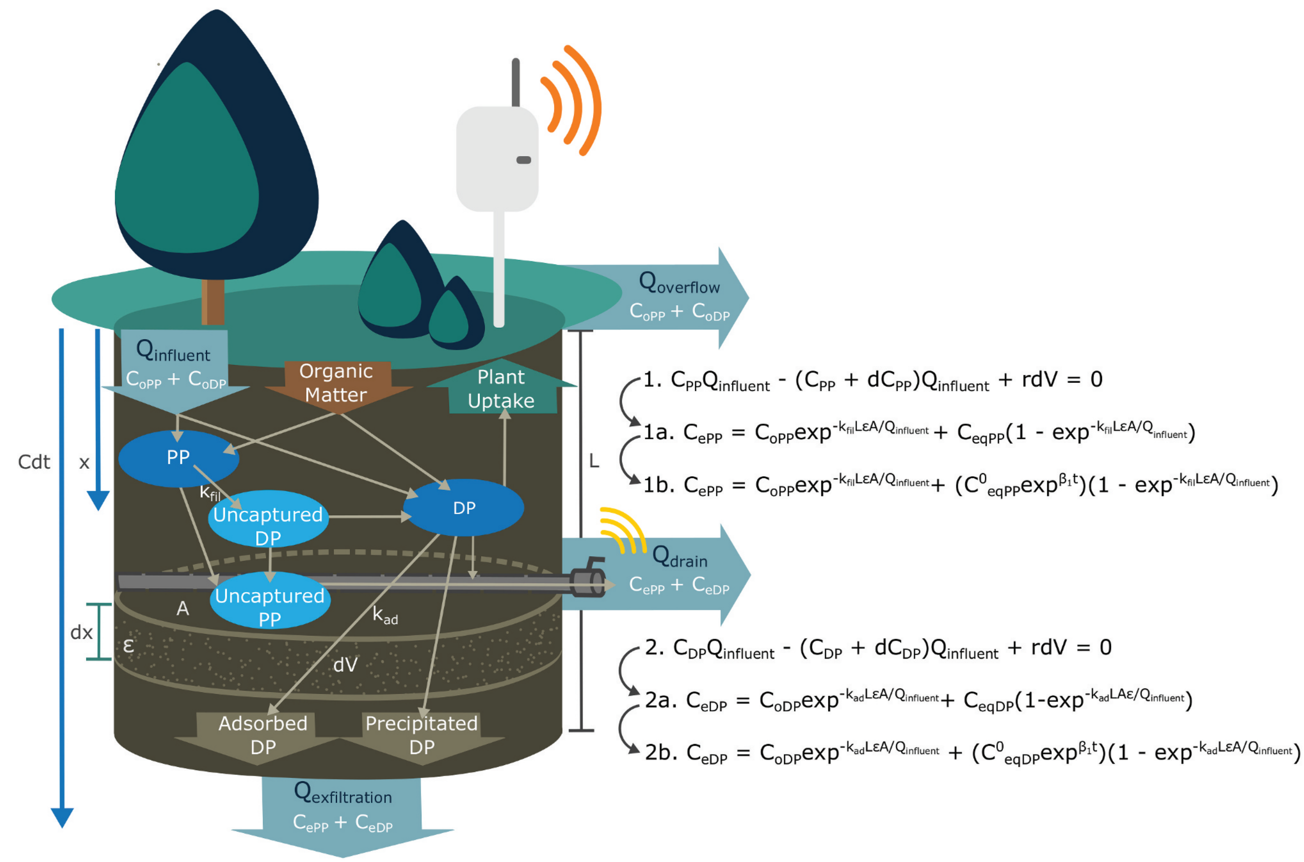

Figure 3. On the left, a controllable bioretention cell modeled as a plug flow reactor showing the dissolved (*DP*) and particulate phosphorus (*PP*) transformations in the soil. The model represents the flow rate (*Q*) through a differential element (*dx*). The pollutant's concentration (*C*) changes as it moves through the length (*L*) of the reactor. The area (*A*), porosity (*ε*), and *Q* determine infiltration. On the right, the mass balance equations. To create Eq. 1a and 2a, the variables were separated and integrated over *L* and the change in concentration (C_o to C_e); and the adsorption and filtration rate constants (k_{ad},k_{fil}) were substituted in for the reaction rates (*r*). To create Eq. 1b and 2b, $C^0_{eq}exp^{\beta_1 t}$ was substituted in for the equilibrium concentration (C_{eq}) to account for the variability in C_{eq} over the lifetime of the soil; where C^0_{eq} is the initial C_{eq} for a storm event, β_1 is a constant describing the rate at which C_{eq} approaches C_o, and *t* is the cumulative time elapsed from the start of a storm event.

height was exceeded. A mass balance of these loads then determined the final value (i.e. color) used in the figure. The figure colors indicate if the overall mass balance resulted in phosphorus capture (blue) or release (red). The black line indicates the transition from phosphorus capture to release.

The baseline scenario released phosphorus during the low influent simulations and removed phosphorus during the high influent simulations (Figure 4(a)). The equilibrium concentration essentially defines the point separating removal from release. When the influent concentration is larger than the equilibrium concentration, removal occurs, otherwise, desorption of the pollutant occurs, resulting in a net increase in the pollutant concentration (Li and Davis 2016).

The autonomous upgrade captured phosphorus during most simulations (Figure 4(b)). During the smaller storms, the controlled underdrain remained closed for most of the simulation, resulting in little to no phosphorus being released. The transition from phosphorus capture to release occurred during the larger storms with lower influent concentrations. Akin to the baseline, this was due to the system trying to reach the equilibrium concentration.

The autonomous upgrade outperformed the baseline scenario (Figure 4(a,b)), aligning with the results of the real-time controlled bioretention column study by Persaud et al. (2019). Since the autonomous upgrade released at least two times less phosphorus load than the baseline during all design storms, the autonomous upgrade could match the pollutant treatment performance of the baseline in half the spatial footprint. This result aligns with other research that has shown that real-time controlled stormwater infrastructure can be built smaller without compromising performance (Mullapudi, Wong, and Kerkez 2017; Mason, Mullapudi, and Kerkez 2021).

The passive upgrade resulted in phosphorus capture for all design storms and influent concentrations (Figure 4(c)). By design, soil amendments have high reaction rate constants and a low equilibrium concentration. Both factors worked together to ensure the cell's phosphorus concentration remained low. Therefore, even though water left the unregulated underdrain, the load released was relatively small.

Although the modeled soil amendments were successful at treating phosphorus, they have several drawbacks. Their efficacy will inevitably deplete over time, requiring the installation of new amendments. Soil amendments are targeted pollutant solutions; they have limited or no impact on other pollutants (Tirpak et al. 2021). Similarly, they do not provide hydrologic benefits, and may even reduce hydraulic conductivity (Ament et al. 2021). Although the water treatment residual amendments are a free by-product from the water treatment plant, there is a cost to excavating and reinstalling the amended soil. For the modeled site at the time of writing, the installation of

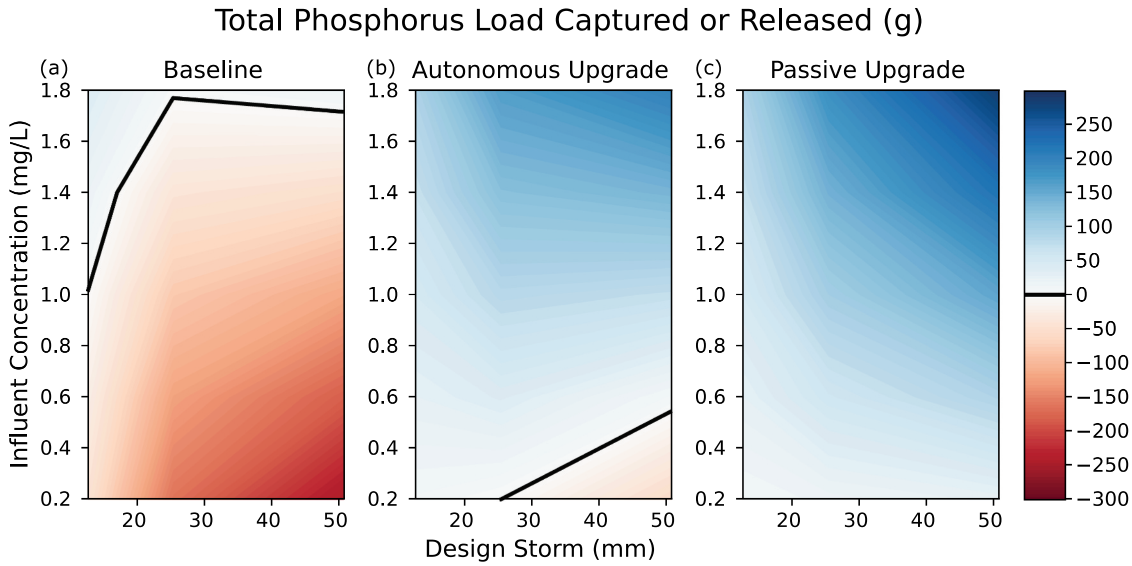

Figure 4. Total phosphorus in grams either captured or released by a bioretention cell over various storm sizes (x-axis) and influent concentrations (y-axis) for the baseline (a), autonomous upgrade (b), and passive upgrade (c) scenarios. The black lines denote a shift from capturing (blue) to releasing (red) phosphorus.

the passive upgrade would cost an estimated $4,800 USD (MPCA 2021). There would be additional costs for monitoring and maintenance but calculating these costs are outside of the scope of this technical note.

Real-time control pushed the autonomous upgrade to perform similarly to the passive upgrade (Figure 4(b,c). The performance was essentially equivalent during the smallest design storm, but the autonomous upgrade released up to seven times more phosphorus load during the larger two storms. By analogy, real-time control enables a bioretention cell to perform as if it has been 'digitally' upgraded to achieve benefits of passive soil amendments. By controlling the flow through the underdrain the system is forced to mimic the pollutant treatment of the passive upgrade. The removal mechanism, however, is different for the autonomous upgrade. Removal is primarily through volume reduction rather than adsorption and filtration. By exfiltrating water and phosphorus, the volume of water leaving the site is reduced, thus also diminishing potential adverse impacts on downstream waterways.

The autonomous upgrade can be used to address a variety of pollutants (e.g., phosphorus, metals, solids) through volume reduction, while the passive upgrade only targets one pollutant through adsorption and filtration. Therefore, the autonomous upgrade provides long-term management flexibility by enabling the cell to be 'reprogrammed' to tailor retention times whenever a new pollutant needs to be treated, or when knowledge of the site's dynamics change. This flexibility is even more pronounced when considering system-level control. Stormwater managers can coordinate a network of autonomously upgraded sites, allowing them to decide where and how pollutants are treated to meet system-level water quality goals (Wong and Kerkez 2018). In addition, the autonomous upgrade is cost-effective ($1,500 USD including parts and installation at the time of writing). That being said, since real-time control is not readily offered as a commercial solution, it is still difficult to project this cost into a future commercial market. Like the passive upgrade, there may be additional costs for monitoring and maintaining the site that are outside of the scope of this technical note.

Dynamic storm analysis

In the previous section, phosphorus removal was evaluated using design storms to better understand performance across the wide range of conditions a bioretention cell may experience. A dynamic storm simulation was carried out to evaluate performance using local, measured storm data. The three scenarios received the same cumulative influent load (5.9 g) (Figure 5(a,d,g)). The differences, however, occur when comparing the cumulative released and captured loads. The cumulative load released from the underdrain (no overflow/runoff occurred) was 7.7 g and 7.1 g for the baseline and passive upgrade scenarios, respectively (Figure 5(h)). These results suggest the baseline and passive upgrades leached phosphorus previously captured in the soil (Figure 5(i)). Leaching is attributed to the wetting/drying cycle in the bioretention soil media. When dried soil is wetted, the phosphorus concentration initially increases as previously captured phosphorus is washed and eluted from the soil media (Li and Davis 2016). The higher phosphorus concentration combined with the larger volumes of water leaving their underdrains (Figure Fb) resulted in net export of phosphorus (Figure 5(e)). The autonomous upgrade also exhibited higher phosphorus concentrations at the start of each storm (due to the wet-dry cycle) but only a fraction of water was released from the underdrain and the rest was exfiltrated (Figure 5(b,c)). This is why the autonomous upgrade captured 5.4 g and released 0.6 g, about twelve times less phosphorus load than the uncontrolled cells (Figure 5(h,i)).

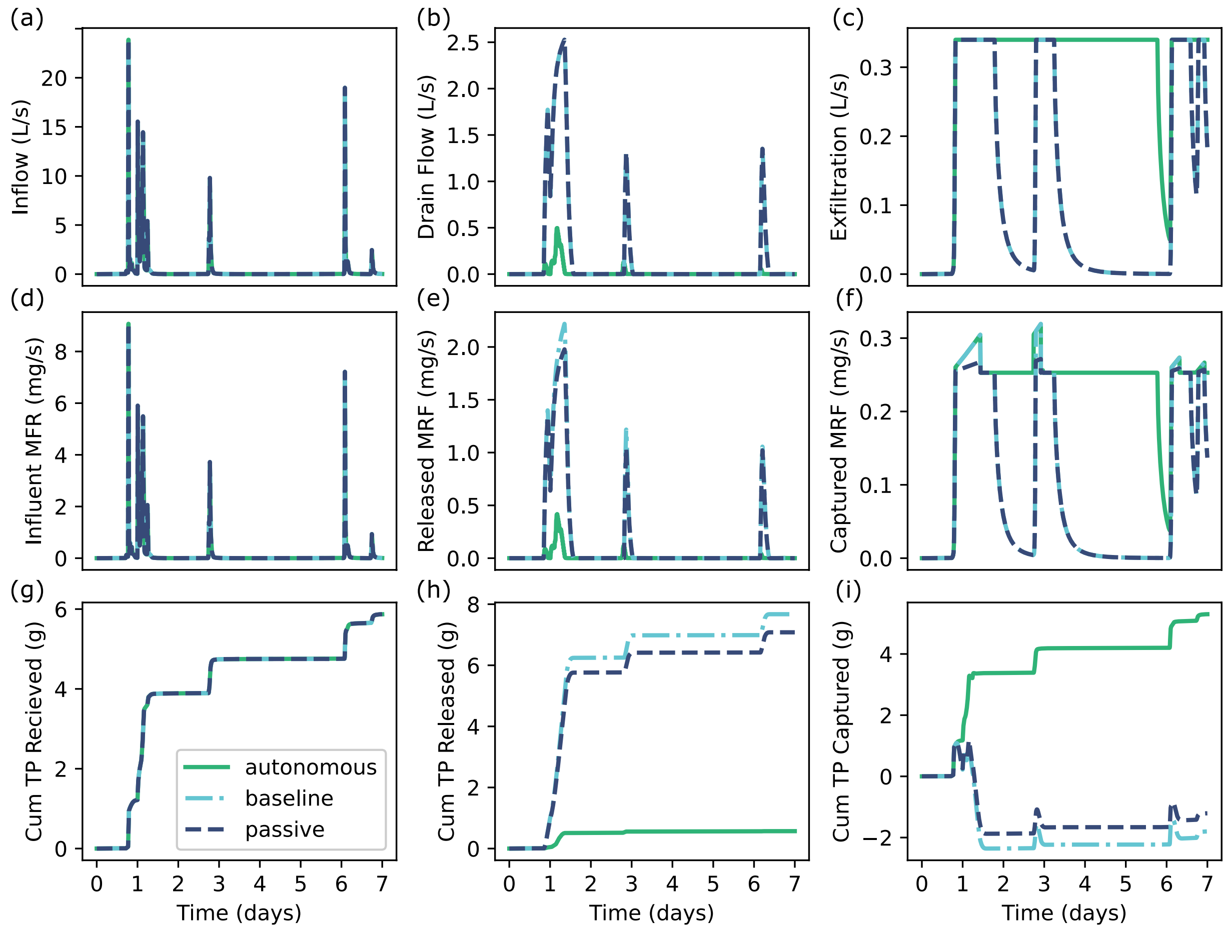

Figure 5. Dynamic storm simulation results showing the inflow (a), drain flow (b), and exfiltration (c) rates; influent (d), released (f), and captured (f) mass flow rates (MFR); and cumulative total phosphorus (TP) load in grams received (g), released (h), and captured (i) for the baseline (light blue), autonomous upgrade (green), and passive upgrade (dark blue) scenarios.

Conclusions

This short technical note explored the early potential of real-time controlled bioretention cells. Using a controlled bioretention cell as motivation, phosphorus removal was simulated for a variety of influent concentrations and storm conditions. Three scenarios were evaluated including the baseline, autonomous upgrade, and passive upgrade. Both the autonomous and passive upgrades improved pollutant removal. Future work should evaluate the benefits of a combined autonomous-passive upgrade and more mathematically complex control algorithms.

The autonomous upgrade was shown to release at least two times less phosphorus load than the baseline during all design storm simulations. Therefore, the autonomous upgrade matched the pollutant treatment performance of the baseline in half the spatial footprint for the system studied here. These findings need to be generalized but may stand to benefit stormwater managers who often cannot design retention systems to the recommended size due to site or cost constraints.

Water quality goals (e.g., phosphorus removal) can be achieved by adding real-time control as illustrated in both the design storm and dynamic storm analyses. Not only does real-time control potentially provide a 'digital' alternative to existing, passive upgrades, like soil amendments, but it also provides long-term management flexibility. This flexibility enables stormwater managers to dynamically balance trade-offs in existing bioretention designs and aids in the larger goal of system-level control. A real-world experiment is necessary to validate these findings in-situ.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data Availability Statement

The data that support the findings of this study are opening available in bemason/RTC_GreenInfrastructure at http://doi.org/10.5281/zenodo.5006910.

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